



Towards Extreme Band Communications



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Evolution of Generations

From 1G to 5G **What is BEYOND 5G?**

1980s
Analog Voice

1G



1990s
Digital Voice
SMS + Email



2G

2000s
Mobile Internet
+ Positioning



3G

2010s
Mobile
Broadband



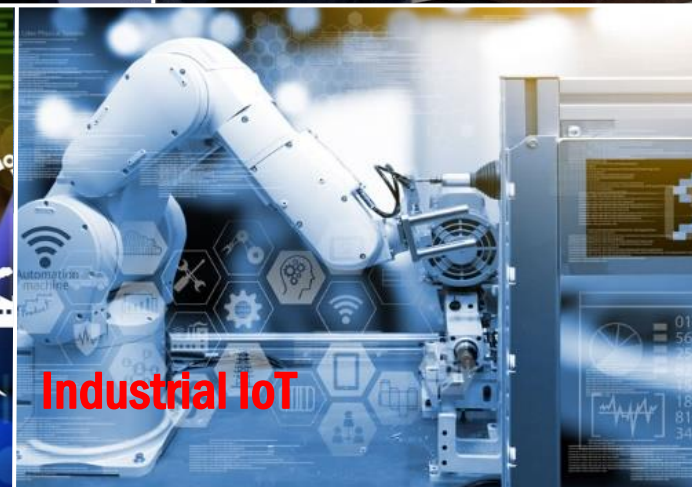
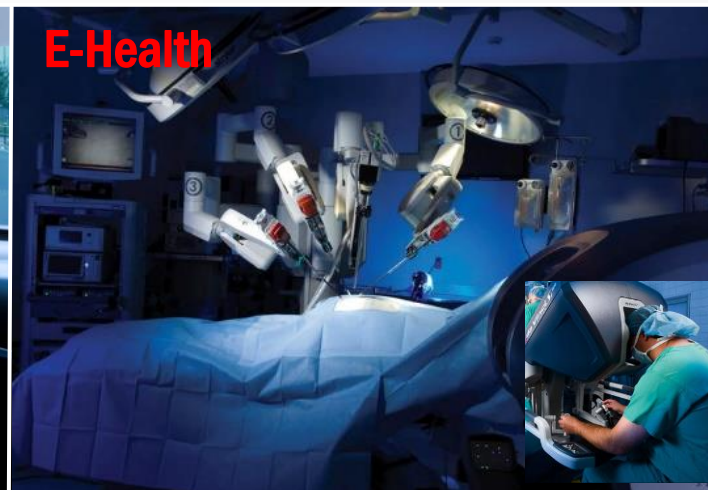
4G

2020
eMBB +
mMTC + URLLC



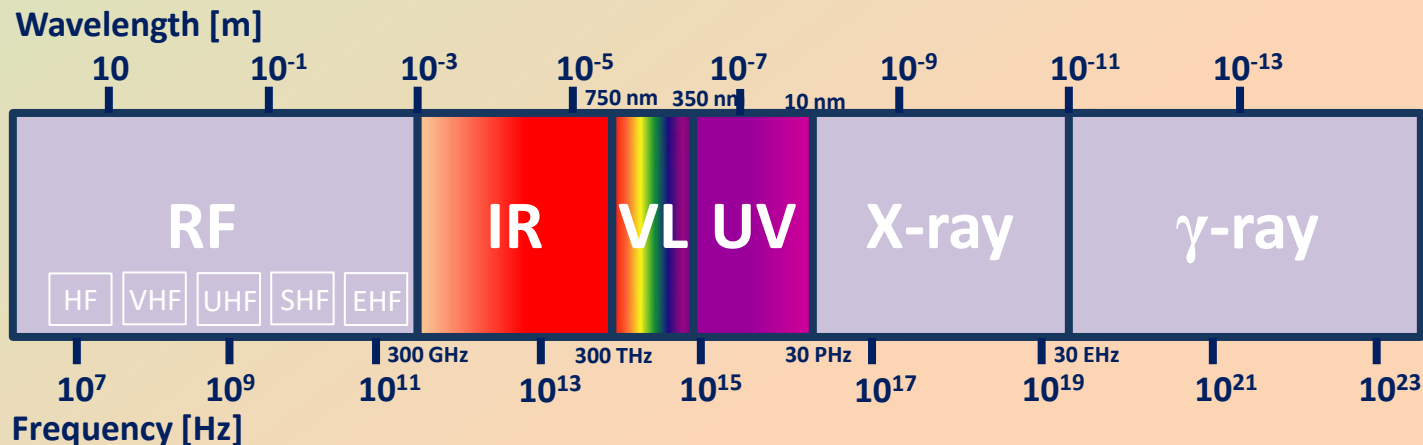
5G

6G Use Cases



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)



Potential Enabling Technologies

$$\frac{\text{bits/s}}{\text{m}^2} = \frac{\text{bits/s}}{\text{Hz} \cdot \text{node}} \cdot \frac{\text{node}}{\text{m}^2} \cdot \text{Hz}$$

**Better Spectral
Efficiency**

**Higher Network
Densification**

**More
Spectrum**

- ☐ Massive MIMO
- ☐ Artificial Radio Space
- ☐ Interference Management
- ☐ Full Duplex Radio

