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King Abdullah University of Science and Technology

Co-Existence of Optical & RF Wireless Communication Systems



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Growth of Mobile Phone Subscribers & Data Traffic

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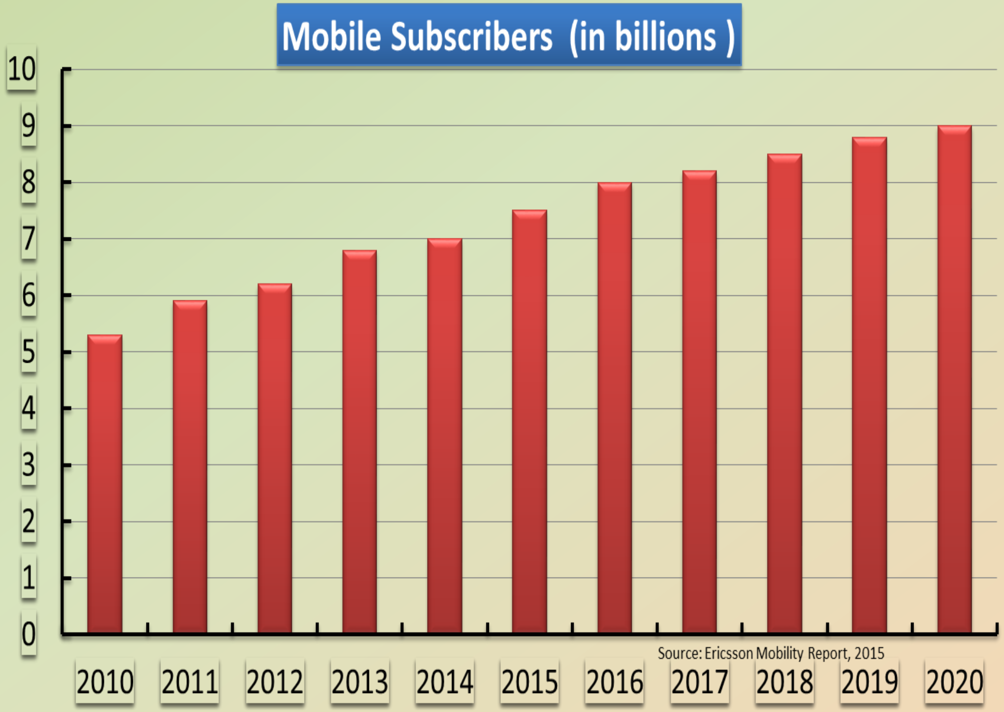
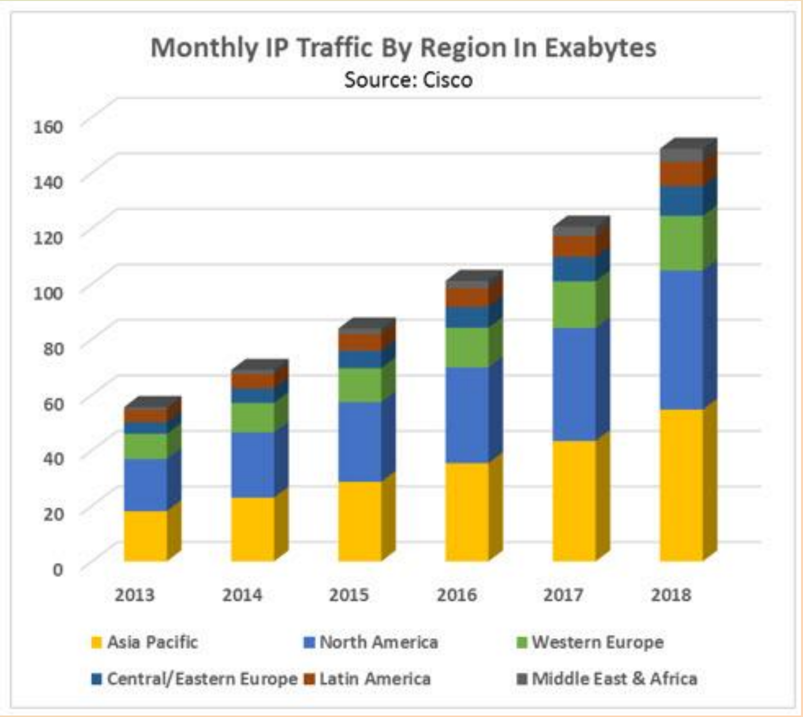
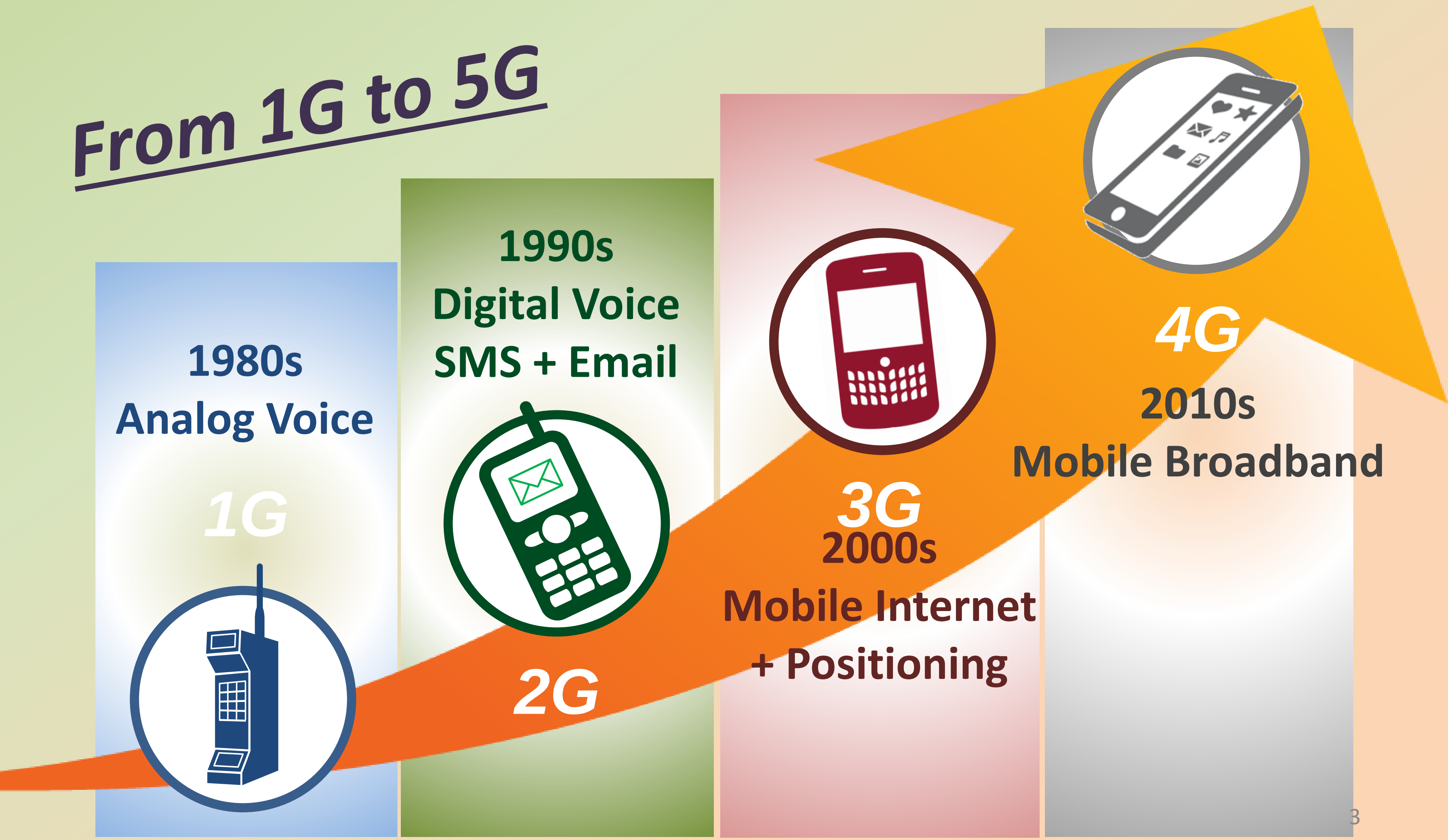




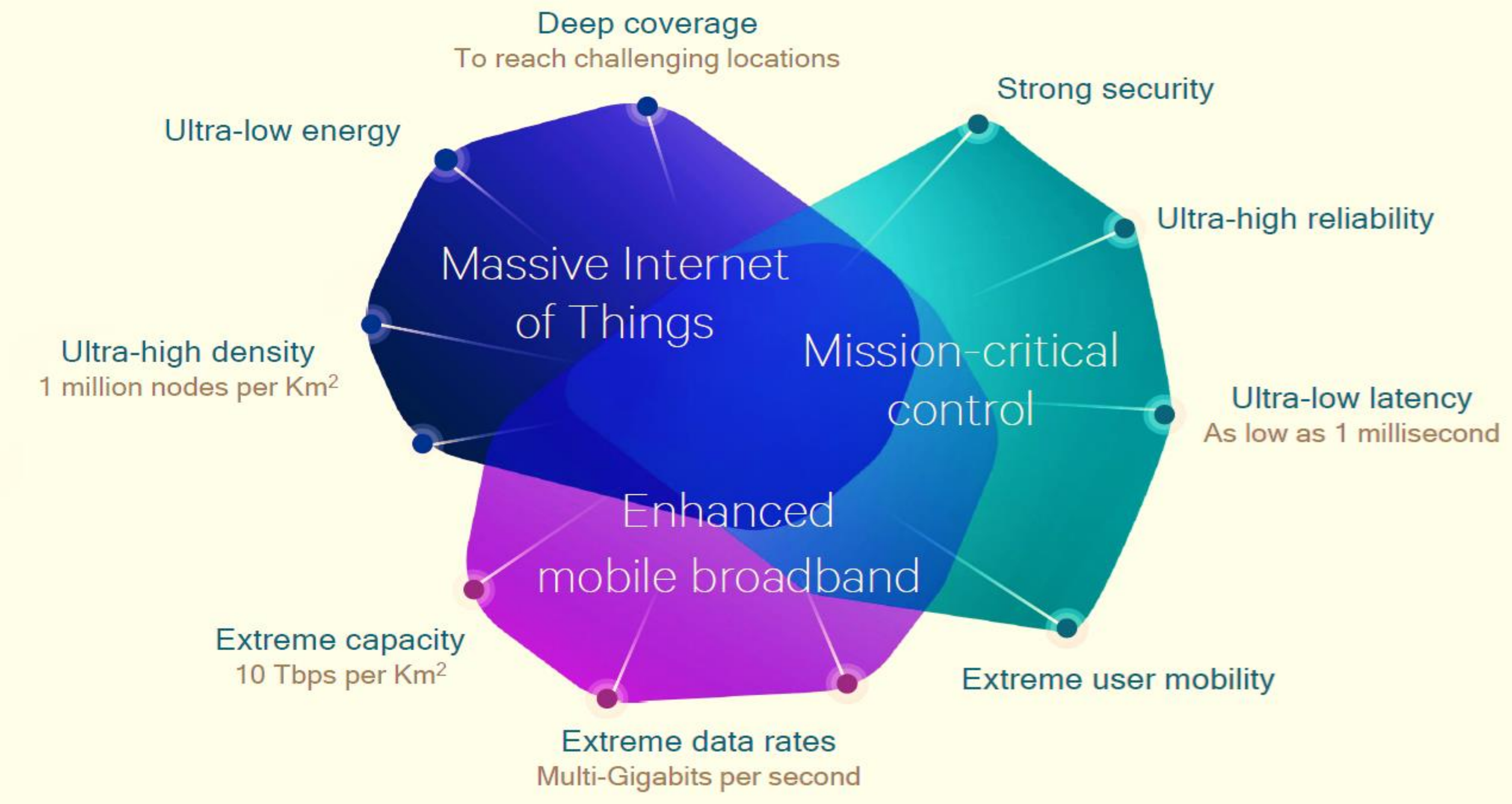
Mobile internet traffic growth is pushing the capacity limits of wireless networks !

Evolution of Generations



Evolution Towards 5G

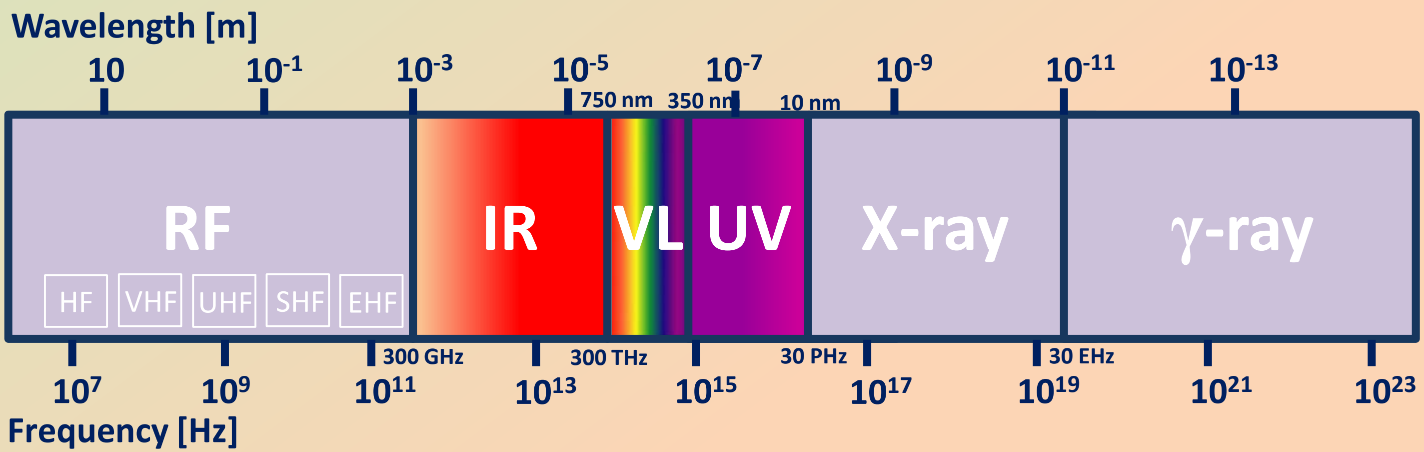
- Connect over 50 billions of wireless capability devices.
- Need to be green and sustainable.



[1] Qualcomm, "5G – Vision for the next generation of connectivity", March, 2015.

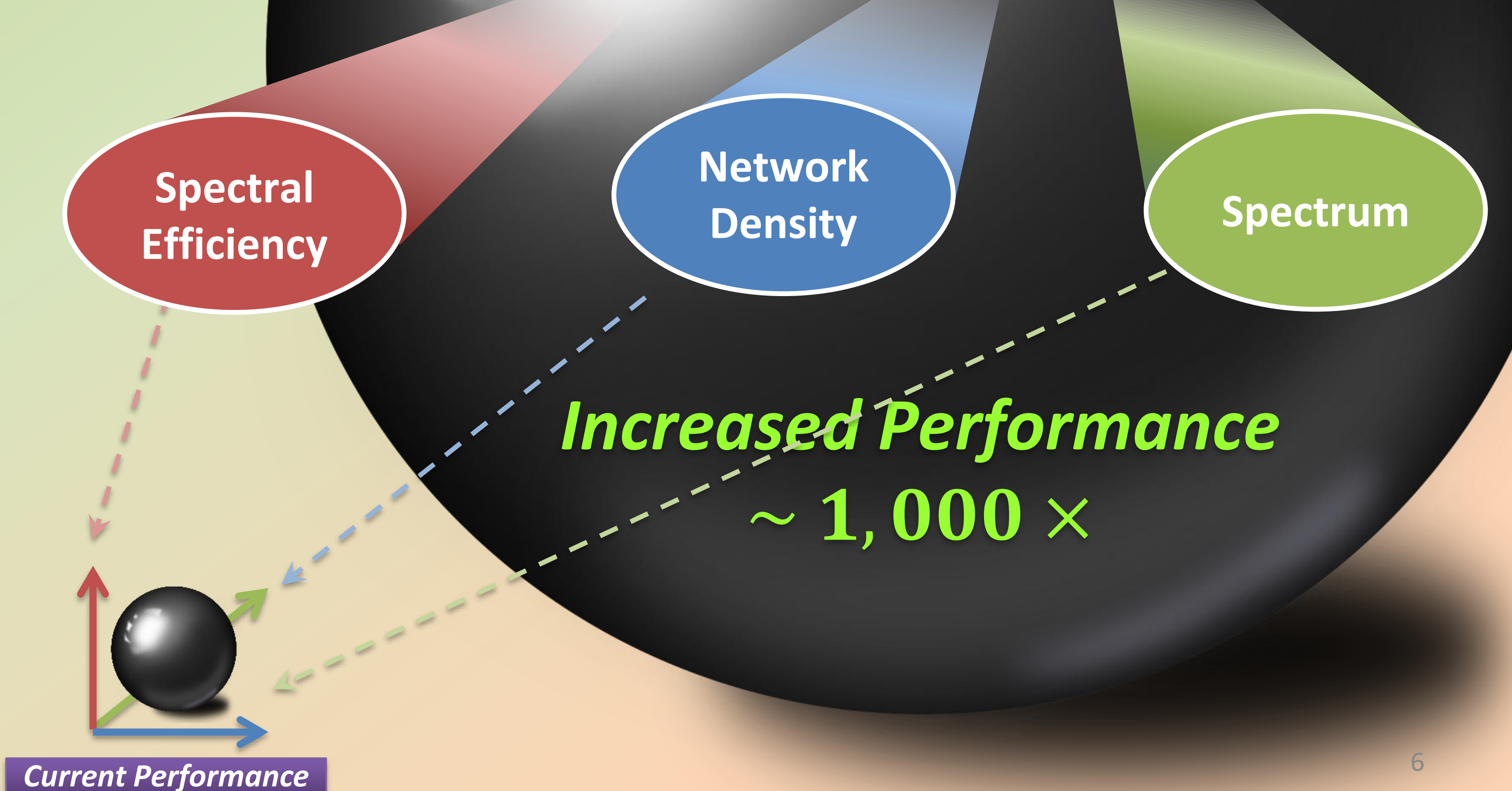
Spectrum

- 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)



Increasing the Area Traffic Capacity

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



Potential Enabling Technologies

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

Better Spectral Efficiency	Higher Network Densification	More Spectrum
❑ Massive MIMO	❑ Spectrum Sharing	❑ Carrier Aggregation
❑ Artificial Radio Space	❑ Cloud-RAN	❑ Mm-Wave (60GHz)
❑ Interference Management	❑ Small Cells	❑ THz Com
❑ Full Duplex Radio	❑ D2D	❑ Optical Wireless Com

Potential Enabling Technologies
- Spectral Efficiency Improvement

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

Better Spectral Efficiency

$$C = W \alpha n \log_2(1 + SINR)$$

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

Source: Qualcomm

Potential Enabling Technologies

- Spectral Efficiency Improvement

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

Better Spectral Efficiency

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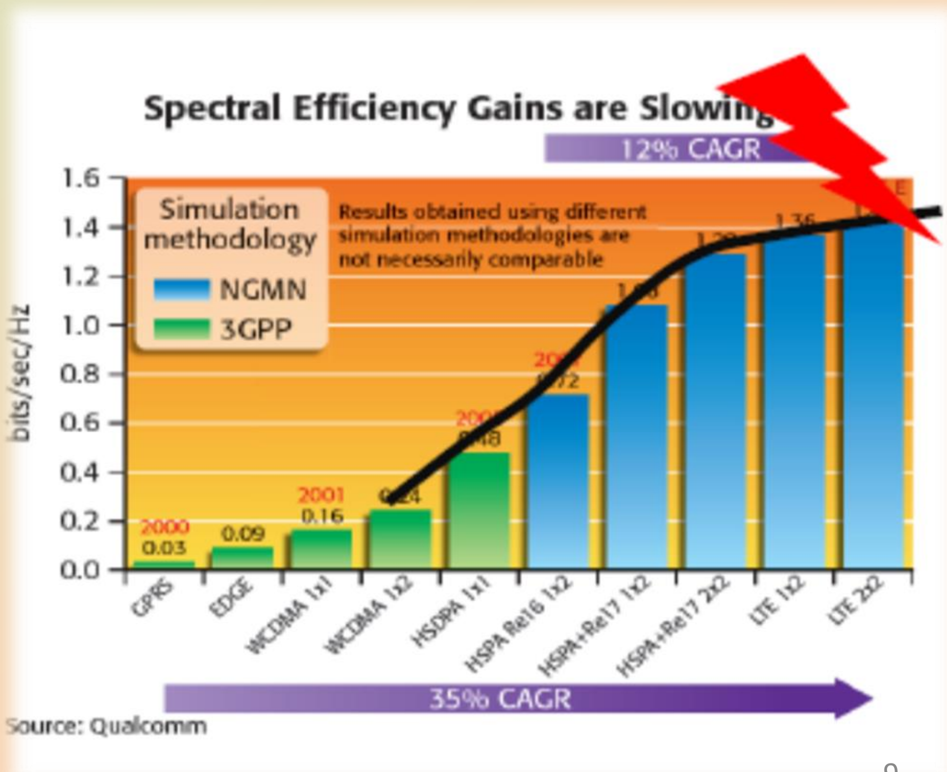
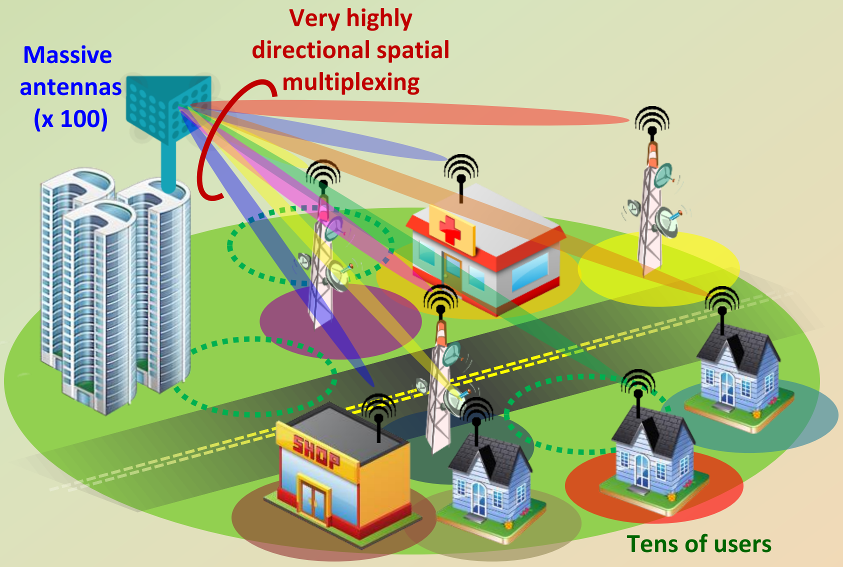
- ❑ Massive MIMO
- ❑ Interference Management
- ❑ Full Duplex Radio



Massive MIMO

Base stations are equipped with a very large number of antennas, thereby scaling up the conventional MIMO systems by many orders of magnitude.



