جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

What Should 6G Be ?

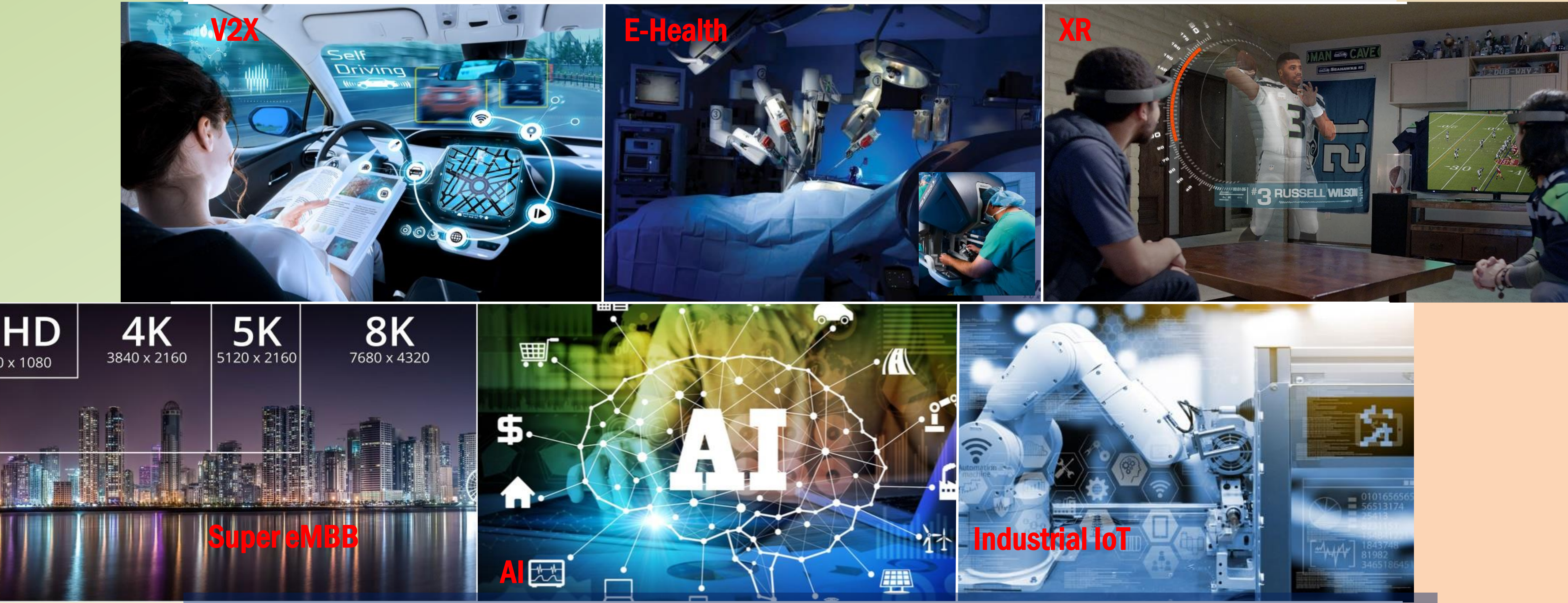
Mohamed-Slim Alouini

Communication Theory Lab. @ KAUST

http://ctl.kaust.edu.sa

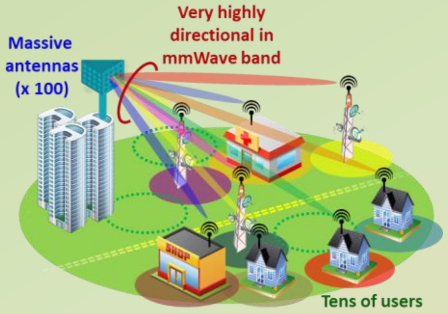
جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

6G is Coming

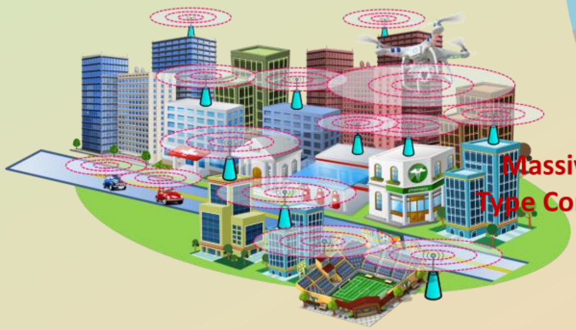


S. Dang, O. Amin, B. Shihada, & M. –S. Alouini, “What Should 6G Be?”, Nature Electronics, January 2020

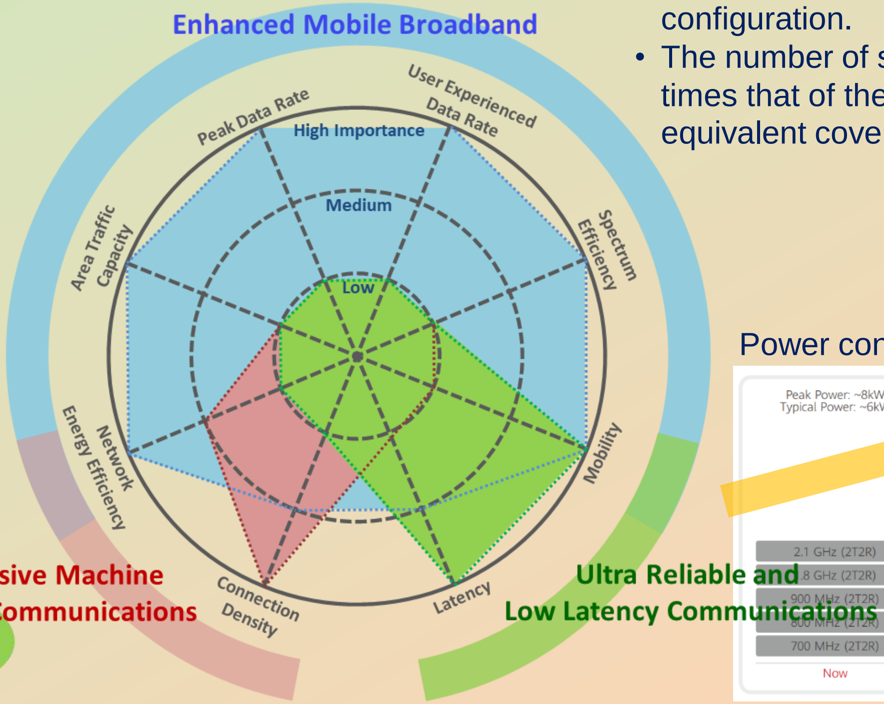
Power Consumption Concern



- Massive antenna arrays and beamforming
- mmWave band

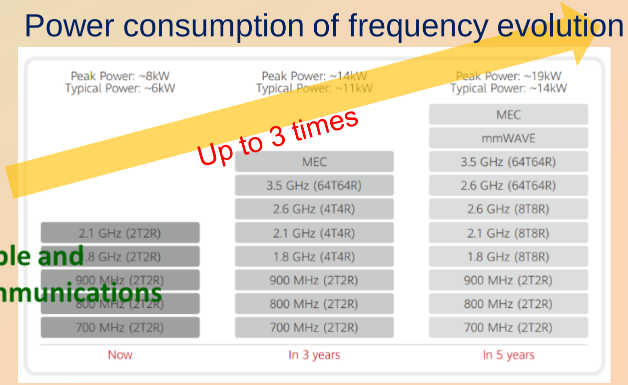


- Densification of 5G sites
- Massive connection of IoT devices



- Power consumption of 5G equipment in some bands is up 3 times of 4G with the same configuration.
- The number of sites is expected to be 2 to 3 times that of the 4G era in order to achieve 4G equivalent coverage.

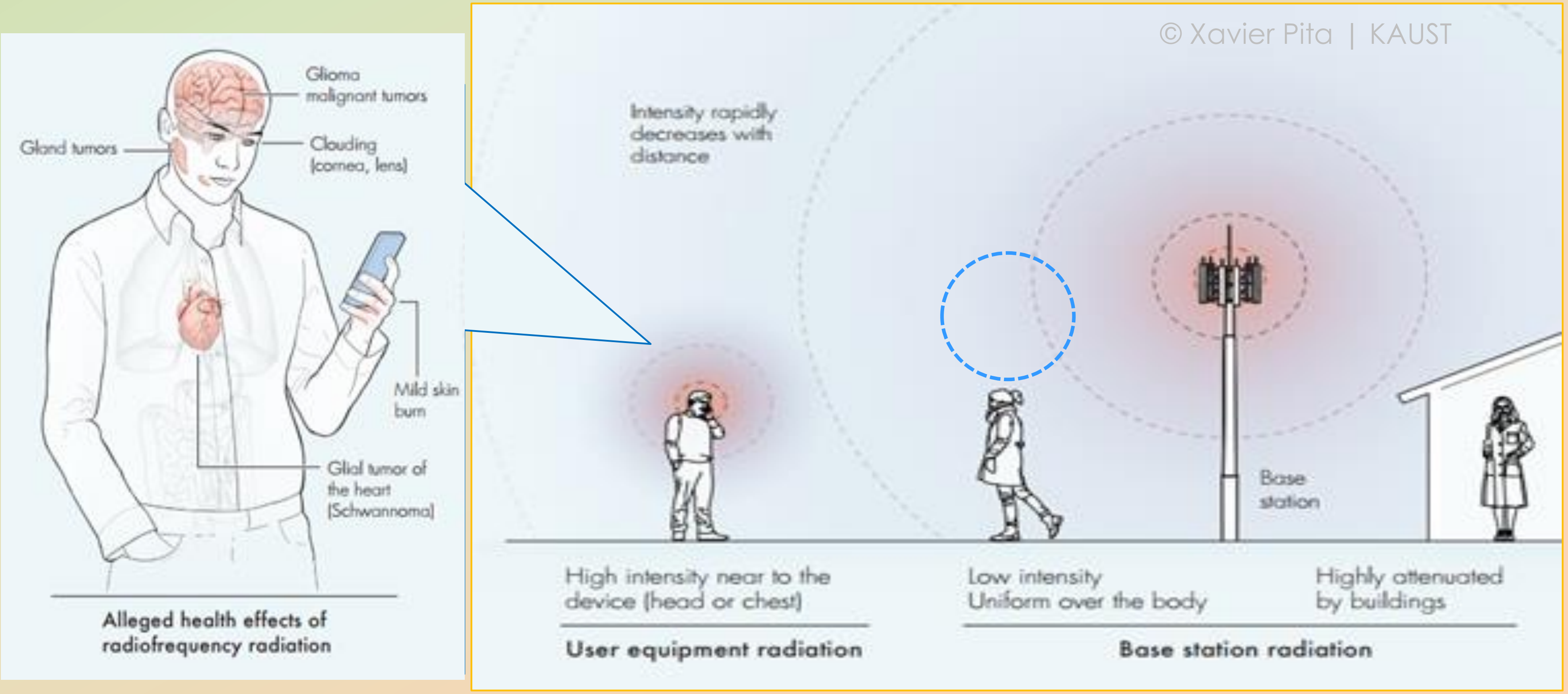
Power consumption of frequency evolution



C. L. I., S. Han, and S. Bian, “Energy-efficient 5G for a greener future”, *Nature Electronics*, April 2020.
Huawei White Paper, “5G telecom power target network,” *5th Global ICT Energy Efficiency Summit*, https://carrier.huawei.com/~/media/CNBGV2/download/products/network-energy/5G-Telecom-Energy-Target-Network-White-Paper.pdf

EMF Radiation Concern

- Concern on electromagnetic field exposure
  - Potential health risks associated with the extra RF emissions from 5G base stations

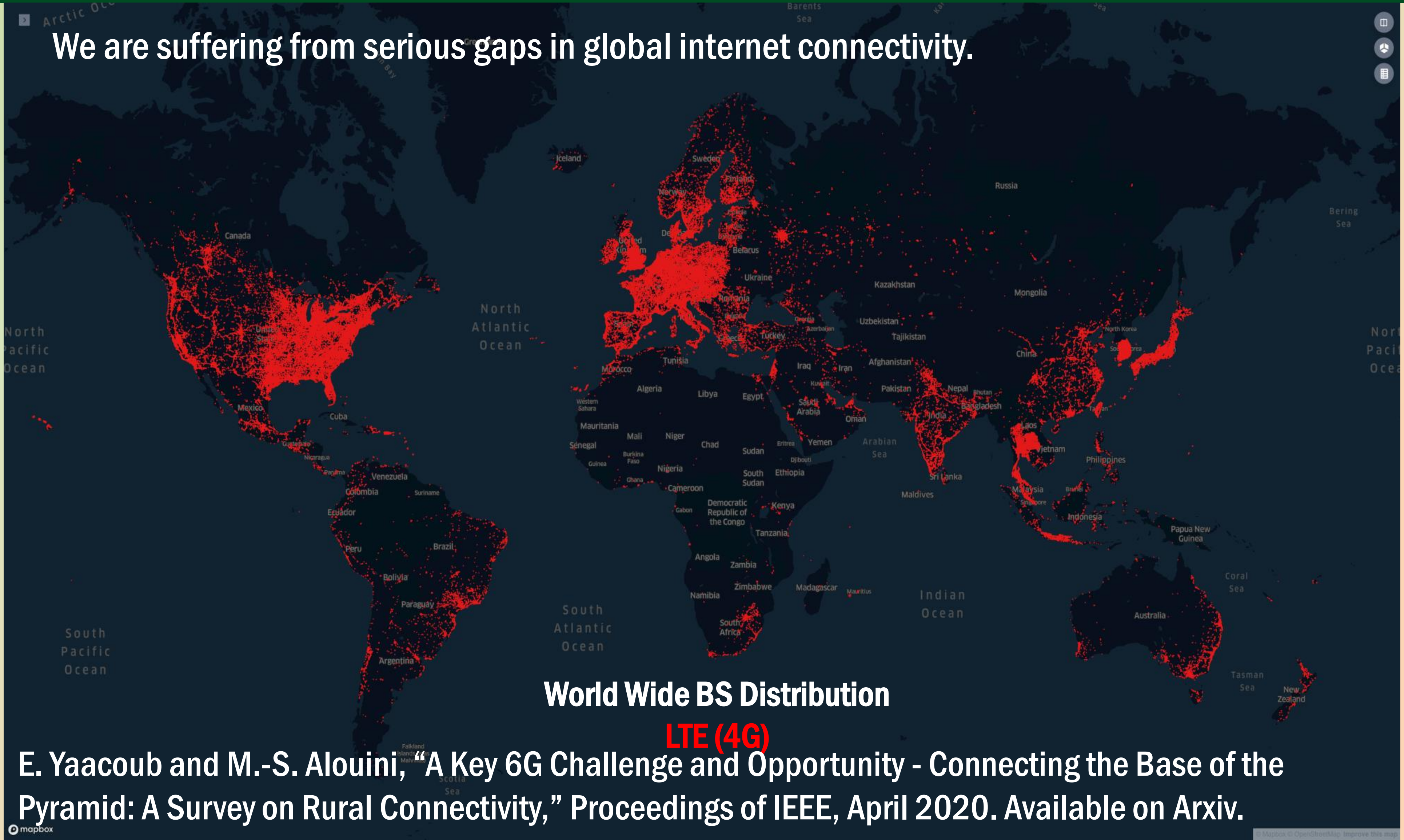


L. Chiaraviglio, A. Elzanaty, and M.-S. Alouini, "Health risks associated with 5G exposure: A view from the communications engineering perspective ", IEEE Open Journal of Communication Society, 2021. Available on Arxiv: https://arxiv.org/pdf/2006.00944.pdf

The Global Connectivity Divide

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

We are suffering from serious gaps in global internet connectivity.