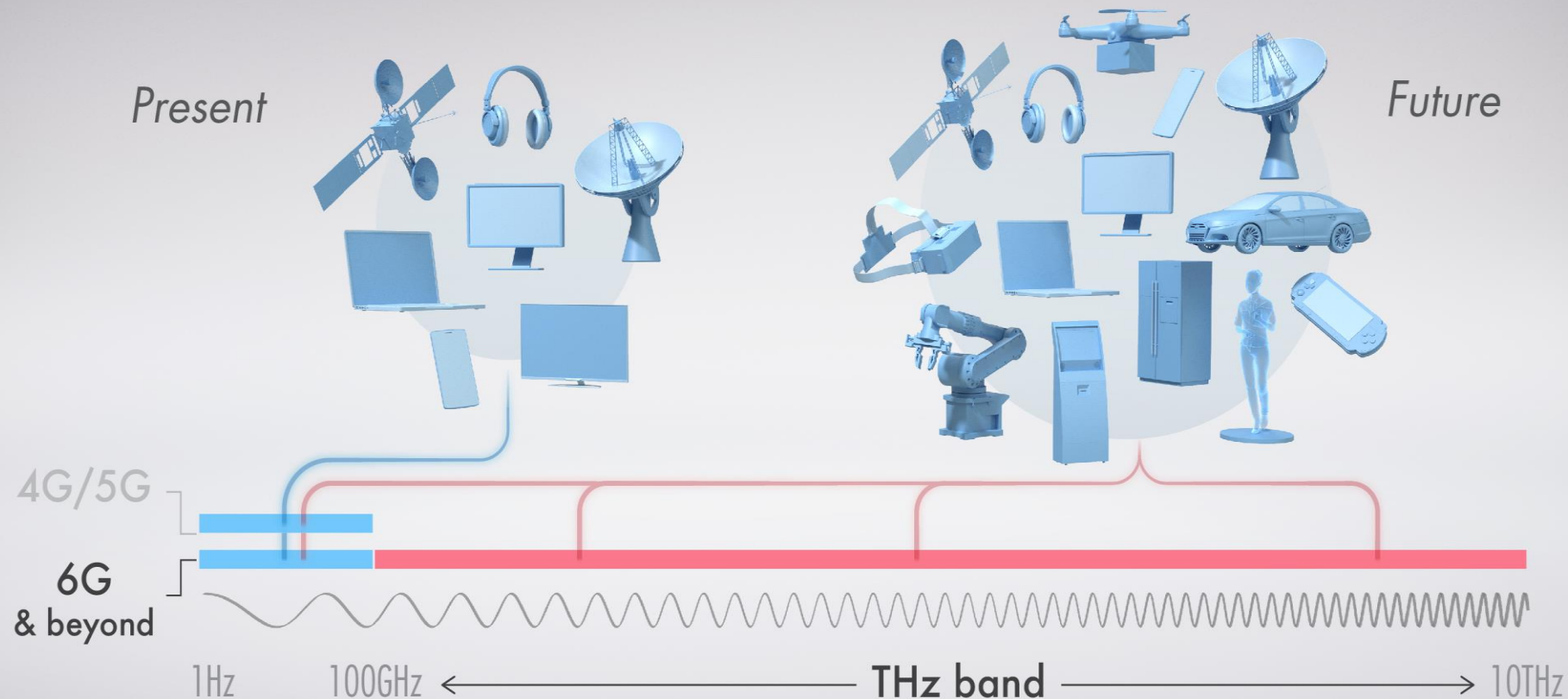
- ☐ Spectrum Sharing
- ☐ Cloud-RAN
- ☐ Small Cells
- ☐ D2D

- ☐ Carrier Aggregation
- ☐ Mm-Wave (60GHz)
- ☐ THz Com
- ☐ Optical Wireless Com

Terahertz Communications: A Rendezvous of Sensing, Imaging, and Localization

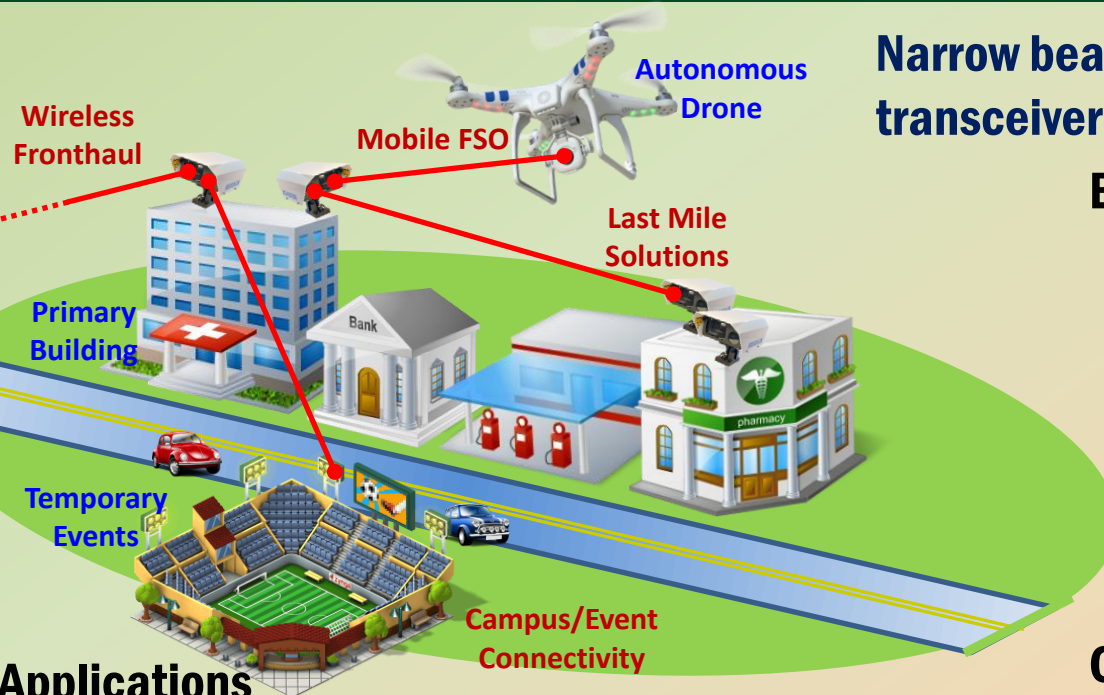
Present

Future



- [1] H. Elayan, O. Amin, B. Shihada, R. M. Shubair, M. -S. Alouini, "Terahertz band: The last piece of RF spectrum puzzle for communication systems", IEEE Open Journal of the Communications Society, January 2020.
- [2] H. Sarieddeen, N. Saeed, T. Al-Naffouri, and M. -S. Alouini, "Next generation terahertz communications: A rendez-vous of sensing, imaging, and localization", IEEE Communication Magazine, Vol. 58, No. 5, pp. 69-75, May 2020.