Potentials:

- Increase the capacity by 10 times or more.
- Improve the radiated energy-efficiency: more directed beams.
- Inexpensive and low-power components.
- Robustness to noise and man-made interference.

Challenges:

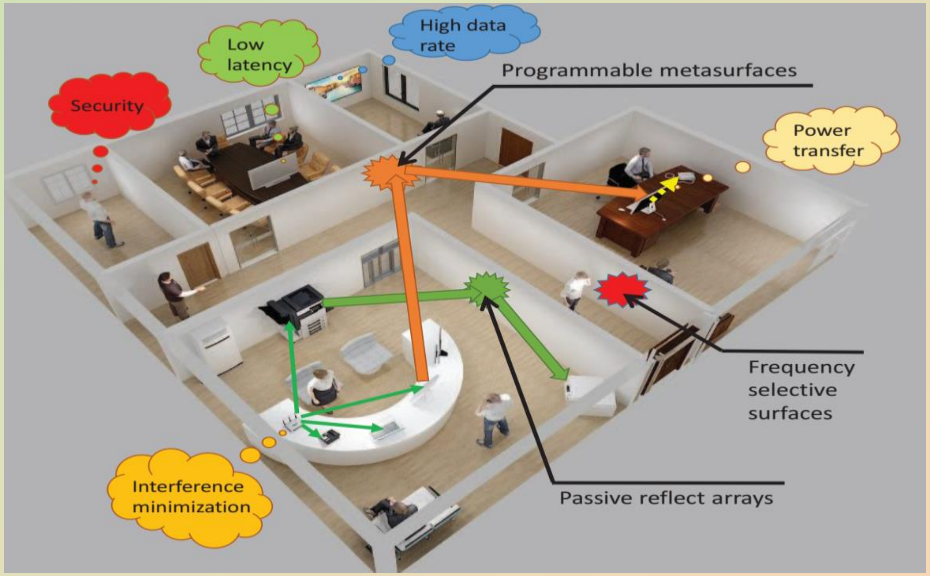
- Design of compact antenna arrays, while minimizing the fading correlation between antenna elements.
- Acquisition of high dimension CSI.
- Increase in pilot overhead.
- Extremely computational demand on classical precoding and receiving techniques

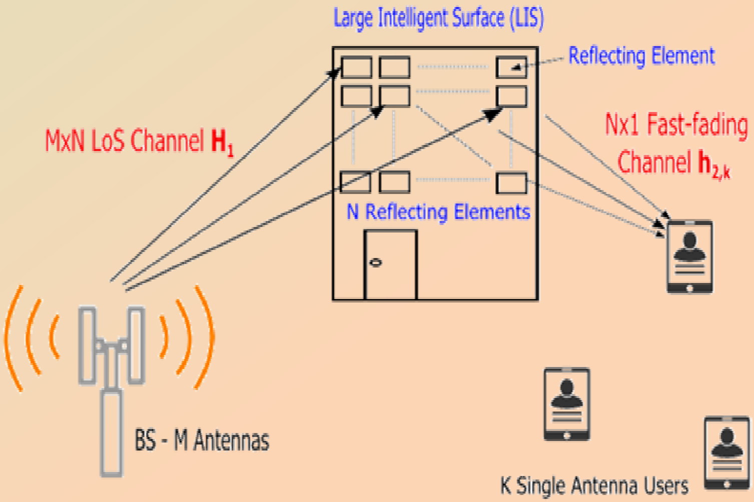
[1] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, “Scaling up MIMO: Opportunities and challenges with very large arrays,” IEEE Signal Processing Magazine, vol. 30, no. 1, pp. 40-46, January 2013.

[2] H. Sifaou, A. Kammoun, L. Sanguinetti, M. Debbah, and M. -S. Alouini, "Max-Min SINR in large-scale single-cell MU-MIMO: Asymptotic analysis and low complexity transceivers", IEEE Transaction on Signal Processing, Vol. 65, No. 7, pp. 1841-1853, April 2017.

Artificial Radio Space

- A new concept to assist **reliable, secure, spectrum- and power- efficient** communications in indoor and outdoor scenarios
- Using a metal/metamaterial surfaces or tunable reflect arrays consisting of low-cost low-power-consuming passive/active reflecting elements
- To make the propagation channel more favorable to satisfy various QoSs
- Easily placed in/on the wall/ceilings of the buildings





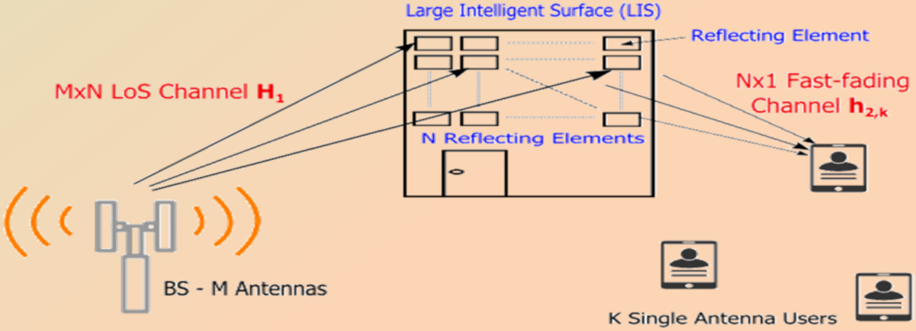
[1] C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, “A new wireless communication paradigm through software-controlled metasurfaces,” *IEEE Commun. Mag.,* vol. 56, no. 9, pp. 162–169, Sep. 2018
[2] C. Huang, A. Zappone, M. Debbah, and C. Yuen, “Achievable rate maximization by passive intelligent mirrors,” in *2018 IEEE ICASSP*, Calgary, Canada, Apr. 2018, pp. 3714–3718.

Large Intelligent Surface (LIS) Assisted Wireless Communication

- A very new concept [2], [3], with the potential of significantly reducing the energy consumption of wireless networks while realizing Massive MIMO gains.
- Base station (BS) communicates with the users through a LIS.
- LIS is a planar array consisting of a large number of nearly **passive, low-cost and low energy consuming, reflecting elements**, with reconfigurable parameters.
- Each element induces a certain phase shift on the incident electromagnetic wave.
- Objective is to make the **propagation channel more favorable** for the users.
- Can be easily integrated into the walls of the building.

Current implementations:

- Reconfigurable reflect arrays,
- Liquid crystal metasurfaces,
- Programmable metamaterials.



[2] C. Huang *et al.*, "Energy efficient multi-user MISO communication using low resolution large intelligent surfaces," in IEEE GLOBECOM, Abu Dhabi, UAE, Dec. 2018.
[3] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network: Joint active and passive beamforming design," in IEEE GLOBECOM, Abu Dhabi, UAE, Dec. 2018.

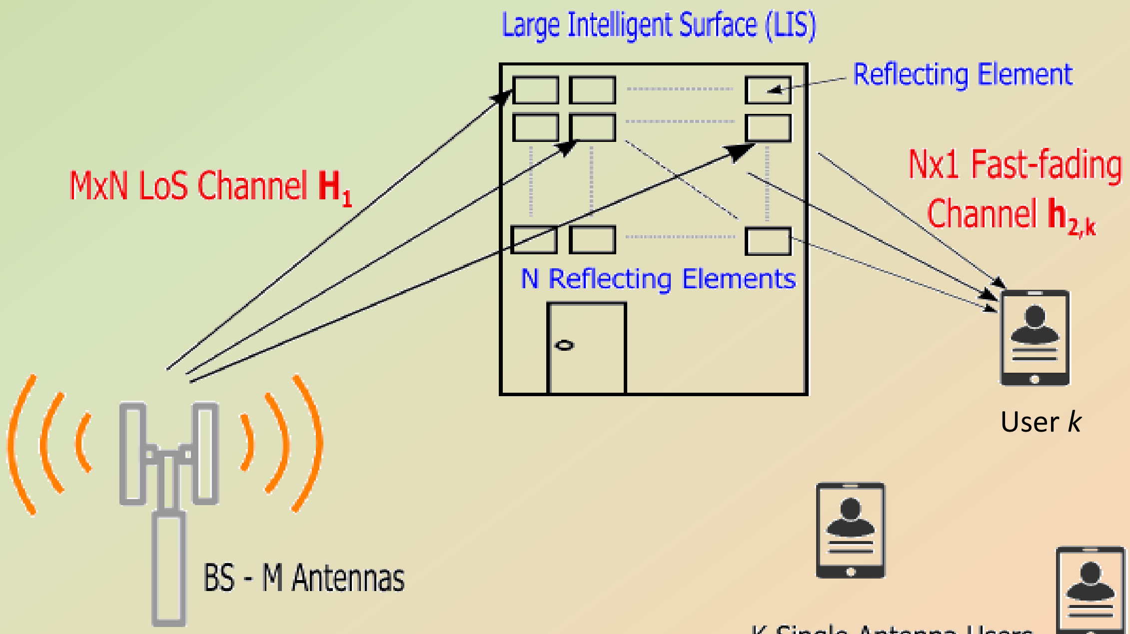
Not to be Confused with:

- **Amplify and Forward Relay [4]**
  - Assists in transmission by actively generating new signals.
  - Requires a dedicated energy source.

- **Active Large Intelligent Surface (LIS) based Massive MIMO [5]**
  - Data transmission with LISs.
  - Massive antenna arrays deployed on these surfaces with a fixed transmit power per volume-unit constraint.
  - Current focus is on indoor scenarios, where the technology is shown to be highly effective in interference suppression.
  - Promising research direction for data-transmission in communication systems beyond Massive-MIMO.

[4] B. Sainath and N. B. Mehta, "Generalizing the amplify-and-forward relay gain model: An optimal SEP perspective," IEEE Transactions on Wireless Communications, vol. 11, no. 11, pp. 4118–4127, Nov. 2012.
[5] S. Hu et al., "Beyond massive MIMO: The potential of data transmission with large intelligent surfaces," IEEE Transactions on Signal Processing, vol. 66, no. 10, pp. 2746–2758, May 2018

LIS Assisted MU-MISO System



M x 1 Channel between the BS and user *k* is modeled as,

$$\mathbf{h}_k = \mathbf{H}_1 \mathbf{\Theta} \mathbf{R}_{\mathrm{LIS}_k}^{1/2} \mathbf{h}_{2,k}$$

- $\mathbf{R}_{\mathrm{LIS}_k}$ represents the correlation matrix of the LIS elements for user *k*.
- $\mathbf{\Theta} = \mathrm{diag}(\Theta_1, \ldots, \Theta_N)$ is a diagonal matrix of effective phase shifts applied by the LIS elements.
- Entries of $\mathbf{h}_{2,k} \sim$ i.i.d. CN(0,1).

Optimal Precoder

- The Tx signal **x** is given as $\mathbf{x} = \sum_{k=1}^{K} \sqrt{p_k}\mathbf{g}_k s_k$, where p_k is the Tx power of symbol s_k for user *k* and $\mathbf{g}_k$ is the precoding vector for user *k*.
- Downlink SINR is defined as $\gamma_k = \frac{p_k |\mathbf{h}_k^H \mathbf{g}_k|^2}{\sum_{\substack{i=1\\i\neq k}}^{K} p_i |\mathbf{h}_k^H \mathbf{g}_i|^2 + \frac{1}{\rho}}$.
- **Problem (P1):**

$$\underset{\mathbf{P},\mathbf{G}}{\text{maximize}} \ \underset{k\in\{1,\ldots,K\}}{\text{minimize}} \ \gamma_k$$
$$\text{subject to} \quad \frac{1}{K}\mathbf{1}^T\mathbf{p} \leq P_{max}, ||\mathbf{g}_k|| = 1, \forall k.$$

- **Solution:**

$$\mathbf{g}_k^* = \frac{\left(\sum_{\substack{i=1\\i\neq k}}^{K} q_i^* \mathbf{h}_i \mathbf{h}_i^H + \frac{1}{\rho}\mathbf{I}_M\right)^{-1} \mathbf{h}_k}{||\left(\sum_{\substack{i=1\\i\neq k}}^{K} q_i^* \mathbf{h}_i \mathbf{h}_i^H + \frac{1}{\rho}\mathbf{I}_M\right)^{-1} \mathbf{h}_k||},$$

$$q_k^* = \frac{\tau^*}{\mathbf{h}_k^H \left(\sum_{\substack{i=1\\i\neq k}}^{K} q_i^* \mathbf{h}_i \mathbf{h}_i^H + \frac{1}{\rho}\mathbf{I}_M\right)^{-1} \mathbf{h}_k},$$

$$\tau^* = \frac{K P_{max}}{\sum_{k=1}^{K} (\mathbf{h}_k^H \left(\sum_{\substack{i=1\\i\neq k}}^{K} q_i^* \mathbf{h}_i \mathbf{h}_i^H + \frac{1}{\rho}\mathbf{I}_M\right)^{-1} \mathbf{h}_k)^{-1}}$$

$$\mathbf{p}^* = (\mathbf{I}_K - \tau^* \mathbf{D}\mathbf{F}/\rho)^{-1} \tau^* \mathbf{D}\mathbf{1}_K/\rho,$$

Case I – Rank-One H_1 ($H_1 = ab^H$)

- Optimal value of SINR is equal to τ^*, so we focus on analyzing τ^*.
- After some tedious calculations involving the use of Woodbury identity, we find,

$$\tau^* = \frac{P_{max}}{Z + P_{max}(K-1)}$$

where $\mathbf{Z} = \frac{1}{K}\sum_{k=1}^{K}\frac{1}{\rho \mathbf{h}_{2,k}^H \mathbf{v}_k \mathbf{v}_k^H \mathbf{h}_{2,k}}$, where $\mathbf{v}_k = \mathbf{R}_{\text{LIS}_k}^{1/2}\mathbf{\Theta}^H \mathbf{b}$.

- Optimal precoder turns out to be matched filter, i.e. $\mathbf{g}_k^* = \frac{\mathbf{h}_k}{||\mathbf{h}_k||}$.

For K=1:

- **Problem (P2):**

$$\underset{\mathbf{\Theta}}{\text{maximize}} \quad \tau^* \qquad \text{subject to} \quad |\Theta_n| = 1, \forall n = 1, \dots, N.$$

$\Rightarrow$

$$\underset{\mathbf{\Theta}}{\text{minimize}} \quad \frac{1}{\mathbf{h}_{2,k}^H \mathbf{R}_{\text{LIS}_k}^{1/2} \mathbf{\Theta}^H \mathbf{b}\mathbf{b}^H \mathbf{\Theta} \mathbf{R}_{\text{LIS}_k}^{1/2} \mathbf{h}_{2,k}} \qquad \text{subject to} \quad |\Theta_n| = 1, \forall n = 1, \dots, N.$$

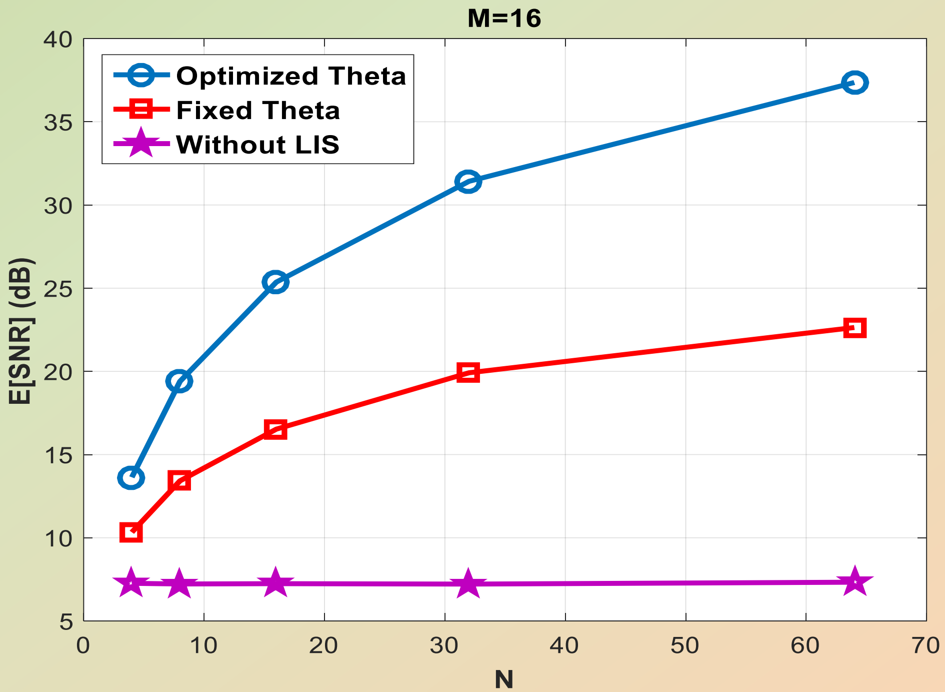
- **Solution:** Let $\mathbf{w} = [\Theta_1, \dots, \Theta_n]^T$, then the (close to) optimal phases are computed as,

$$\mathbf{w}^* = \exp(j\arg(\bar{\mathbf{w}}^*)),$$

$$\bar{\mathbf{w}}^* = \text{Eigenvector corresponding to the max eigenvalue of } \bar{\mathbf{V}}\bar{\mathbf{V}}^H,$$

$$\bar{\mathbf{V}} = (\text{diag}(\mathbf{h}_2^H)\mathbf{R}_{\text{LIS}}^{1/2})^T \mathbf{b}$$

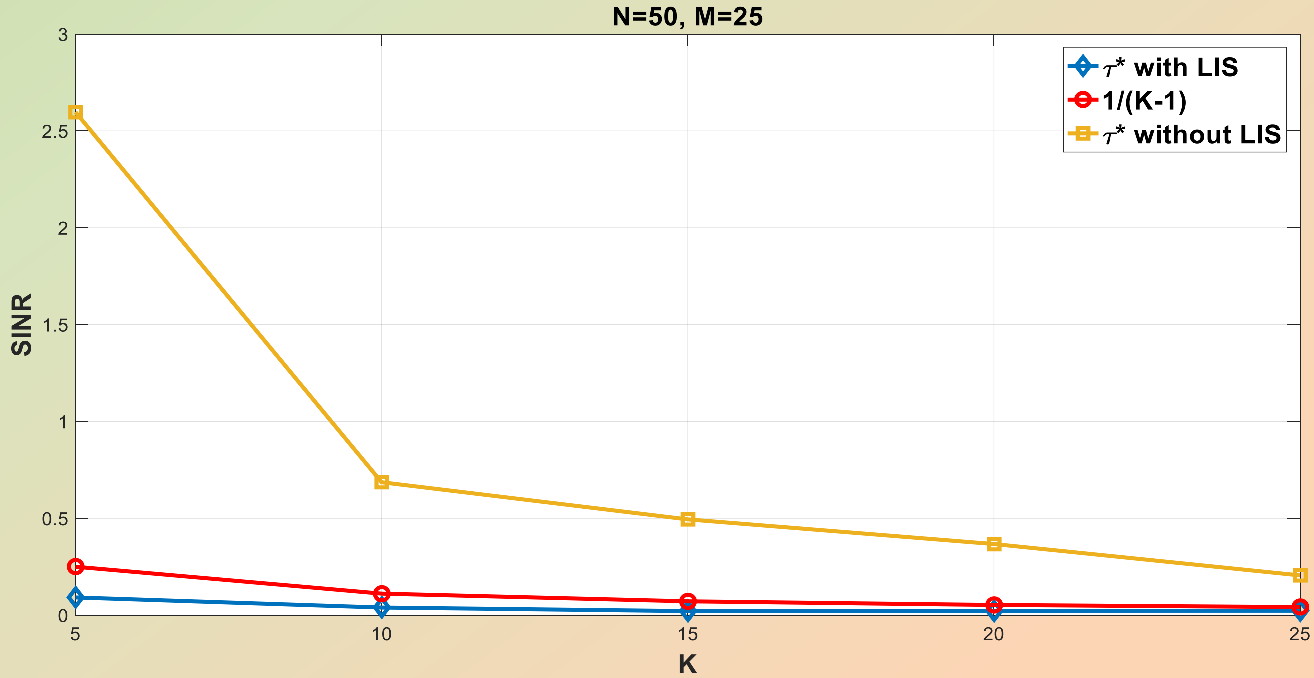
Performance (K=1)