World Wide BS Distribution

LTE (4G)

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, April 2020. Available on Arxiv.

Sustainability Development Goals (SDGs)

- **In 2016, the United Nations (UN) released 17 Sustainability Development Goals (SDGs) for the 2030 Agenda**

SDGs & 6G

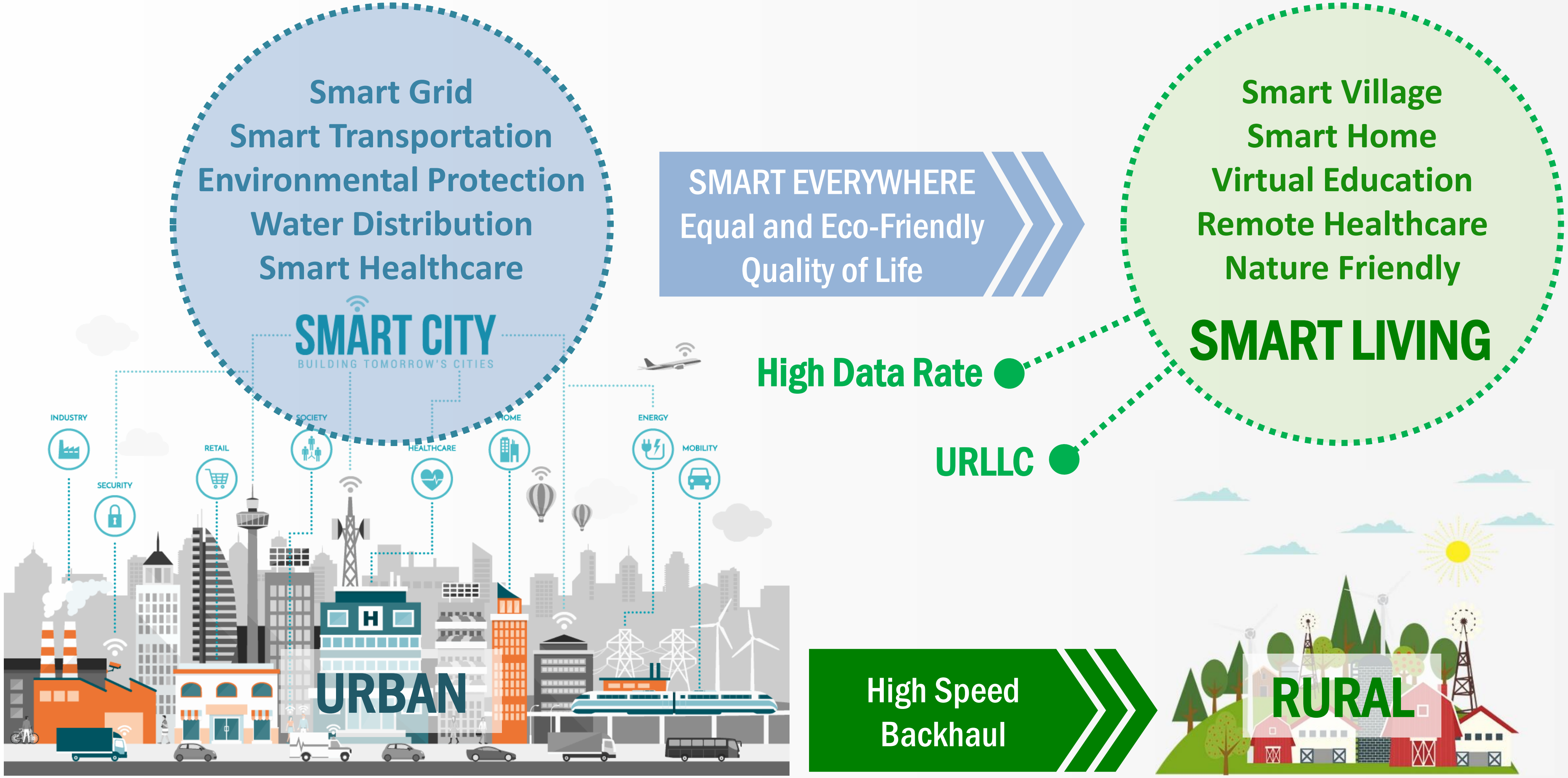
- The UN SDGs should drive the evolution of 6G
- 6G should target:
  - Improved Energy Efficiency
  - No Bad Effects on Environment & Human Health
  - Digital Inclusion
  - More Security and Privacy
  - Resilience, Robustness, and Dependability

Bridging Connectivity Divide

- **Cooperation needed to bring reliable internet to those without it**

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, April 2020. Available at https://arxiv.org/abs/1906.11541

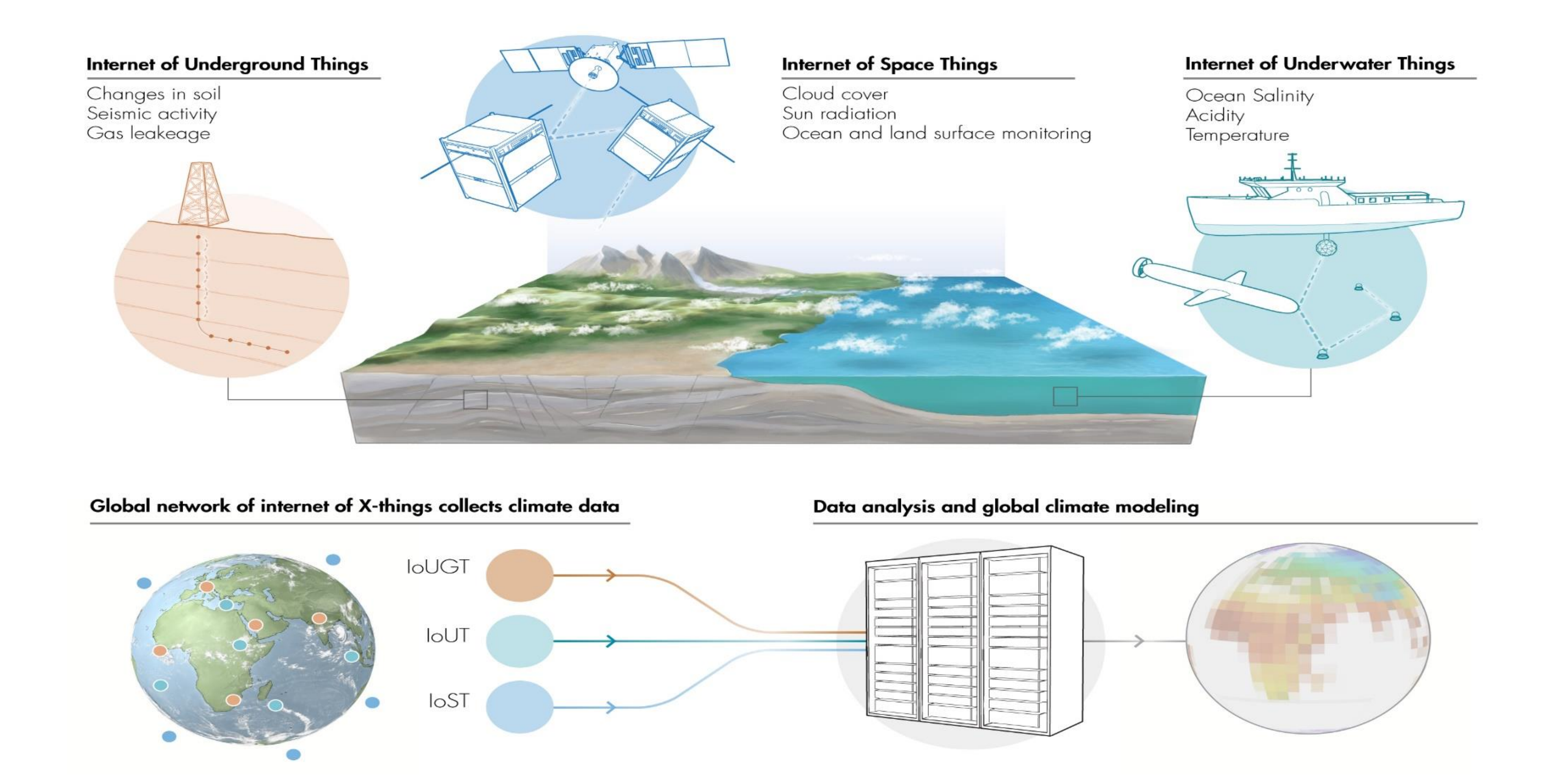
From Smart Cities to Smart Living



E. Yaacoub and M.-S. Alouini, "Efficient Front-haul and Back-haul Connectivity for IoT Traffic in Rural Areas," IEEE IoT Magazine , March 2021 (Available on TechRxiv)

Resilience with On-Demand Pop-up Networks

Climate Monitoring Using Internet of X-Things



[1] N. Saeed, A. Celik, T. Al-Naffouri, and M. -S. Alouini, "Underwater optical wireless communications, networking, and localization: A survey", Elsevier Adhoc Networks, 2019.

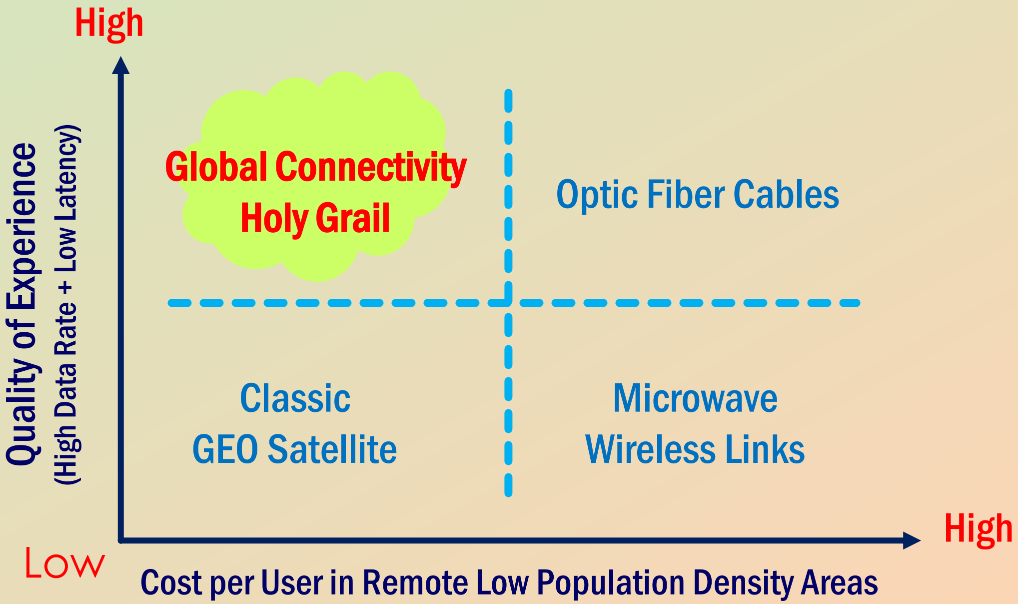
[2] N. Saeed, T. Al-Naffouri, and M. -S. Alouini, "Towards the Internet of underground things: A systematic survey", IEEE Communications Surveys and Tutorials, 2019.

[3] N. Saeed, A. Elzanaty, H. Almorad, H. Dahrouj, T. Y. Al-Naffouri, M -S. Alouini, "CubeSat communications: Recent advances and future challenges", IEEE Com Surveys and Tutorials 2020