Free Space Optical 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

Challenges

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

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

[1] M. Esmail, A. Raghd, 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

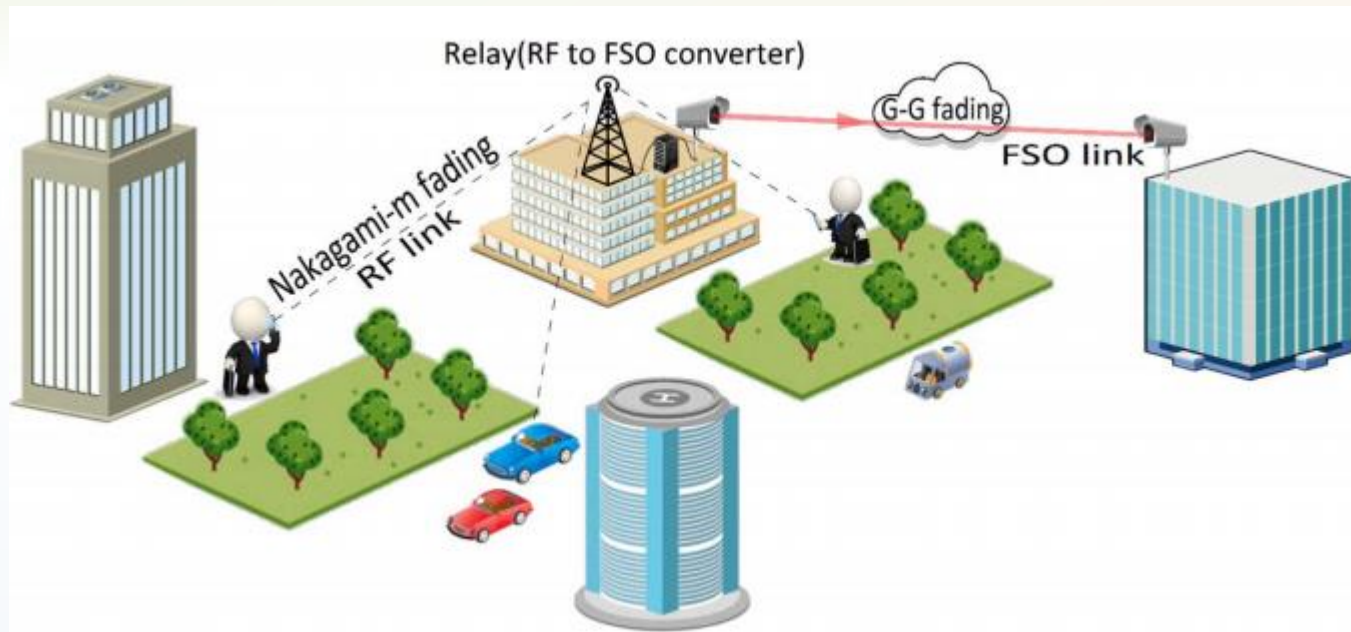


Cascaded THz/FSO Systems



Dual-Hop RF/FSO System Model

- Multiple RF users multiplexed and sent over the FSO link.

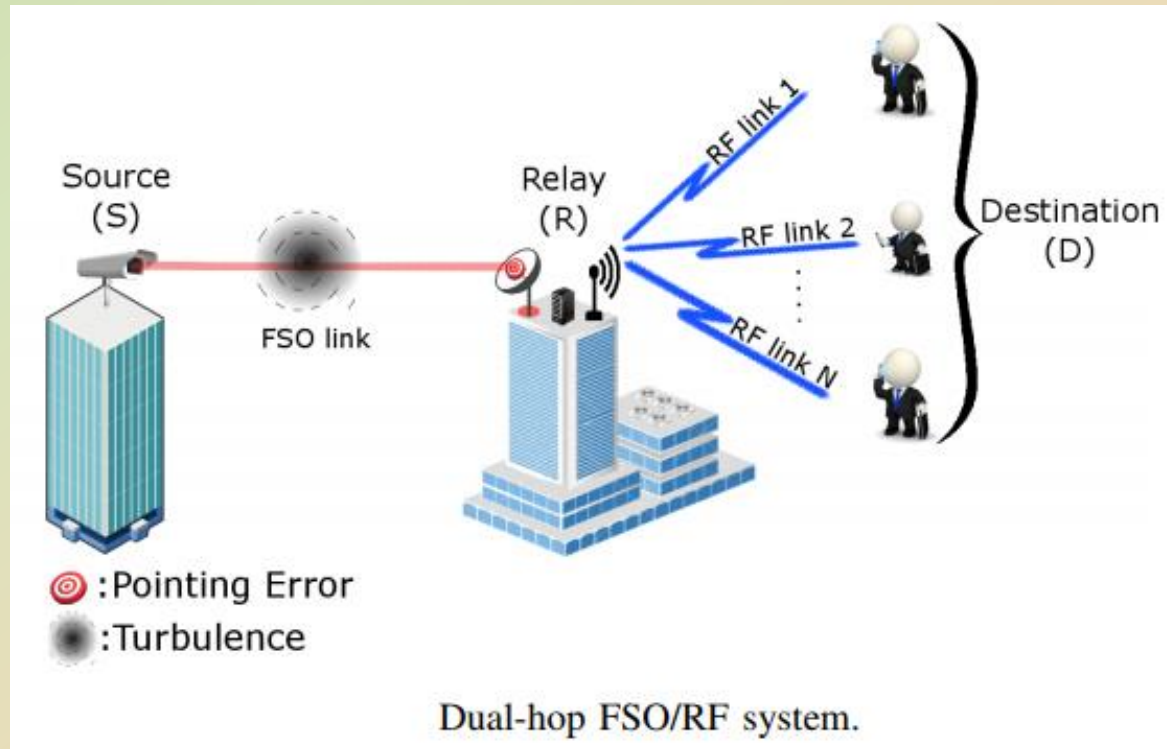


[1] E. Zedini, I. Ansari, and M. -S. Alouini, "On the performance of mixed Nakagami-m/Gamma-Gamma dual-hop transmission systems", IEEE Photonics Journal, Vol. 7, No. 1, February 2015.

[2] I. Ansari, F. Yilmaz, and M. -S. Alouini, "Impact of pointing errors on the performance of mixed RF/FSO dual-hop transmission systems", IEEE Wireless Commun. Letters, Vol. 2, No. 3, pp. 351-354, June 2013.

Dual-hop FSO/RF System Model

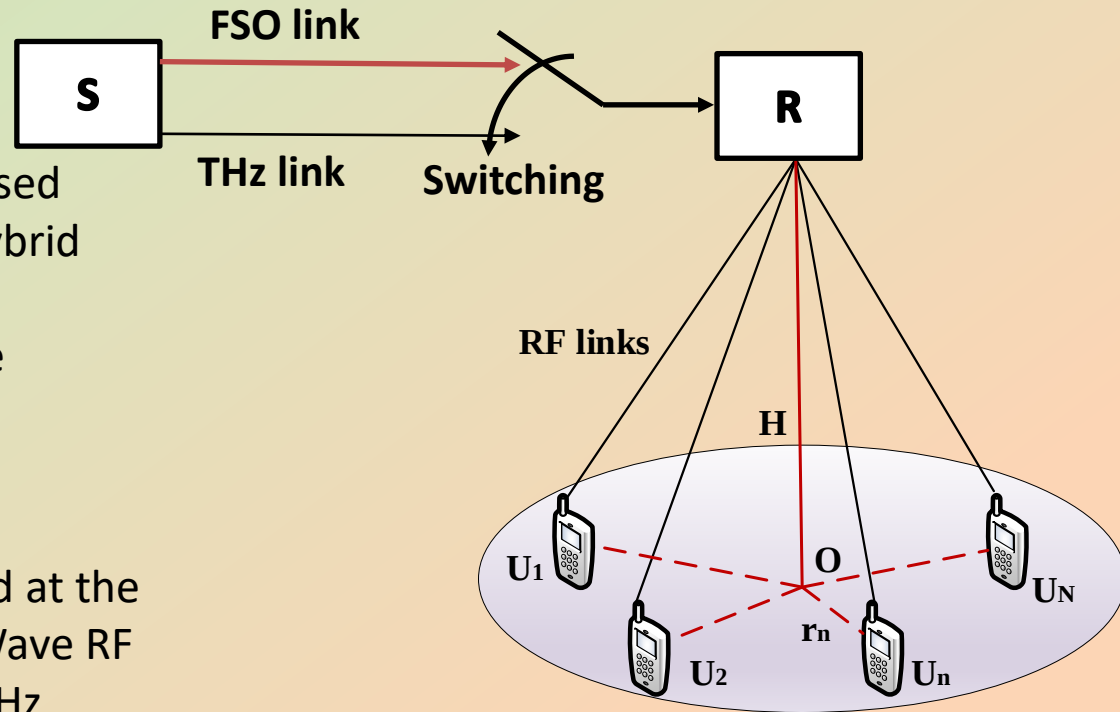
- FSO is a broadcast channel that serves multiple RF users.