- Comparison done with direct channel between the BS and user, $\mathbf{h}_d = \mathbf{R}_{BS}^{1/2}\mathbf{h}_3$, where entries of $\mathbf{h}_3 \sim \mathcal{CN}(0,1)$, with optimal Tx beamforming, i.e. $\mathbf{g}^* = \frac{\mathbf{h}_d}{||\mathbf{h}_d||}$.
- Average optimal SNR scales with the number of reflecting elements in the order N^2.
- **Array gain of N** and **beamforming gain of N.**
- Significant improvement with only passive phase shifters – **more spectral and energy efficient.**

Multi-User (MU) Setting

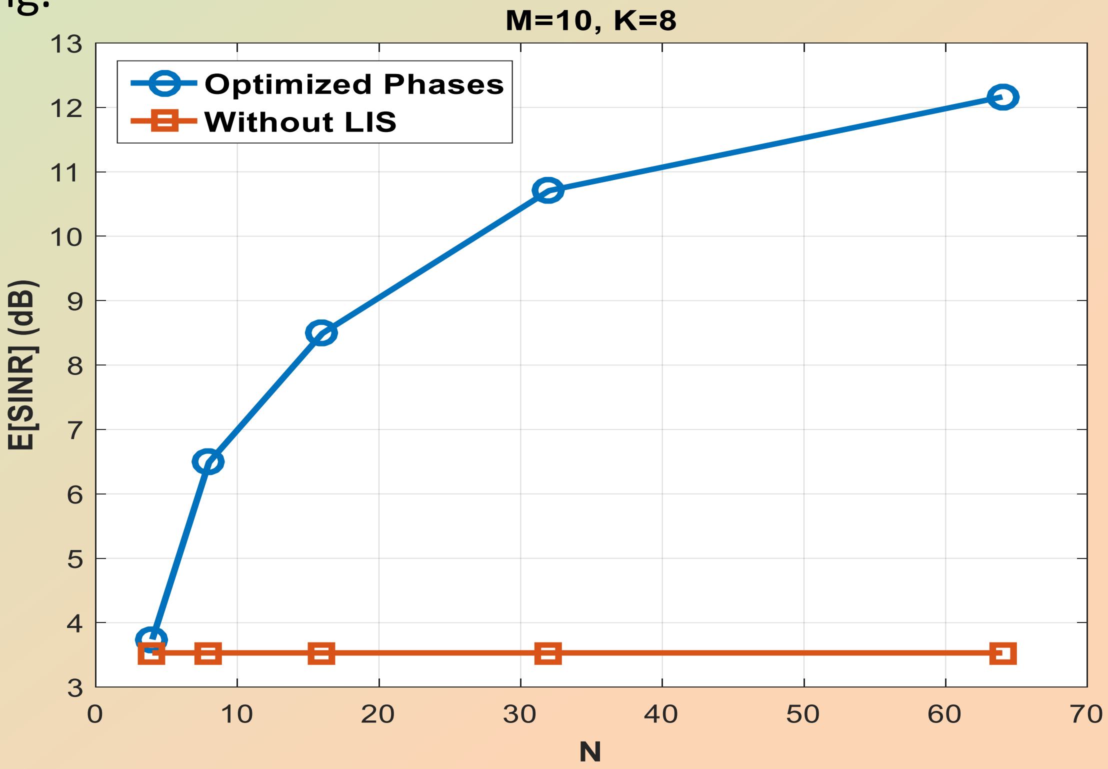
During our derivations we find that with a rank-one channel between the BS and the LIS the optimal SINR is bounded as, $\tau^* \leq \frac{1}{K-1}, \quad \text{for } K > 1$



- **Received average SINR of each user remains within a bound that goes to 0, no matter what value of N or what phases are used.**
- **Harmful to deploy LIS in a MU setting with a rank-one LoS BS-to-LIS channel.**

Case II – Full Rank H_1

- Phases that maximize the deterministic equivalent of τ^* are computed using projected gradient descent.
- Performance compared with the case where BS directly communicates with the users using optimal precoding and power allocation.
- Result shows that by introducing rank in $\mathbf{H}_1$, average optimal SINR scales even in the MU setting.



Further Research Directions

- Low-overhead signal exchange and channel estimation design to provide the LIS with the CSI to adapt the phases.

- Optimal positioning of the LIS, such that the channel is LoS but not rank-one.

- Correlation characterization for the LIS, based on the underlying technology used.
- Hardware limitations: low resolution phase shifters

Potential Enabling Technologies
- More Spectrum

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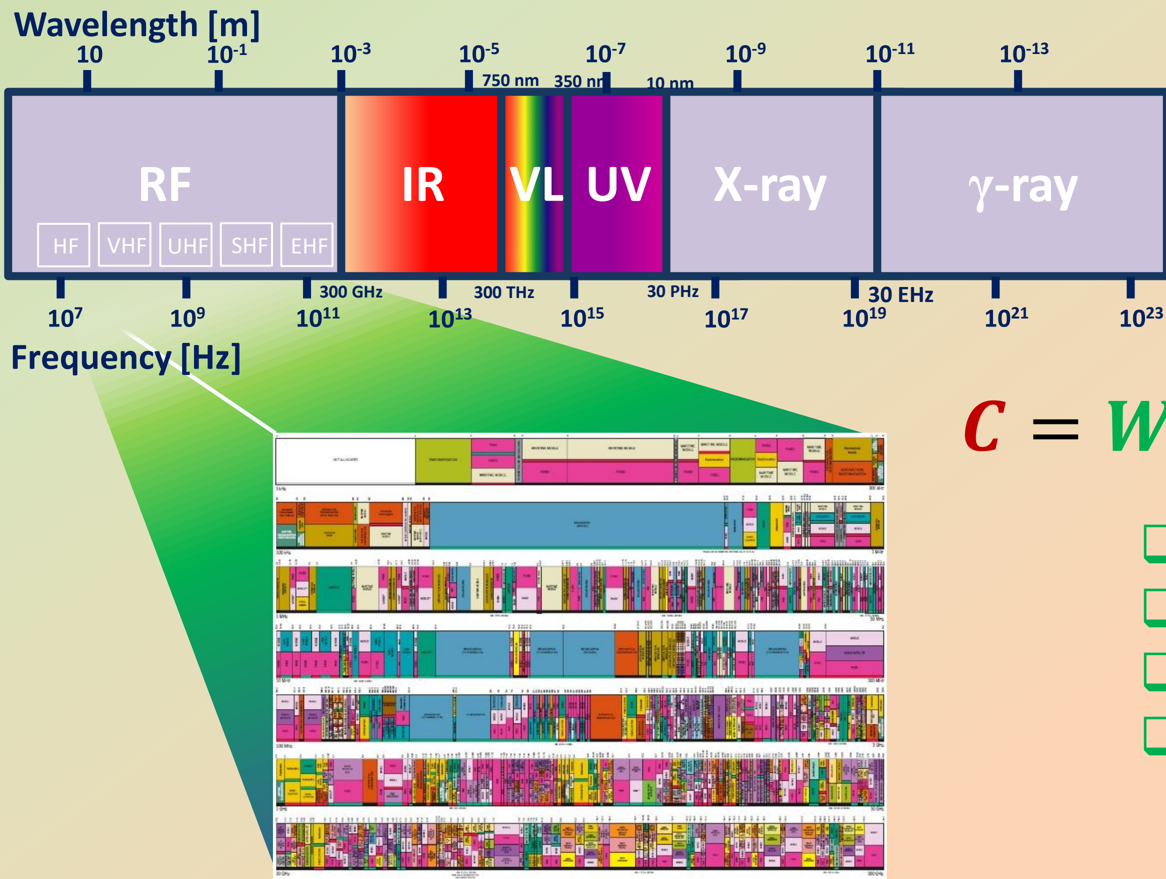
$$\frac{bits/s}{m^2} = \frac{bits/s}{Hz \cdot node} \cdot \frac{node}{m^2} \cdot Hz$$

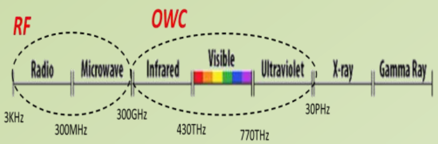


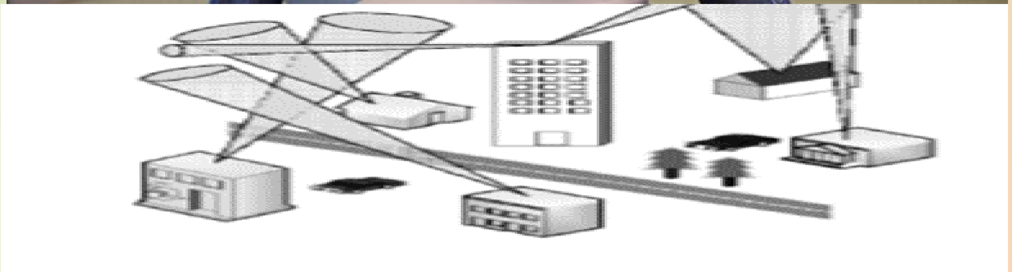
More Spectrum

$$C = W\alpha n \log_2(1 + SINR)$$

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

Optical Wireless Communications





- Point-to-point **free space optical communications (FSO)** using lasers in the near IR band (750 nm -> 1600 nm)
- **Visible light communications** (known also as **Li-Fi**) using LEDs in the 390 nm -> 750 nm band.
- **NLOS UV communication** in the 200 nm to 280 nm band.

[1] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, “Cellular architecture and key technologies for 5G wireless communication networks,” *IEEE Communications Magazine*, vol. 52, no. 2, pp. 122-130, Feb. 2014.
[2] A. Chaaban, Z. Rezki, and M. -S. Alouini, "Fundamental limits of parallel optical wireless channels: Capacity results and outage formulation", IEEE Transactions on Communications, vol. 65, no. 1, pp. 296-311, January 2017.

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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

Applications

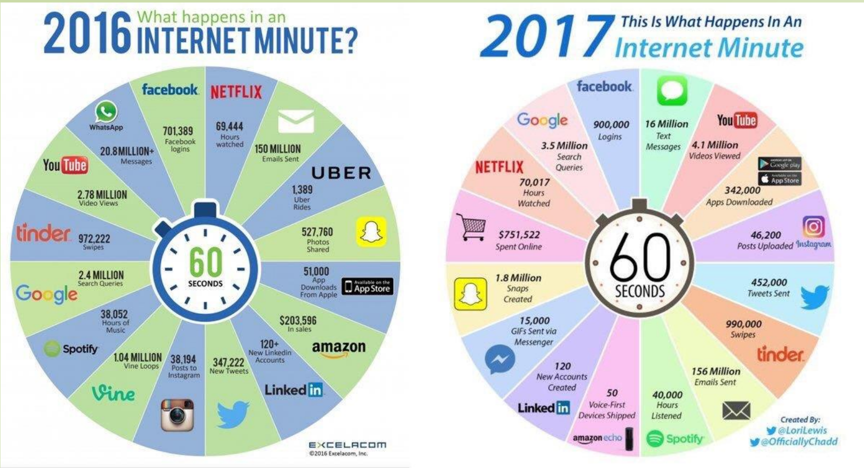
- Initially used for secure military and in space
- Last mile solution
- Optical fiber back-up
- High data rate temporary links
- Wireless Fronthaul/Backhaul in celluar network

Challenges

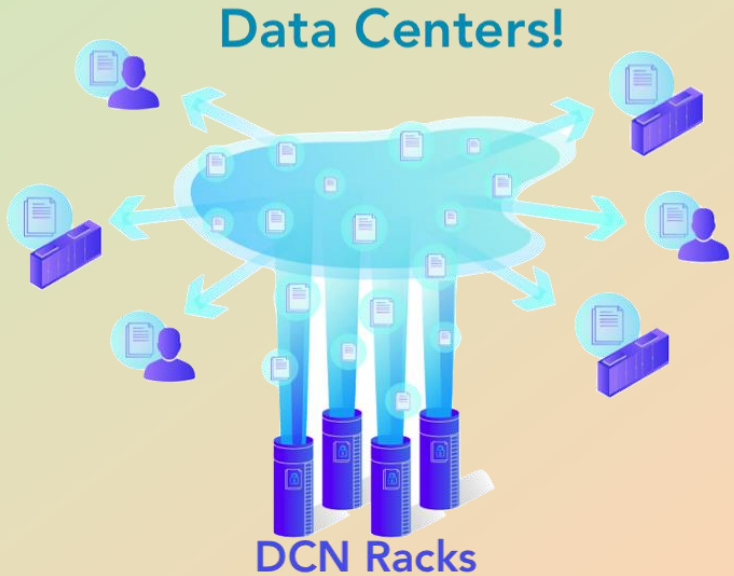
- Additive noise and background radiation
- Atmospheric path loss
- Atmospheric Turbulences
- Alignment and tracking

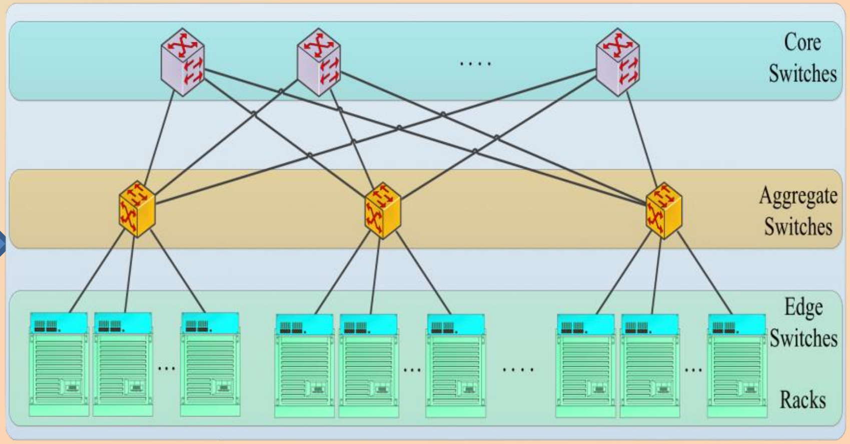
[1] M. Esmail, A. Raghed, H. Fathallah, and M. -S. Alouini, "Investigation and demonstration of high speed full-optical hybrid FSO/fiber communication system under light and storm condition", IEEE Photonics Journal, vol. 9, no. 2, February 2017.
[2] M. Esmail, A. Ragheb, H. Fathallah, and M. -S. Alouini, "Experimental demonstration of outdoor 2.2 Tbps super-channel FSO transmission system", in Proc. Optical Wireless Communications Workshop in conjunction with Proceedings IEEE International Conference on Communications (ICC'2016), Kuala Lumpur, Malaysia, May 2016.

Data Center Communications



Using this analogy, what should an oil refinery or a power plant refer to?

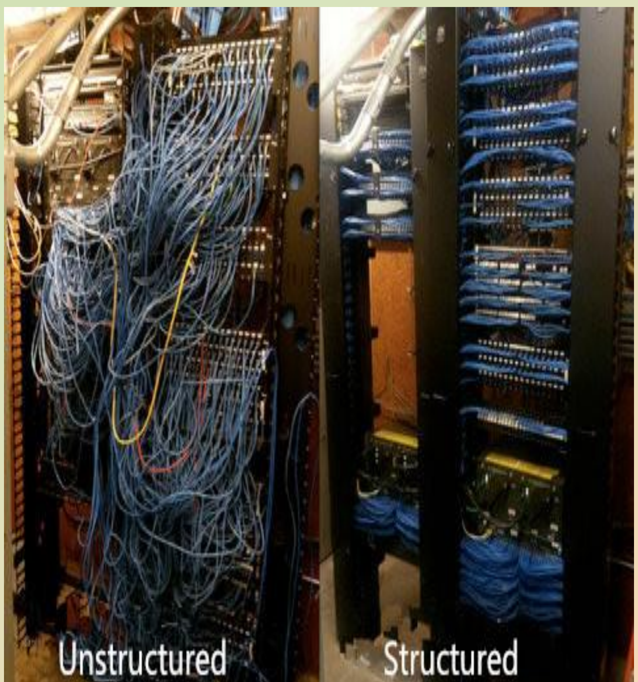




Wireless Data Center Networks

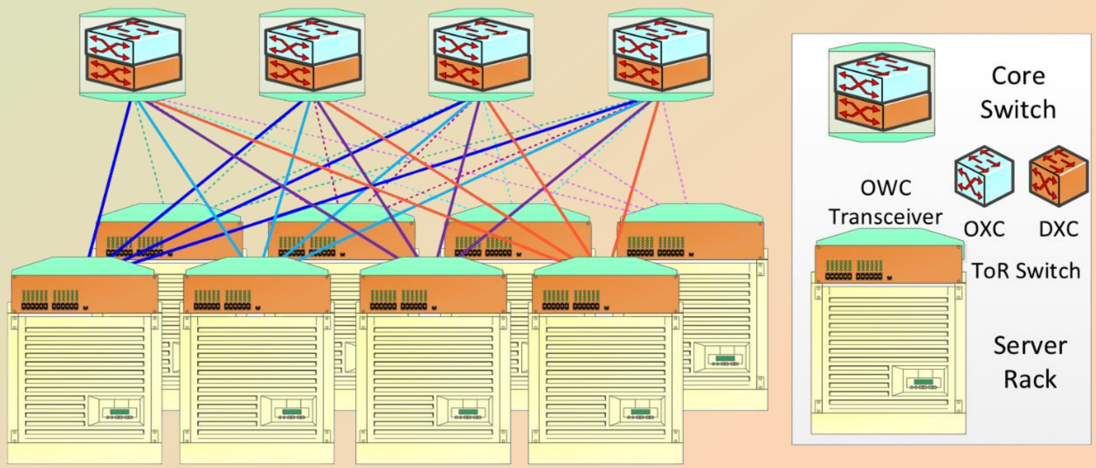
Motivations for WDCNs

1. Reduced cabling cost & complexity
2. Adaptive bandwidths via flexible links.
3. Ability to handle oversubscriptions
4. Convenient deployment, management, and maintenance.