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

Backhaul Challenge

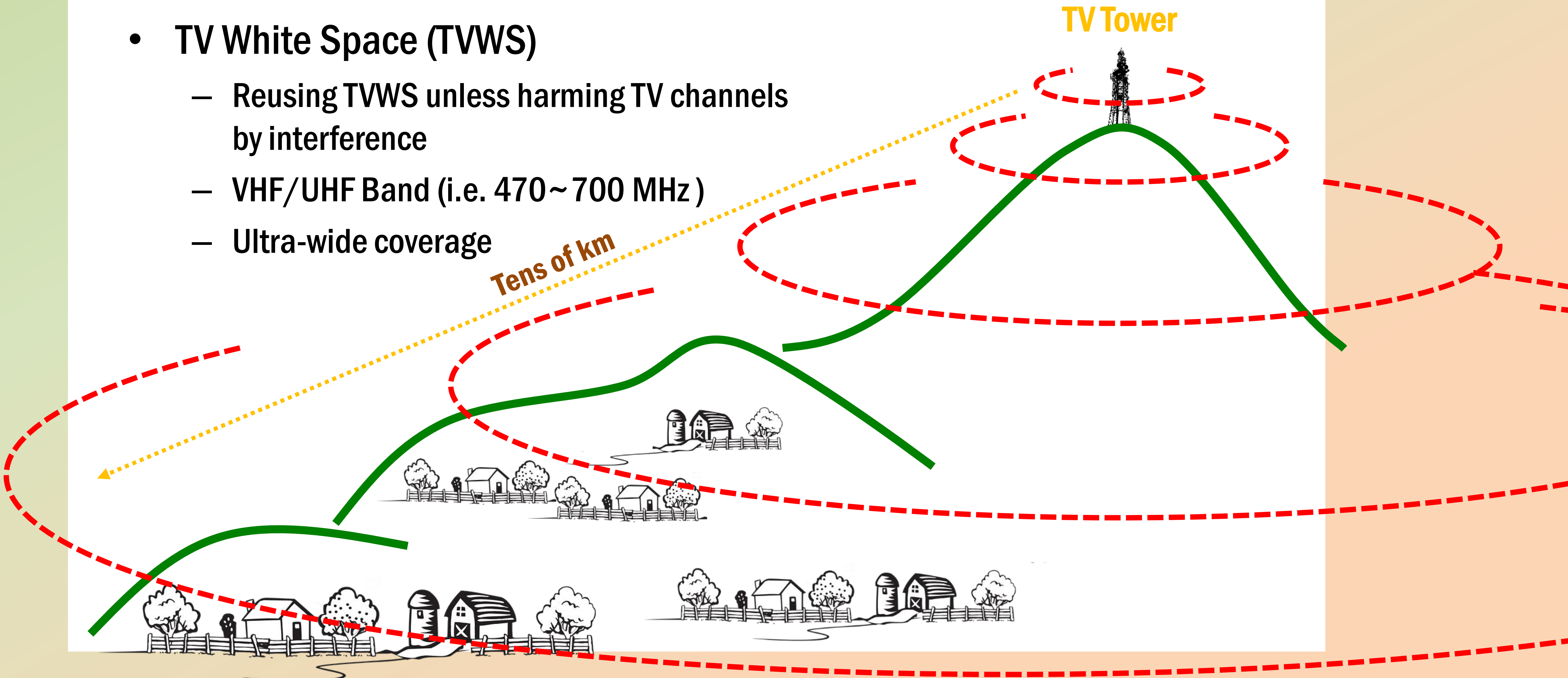
Global Connectivity Holy Grail



"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*

Existing TV Infrastructure

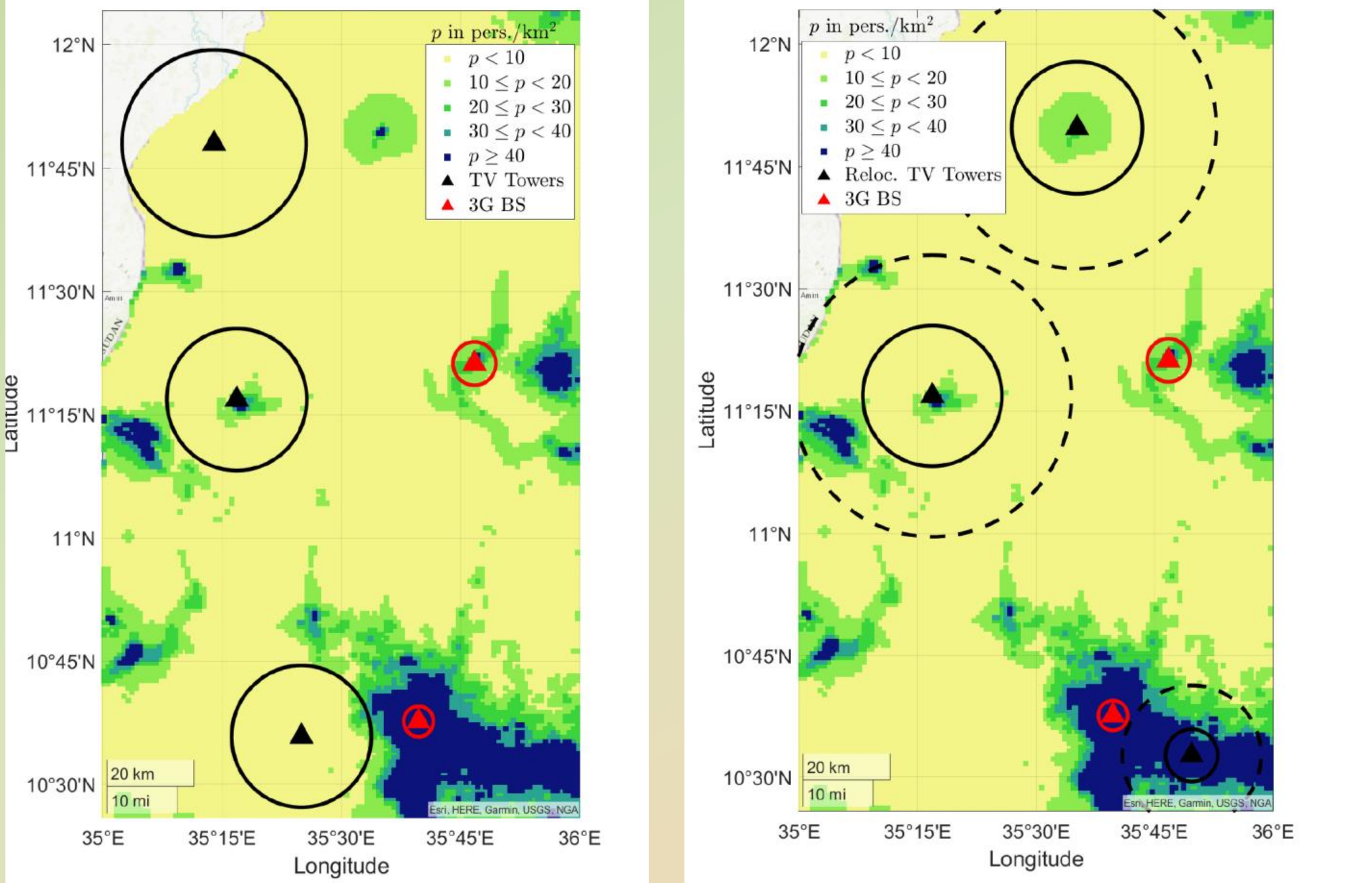
- TV White Space (TVWS)
  - Reusing TVWS unless harming TV channels by interference
  - VHF/UHF Band (i.e. 470~700 MHz)
  - Ultra-wide coverage



A. El Falou and M. -S. Alouini, "Enhancement of Rural Connectivity by Recycling TV Towers with Massive MIMO Techniques", IEEE Communication Magazine 2023.

Recycling TV Towers with Massive MIMO Techniques

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology



(a) Current TV towers (b) Relocated towers

- **Observations:**
  - ❑ A large part of the considered area is not covered by any 3G BS.
  - ❑ Legacy BSs are located in some places with high population densities.
  - ❑ 4G BSs are not available in the considered area.
  - ❑ Some TV towers are available in the considered area

- **Observations:**
  - ❑ Only 9,000 persons out of the total population of 200, 000 is covered (4.5%)
  - ❑ 19,500 more persons can be covered (14.25%)
  - ❑ Number of covered persons can be increased to 30,000 (19.5%)

A. El Falou and M. -S. Alouini, "Enhancement of Rural Connectivity by Recycling TV Towers with Massive MIMO Techniques", IEEE Communication Magazine 2023.

Tethered Balloons/Airships/Aerostats

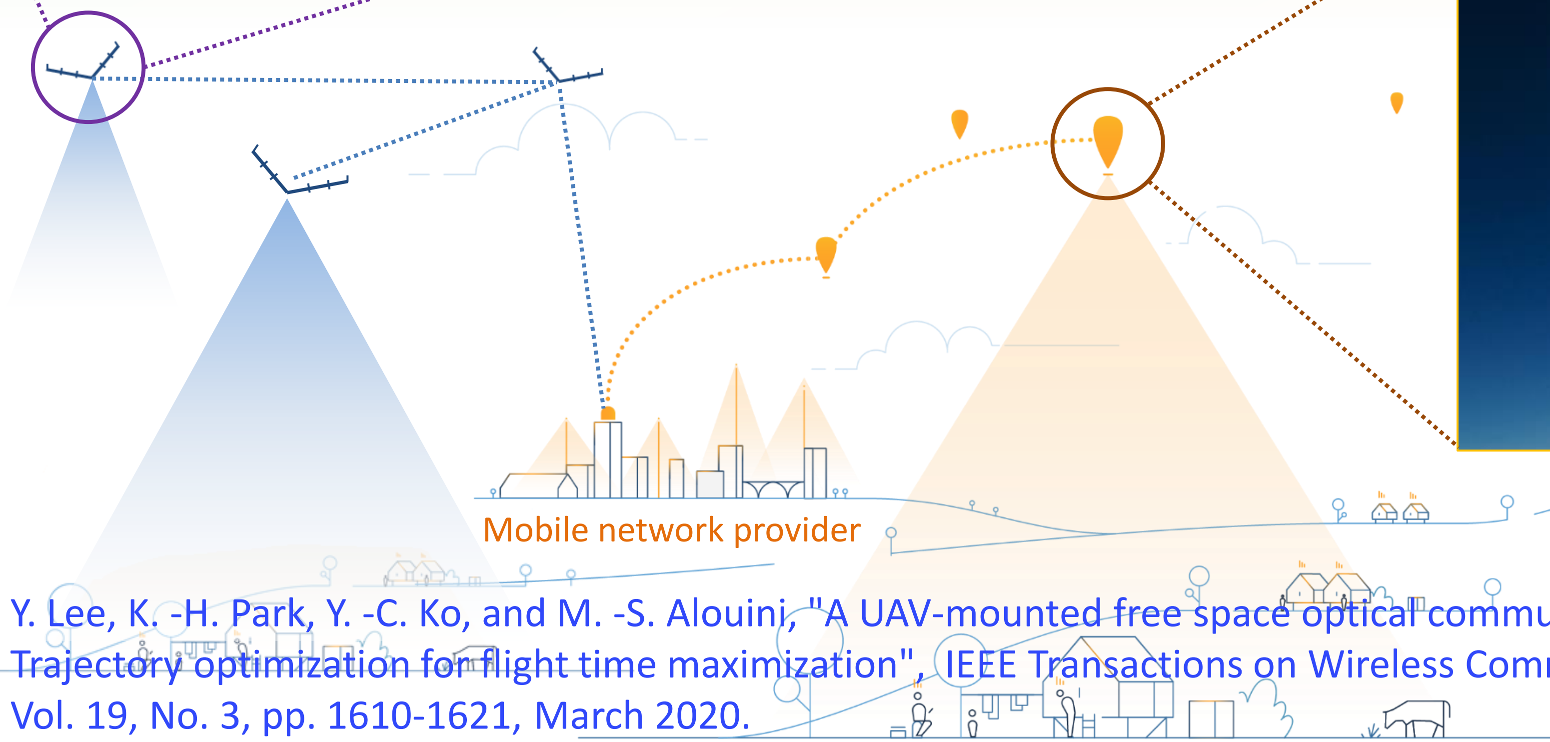
T. Staedter, "Soaring 'Super Towers' Aim to Bring Mobile Broadband to Rural Areas," IEEE. Spectrum, April 2018.

B.E.Y. Belmekki and M.-S. Alouini, "Unleashing the Potential of Tethered Networked Flying Platforms: Prospects, Challenges, and Applications," IEEE Open Journal of Vehicular Technology, 2022.

High Altitude Platform Stations (HAPS)

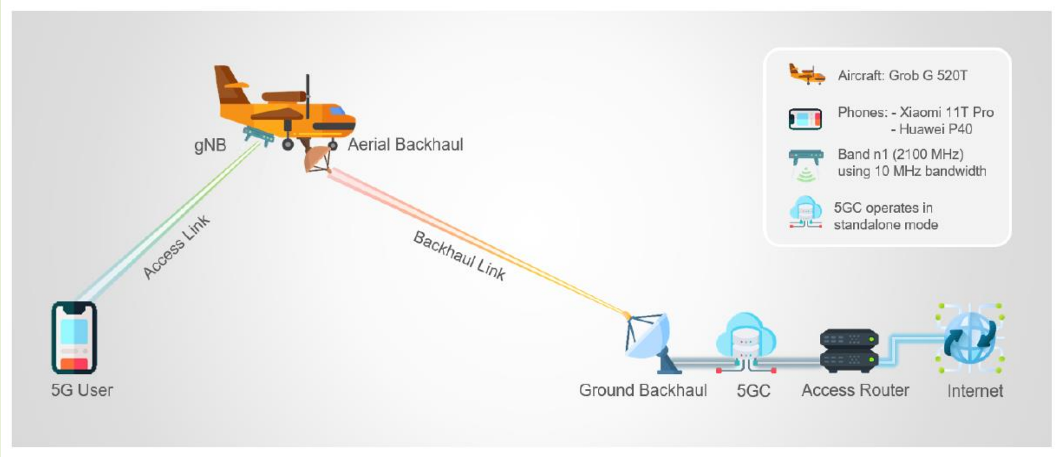
"Tower-in-the-air"

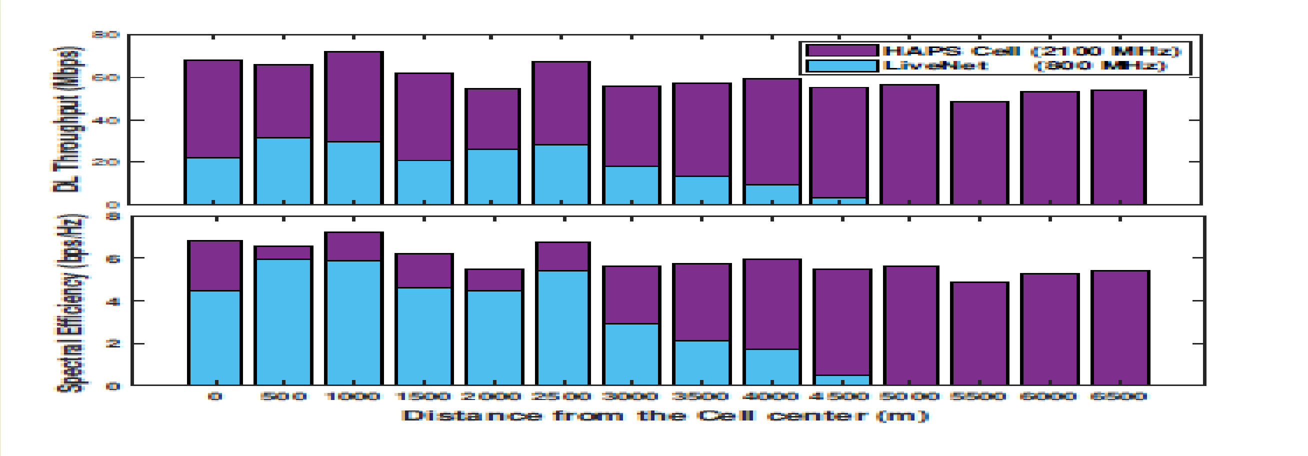
- Solar-powered swarm of HAPs in the backbone network at a height of 18-28 km

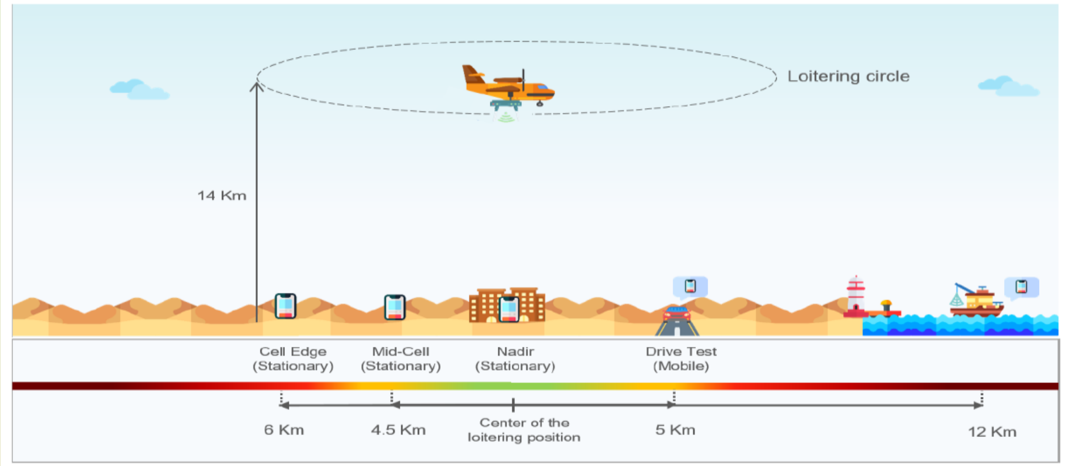


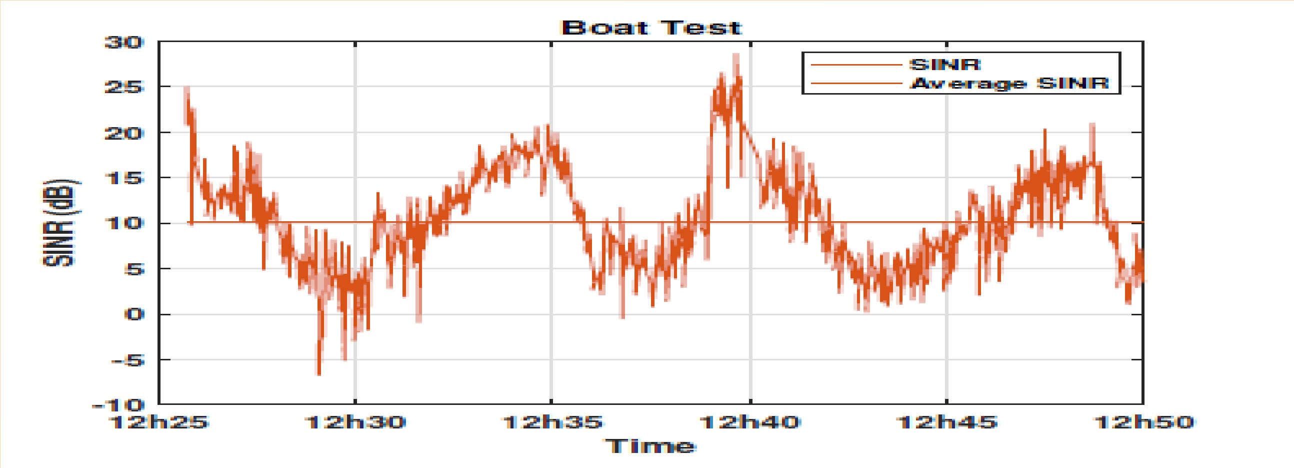
Y. Lee, K. -H. Park, Y. -C. Ko, and M. -S. Alouini, "A UAV-mounted free space optical communication: Trajectory optimization for flight time maximization", IEEE Transactions on Wireless Communications, Vol. 19, No. 3, pp. 1610-1621, March 2020.