[1] E. Zedini, H. Soury, and M. -S. Alouini, "On the performance analysis of dual-hop mixed FSO/RF systems", in IEEE Transaction on Wireless Communication, Vol. 15, No. 5, pp. 3679-3689, May 2016.

Hybrid THz/FSO System Model

- A backhaul hybrid FSO/THz link
- between two buildings of 50-100 m altitude, situated 100 m apart.
- Both the hard and soft switching based operations are performed for the hybrid FSO/THz link.
- N_r antennas at the THz receiver are considered for improved THz link performance, operating at 118 GHz frequency.
- N_t transmit antennas are considered at the RF transmitter to improve the mmWave RF link performance, operating at 28 GHz frequency.
- Due to size limit constraint, only single antenna is considered at the MUs.



Hybrid FSO/THz Link with Hard Switching

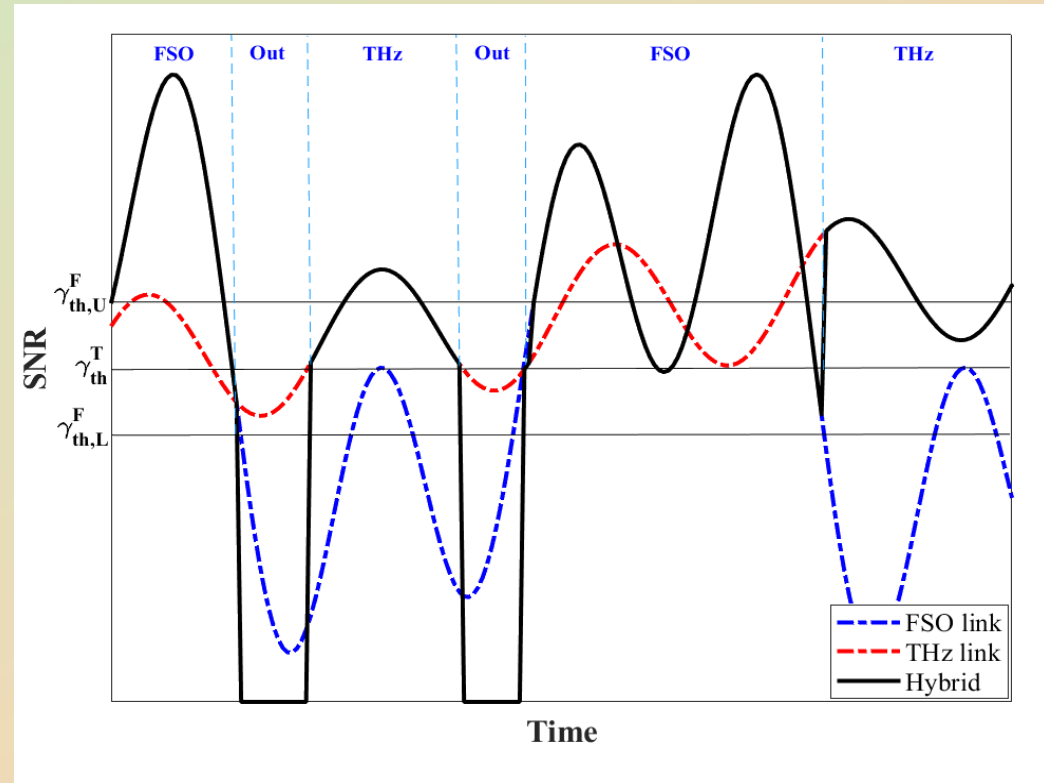
- FSO link is active if γ_F is greater than or equal to a predefined threshold γ_{th} .
- If $\gamma_F < \gamma_{th}$, receiver generates a feedback to initiate the THz link if $\gamma_T \geq \gamma_{th}$.
- Instantaneous received SNR γ_c of the mixed FSO/RF link is

$$\gamma_c = \begin{cases} \gamma_F, & \text{if } \gamma_F \geq \gamma_{th} \\ \gamma_T, & \text{if } \gamma_F < \gamma_{th}, \gamma_T \geq \gamma_{th} \end{cases}$$