Advantages of WDM-FSO

1. High speeds in the order of Tbps.
2. High fan-out thanks to wavelength division multiplexing (WDM).



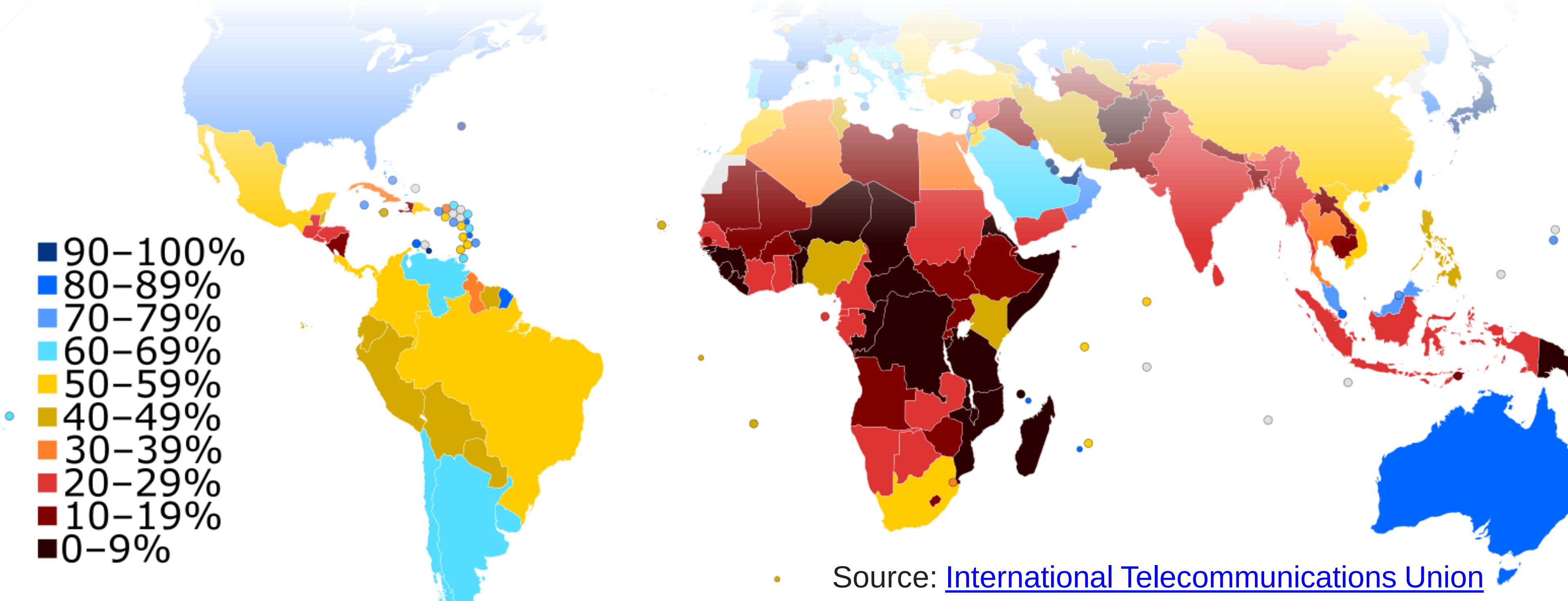
Considered physical topology for the WDM-FSO based WDCNs.

[1]- A. Celik, A. Al-Ghadhban, B. Shihada, and M-S. Alouini, "Design and Provisioning of Optical Wireless Data Center Networks: A Traffic Grooming Approach," in Proc. IEEE WCNC, Apr. 2018. Journal version to appear in IEEE Trans. Communications.

[2]- A. AlGhadhban, A. Celik, B. Shihada, and M-S. Alouini, "LightFD: A Lightweight Flow Detection Mechanism for Traffic Grooming in Optical Wireless DCNs" in Proc. IEEE GLOBECOM, Dec. 2018.

Global Connectivity

- **Billions of people around the world are still without internet access.**
  - Cooperation needed to bring reliable internet to those without it.
  - High-quality connectivity enables richer/denser communities to share knowledge and strengthen the economies of less fortunate/dense communities.



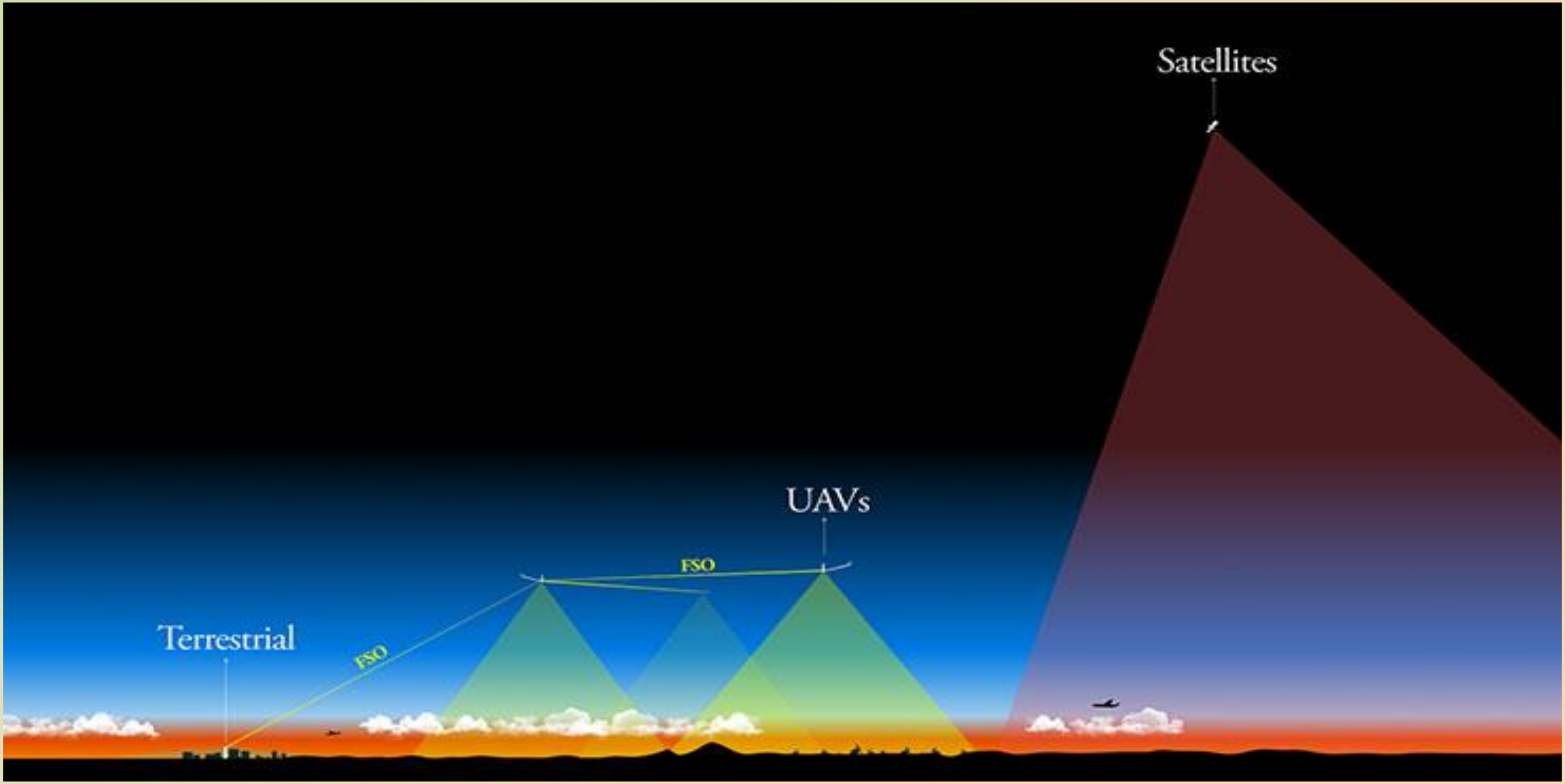
Source: International Telecommunications Union

High-Altitude Connectivity (1)

- Connecting remote communities using existing, conventional technologies such as optical fiber or microwave links on towers is often expensive and unsustainable.
- Connectivity with better channel quality and accessibility throughout the atmosphere and extend existing backhaul at lower costs.
- ***Facebook Project AQUILA*** (2014-2018)
  - A pioneering solar-powered drone flying 25 km up and intended to act as relay stations for providing internet access to remote areas.

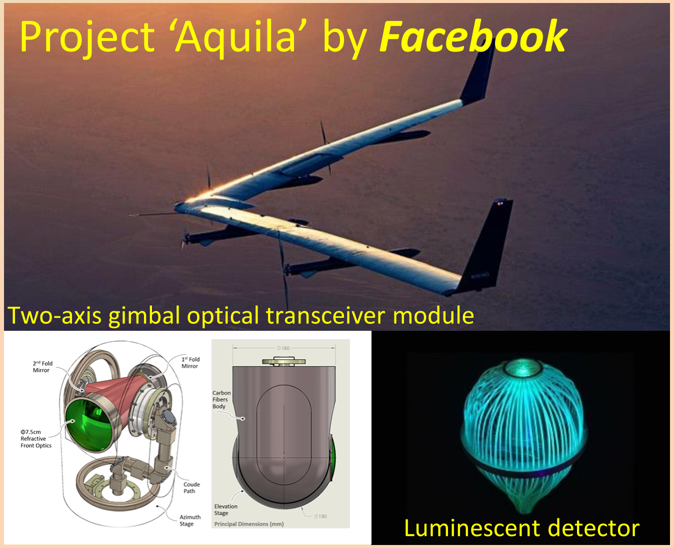
FSO for UAV Communication

Facebook Aquila Project



UAV Communication

- **Unmanned Aerial Vehicle (UAV)-Assisted Communication**
  - Service Areas
    - Air-traffic controls, traffic and environmental monitoring, border surveillance, disaster control and military security.
    - Temporary events where permanent infrastructure does not exist or costly to deploy.
  - Applications
    - Wireless backhauling, data offloading, and relaying
    - Periodic sensing and data collection from sensors
- **UAV-FSO Communication**
  - Keeping the advantages via FSO, while experiencing better channel quality.
  - Pointing, acquisition, tracking (PAT) and link alignment are challenging.
  - Efficient flight trajectory improves the link lifetime and performance.



Trajectory Optimization

- Flight Time Maximization

- **Maximizing service time in a target area**
  - Fixed-wing UAV ($v_{min} > 0$) flies on a fixed height.
  - UAV supports the rate above a rate threshold.
  - The power consumption is dominated by propulsion energy on flight.
  - Non-convex optimization problem can be sub-optimally solved by combining a bisection method and sequential convex optimization.

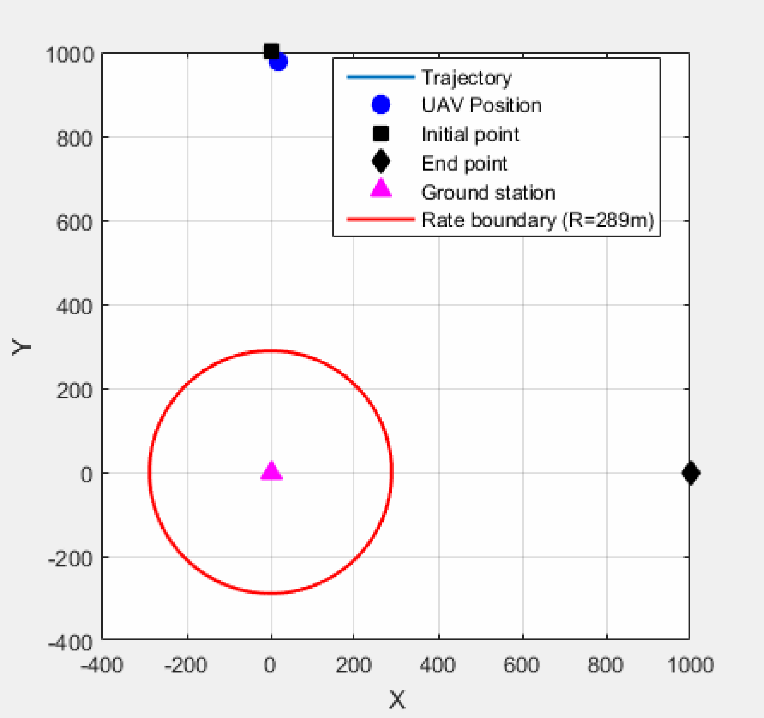


Table: Comparison with conventional paths

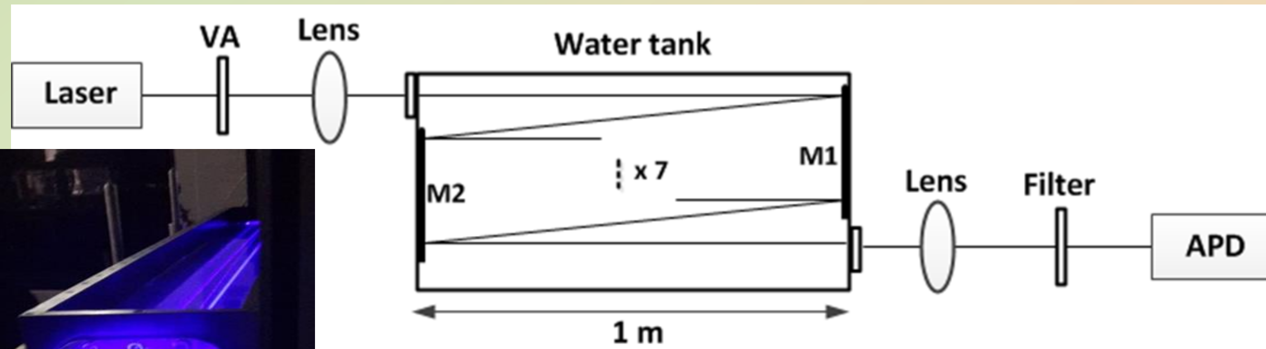
	Spectral efficiency (bps/Hz)	Consumption energy for $N_{\text{service}} = 400$ s (kJoule)	Ratio of service-time and E_{total} (s/kJoule)
Straight path	8.4982	484.4203	0.8257
Circular path ($d_{cir} = 862$ m)	7.9357	65.8696	6.0726
Flight time maximized path ($d(R_{\text{th}}) = 862$ m)	8.3991	45.7058	**8.7516**

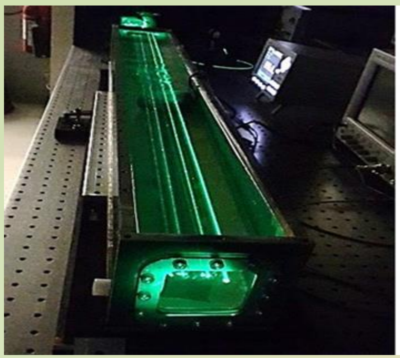
J.-H. Lee, K.-H. Park, M.-S. Alouini, and Y.-C. Ko, "Free space optical communication using UAV: Optimization for flight-time and energy-efficiency" Submitted to IEEE Trans. Wireless Comm.

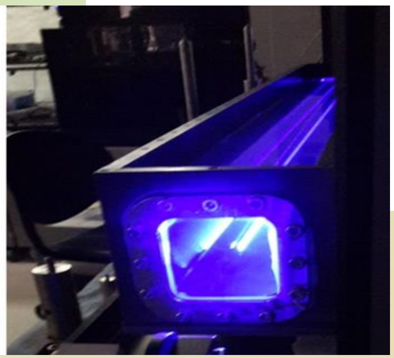
Emergency Connectivity

After Hurricane in Puerto Rico in 2017, *Project Loon* supported emergency connectivity while mobile networks were being recovered.

Underwater Optical Wireless Communications (UOWC)







- Developed a fast simulator to calculate accurately UWOC channel path loss & UOWC system performance
- Demonstrated 1.5 Gb/s transmission rates over 20 m.

[1] E. Zedini, H. Oubei, A. Kammoun, M. Hamdi, Bo. Ooi, and M. -S. Alouini, "A new simple model for underwater wireless optical channels in the presence of air bubbles", in Proc. IEEE Global Communications Conference (GLOBECOM'2017), Singapore, December 2017. Journal version to appear in IEEE Trans. on Communications.

[2] S. Chao, Y. Guo, H. Oubei, G. Liu, K. -H. Park, K. Ho, M. -S. Alouini, and B. Ooi, "20-meter underwater wireless optical communication link with 1.5 Gbps data rate", in Optics Express , Vol. 24, No. 22, pp. 25502-25509, 2016.

[3] C. Li, K. -H. Park, and M. -S. Alouini, "A direct radiative transfer equation solver for path loss calculation of underwater optical wireless channels", IEEE Wireless Commun. Letters , October 2015.

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Optical Wireless Backhauling

Impact of Pointing Errors

Impact of Pointing Errors

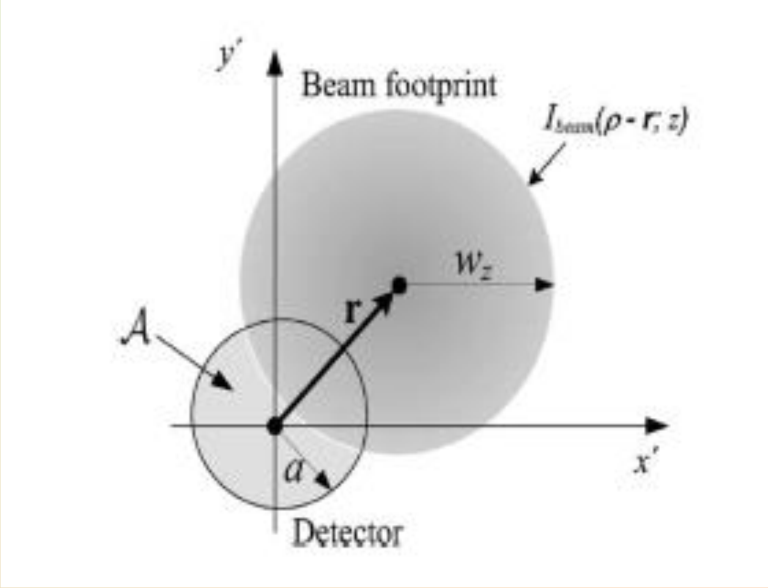
- **Effect on Communication:** These pointing errors may lead to an additional performance degradation and are a serious issue in urban areas, where the FSO equipments are placed on high-rise buildings.

- **Model:** The pointing error model developed and parameterized by ξ which is the ratio between the equivalent beam radius and the pointing error jitter can be:

  - With pointing error: ξ is between 0 and 7
  - Without pointing error: $\xi \to \infty$

Original Pointing Error Model

$$I = I_a I_p$$



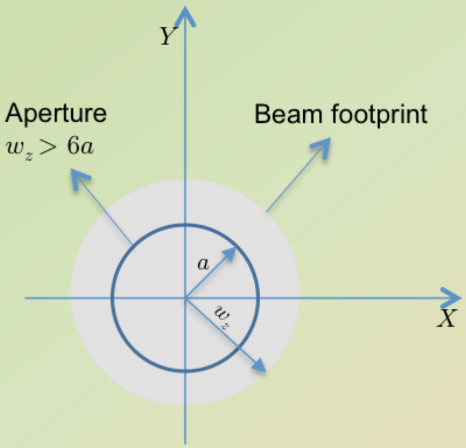
- The fraction of collected power at the receiver can be approximated by [Farid and Hranilovic, IEEE/OSA JLT 2007]

$$I_p \approx A_0 \exp\left(\frac{2r^2}{w_{z_{eq}}^2}\right)$$

where $\mathbf{r} = [x\ y]^t$, $r = \sqrt{x^2 + y^2}$

Other Pointing Errors Models

- The general model reduces to special cases as follows



No misalignment

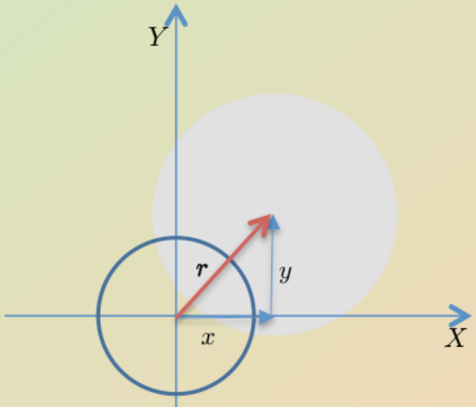


Figure : $\mu_x = \mu_y = 0$ and $\sigma_x^2 = \sigma_y^2$ (Rayleigh)

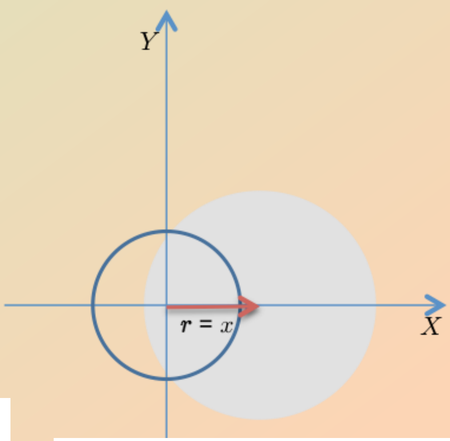


Figure : $\mu_x = \mu_y$ and $\sigma_y^2 = 0$ (Gaussian) .

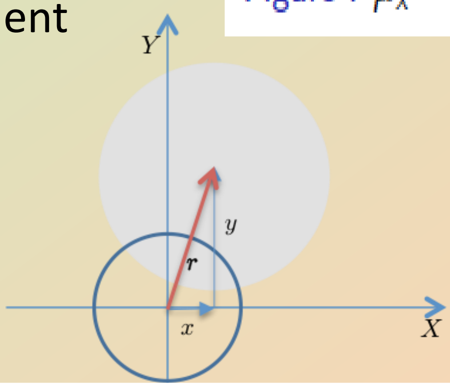


Figure : $\mu_x = \mu_y = 0$ and $\sigma_x^2 \neq \sigma_y^2$ (Hoyt).

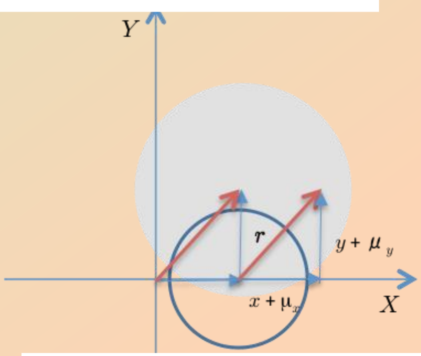


Figure : $\mu_x \neq \mu_y$ and $\sigma_x^2 = \sigma_y^2$ (Rician).