Cellular Access from the Stratosphere









B. Belmekki, A. Aljohani, A. Althubaity, A. Al Harthi, K. Bean, A. Aijaz, and M. -S. Alouini, “Cellular access from the stratosphere", Under review, 2023.

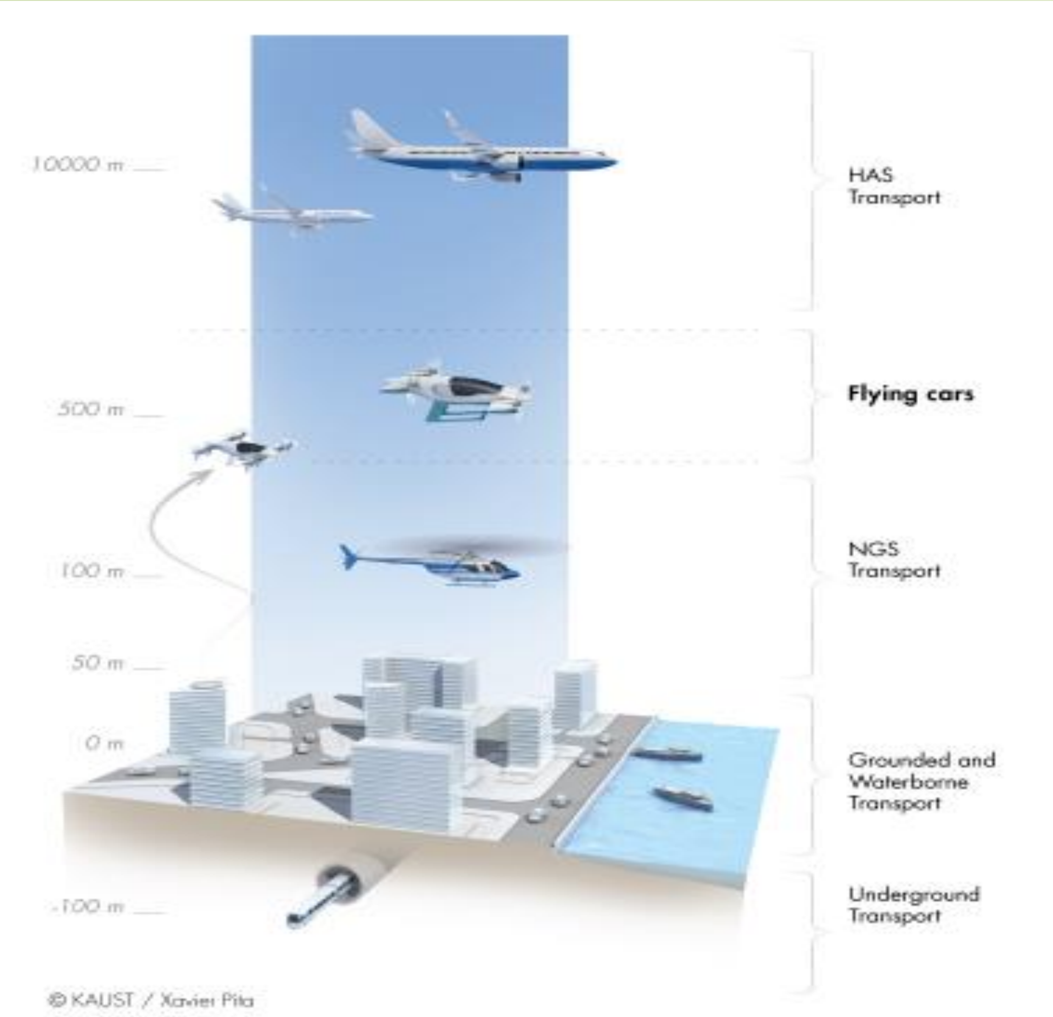
Satellite Constellations Backhaul

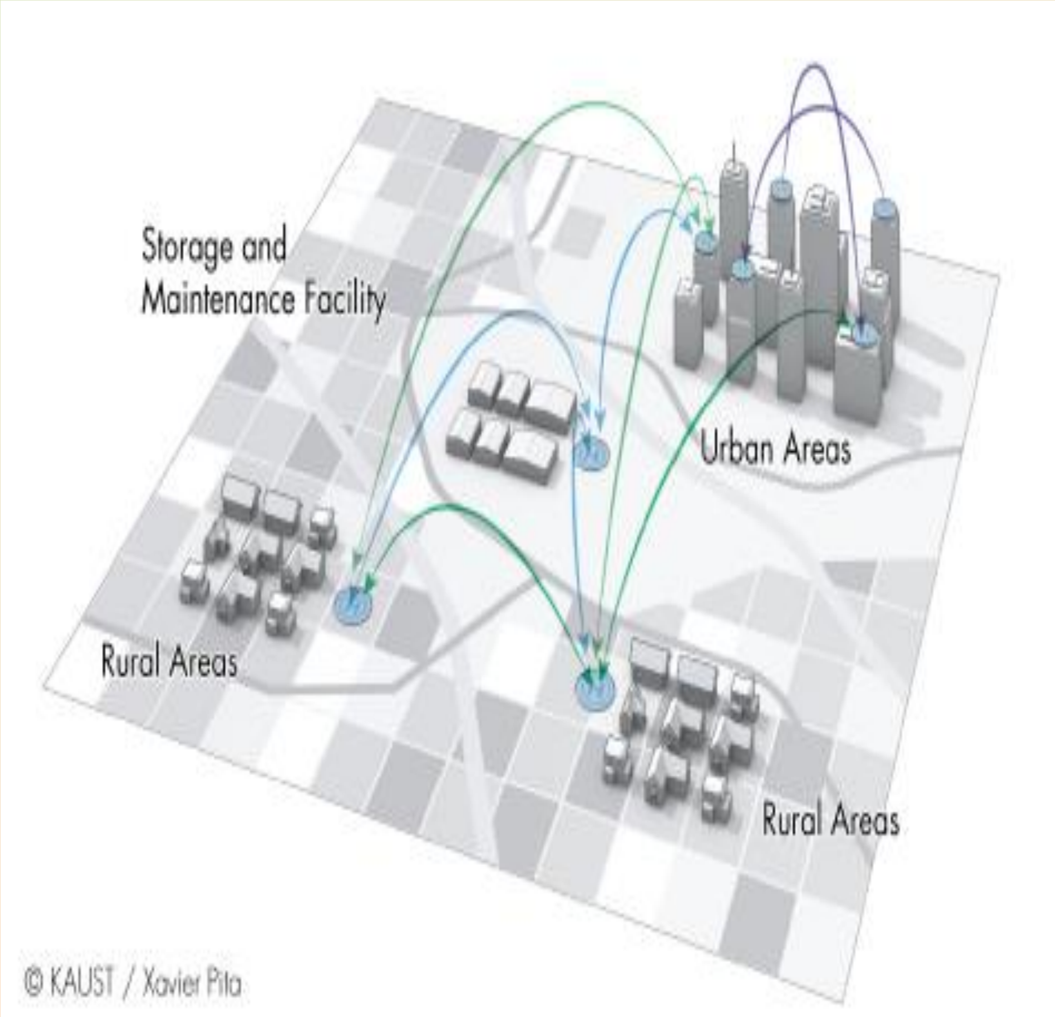
Manufacturing Cost Down => Mass Production

- 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, Curvanet

Integrated Space-Air-Ground Networks

To Be Ready for Emerging and Future Transportation Systems





[1] G. Pan and M. -S. Alouini, "Flying car transportation systems: Advances, techniques, and challenges", IEEE Access 2021.
[2] N. Saeed, T. Y. Al-Naffouri, M -S. Alouini, "Wireless communications for flying cars", Frontiers in Communications and Networking 2021.

جامعة الملك عبدالله
للعلوم والتقنية

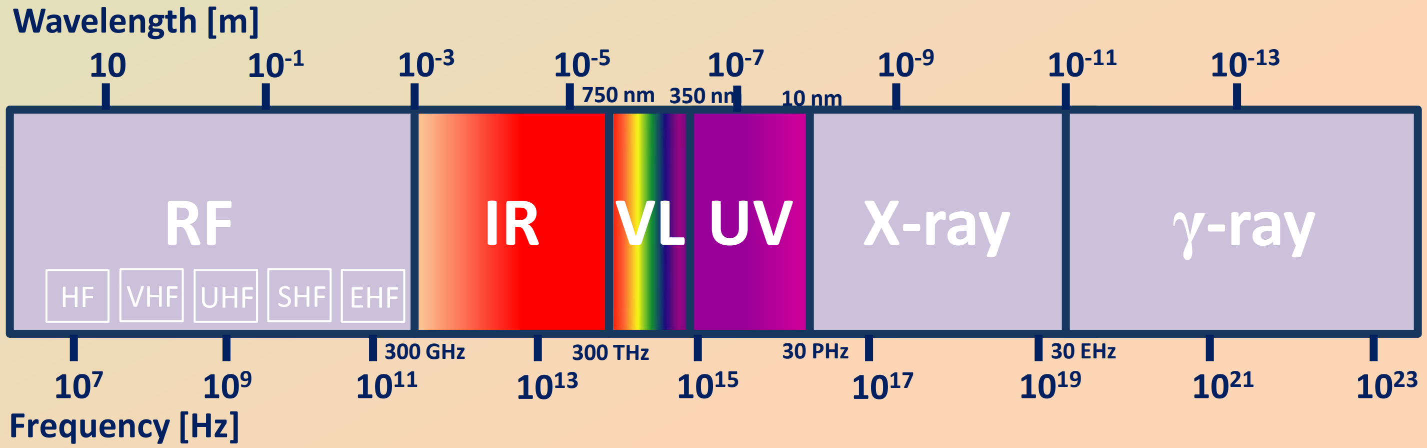
King Abdullah University of
Science and Technology

A Light in Digital Darkness

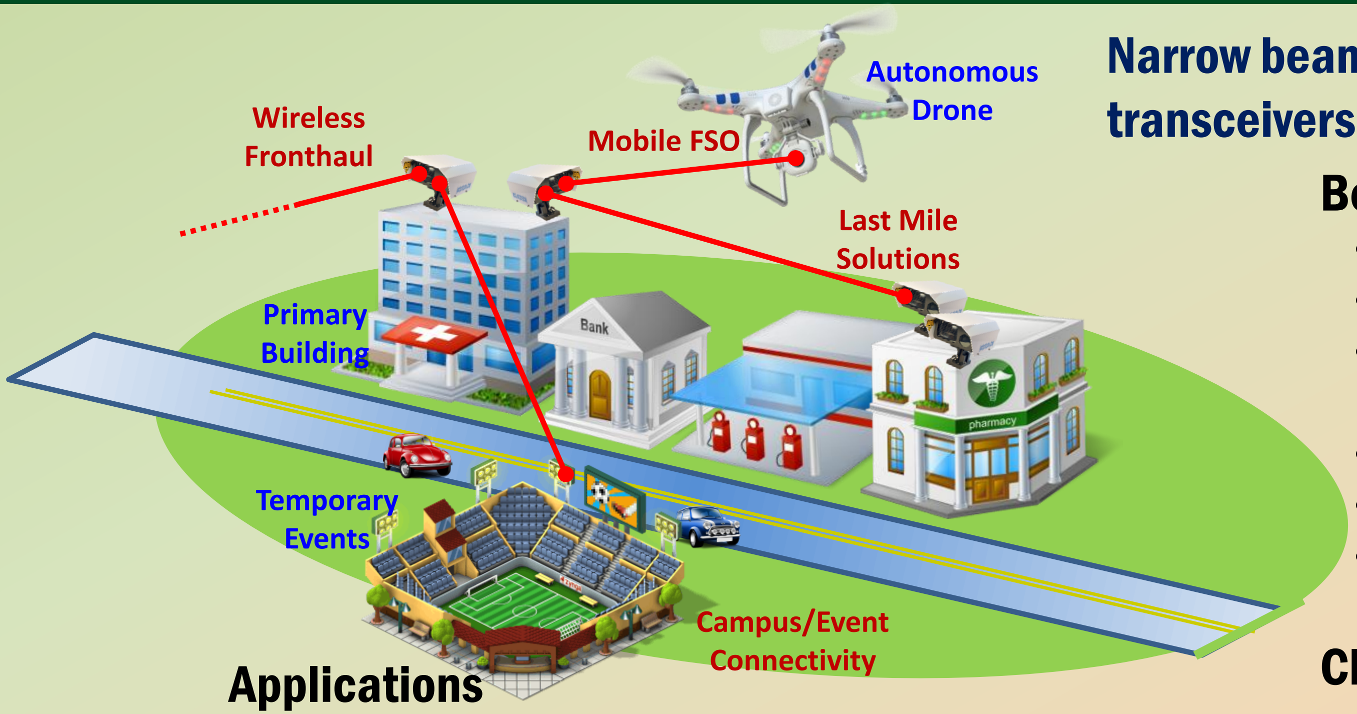


Spectrum

- RF spectrum typically refers to the full frequency range from 3 KHz to 30 GHz.
- RF spectrum is a national resource that is typically considered as an exclusive property of the state.
- RF spectrum usage is regulated and optimized
- RF spectrum is allocated into different bands and is typically used for
  - Radio and TV broadcasting
  - Government (defense and public safety) and industry
  - Commercial services to the public (voice and data)