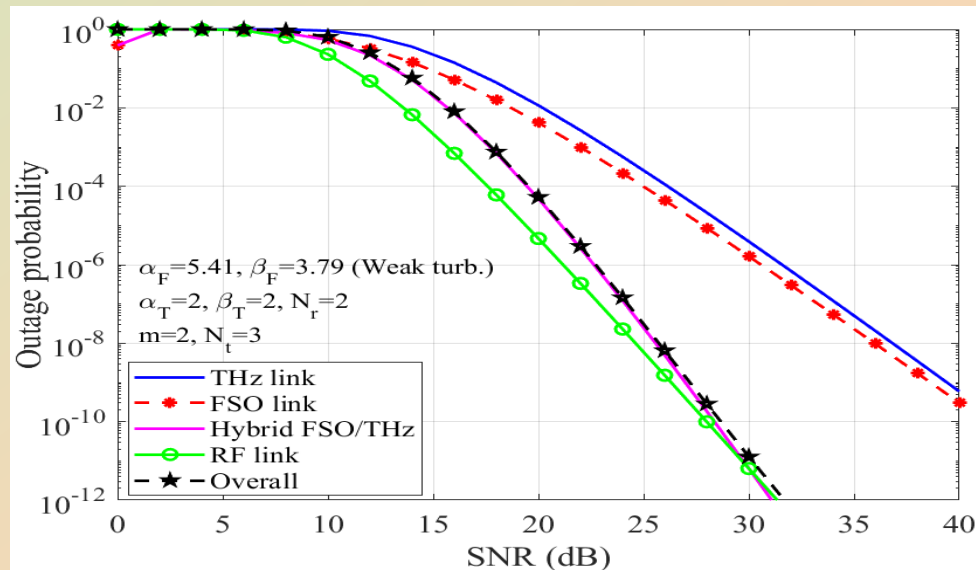
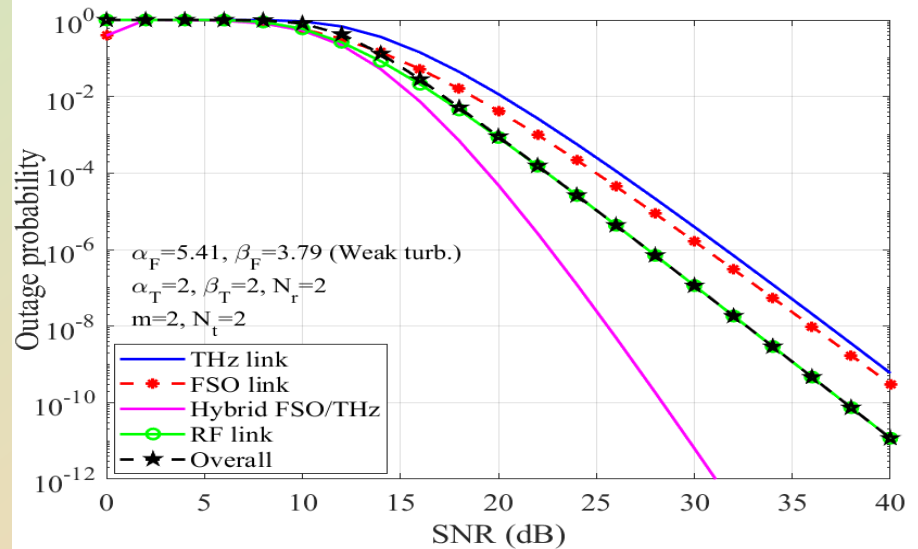
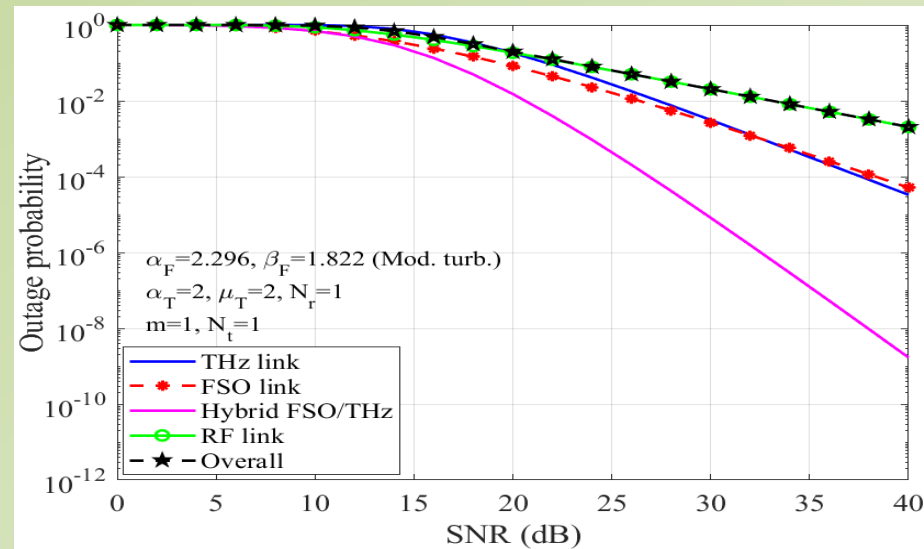
Hybrid FSO/THz Link with Soft Switching



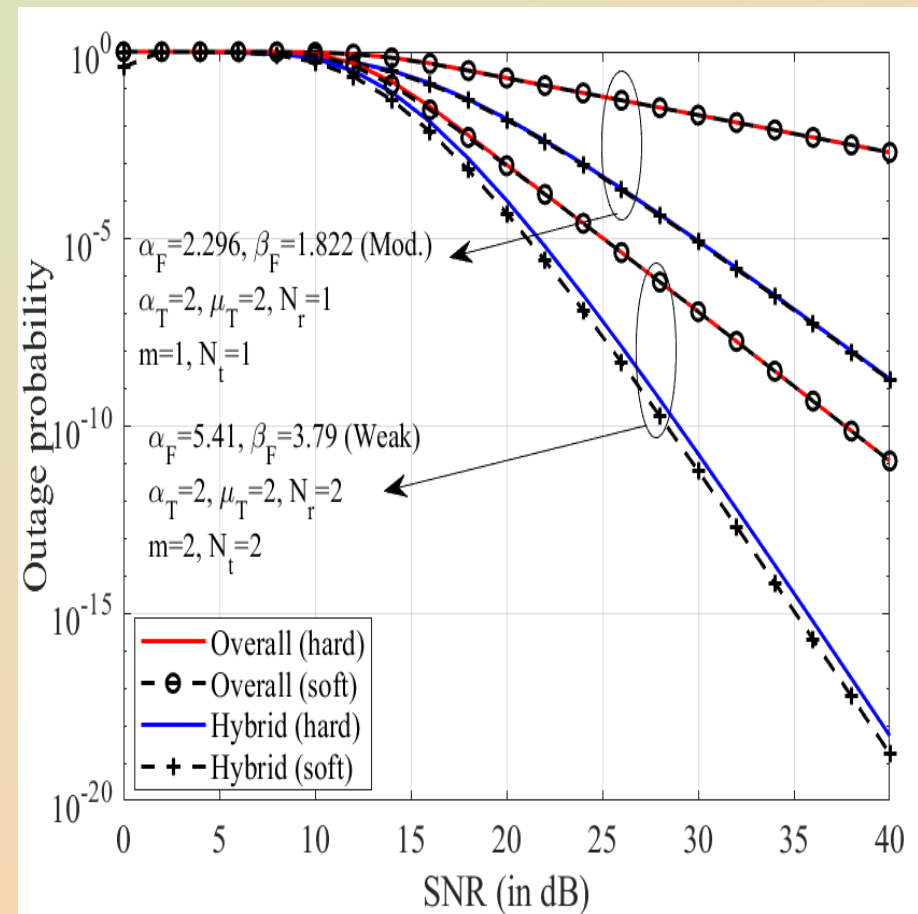
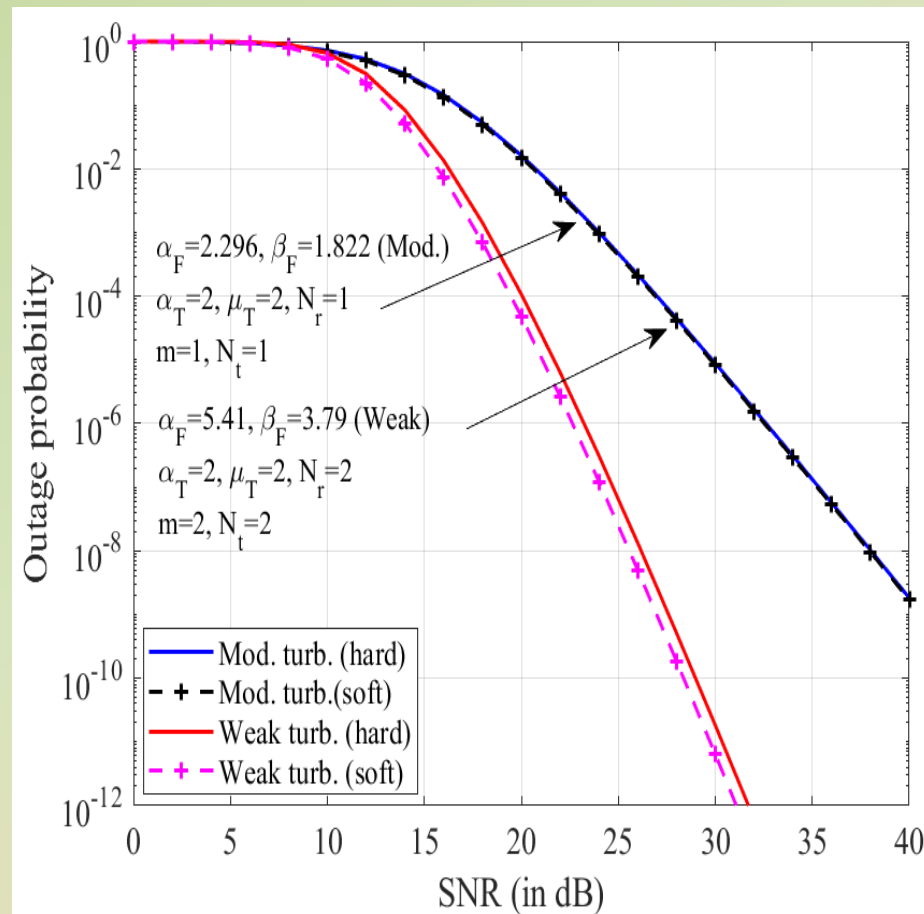
- If $\gamma_F \geq \gamma_{th,U}^F$, FSO link is active.
- If $\gamma_{th,L}^F < \gamma_F < \gamma_{th,U}^F$, given $\gamma_F \geq \gamma_{th,U}^F$ previously, FSO link is active irrespective of the THz link.
- If $\gamma_{th,L}^F < \gamma_F < \gamma_{th,U}^F$, given $\gamma_F < \gamma_{th,L}^F$ previously, THz link is active if $\gamma_T \geq \gamma_{th}^T$.
- If $\gamma_{th,L}^F < \gamma_F < \gamma_{th,U}^F$, but $\gamma_F < \gamma_{th,L}^F$ previously and $\gamma_T < \gamma_{th}^T$, hybrid link is in outage.
- If $\gamma_F < \gamma_{th,L}^F$ and $\gamma_T < \gamma_{th}^T$, hybrid link is in outage.