Generalized Pointing Error Model

- The fraction of collected power at the receiver can be approximated by [Farid and Hranilovic, IEEE/OSA JLT, 2007]

$$I_p \approx A_0 \exp\left(\frac{2r^2}{w_{z_{eq}}^2}\right), \text{ where } r = \sqrt{x^2 + y^2} \text{ and } x \sim \mathcal{N}(\mu_x, \sigma_x^2), \quad y \sim \mathcal{N}(\mu_y, \sigma_y^2)$$

$$f_r(r) = \frac{r}{2\pi\sigma_x\sigma_y}\int_0^{2\pi} \exp\left(-\frac{(r\cos\theta - \mu_x)^2}{2\sigma_x^2} - \frac{(r\sin\theta - \mu_y)^2}{2\sigma_y^2}\right) d\theta.$$

The random variable *r* follows a **Beckman** distribution

Moments of the Irradiance

$$\mathbb{E}[I_p^n] = \mathbb{E}\left[A_0^n \exp\left(-\frac{2nr^2}{w_{z_{eq}}^2}\right)\right] = A_0^n \mathcal{M}_{r^2}\left(-\frac{2n}{w_{z_{eq}}^2}\right)$$

$$\mathbb{E}[I_p^n] = \frac{A_0^n \xi_x \xi_y}{\sqrt{(n+\xi_x^2)(n+\xi_y^2)}} \exp\left(-\frac{2n}{w_{z_{eq}}^2}\left[\frac{\mu_x^2}{1+\frac{n}{\xi_x^2}} + \frac{\mu_y^2}{1+\frac{n}{\xi_y^2}}\right]\right),$$

where $\xi_x = \frac{w_{z_{eq}}}{2\sigma_x}$ and $\xi_y = \frac{w_{z_{eq}}}{2\sigma_y}$, are the ratio between the equivalent beam width and jitter variance for each direction.

$$\mathbb{E}[I^n] = \mathbb{E}[I_a^n]\mathbb{E}[I_p^n] = A_0^n \mathbb{E}[I_a^n]\, \mathcal{M}_{r^2}\left(-\frac{2n}{w_{z_{eq}}^2}\right).$$

$\mathcal{M}_{r^2}(.)$ is the moment-generating function of the random variable r^2

Asymptotic Ergodic Capacity

- The asymptotic ergodic capacity can be obtained as

$$\overline{C} \underset{\overline{\gamma}\gg 1}{\approx} \frac{\partial}{\partial n}\mathbb{E}[\gamma^n]\Big|_{n=0} = \frac{\partial}{\partial n}\mathbb{E}[I_a^{rn}]\Big|_{n=0} - \frac{2}{w_{z_{eq}}}\mathcal{M}'_{r^2}(0)$$

- The moments of I_a are known for both lognormal (LN) and Gamma-Gamma (ΓΓ). Then, the asymptotic capacity can be written as

$$\overline{C}|_{\Gamma\Gamma} \underset{\overline{\gamma}\gg 1}{\approx} \log\left(\frac{\sqrt{(r+\xi_x^2)(r+\xi_y^2)}\,\Gamma(\alpha)\Gamma(\beta)}{\xi_x\xi_y\Gamma(r+\alpha)\Gamma(r+\beta)}\overline{\gamma}\right) + \frac{2r}{w_{z_{eq}}^2}\left(\frac{\mu_x^2\xi_x^2}{r+\xi_x^2}+\frac{\mu_y^2\xi_y^2}{r+\xi_y^2}\right) - \frac{r}{2}\left(\frac{4(\mu_x^2+\mu_y^2)}{w_{z_{eq}}^2}+\frac{1}{\xi_x^2}+\frac{1}{\xi_y^2}\right) + r\psi(\alpha) + r\psi(\beta)$$

Asymptotic Ergodic Capacity

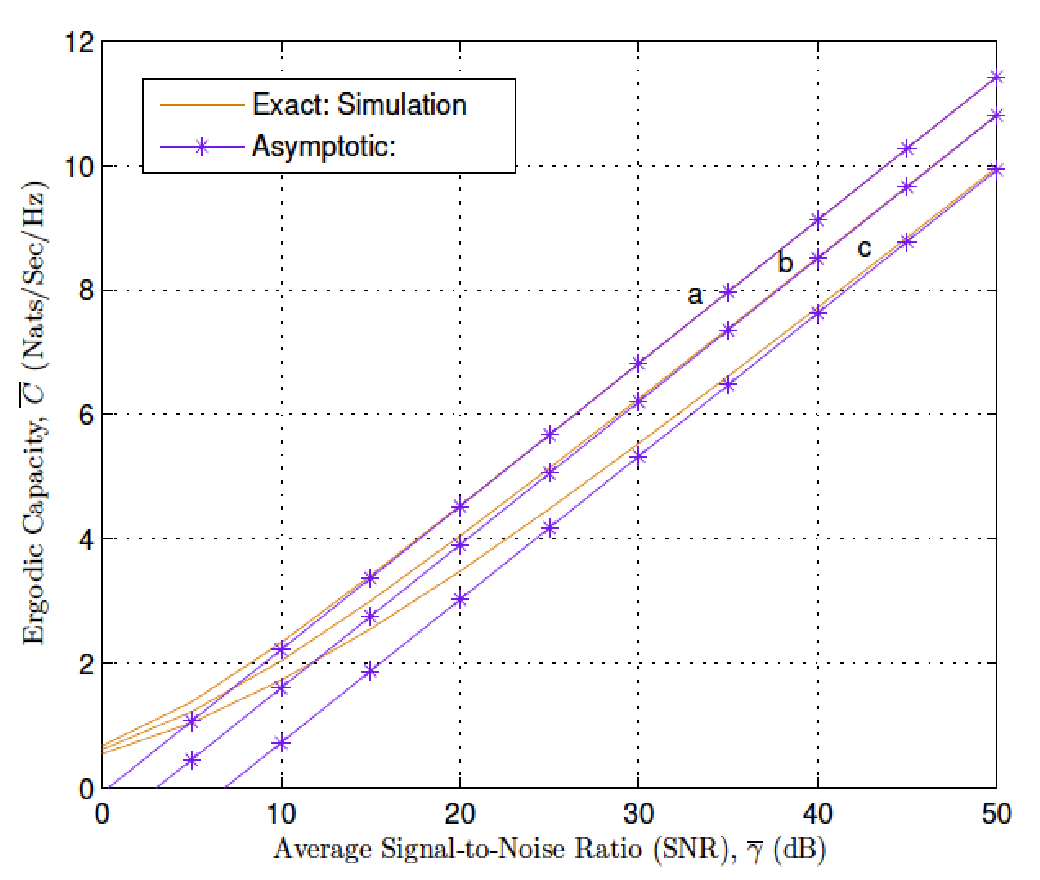


Figure: The ergodic capacity for:

(a) $\xi_x = 6.7$ and $\xi_y = 5.1$

(b) $\xi_x = 6.7$ and $\xi_y = 0.9$

(c) $\xi_x = 0.8$ and $\xi_y = 0.9$

Reference: H. Al-Quwaiee, H.-C. Yang, and M. -S. Alouini, "On the asymptotic ergodic capacity of FSO Links with Generalized pointing error model", in Proceedings IEEE ICC'15, London, UK, June 2015. Journal version in IEEE Trans. Wireless Communications, Sept 2016.

Op

Outage Capacity

- FSO channels are typically viewed as slowly varying channels => Coherence time is greater than the latency requirement
- Outage capacity is considered to be a more realistic metric of channel capacity for FSO systems
- Closed-form expressions are not possible => Importance sampling-based Monte Carlo simulations

C. Ben Issaid, K. -H. Park, R. Tempone, and M. -S. Alouini, "Fast outage probability simulation for FSO links with a generalized pointing error model", in Proc. IEEE Global Communications Conference (GLOBECOM'2016), Washington DC, December 2016. Journal version in IEEE Transaction on Wireless Communications, October 2017.

Importance Sampling (IS)

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$$P=\mathbb{P}(\gamma<\gamma_{th}) = \mathbb{P}(I=I_a I_p <I_{th}) = \mathbb{P}(y_a + y_p < \varepsilon)$$

where $y_a=\log(I_a)$, $y_p=\log(I_p)$, and $\varepsilon = \log(I_{th})$

- IS estimator:

$$I^* = \frac{1}{N^*}\sum_{n=1}^{N^*} 1_{(y^*_{a,n}+y^*_{p,n}<\varepsilon)} w_{y_a}(y^*_{a,n}) w_{y_p}(y^*_{p,n})$$

where $y_k^*(.) \sim f^*_{y_k}(.) = \frac{f_{y_k}(.)}{w_{y_k}(.)}, \qquad k = a, p$

IS Exponential Twisting

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- Weighting Choice: $w_{y_k}(x) = e^{-\theta x} M_{y_k}(\theta)$

where $M_{y_k}(.)$ is the MGF of y_k

- IS Estimator:

$$I^* = \frac{1}{N^*} \sum_{n=1}^{N^*} 1_{(y_{a,n}^* + y_{p,n}^* < \varepsilon)} e^{-\theta(y_{a,n}^* + y_{p,n}^*)} M_{y_a}(\theta) M_{y_p}(\theta)$$

- ❑ $M_{y_a}(\theta) = E\left[h_a^\theta\right] = \exp(\frac{1}{2}\theta(\theta - 1)\,\sigma_R^2)$ (LN fading)
- ❑ $M_{y_a}(\theta) = E\left[h_a^\theta\right] = \frac{(\alpha\beta)^{-\theta}\Gamma(\alpha+\theta)\Gamma(\beta+\theta)}{\Gamma(\alpha)\Gamma(\beta)}$ (G-G fading)
- ❑ $M_{y_p}(\theta) = E\left[h_p^\theta\right] = \frac{\xi_x \xi_y A_0^\theta \exp\left(-\frac{2\theta}{w_{zeq}^2}\left[\frac{\mu_x^2 \xi_x^2}{\xi_x^2+\theta} + \frac{\mu_y^2 \xi_y^2}{\xi_y^2+\theta}\right]\right)}{\sqrt{(\xi_x^2+\theta)(\xi_y^2+\theta)}}$

Optimal θ

- Minimization problem:

$$\min_{\theta} E\left[1_{(y_a+y_p<\epsilon)} w_{y_a}^2(y_a,\theta) w_{y_p}^2(y_a,\theta)\right]$$

→Stochastic optimization problem: Not feasible analytically except for a few simple cases.

→Alternative: Find a sub-optimal θ:

  – Cumulant generating function:

$$\mu(\theta) = \log\left(E\left[e^{\theta(y_a+y_p)}\right]\right) = \log(M_a(\theta)) + \log\left(M_p(\theta)\right)$$

  – Sub-optimal θ:

$$\mu'(\theta) = \epsilon$$

Sub-Optimal θ

- Weak turbulence:

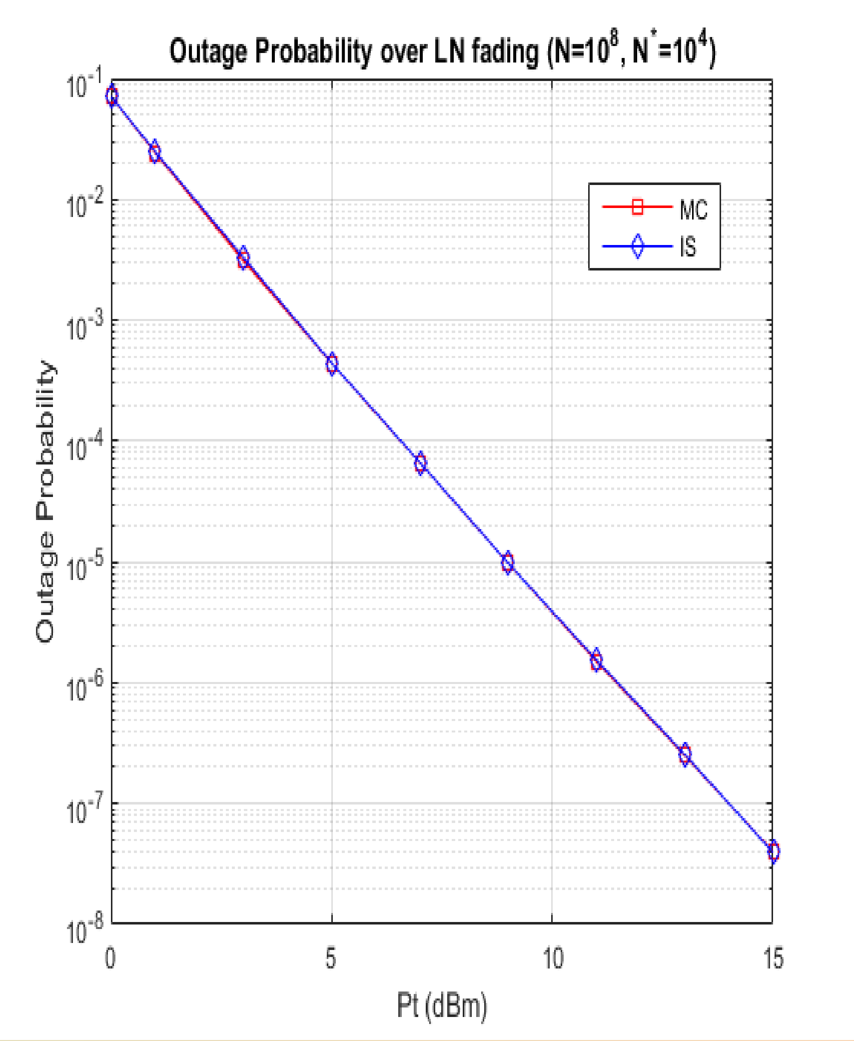
$$\log(A_0) + \frac{\sigma_R^2}{2}(2\theta - 1) - \frac{\xi_x^2 + \xi_y^2 + 2\theta}{2(\xi_x^2 + \theta)\left(\xi_y^2 + \theta\right)}$$
$$- \frac{2\theta}{w_{zeq}^2}\left[\frac{\mu_x^2 \xi_x^4}{(\xi_x^2 + \theta)^2} + \frac{\mu_y^2 \xi_y^4}{(\xi_y^2 + \theta)^2}\right] = \epsilon$$

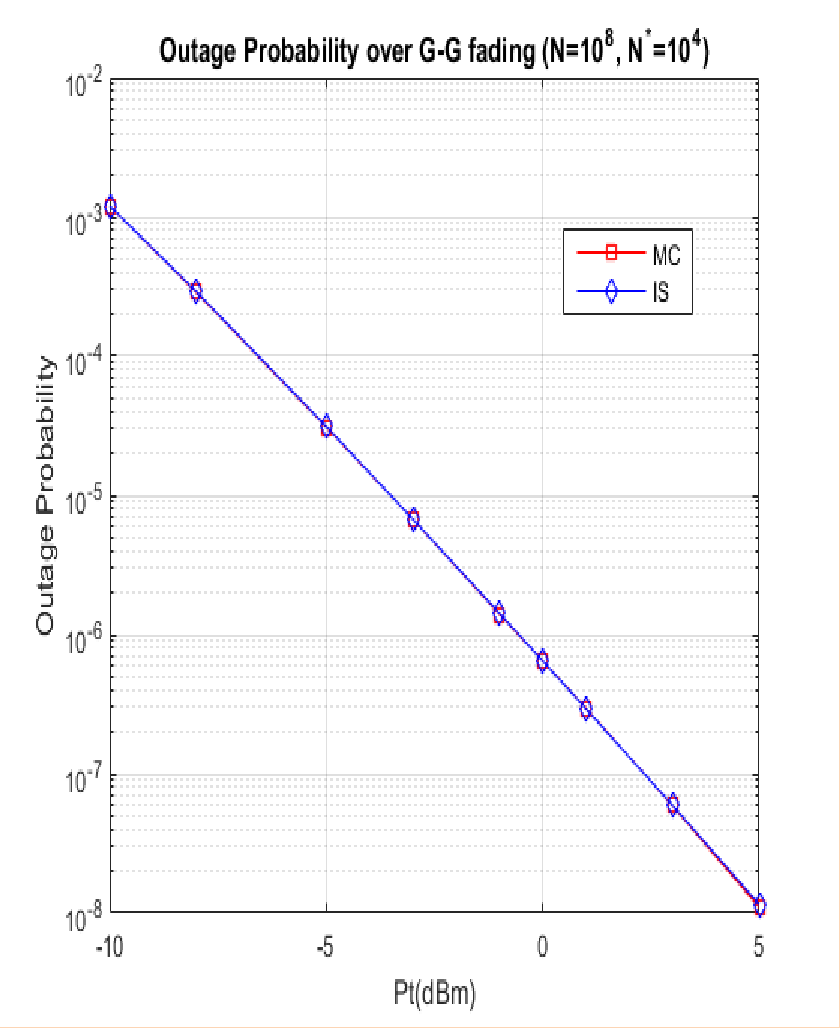
- Strong turbulence:

$$\log\left(\frac{A_0}{\alpha\beta}\right) - \frac{\xi_x^2 + \xi_y^2 + 2\theta}{2(\xi_x^2 + \theta)\left(\xi_y^2 + \theta\right)}$$
$$- \frac{2\theta}{w_{zeq}^2}\left[\frac{\mu_x^2 \xi_x^4}{(\xi_x^2 + \theta)^2} + \frac{\mu_y^2 \xi_y^4}{(\xi_y^2 + \theta)^2}\right] + \psi(\alpha + \theta) + \psi(\beta + \theta) = \epsilon$$

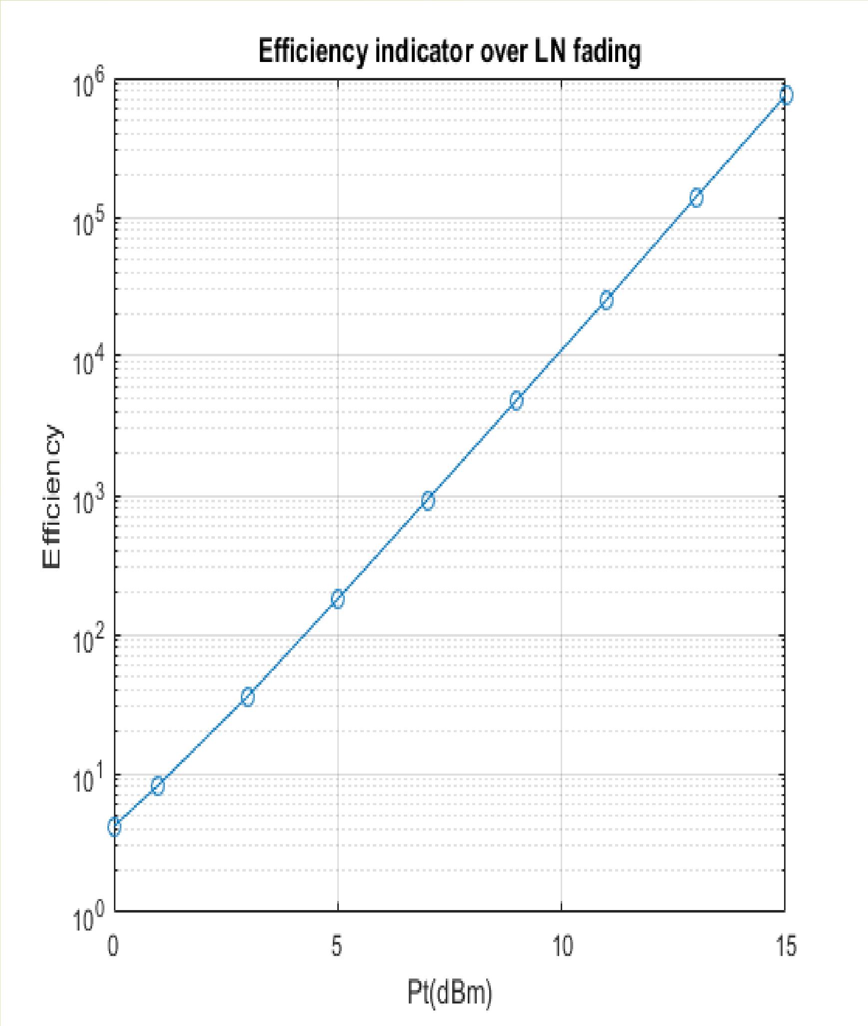
where $\psi(x) = \frac{\Gamma'(x)}{\Gamma(x)}$