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

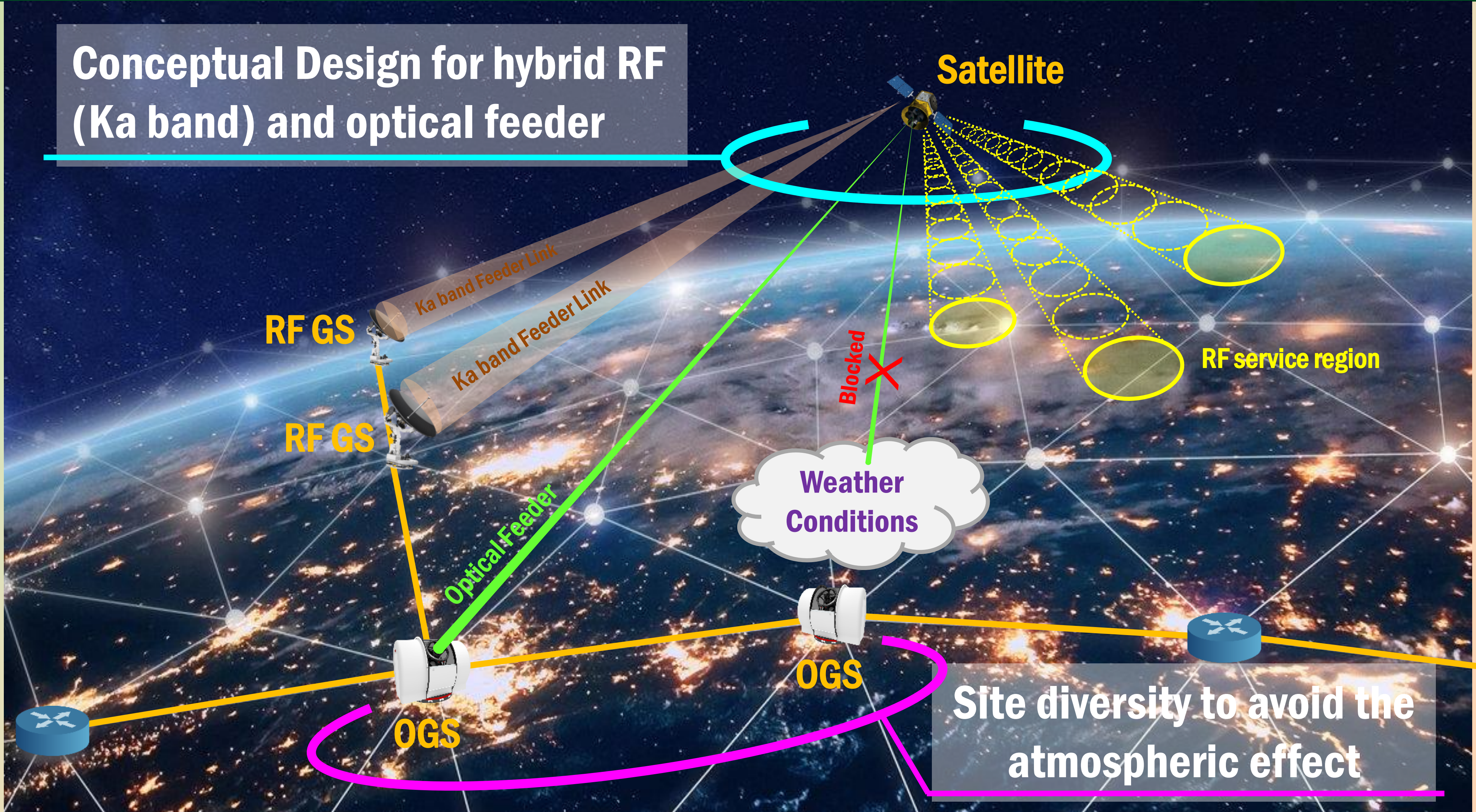
- Additive noise and background radiation
- Atmospheric path loss and attenuation
- Atmospheric Turbulences
- Alignment and tracking

[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, Vol. 9, No. 1, February 2017.
[2] M. -A. Lahmeri, M. Kishk, and M. -S. Alouini, "Stochastic geometry-based analysis of airborne base stations with Laser-powered UAVs," IEEE Communication Letters, Vol. 24, No. 1, pp. 173-177, January 2020.
[3] A. Trichili, M. Cox, B. S. Ooi, and M.-S. Alouini, , ‘’Roadmap to free space optics,’ Journal of Optical Society of America B, 2020

A Light in Digital Darkness

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

Hybrid VHT Satellite with Site Diversity



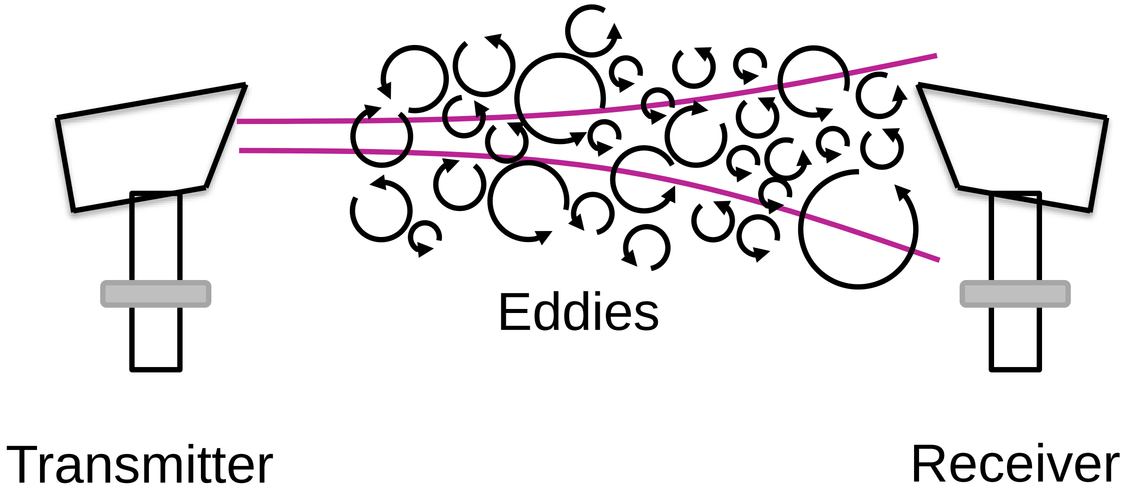
E. Zedini, A. Kammoun, and M. –S. Alouini, "Performance of multibeam very high throughput satellite systems based on FSO feeder links with HPA nonlinearity, IEEE Trans. On Wireless Communications, 2020

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

Atmospheric Turbulence

Atmospheric Turbulence

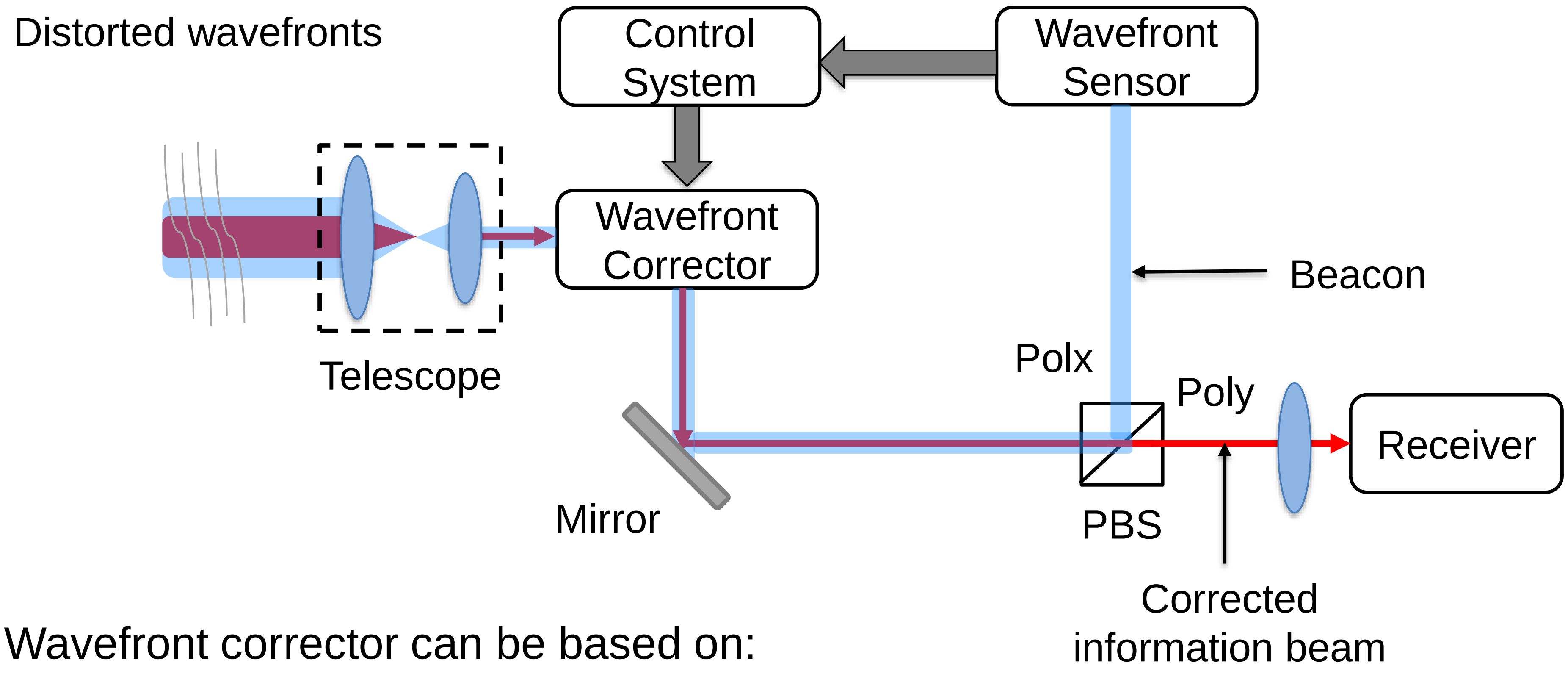
Propagation through turbulent atmosphere:



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

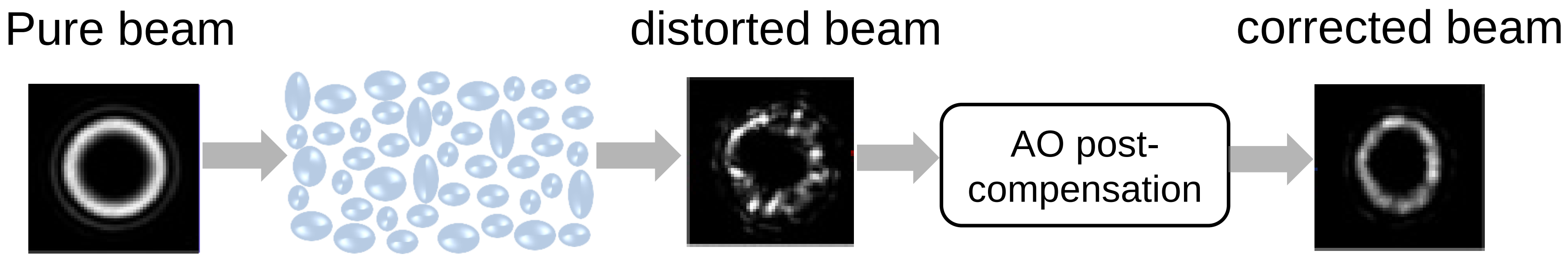


Wavefront corrector can be based on:

- A liquid crystal display (slow)
- An array of deformable mirrors (fast)

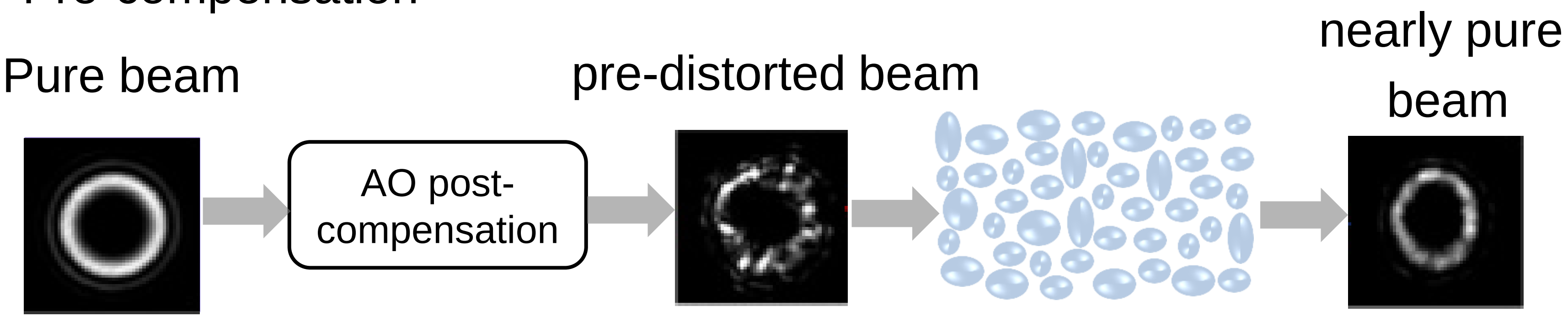
Adaptive Optics Schemes

- Post-compensation



Requires a beacon Gaussian beam from the transmitter.

- Pre-compensation



Requires a beacon Gaussian beam from the receiver.