End-to-End Performance



Hard vs. Soft Switching

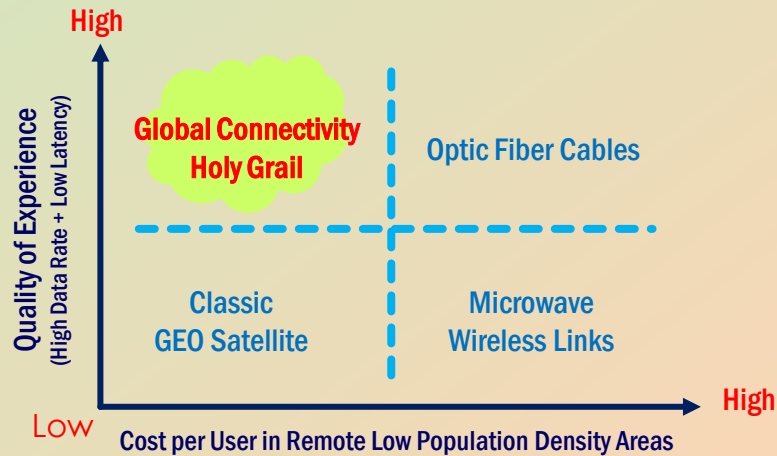
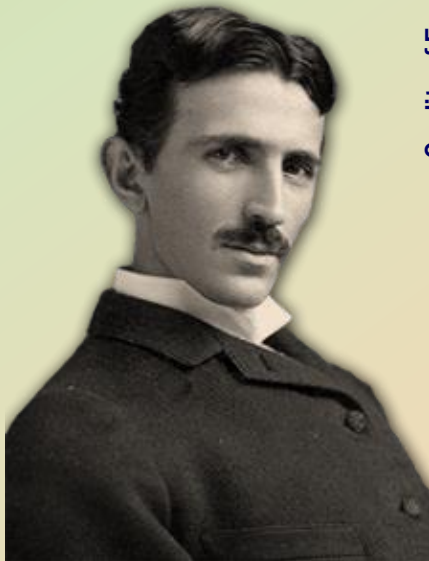




Hybrid THz/FSO Systems



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.”