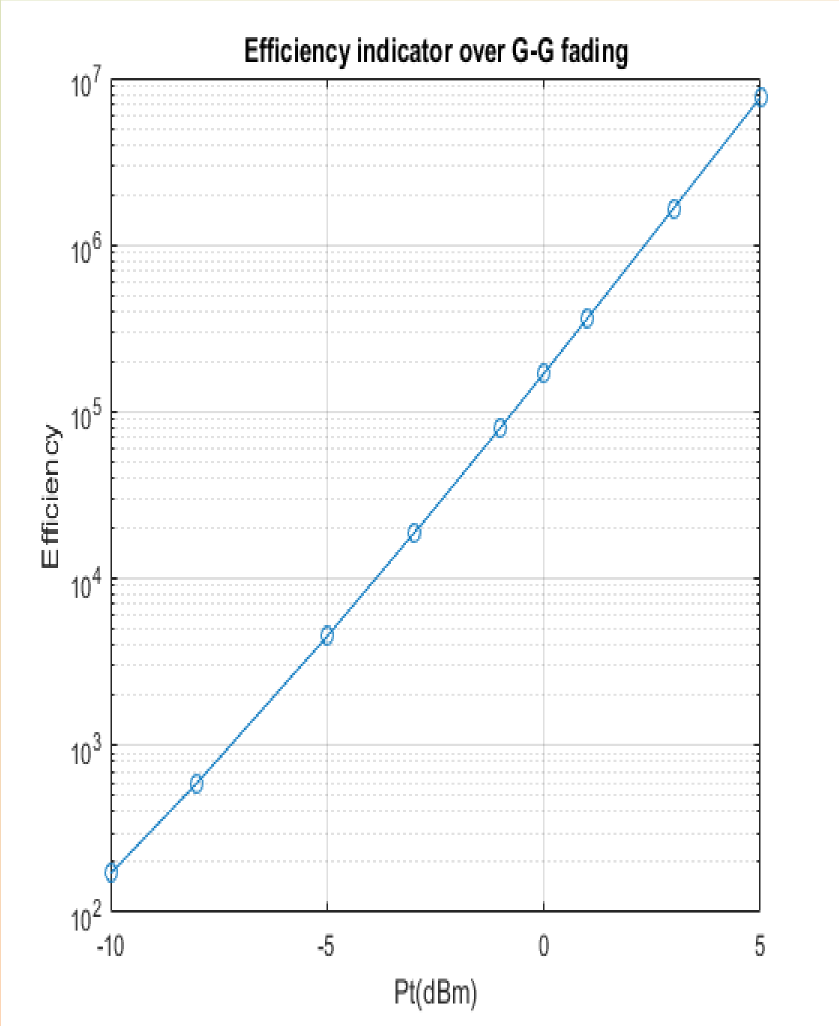
Outage Probability



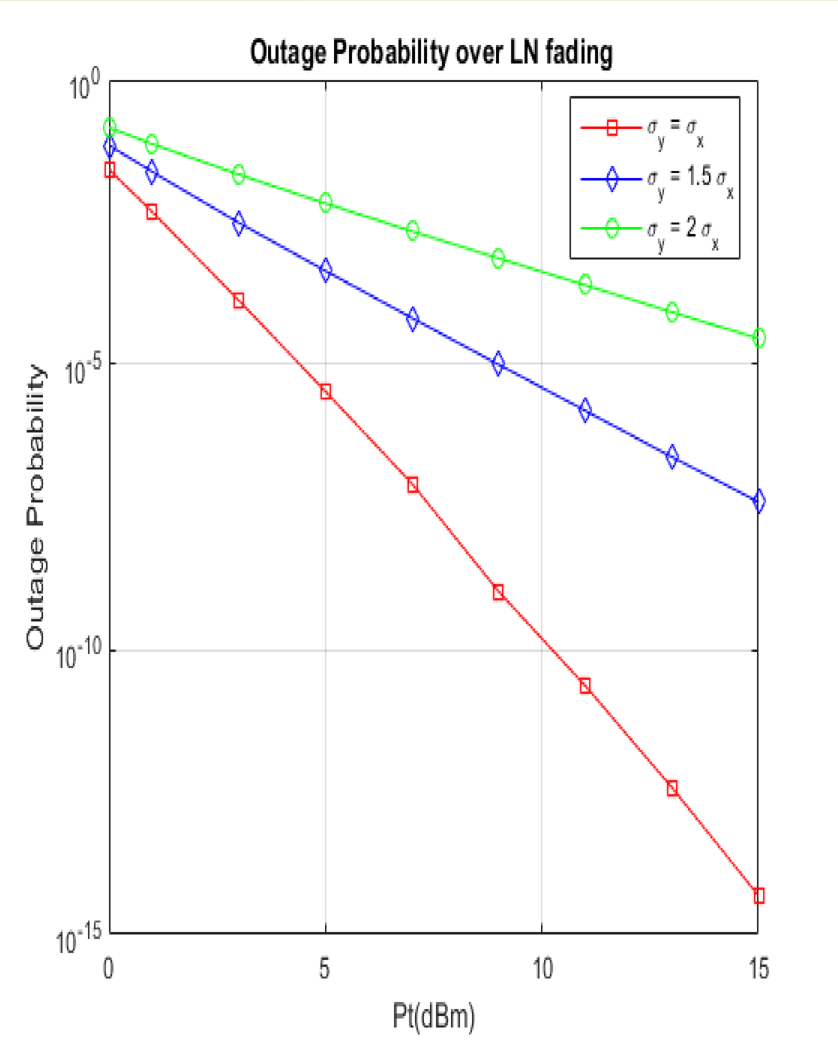


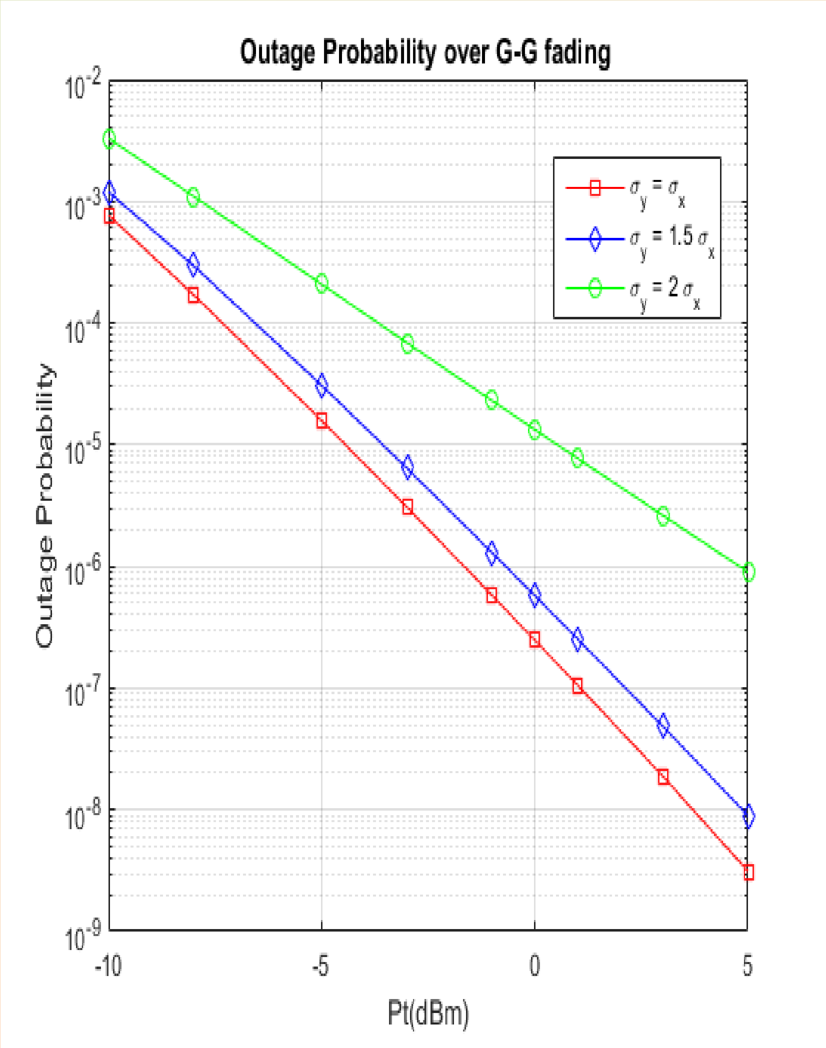
Efficiency Indicator





Impact of Jitter Unbalance on Outage Probability



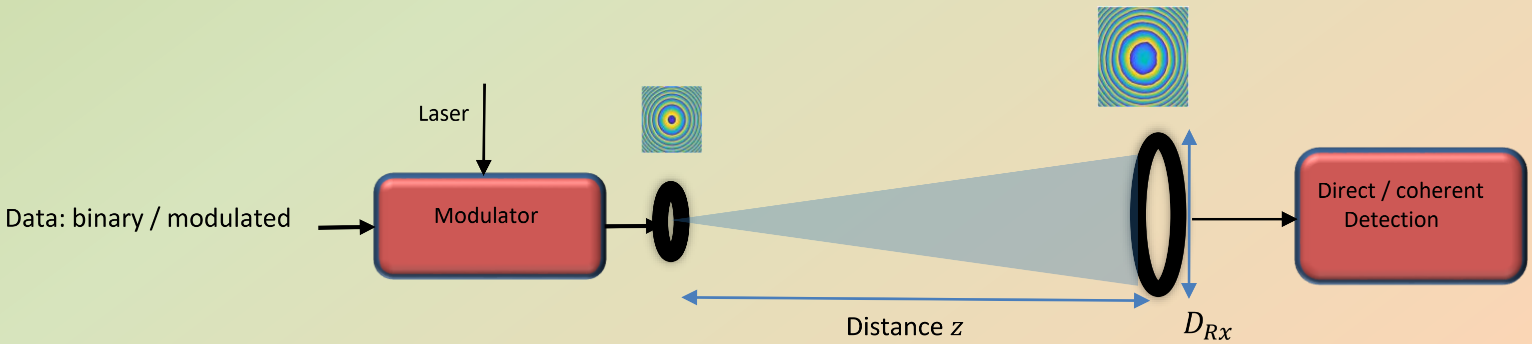


Optical Wireless Backhauling

Impact of Turbulence

Classical FSO System

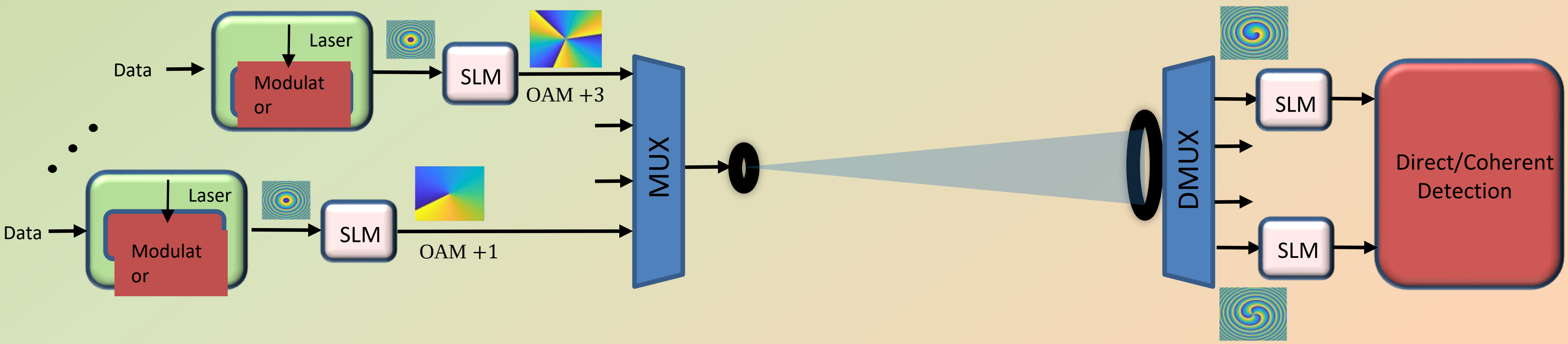
➢Gaussian beam transmission



- Receiver aperture: $D_{Rx} = 2\omega(z)$
- $\omega(z) = \omega_0\sqrt{1 + z/z_R}$, beam radius at the receiver
- ω_0 Gaussian beam radius at transmitter
- $z_R = \pi\omega_0^2\lambda$

Scaling Capacity of FSO Systems

➢ Orbital angular momentum (OAM) transmission

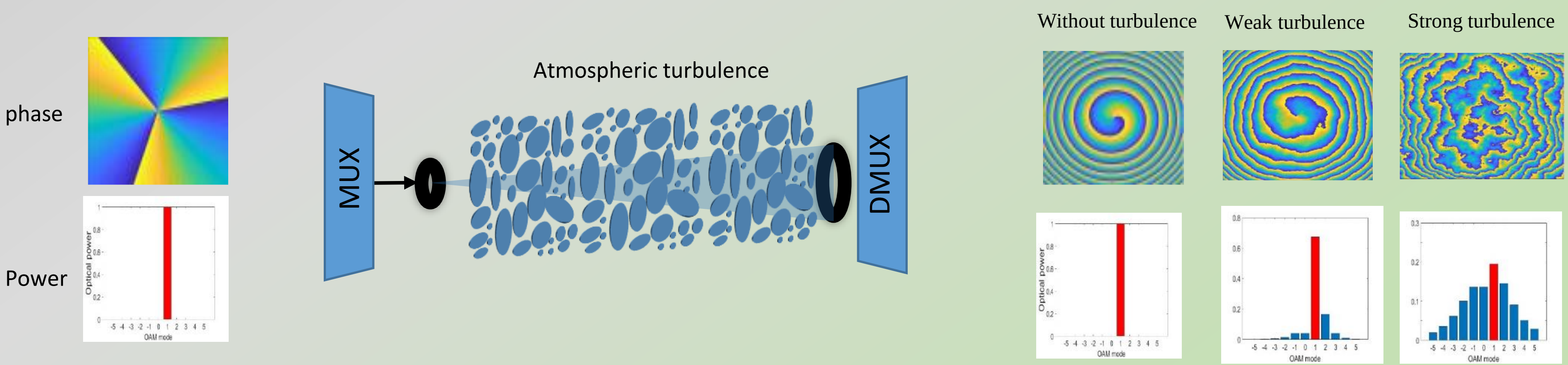


- Topological charge of OAM $\mathrm{m} \in \mathbb{Z}$
- Receiver aperture: $D_{Rx} = 2\omega(z)\sqrt{\mathrm{m}_0}$
- m_0: largest topological charge
- SLM: Spatial light modulator

A. E. Willner, J. Wang, and H. Huang, “A different angle on light communications,” Science, vol. 337, pp. 655–656, 2012.

Impact of Atmospheric Turbulence on OAM (1)

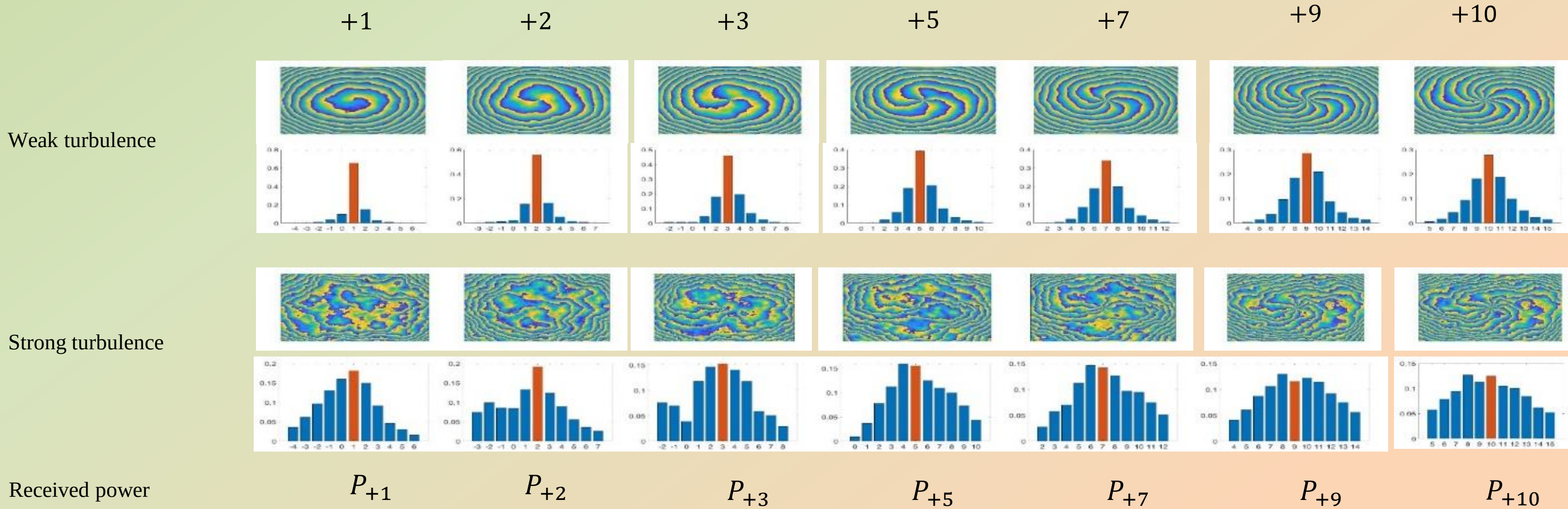
- **Example: OAM +1**



- Power spread to other OAM modes
  - ➢Power loss on OAM +1
  - ➢Crosstalk between OAM +1 and other OAM modes

Impact of Atmospheric Turbulence on OAM (2)

- **Effect of turbulence on different OAM modes**



- OAM modes arrive with different powers
  - ➢SNR imbalance

Which OAMs to use ?

OAM Mode Selection for a 2×2 Transmission

• Minimization of the mode-dependent loss (MDL)

- System parameters:
  - S: Set of possible OAMs for transmission (limited by the Rx aperture).
  - $\mathrm{S_p}$: Subset of possible modes for transmission (limited by available equipment).
  - $\mathrm{S_{opt}}$: Subset of optimal OAM modes for transmission

- MDL=$10\log(\frac{\mathrm{P_{max}}}{\mathrm{P_{min}}})$
  - $\mathrm{P_{max}}$: highest received power
  - $\mathrm{P_{min}}$: Lowest received power

- $\mathrm{S_{opt}} = \underset{\mathrm{S_p} \subset \mathrm{S}}{\operatorname{argmin}}\, \mathrm{MDL}$

E-M. Amhoud, A. Trichili, B. S. Ooi, and M.-S. Alouini, "OAM mode selection and space-time coding for turbulence mitigation in FSO communications," submitted to IEEE Communications Magazine.

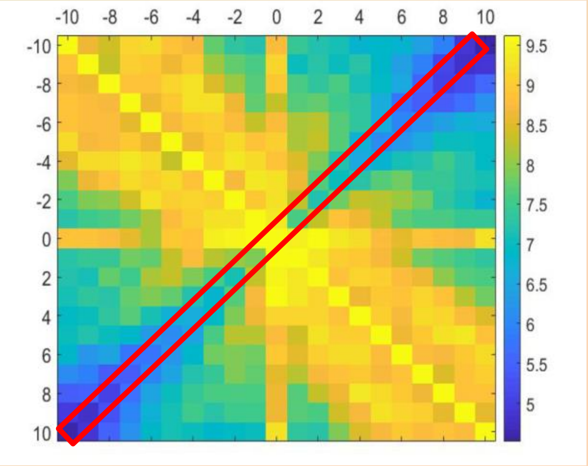
OAM Mode Selection for a 2×2 Transmission

• Minimization of the mode-dependent loss (MDL)

- System parameters:
  - ➢ S: Set of possible OAMs for transmission (limited by the Rx aperture).
  - ➢ S_p: Subset of possible modes for transmission (limited by available equipment).
  - ➢ S_{opt}: Subset of optimal OAM modes for transmission

- MDL=$10\log(\frac{P_{max}}{P_{min}})$
  - ➢ P_{max}: highest received power
  - ➢ P_{min}: Lowest received power

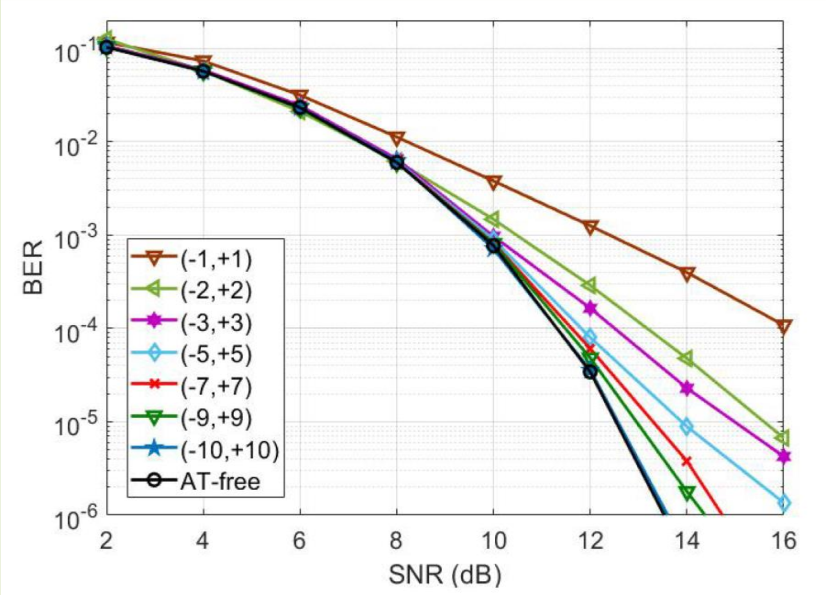
- $S_{opt} = \underset{S_p \subset S}{\operatorname{argmin}} \text{MDL}$



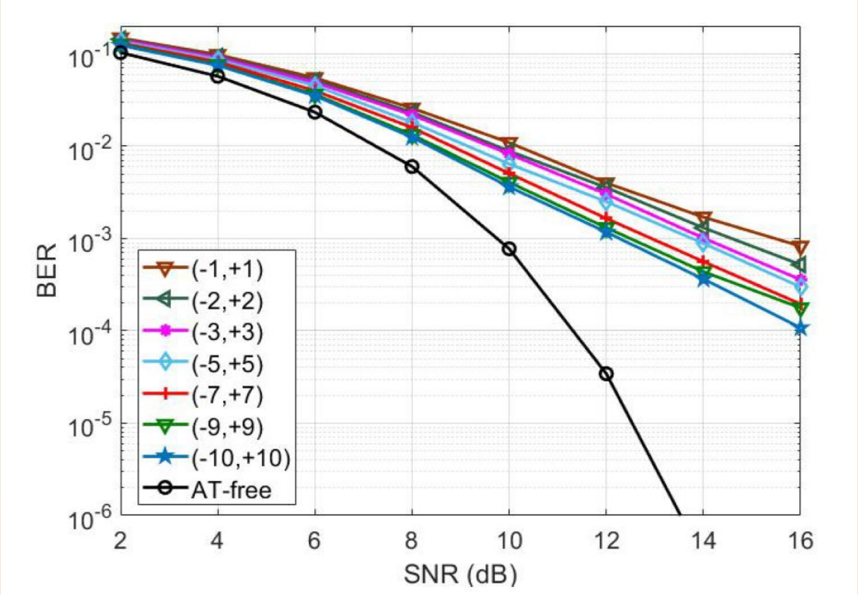
- S={-10,-9,…,+9,10}, $\text{card}(S_p) = 2$
- MDL decreases as topological charge increase
- Modes with opposite topological chares have minimum MDL

BER Performance of OAM Selection

Weak AT



Strong AT



- Performance increases with higher topological charges
- For weak turbulence, (-10,10) achieves same as turbulence-free channel

How to further enhance performance against strong turbulence ?