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

Outage Probability Performance

Closed-Forms for the 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

$$P_{out} = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}} \eta_s^2 h_{af} e^{-\frac{\sigma_0^2}{2}} {}_1F_1\left(-\frac{1}{2}, \frac{1}{2}; \frac{\sigma_0^2}{2}\right)}{A_0^{(\alpha+\beta)/2} \Gamma(\alpha)\Gamma(\beta) h_{al}^{(\alpha+\beta)/2}} h_{th}^{\frac{\alpha+\beta}{2}} \times G_{2,4}^{3,1}\left(\frac{\alpha\beta}{A_0 h_{al}} h_{th} \middle| \begin{matrix} \frac{2-\alpha-\beta}{2}, \frac{2-\alpha-\beta+2\eta_s^2}{2} \\ \frac{-\alpha-\beta+2\eta_s^2}{2}, \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}, \frac{-\alpha-\beta}{2} \end{matrix}\right).$$

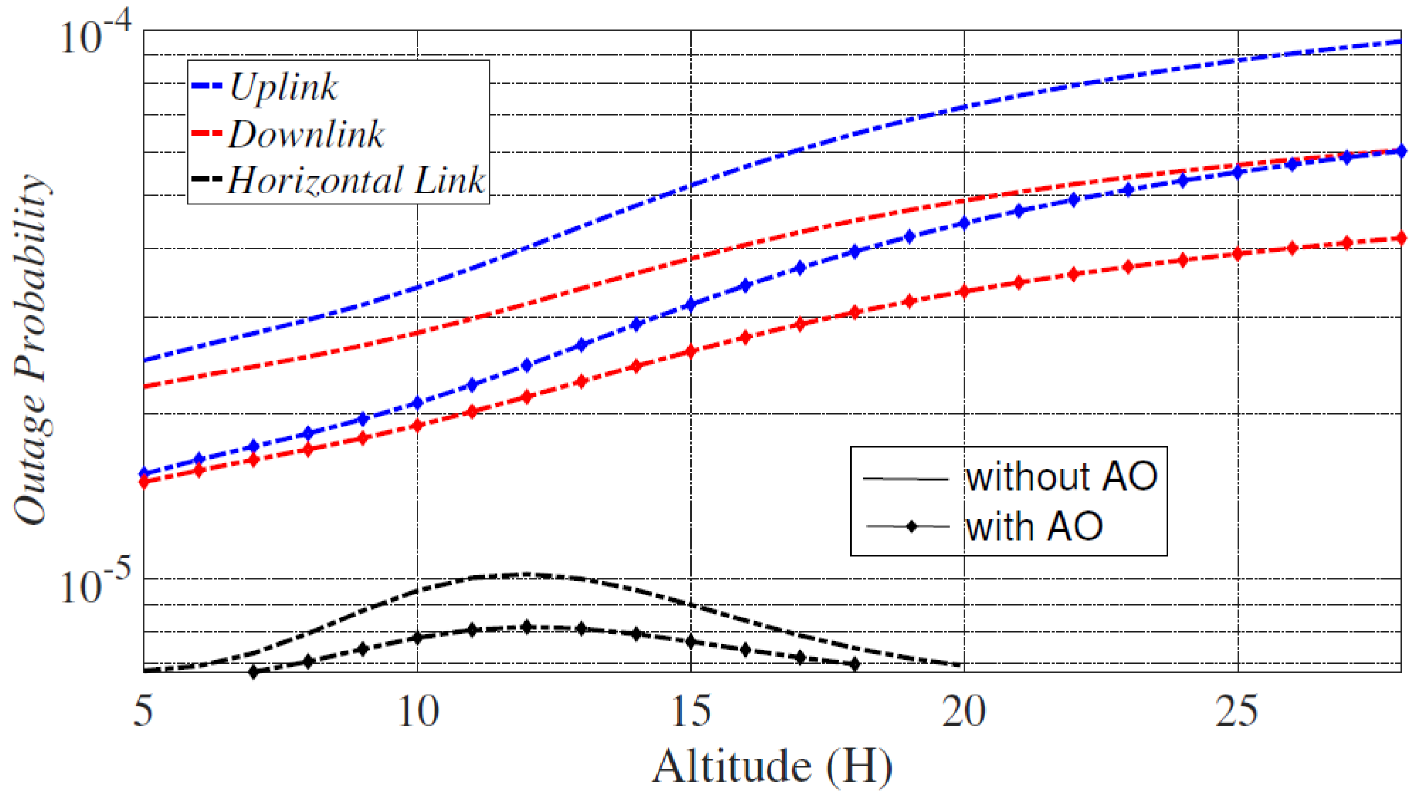
Y. Ata and M.-S. Alouini, " HAPS based FSO links performance analysis and improvement with adaptive optics correction," IEEE Trans. on Wireless Com, 2023.

Closed-Forms for the Outage Probability Lognormal Turbulence Model

$$
\begin{aligned}
P_{out} = & \frac{\exp(-\sigma_l^2/8)\exp(-\sigma_0^2/2)h_{af}}{4\pi q_H} {}_1F_1\left(-\frac{1}{2},\frac{1}{2};\frac{\sigma_0^2}{2}\right) \\
& \times \int_{-\pi}^{\pi} \exp\left[\frac{\sigma_l^2\left(\eta_s^2\xi(\varphi)+1/2\right)^2}{2}\right] \frac{\exp\left[-\sigma_l^2\eta_s^2\xi(\varphi)\left(\eta_s^2\xi(\varphi)+1/2\right)\right]}{\xi(\varphi)} \\
& \times \left\{\exp\left[\eta_s^2\xi(\varphi)\ln\left(\frac{h_{th}}{A_0 h_{al}}\right)+\sigma_l^2\eta_s^2\xi(\varphi)\left(\eta_s^2\xi(\varphi)+1/2\right)\right]\right. \\
& + \exp\left(\sigma_l^2\eta_s^4\xi^2(\varphi)/2\right) erfc\left(\sqrt{2\sigma_l^2}\eta_s^2\xi(\varphi)/2\right) \\
& - \exp\left(\sigma_l^2\eta_s^4\xi^2(\varphi)/2\right) erf\left(\frac{\sqrt{2\sigma_l^2}\eta_s^2\xi(\varphi)}{2}-\frac{ln(\frac{h_{th}}{A_0 h_{al}})}{\sqrt{2\sigma_l^2}}-\frac{\sqrt{2\sigma_l^2}\left(\eta_s^2\xi(\varphi)+1/2\right)}{2}\right) \\
& + \exp\left(\sigma_l^2\eta_s^4\xi^2(\varphi)/2\right) erf\left(\sqrt{2\sigma_l^2}\eta_s^2\xi(\varphi)/2\right) \\
& - \exp\left[\eta_s^2\xi(\varphi)\ln\left(\frac{h_{th}}{A_0 h_{al}}\right)+\sigma_l^2\eta_s^2\xi(\varphi)\left(\eta_s^2\xi(\varphi)+1/2\right)\right] \\
& \left.\times erf\left(\frac{ln(\frac{h_{th}}{A_0 h_{al}})}{\sqrt{2\sigma_l^2}}+\frac{\sqrt{2\sigma_l^2}\left(\eta_s^2\xi(\varphi)+1/2\right)}{2}\right)\right\} d\varphi.
\end{aligned}
$$

Y. Ata and M.-S. Alouini, "Performance of Integrated Ground-Air-Space FSO networks in Various Turbulent Environments," IEEE Photonics Journal, 2022.

Uplink, Downlink, Horizontal Link Comparison



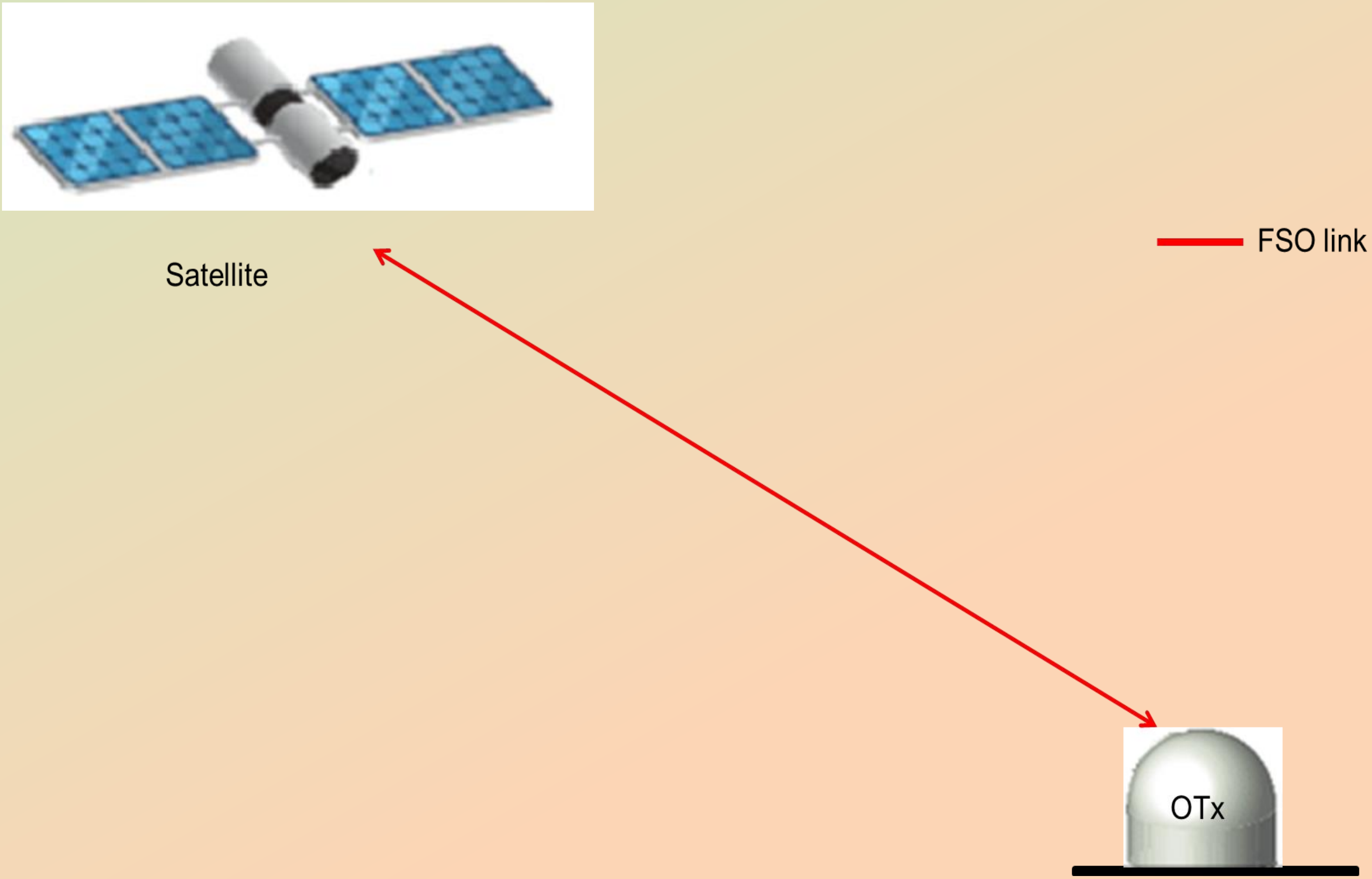
Y. Ata and M.-S. Alouini, " HAPS based FSO links performance analysis and improvement with adaptive optics correction," IEEE Trans. On Wireless Com., 2023.

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

Hybrid SAG-FSO/RF
Satellite Communication Systems

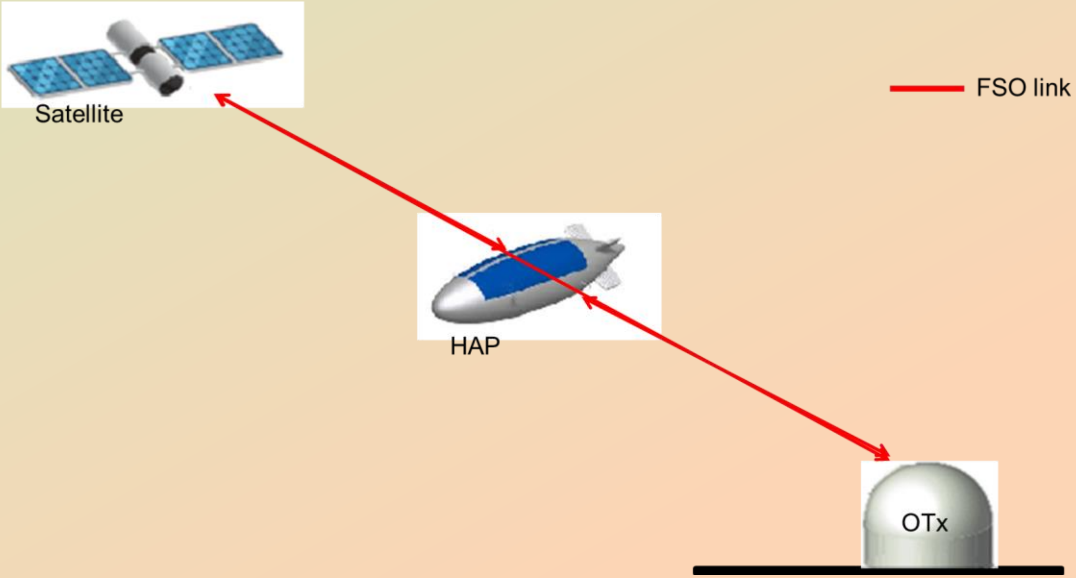
FSO for Sat-Com

- FSO can achieve Terabits/s data rate in GEO-equivalent turbulent channel.
- Pointing errors, induced by beam-wander and misalignment, affect FSO-link reliability.
- FSO transmission is susceptible to atmospheric turbulence, beam divergence, free-space loss, and weather conditions, such as clouds, fog, and haze.



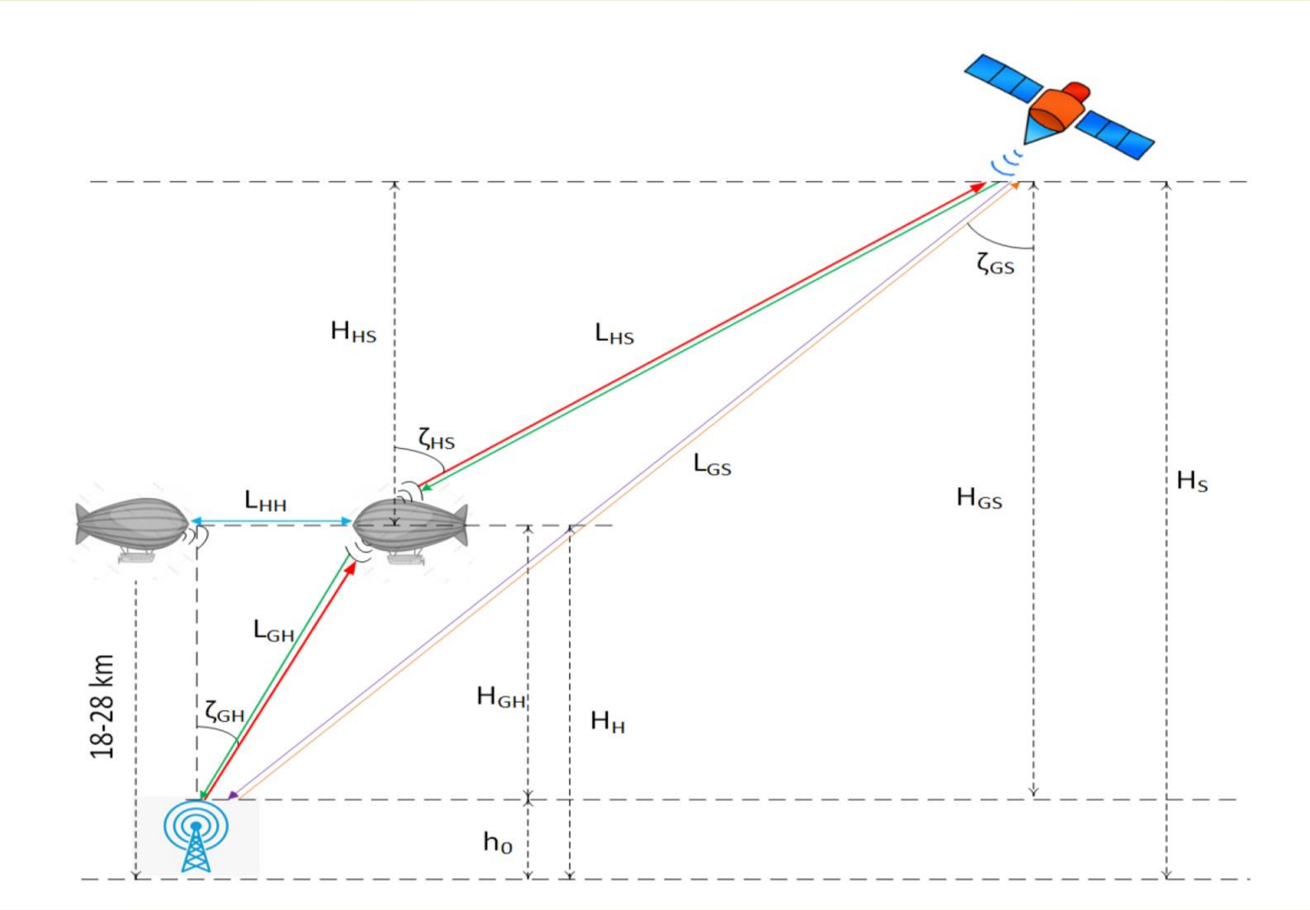
Space-Air-Ground (SAG) FSO Network

- Introduce a HAPS with FSO relaying capability to create a SAG FSO network.
- Reduce beam-wandering effect with two short hops and achieve a gain of 4 dB.
- Ground-to-HAP hop experiences similar amount of turbulence as direct link.