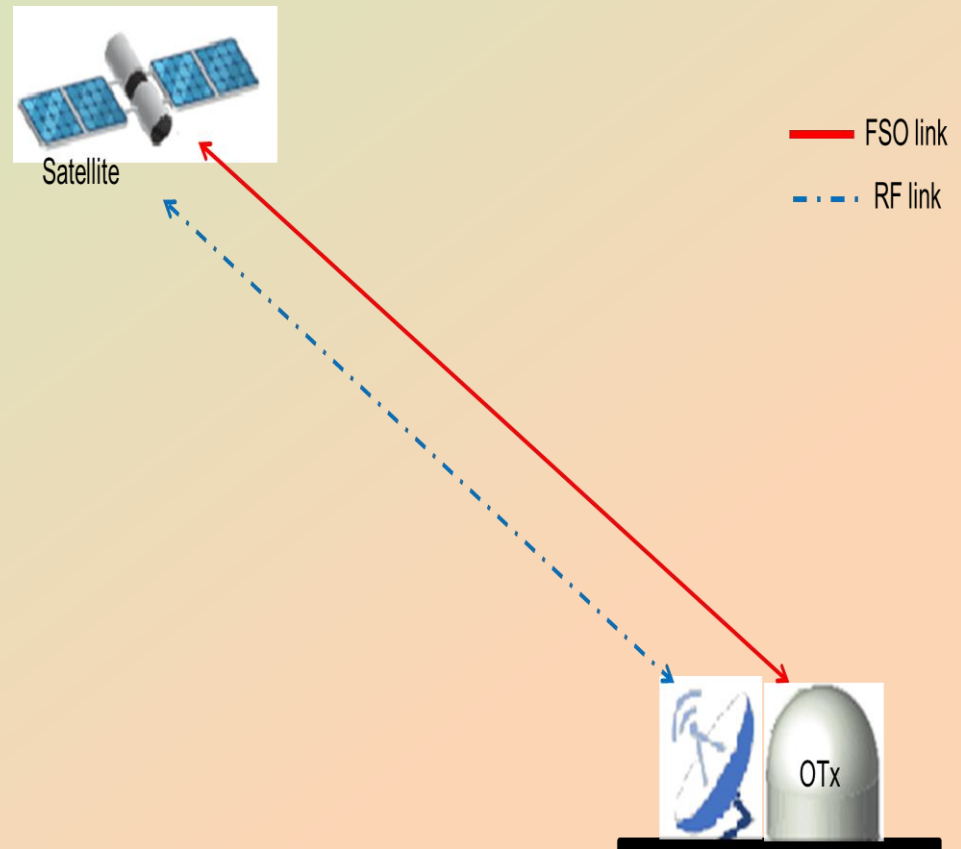
— Nikola Tesla 1919

Integrated Space-Air-Ground Networks



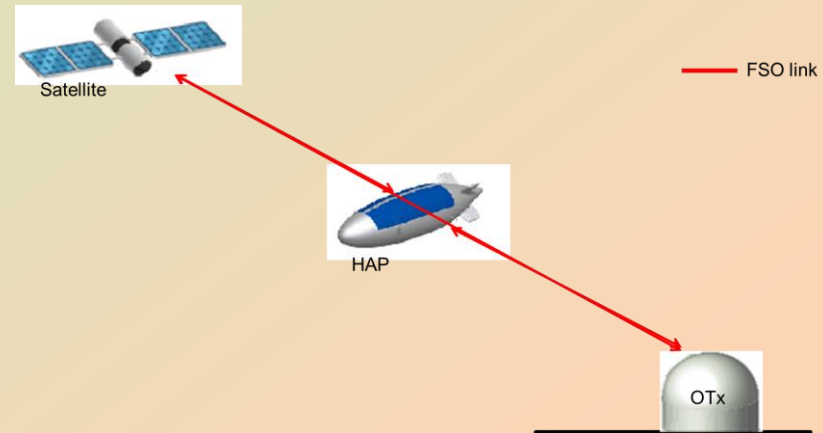
Hybrid FSO/RF Transmission

- RF transmission exhibits complementary characteristics to FSO transmission.
- When FSO link becomes unacceptable, the system switches to RF backup link.
- However, switching to RF link reduces overall system throughput.



Space-Air-Ground (SAG) FSO Network

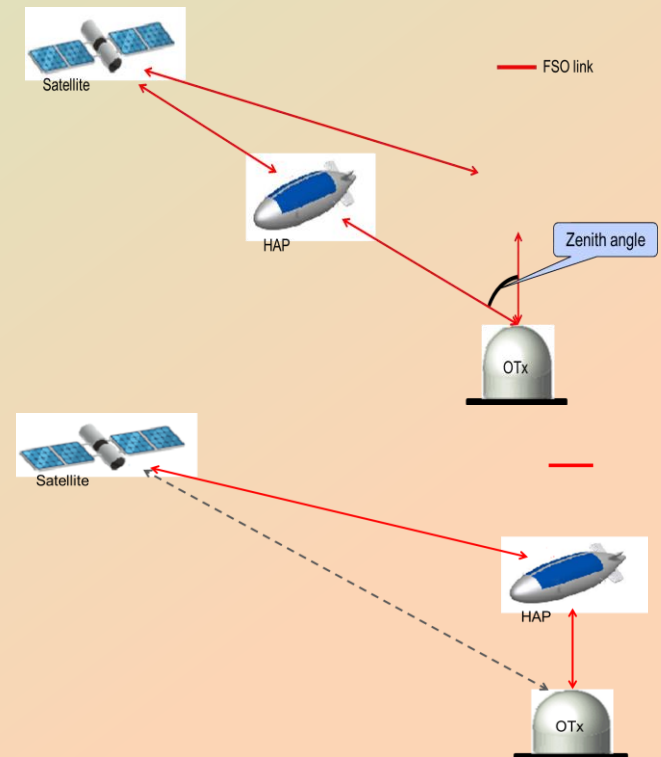
- Introduce a HAPS with FSO relaying capability to create a SAG FSO network.
- Reduce beam-wandering effect with two short hops and achieve a gain of 4 dB.
- Ground-to-HAP hop experiences similar amount of turbulence as direct link.



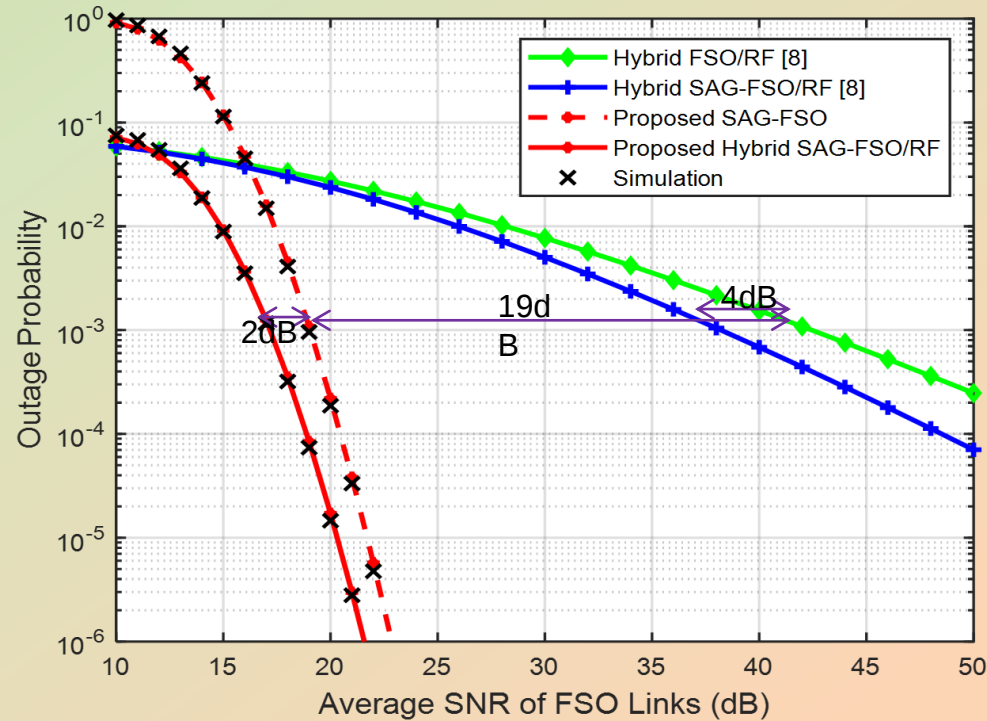
R. Swaminathan, S. Sharma, N. Vishwakarma, and A. Madhukumar, "HAPS-based relaying for integrated space-air-ground networks with hybrid FSO/RF communication: A performance analysis," IEEE Transactions on Aerospace and Electronic Systems, 2021

Improving SAG-FSO Networks

- Propagation distance through strong turbulence region increases with zenith angle.
- To effectively reduce the atmospheric turbulence experienced by ground-to-HAP hop, we propose to dispatch a HAPS with FSO relay directly above the ground station.