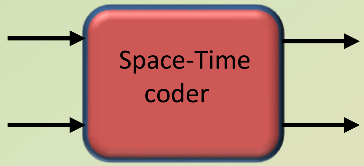
Space-Time Coding for Turbulence Mitigation

- **Principle of Space-Time (ST) coding:**

Signal 1
Signal 2

$$\left[\begin{array}{c|c} s_1 & s_3 \\ s_2 & s_4 \end{array}\right]$$

T_1 T_2



Signal 1
Signal 2

$$\left[\begin{array}{c|c} f_1(s_1, s_2, s_3, s_4) & f_3(s_1, s_2, s_3, s_4) \\ f_2(s_1, s_2, s_3, s_4) & f_4(s_1, s_2, s_3, s_4) \end{array}\right]$$

T_1 T_2

$\mathrm{f_i}$: Linear function

- Example of 2×2 ST codes

➢ **Golden Code** [1]

$$X_{GC} = \begin{pmatrix} \alpha(s_1 + \theta s_2) & \alpha(s_3 + \theta s_4) \\ i\bar{\alpha}\,(s_3 + \bar{\theta} s_4) & \bar{\alpha}\,(s_1 + \bar{\theta} s_2) \end{pmatrix}$$

α, θ: complex parameters

- Best code for Rayleigh fading
- Full-rate

➢ **Silver Code** [2]

$$X_S = \frac{1}{\sqrt{2}}\begin{pmatrix} s_1 & -s_2^\dagger \\ s_2 & s_1^\dagger \end{pmatrix} + \frac{1}{\sqrt{2}}\begin{pmatrix} z_1 & -z_2^\dagger \\ z_2 & z_1^\dagger \end{pmatrix}$$

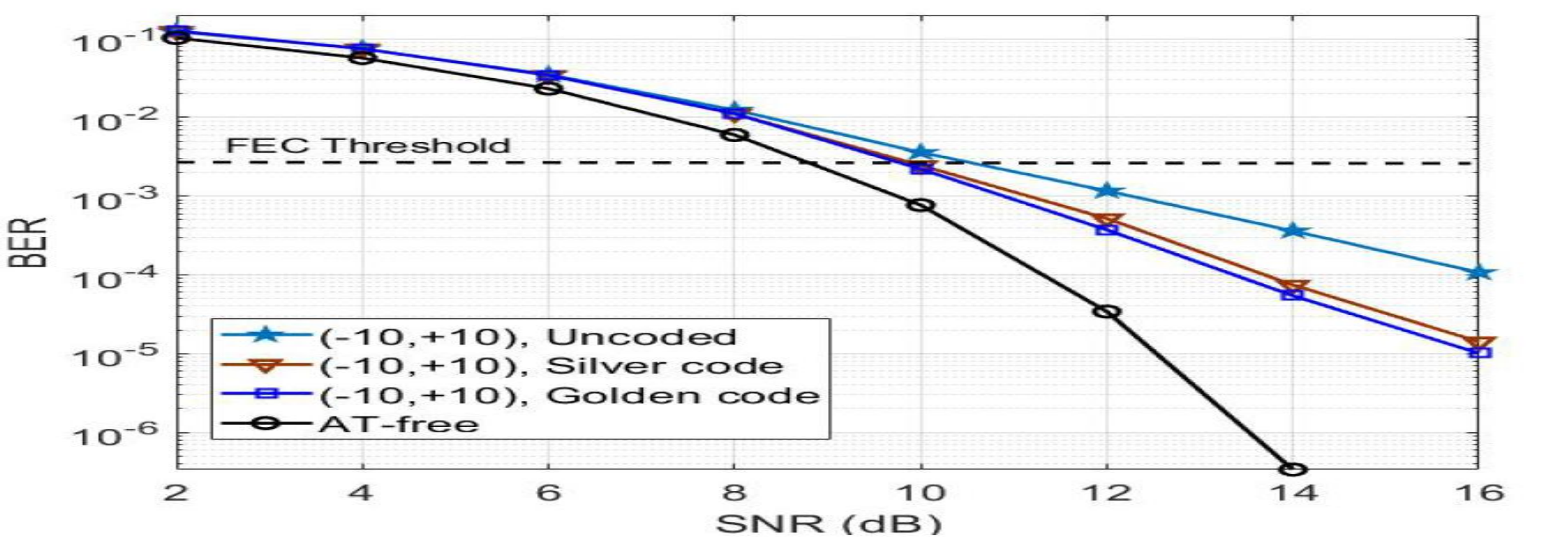
z_i: linear combination of s_1& s_2

- Reduced complexity decoding
- Full-rate

[1] J.-C. Belfiore, G. Rekaya, and E. Viterbo, “The Golden code: a 4×4 full-rate space-time code with non-vanishing determinants,” in Proceedings of the International Symposium on Information Theory, ISIT’2004, pp. 310–310.
[2] O. Tirkkonen and A. Hottinen, “Improved MIMO performance with non-orthogonal space-time block codes,” in IEEE Global Telecommunications Conference, Globecom’2001, pp. 1122–1126.

Performance with ST Coding

Strong AT



- 2.4 dB coding gain by the Golden code
- Same performance of the Golden and Silver at FEC threshold of $3.8\ 10^{-3}$.

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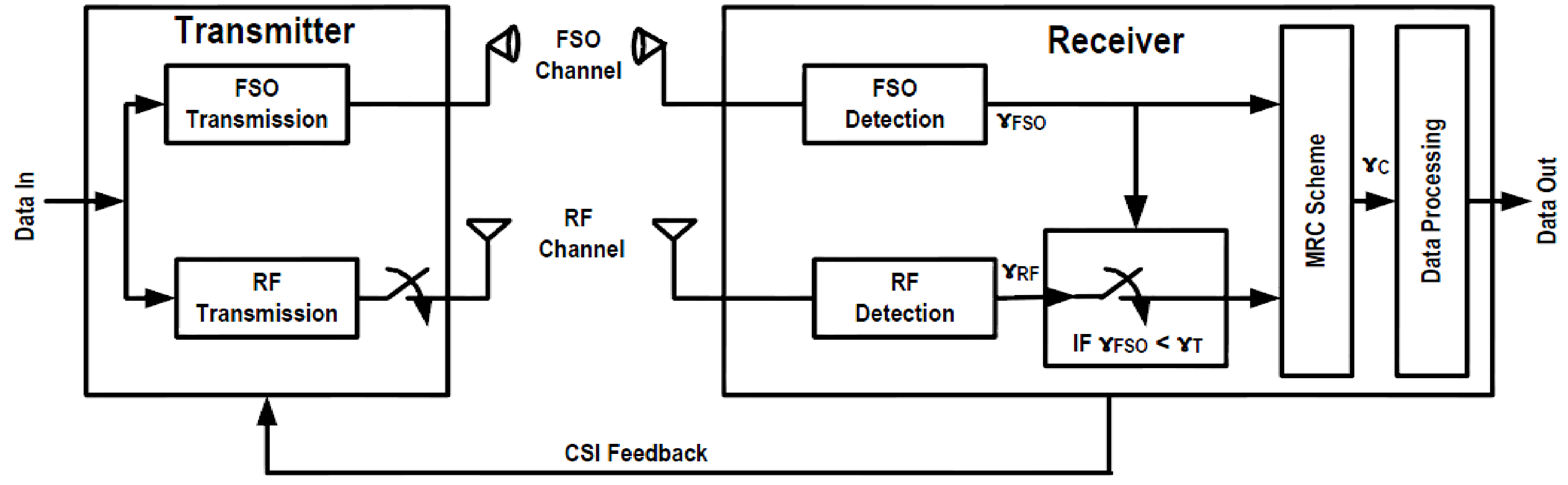
Hybrid OWC/RF Systems



Hybrid FSO/RF System Adaptive Combining Scheme

- **The proposed system consists of two modes of operation:**
  - FSO only mode, as long as $\gamma_{\mathrm{FSO}} \geq \gamma_{\mathrm{T}}$
  - Combined FSO/RF mode, as long as $\gamma_{\mathrm{FSO}} < \gamma_{\mathrm{T}}$



[1] T. Rakia, H. -C. Yang, and M. -S. Alouini, "Outage analysis of practical FSO/RF hybrid system with adaptive combining", IEEE Communication Letters, Vol. 19, No. 8, pp. 1366-1369, August 2015.

CDF of Received SNR

- The received SNR of the proposed hybrid system is given by:

$$\gamma_c = \begin{cases} \gamma_{FSO} & \text{if } \gamma_{FSO} \geq \gamma_T \\ \gamma_{FSO} + \gamma_{RF} & \text{if } \gamma_{FSO} < \gamma_T \end{cases}$$

- The cumulative distribution function is given by:

$$F_{\gamma_c}(x) = \begin{cases} F_1(x) & \text{if } x \leq \gamma_T \\ F_{\gamma_{FSO}}(x) - F_{\gamma_{FSO}}(\gamma_T) + F_2(x) & \text{if } x > \gamma_T, \end{cases}$$

$$F_{\gamma_{FSO}}(\gamma_{FSO}) = \frac{2^{\alpha+\beta-2}}{\pi\Gamma(\alpha)\Gamma(\beta)} G_{1,5}^{4,1}\left(\frac{(\alpha\beta)^2}{16\bar{\gamma}_{FSO}}\gamma_{FSO} \;\middle|\; \begin{matrix} 1 \\ \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{\beta}{2}, \frac{\beta+1}{2}, 0 \end{matrix} \right)$$

CDF of Received SNR

- **The received SNR of the proposed hybrid system is given by:**

$$\gamma_c = \begin{cases} \gamma_{FSO} & \text{if } \gamma_{FSO} \geq \gamma_T \\ \gamma_{FSO} + \gamma_{RF} & \text{if } \gamma_{FSO} < \gamma_T \end{cases}$$

- **The cumulative distribution function is given by:**

$$F_{\gamma_c}(x) = \begin{cases} F_1(x) & \text{if } x \leq \gamma_T \\ F_{\gamma_{FSO}}(x) - F_{\gamma_{FSO}}(\gamma_T) + F_2(x) & \text{if } x > \gamma_T, \end{cases}$$

$$F_{\gamma_{FSO}}(\gamma_{FSO}) = \frac{2^{\alpha+\beta-2}}{\pi\Gamma(\alpha)\Gamma(\beta)} G_{1,5}^{4,1}\left(\frac{(\alpha\beta)^2}{16\bar{\gamma}_{FSO}}\gamma_{FSO} \;\middle|\; \begin{matrix} 1 \\ \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{\beta}{2}, \frac{\beta+1}{2}, 0 \end{matrix} \right)$$

CDF of Received SNR

$$F_1(x) = \frac{2^{\alpha+\beta-2}\left(\frac{mx}{\bar{\gamma}_{RF}}\right)^m}{\pi\Gamma(\alpha)\Gamma(\beta)\Gamma(m)} \left\{ \sum_{n=0}^{\infty} \frac{\left(\frac{mx}{\bar{\gamma}_{RF}}\right)^n}{n!} \sum_{i=0}^{m-1} \binom{m-1}{i} (-1)^i \right.$$

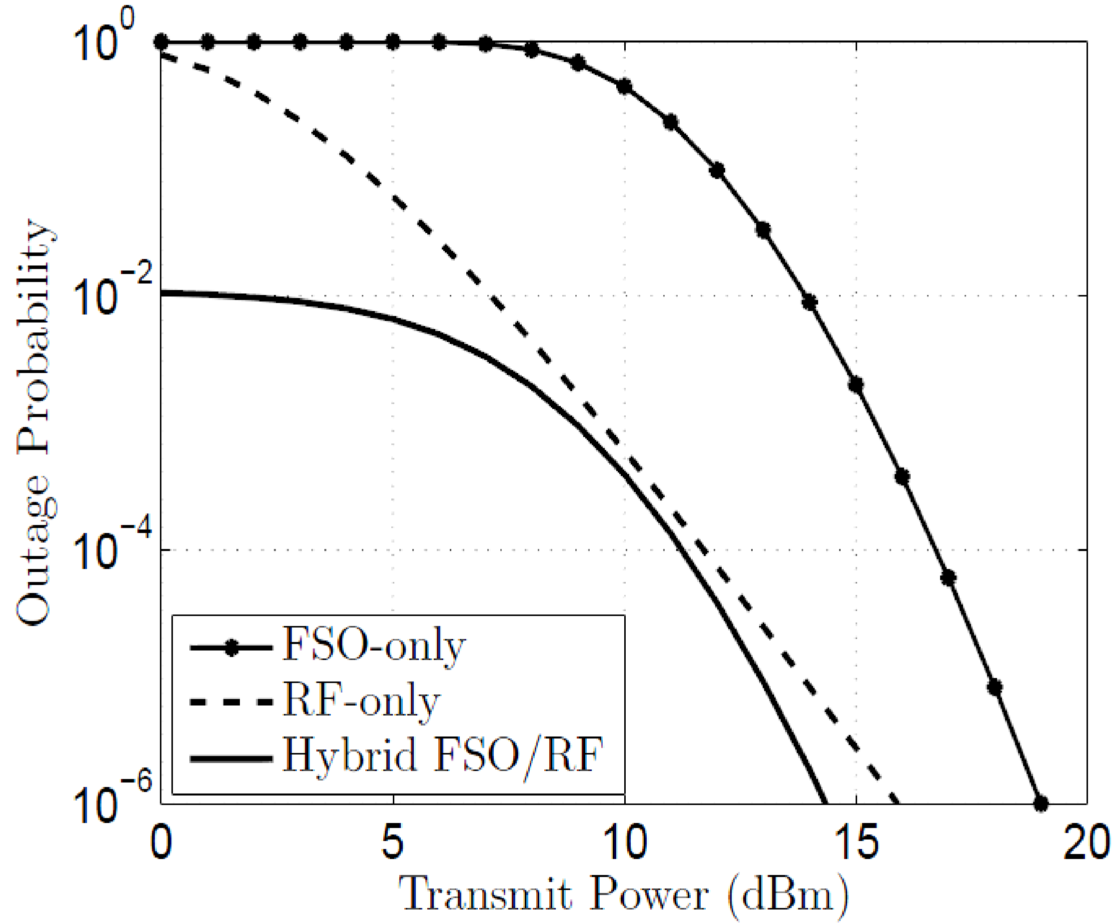
$$\left. \sum_{k=0}^{\infty} \frac{\left(\frac{-mx}{\bar{\gamma}_{RF}}\right)^k}{k!} G_{2,6}^{4,2}\left(\frac{(\alpha\beta)^2 x}{16\bar{\gamma}_{FSO}} \middle| \begin{matrix} 1-n-i, 1-k-n-m \\ \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{\beta}{2}, \frac{\beta+1}{2}, -k-n-m, -n-i \end{matrix} \right) \right\}.$$

$$F_2(x) = \frac{(m-1)!}{\Gamma(m)} F_{\gamma_{FSO}}(\gamma_T) - \left\{ \frac{2^{\alpha+\beta-2} e^{\frac{-mx}{\bar{\gamma}_{RF}}} (m-1)!}{\pi\Gamma(\alpha)\Gamma(\beta)\Gamma(m)} \sum_{n=0}^{\infty} \frac{(m\gamma_T/\bar{\gamma}_{RF})^n}{n!} \right.$$

$$\left. \sum_{k=0}^{m-1} \frac{(mx/\bar{\gamma}_{RF})^k}{k!} \sum_{j=0}^{k} \binom{k}{j} \left(\frac{-\gamma_T}{x}\right)^j G_{1,5}^{4,1}\left(\frac{(\alpha\beta)^2 \gamma_T}{16\bar{\gamma}_{FSO}} \middle| \begin{matrix} K_5 \\ K_6 \end{matrix} \right) \right\},$$

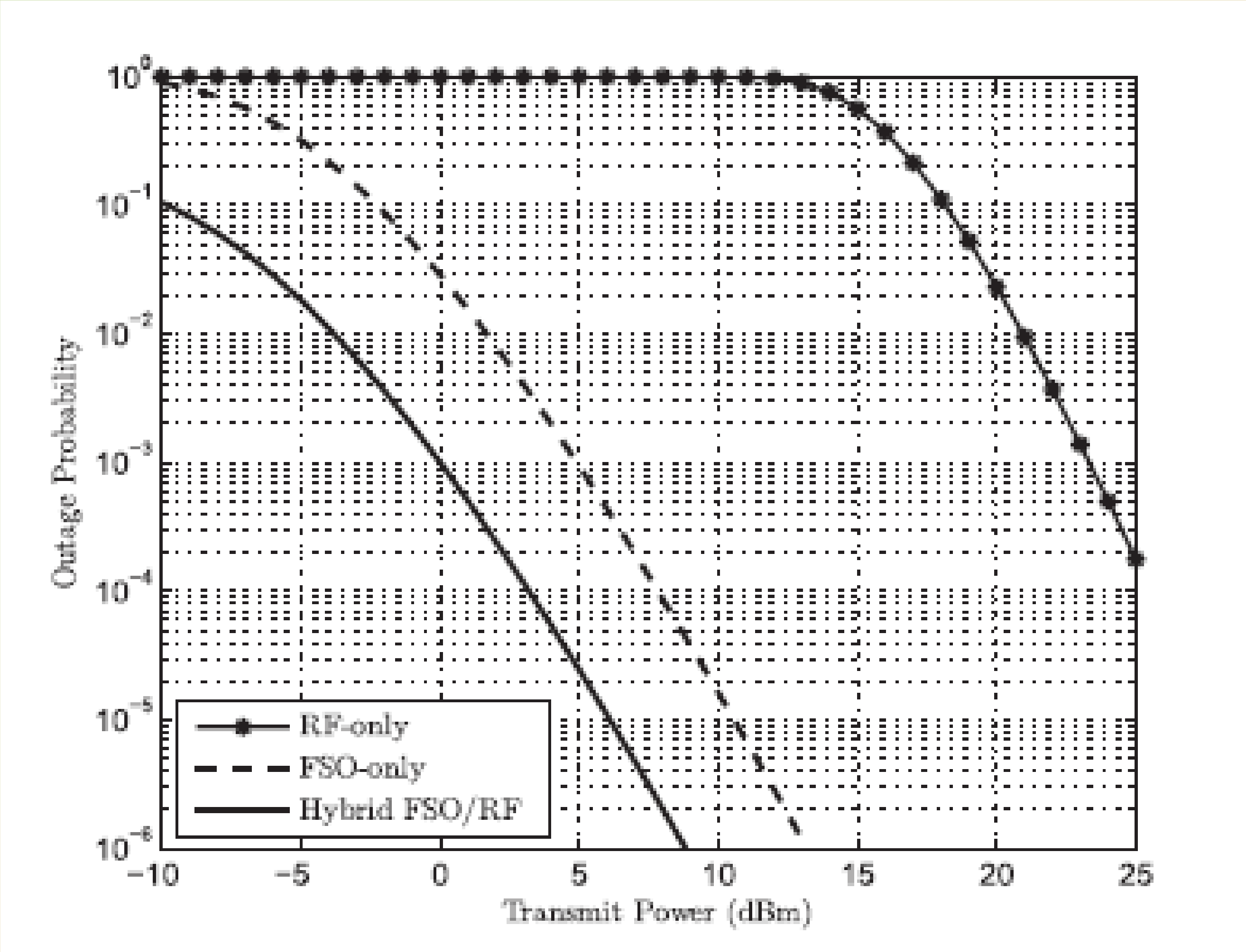
where $K_5 = 1 - n - j$ and $K_6 = \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{\beta}{2}, \frac{\beta+1}{2}, -n - j$.