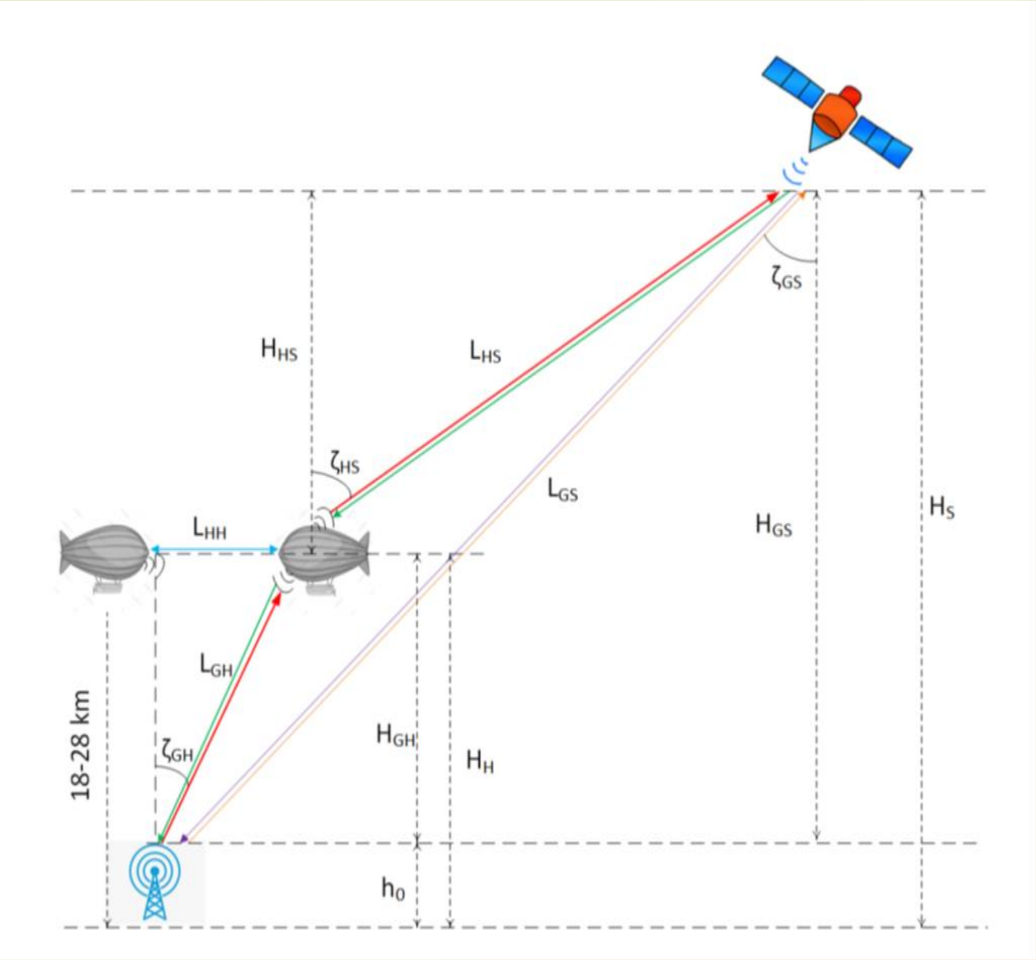
R. Swaminathan, S. Sharma, N. Vishwakarma, and A. Madhukumar, "HAPS-based relaying for integrated space-air-ground networks with hybrid FSO/RF communication: A performance analysis," IEEE Transactions on Aerospace and Electronic Systems, 2021

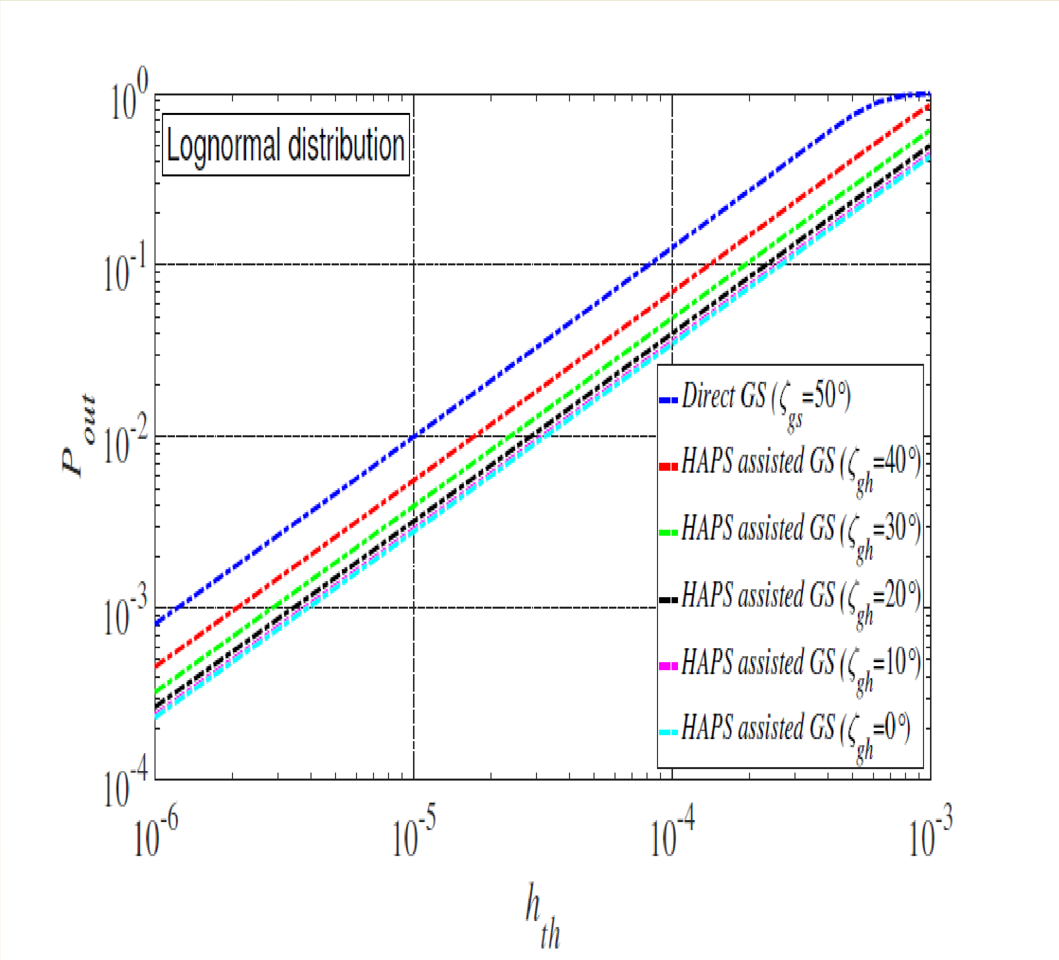
System under Consideration



- R. Zaghloul, H. –C. Yang, T. Rakia, and M. -S. Alouini, “Space-Air-Ground FSO Networks for High-Throughput Satellite Communications", IEEE Communication Magazine, 2022
- Y. Ata and M. -S. Alouini, “Performance of Integrated Ground-Air-Space FSO Networks in Various Turbulent Environments", IEEE Photonics Journal 2022.

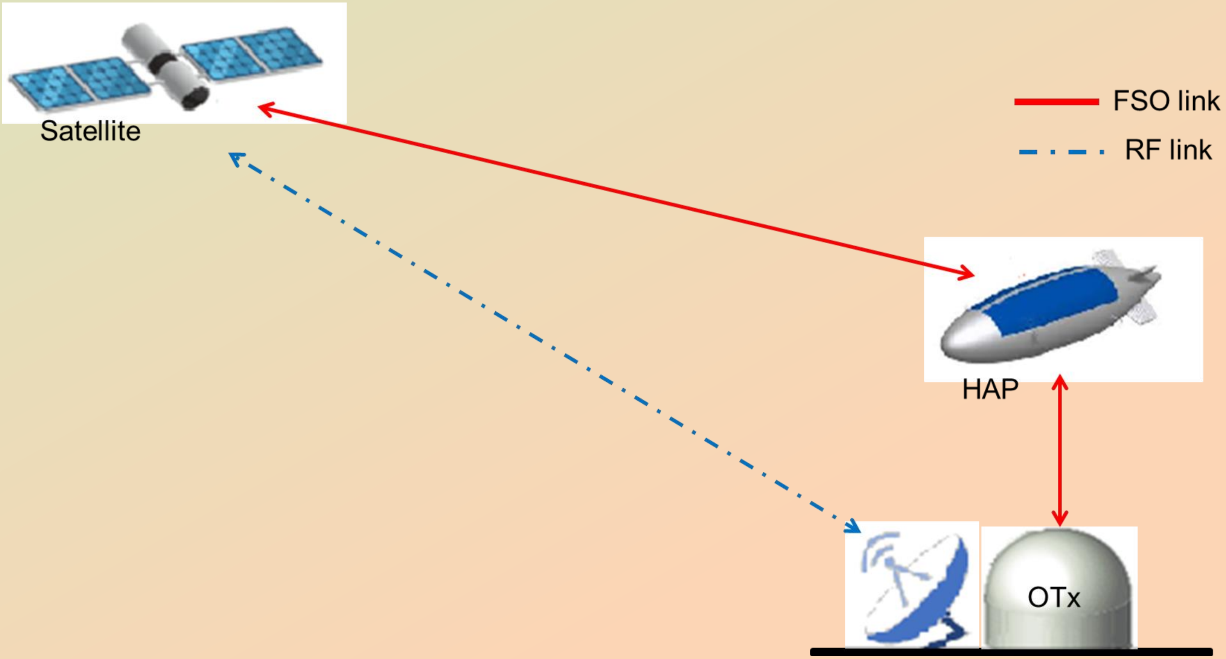
Comparison Direct vs. Relayed Transmission





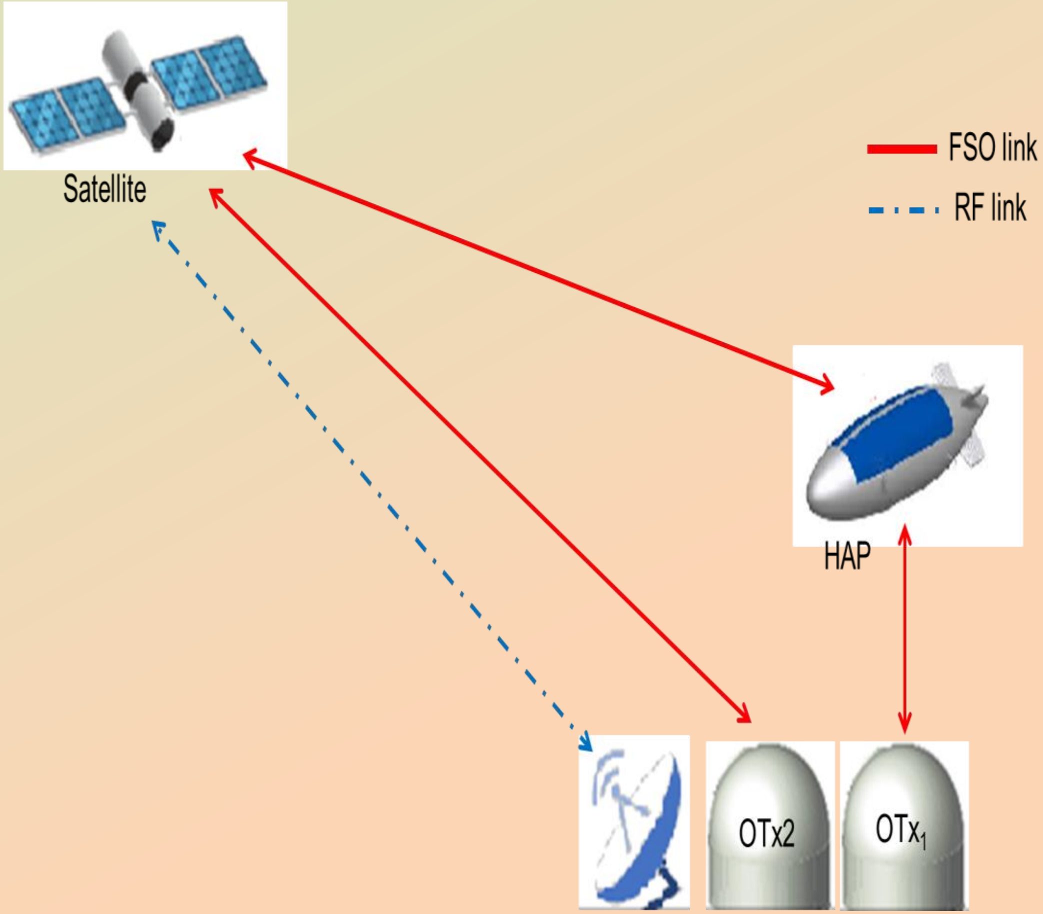
Hybrid SAG-FSO/RF Transmission System

- Introduce ground-to-SAT RF link as a backup to improve system reliability.
- Most satellites are already equipped with RF receivers.
- Sole FSO payload at HAPS to reduce its hardware complexity and power consumption.