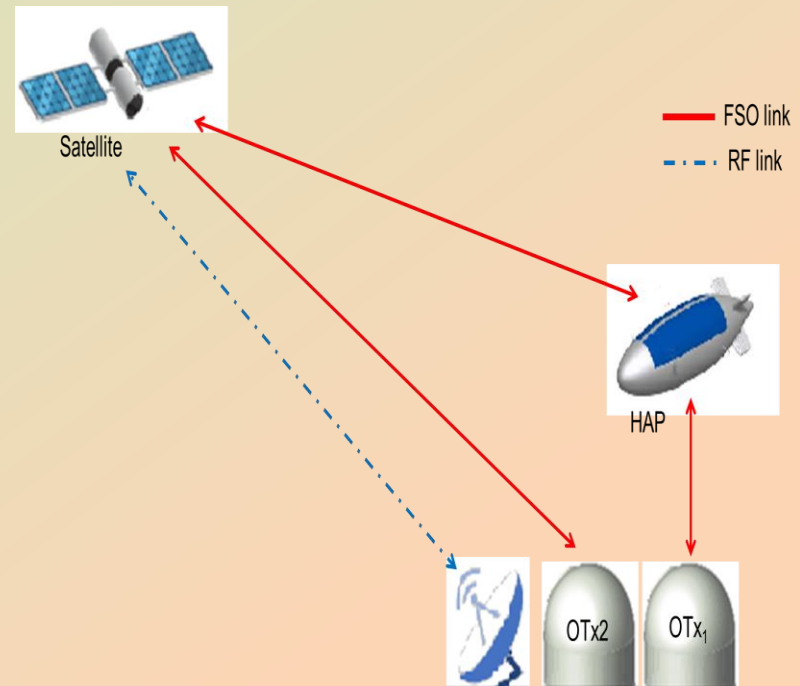
End-to-End Outage Probability



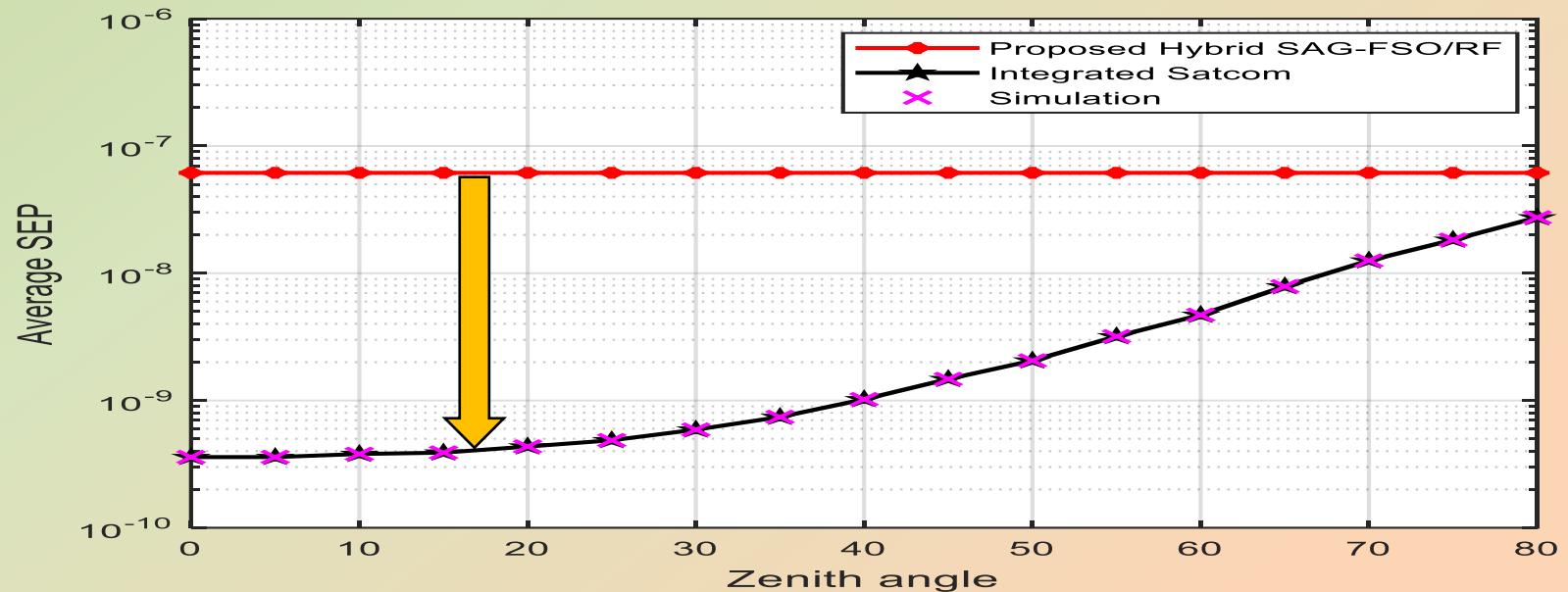
Proposed SAG-FSO/RF design outperforms previous ones by at least 20 dB at outage level of 10^{-3} .

Reliable High-Throughput Satcom System

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



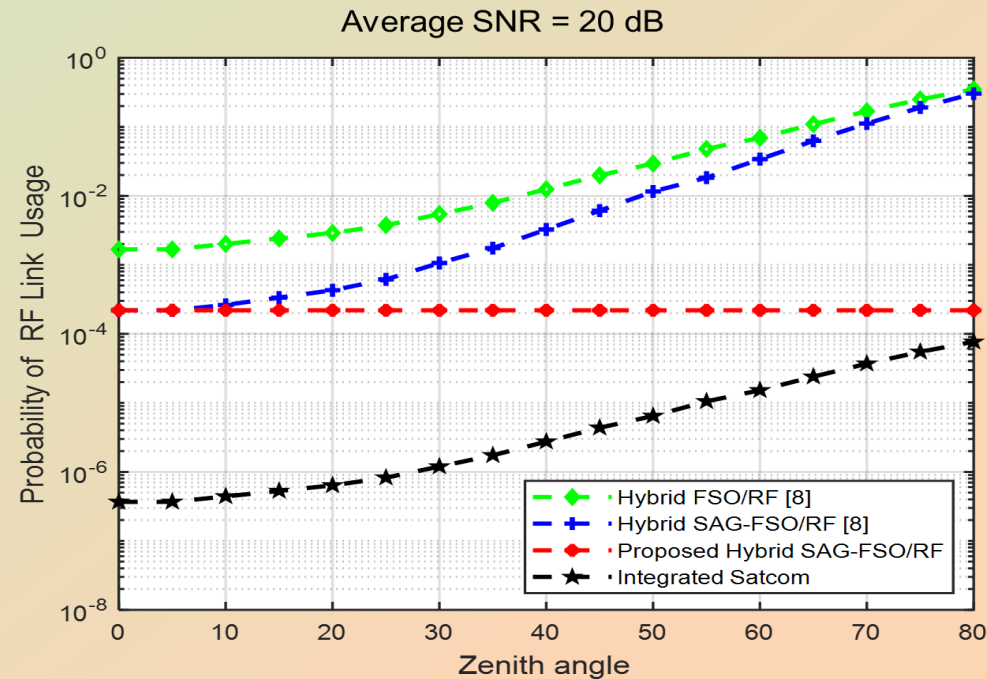
End-to-End Average Symbol Error Probability



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

- 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.

Nikola Tesla

(10 July 1856 – 7 January 1943)

"When wireless is perfectly applied, the whole earth will be converted into a huge brain, which in fact it is, all things being particles of a real and rhythmic whole. We shall be able to communicate with one another instantly, irrespective of distance."

Nikola Tesla (1925)



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Thank You
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