Outage Probability (Fog)



Foggy Weather

Outage Probability (Rain)

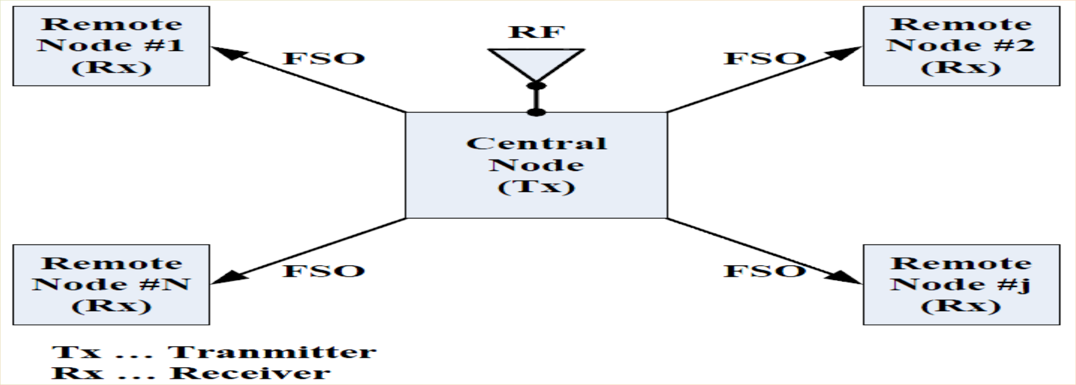


Point-to-Multi-Points (P2MP) Hybrid FSO/RF Networks

- **P2MP topology is a common network architecture for outdoor wireless networks to connect multiple locations to one single central location.**
- **A direct application of the proposed P2MP hybrid FSO/RF network is wireless Internet service provider (WISP) networks.**
- **In a WISP network:**
  - Subscribers are connected at the edge of the network using a client device typically mounted on the roof of their houses.
  - The central base station is mounted on a high building where it has line of sight with the client devices.

Proposed P2MP Hybrid FSO/RF Network Modeling

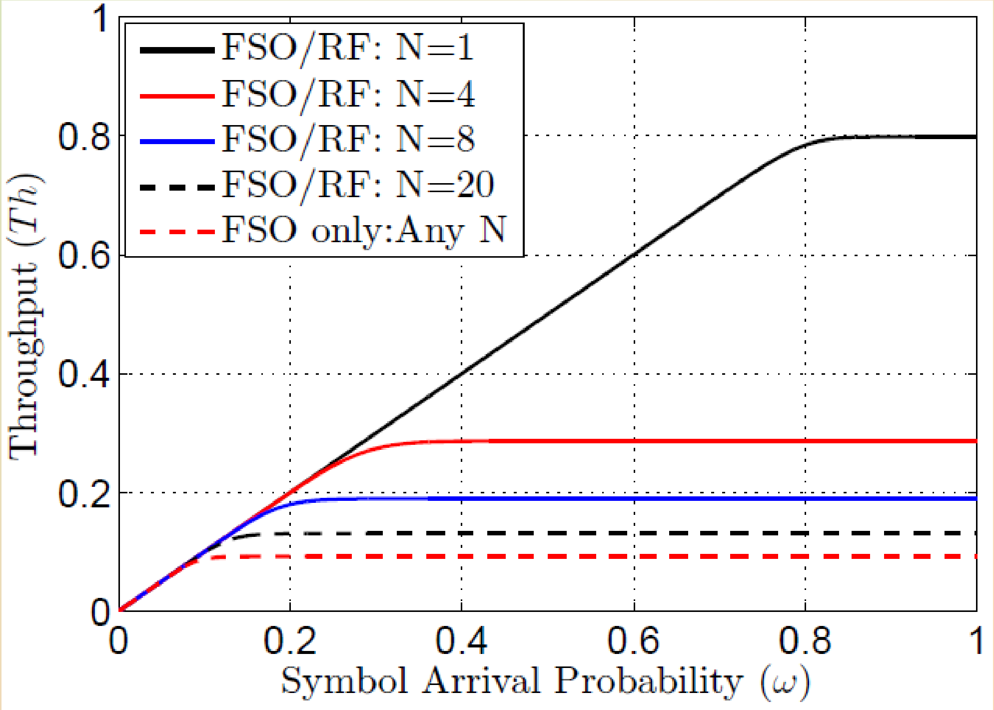
- The central node is equipped with *N* optical transmitters and one RF transmitter.
- Each remote node in the network is equipped with one optical receiver and one RF receiver.
- Each remote node is connected to the central node via a separable primary FSO link.
- A common backup RF link is shared among all the remote nodes.



[1] T. Rakia, H. -C. Yang, F. Gebali, and M. -S. Alouini, "Cross layer analysis of point-to-multi-point hybrid FSO/RF network", IEEE/OSA Journal of Optical Communications and Networking, Vol. 9, No. 3, pp. 234-243, March 2017.

Simulation Results

- **Throughput as function of Symbol Arrival Probability for Different Numbers of Nodes**
  - The throughput decreases with increasing N due to the increasing competition to access the shared RF link.
  - The throughput is improved by using a common backup RF link.



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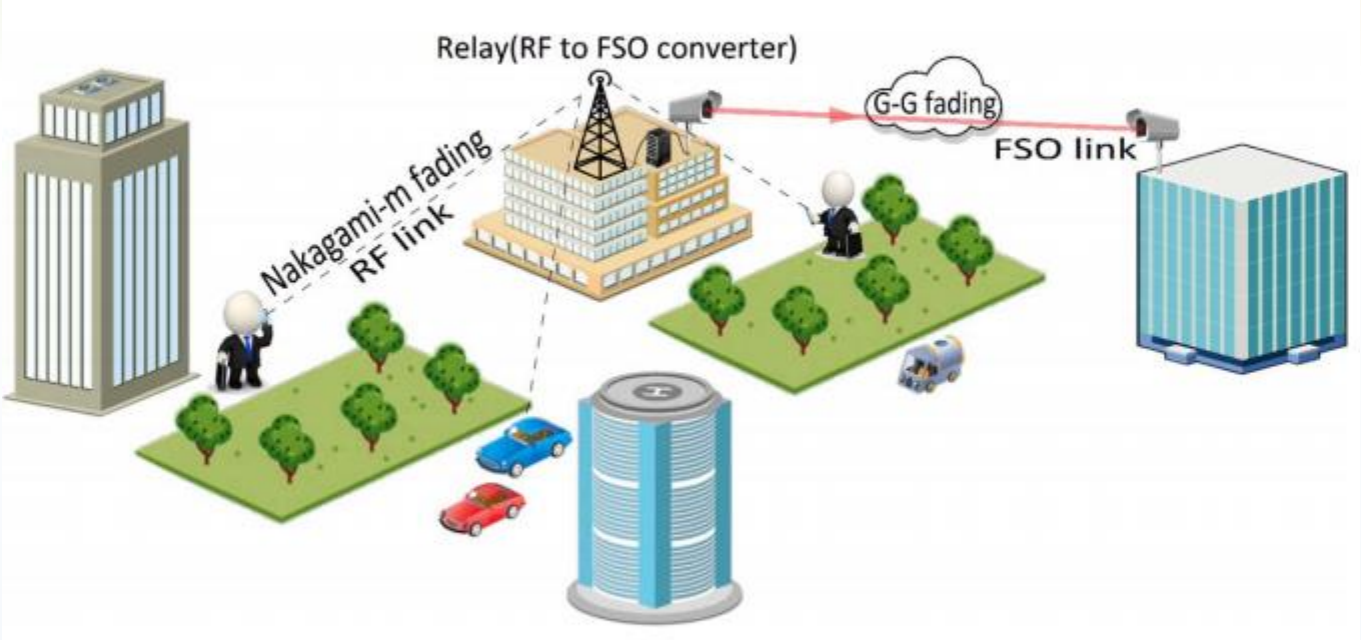
Cascaded RF/FSO Systems

Dual-Hop RF/FSO System Model

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

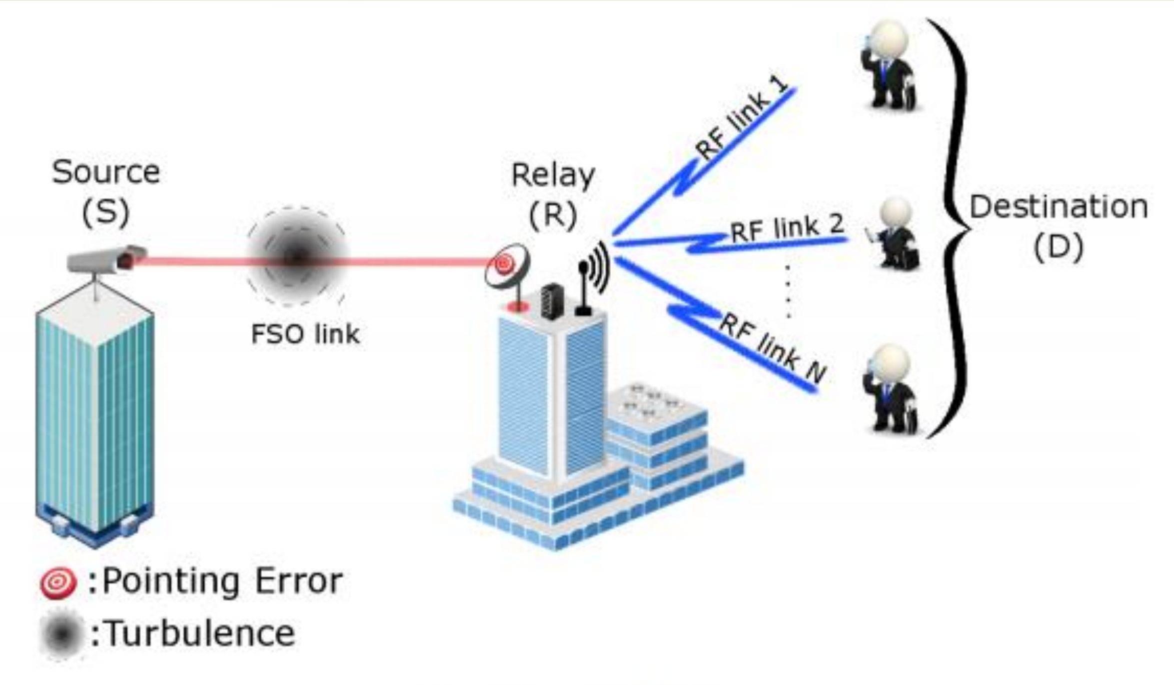


[1] E. Zedini, I. Ansari, and M. -S. Alouini, "On the performance of mixed Nakagami-m/Gamma-Gamma dual-hop transmission systems", IEEE Photonics Journal, Vol. 7, No. 1, February 2015.

[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.**



Dual-hop FSO/RF system.

[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.

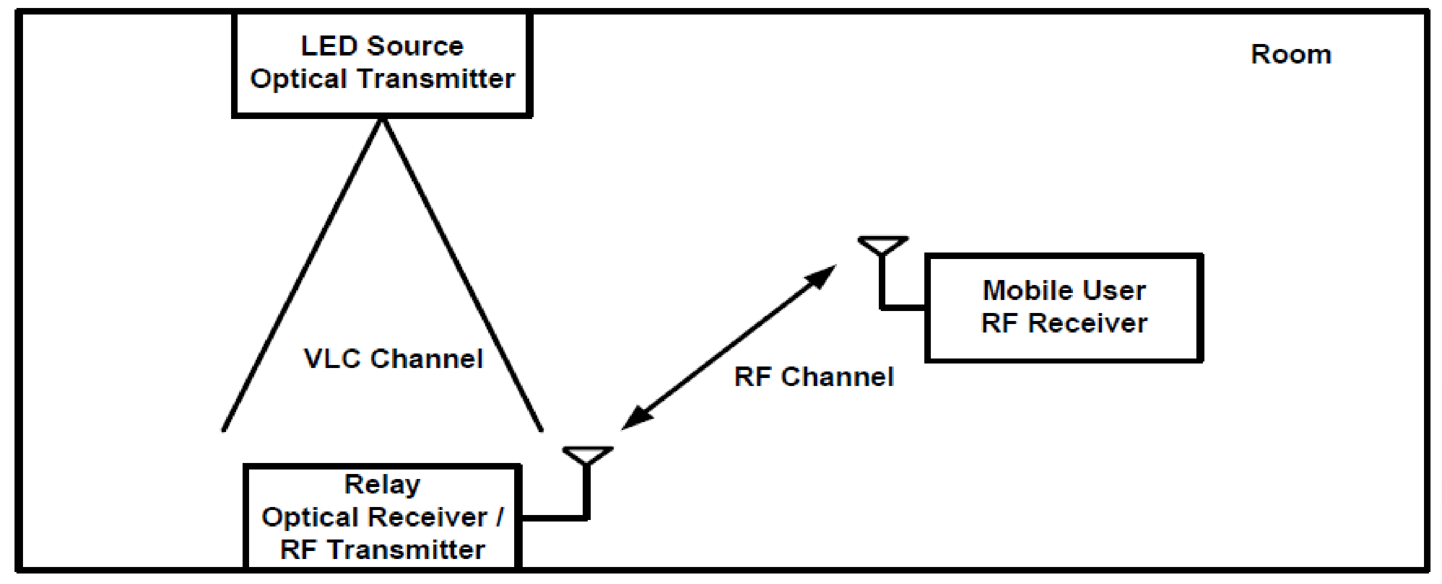
VLC/RF Coverage Extension

- **The light of a Light Emitting Diode (LED) is used for simultaneous:**
  - Illumination.
  - Data communication at high data rates.
- **The light originating from a LED source is:**
  - Naturally conned to a small area.
  - Susceptible to shadowing and blockages.
- **Hybrid VLC/RF systems provide coverage extension of VLC systems.**

[1] T. Rakia, H. -C. Yang, F. Gebali, and M. -S. Alouini, "Optimal design of dual-hop VLC/RF communication system with energy harvesting", IEEE Communication Letters, Vol. 20, No. 10, pp. 1979-1982, October 2016.

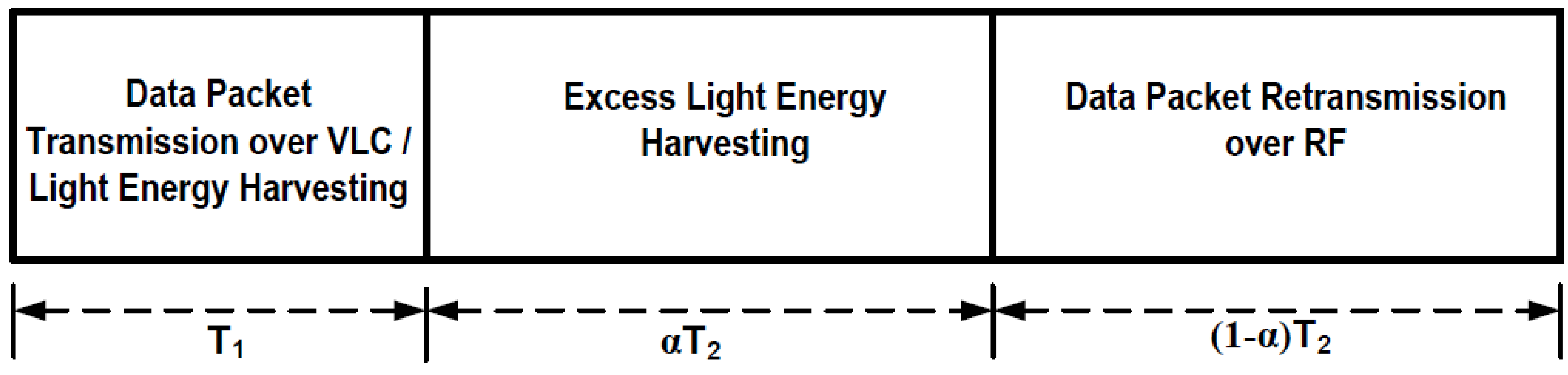
Dual-hop VLC/RF Transmission System with a Light Energy Harvesting Relay

- The relay terminal is located in a fixed position, while the designated user can move freely within the room.
- The relay can harvest indoor light energy.
- The proposed system provides a low complexity and energy efficient solution for coverage extension of VLC systems.



Time Division Relaying Scheme of Proposed Dual-hop VLC/RF System

- To comply with a certain QoS requirement, the total time to transmit one data packet must not exceed a strict delay constraint value.
- There is a trade-off between the two time portions αT_2 and $(1-\alpha)T_2$.
- We optimize the parameter α in terms of minimizing the data packet loss probability.

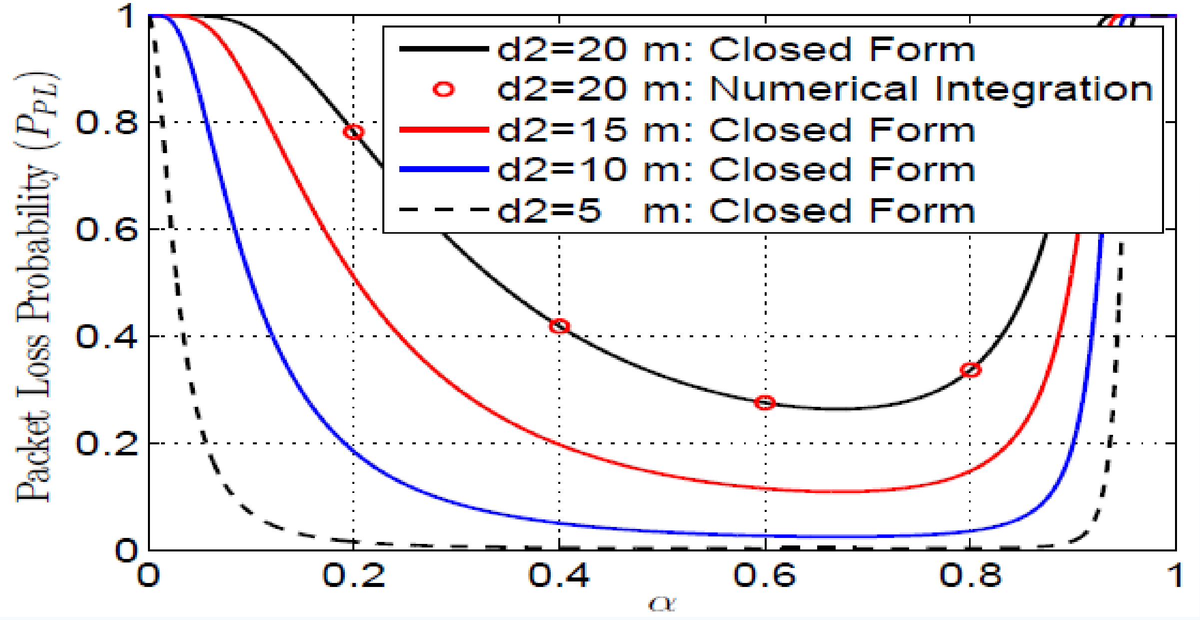


Packet Loss Probability of Proposed Dual-hop VLC/RF System

- **Packet loss probability is given by:**

$$P_{PL} = \frac{1}{\sqrt{\pi}\Gamma(m)} \sum_{i=1}^{N} \omega_i \, \gamma\left(m, mAe^{-(\sqrt{2}\sigma_{\ln y} t_i + \mu_{\ln y})}\right)$$

  - $A = G_2 \sigma \gamma_{2T} (1-\alpha) T_2 / (T_1 + \alpha T_2)$ and t_i and ω_i are abscissas and weight factors for the Gaussian-Hermite integration.



Conclusion and Current Work

- Spectrum scarcity is becoming a reality
- This scarcity can be relieved through:
  - Links with higher spectral efficiency
  - Heterogeneous networks
  - Extreme bandwidth communication systems in the optical & THz bands co-existing with RF communication systems
- Analytical and fast simulation results of these systems can be used to perform initial system level trade-offs
- On-going deployment and testing the capabilities of optical wireless communication systems in a variety of environments and with different conditions

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Thank You

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