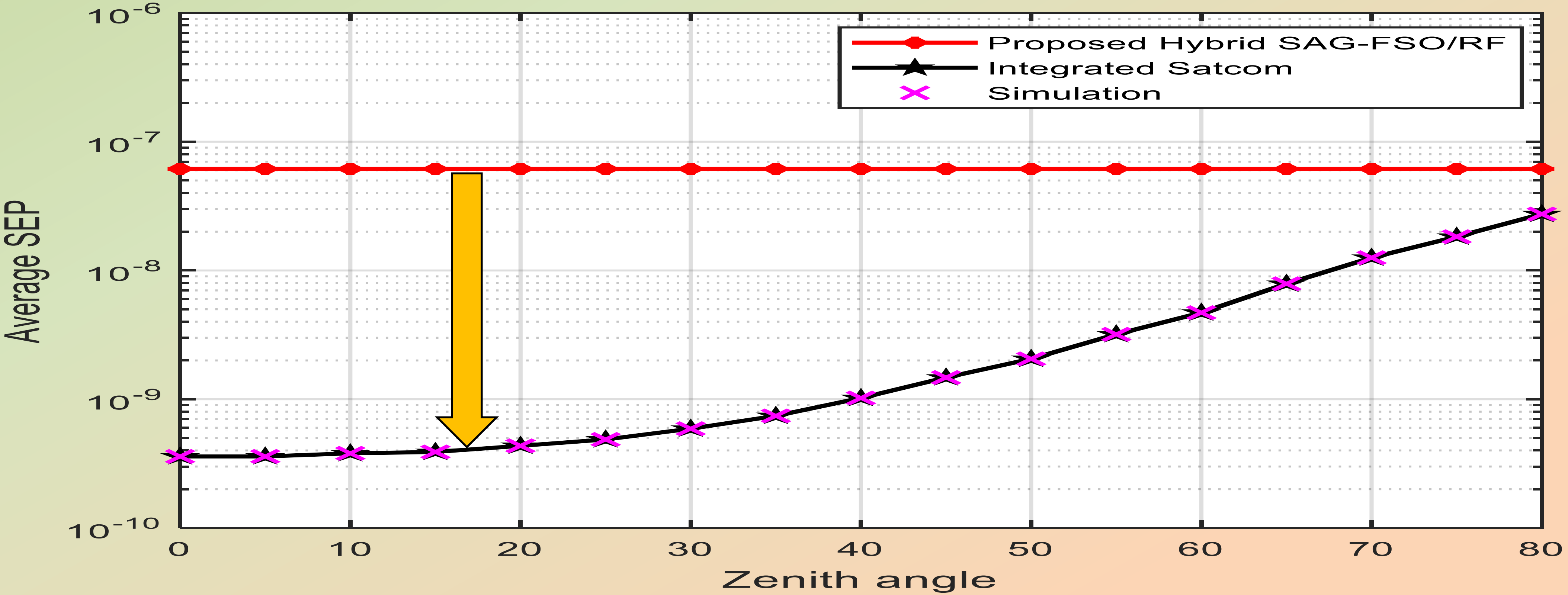


Reliable High-Throughput Satcom System

- Integrate proposed SAG-FSO design with conventional hybrid FSO/RF
    1. SAG-FSO link is used as long as its quality is acceptable.
    2. The system will switch to single-hop (SH) FSO when SAG-FSO link becomes unacceptable
    3. RF link is used only when both SAG-FSO and SH-FSO links are unacceptable.



End-to-End Average Symbol Error Probability

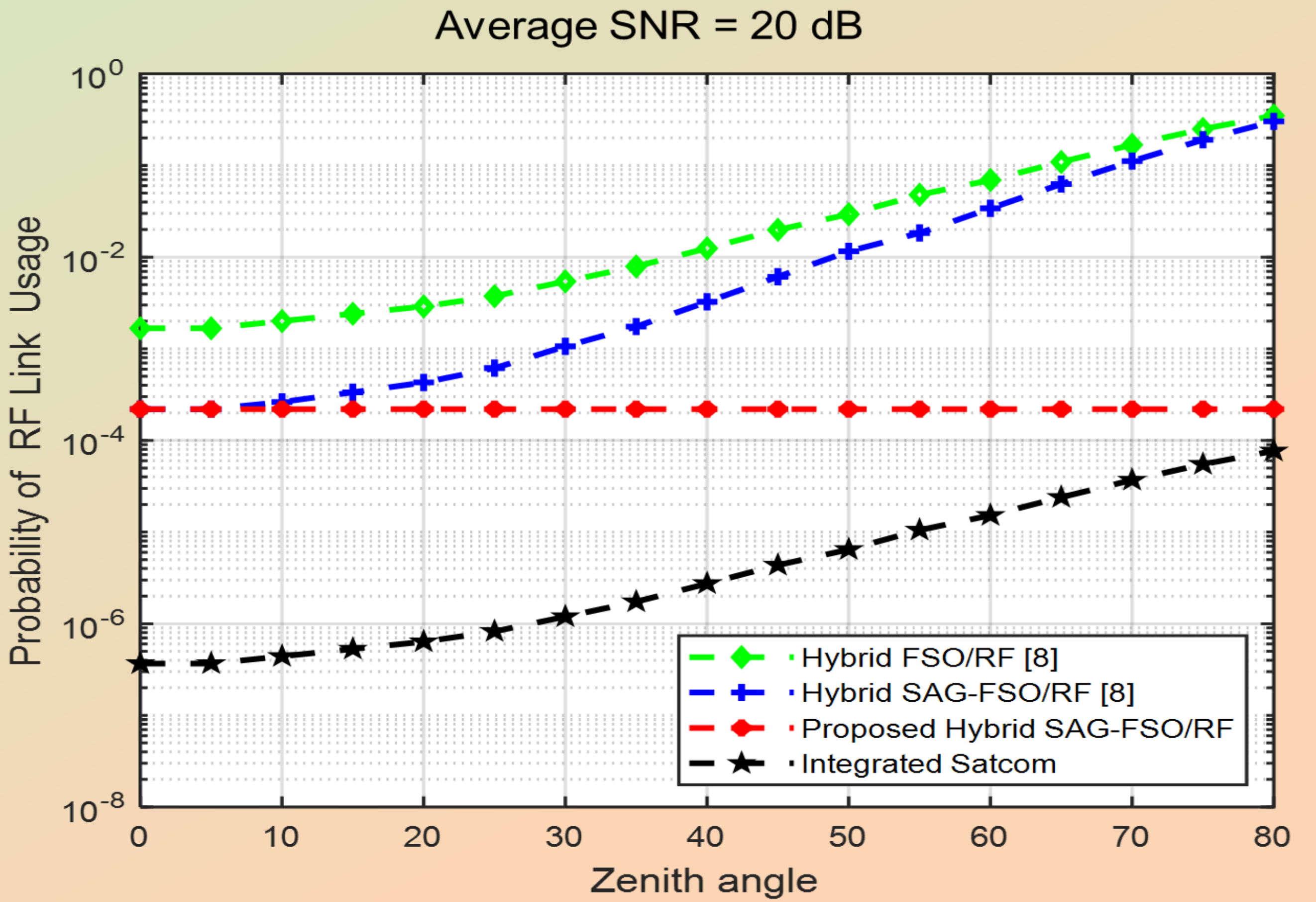


The integrated Satcom system outperforms hybrid SAG-FSO/RF over all zenith angles, despite a slight performance degradation for high zenith angles.

Probability of RF Link Usage

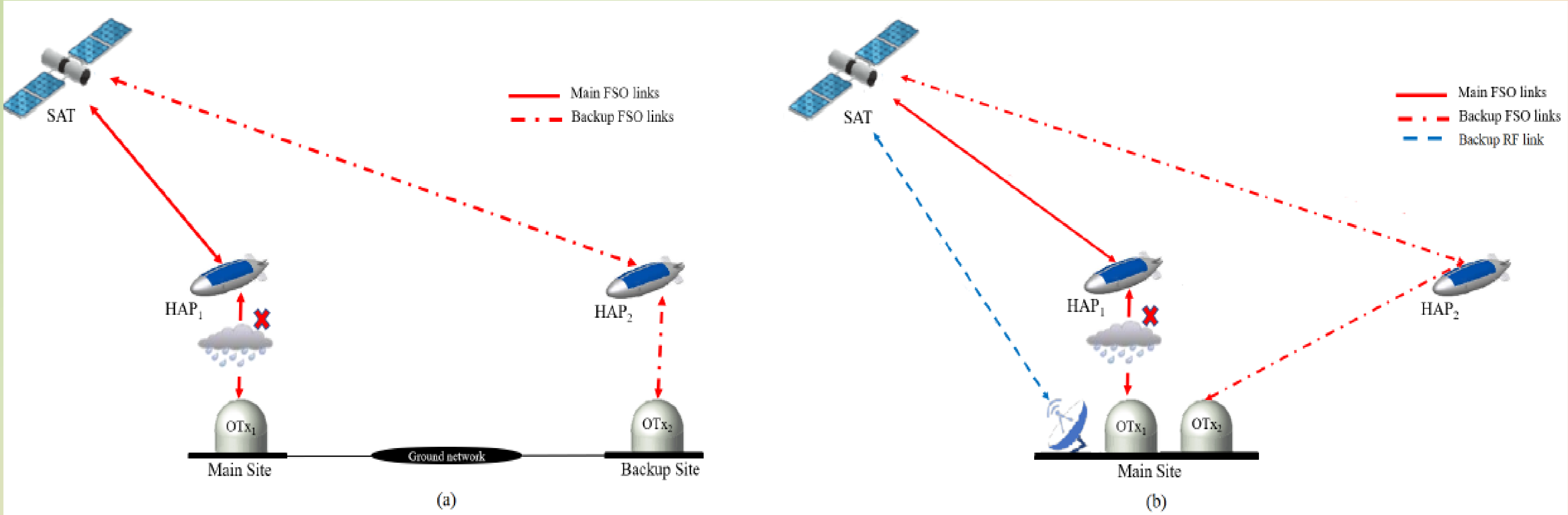
جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

- Throughput performance of SatCom systems degrades when switching to RF link.
- Probability of RF link usage serves as a measure of system overall throughput.



Proposed SAG-FSO transmission systems greatly reduce the probability of RF link usage, especially at median to high zenith angle.

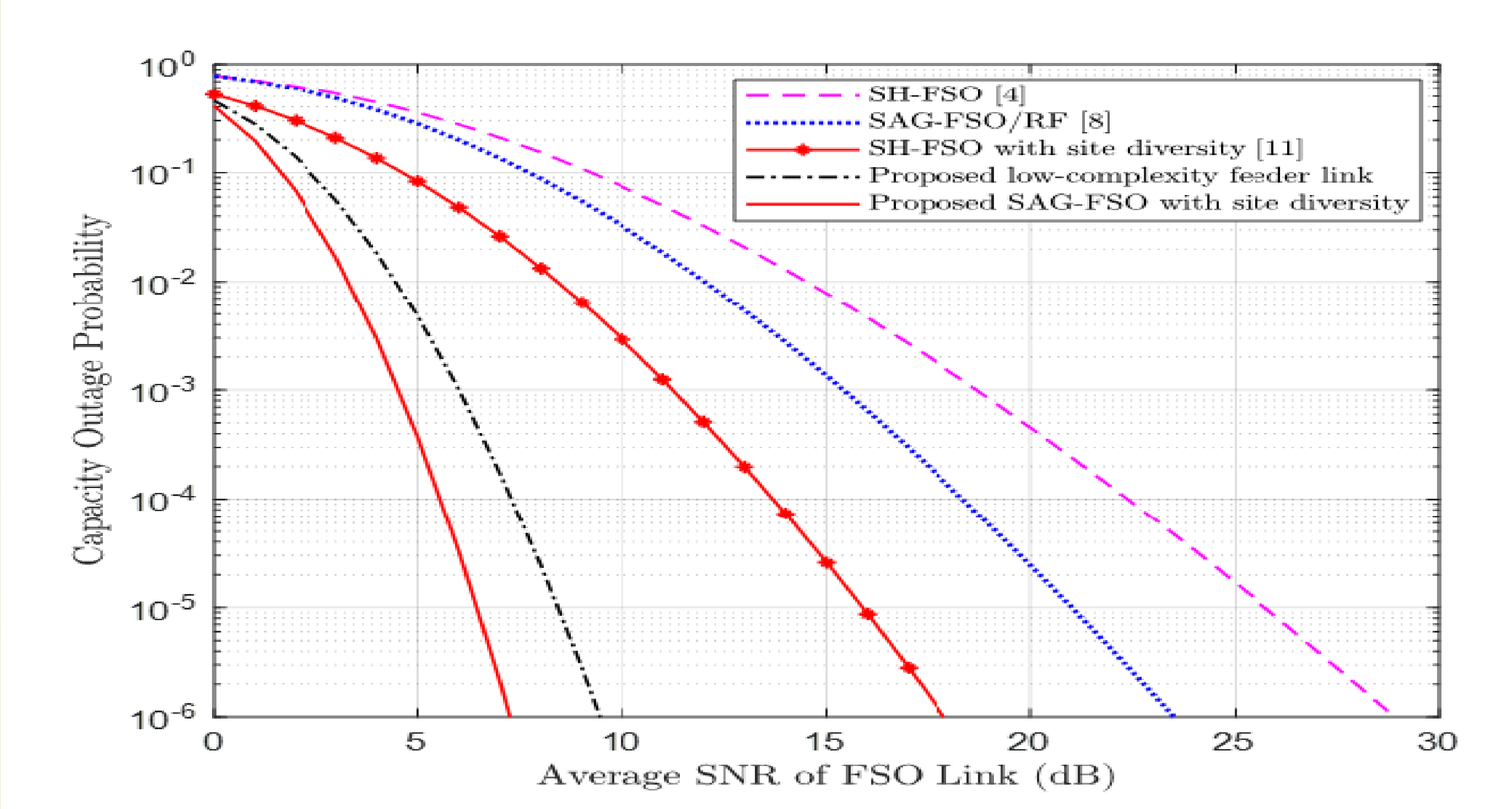
Mitigating Weather Conditions



(a) Site Diversity **(b) Multiple HAP Relays**

R. Samy, H. –C. Yang, T. Rakia, and M. -S. Alouini, "Reliable Terabits Feeder Link for Very High-Throughput Satellite Systems with SAG-FSO Transmission", Under Review.

Comparison



R. Samy, H. –C. Yang, T. Rakia, and M. -S. Alouini, "Reliable Terabits Feeder Link for Very High-Throughput Satellite Systems with SAG-FSO Transmission", Under Review.

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 **FSO communication technology** to capitalize on its unique advantages to enter this expected mass market demands
- Emerging schemes for (i) adaptive optics, (ii) integrated space-air-ground networks, (iii) site and/or RF back-up diversity, (iv) practical low-cost PAT systems, (v) optical waveform design, and (vi) in-house space qualification for standard electronic/photonics to enable our **global, reliable, and affordable** broadband connectivity holy grail objective.

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

Nikola Tesla
(10 July 1856 – 7 January 1943)

“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

Thank You

ctl.kaust.edu.sa