Enabling Tb/s Free Space Optical Communications

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(3) Thales Alenia Space in Switzerland, Switzerland
(4) Thales Alenia Space in France, France
(5) Polariton Technologies AG, Switzerland

Outline

- The Institute of Electromagnetic Fields (IEF) at ETH Zurich
- Introduction to FSO
- A Field Trial: Jungfraujoch – Bern
- The 5 Secrets

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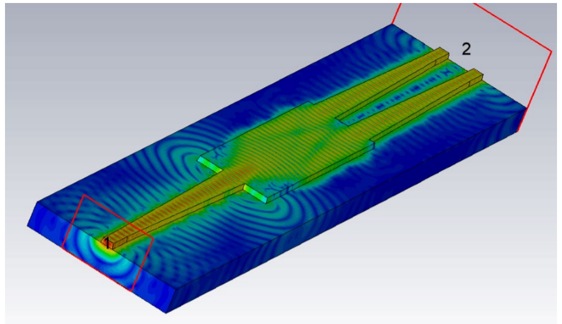
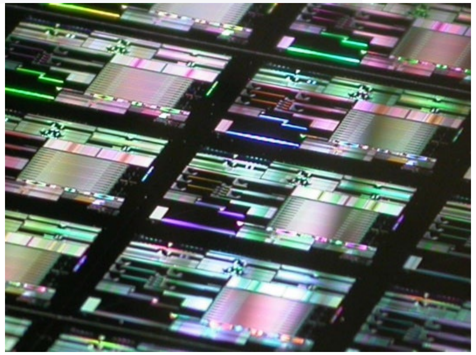
The Institute of Electromagnetic Fields (IEF) at ETH

Theory
& Design



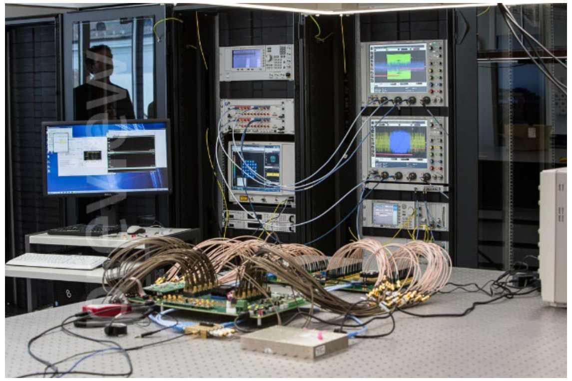
Design of novel integrated
Optical & electrical chips

Fabrication

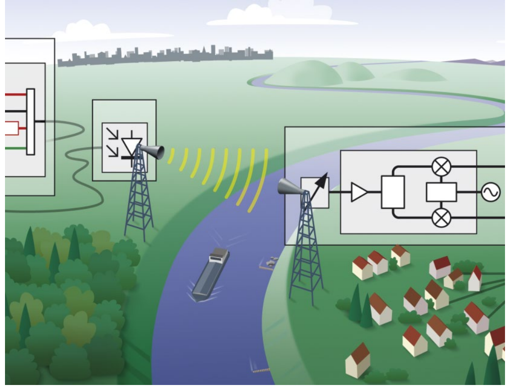


Fabrication:
In-House in Rüschlikon or
Fabless

System
Level
Testing



Tbit/s Fiber Transmission



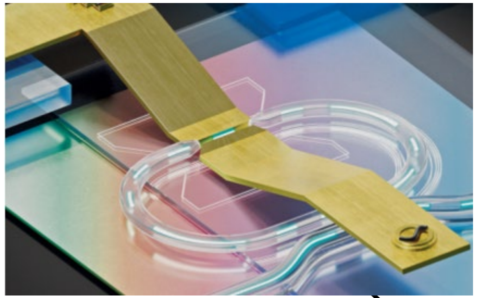
200 Gbit/s wireless link

Novel Systems
& Real-time DSP

The Institute of Electromagnetic Fields (IEF) at ETH

Developing the critical components to enable operation at any frequency up to 500 GHz and beyond.

Modulators, Phased Arrays

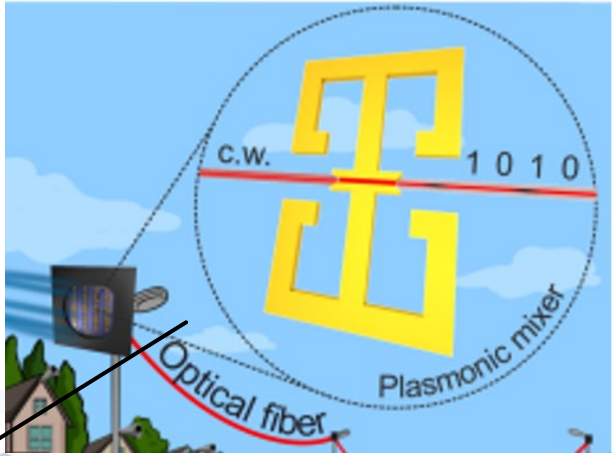


M. Eppenberger et al, Nature Photonics 2023

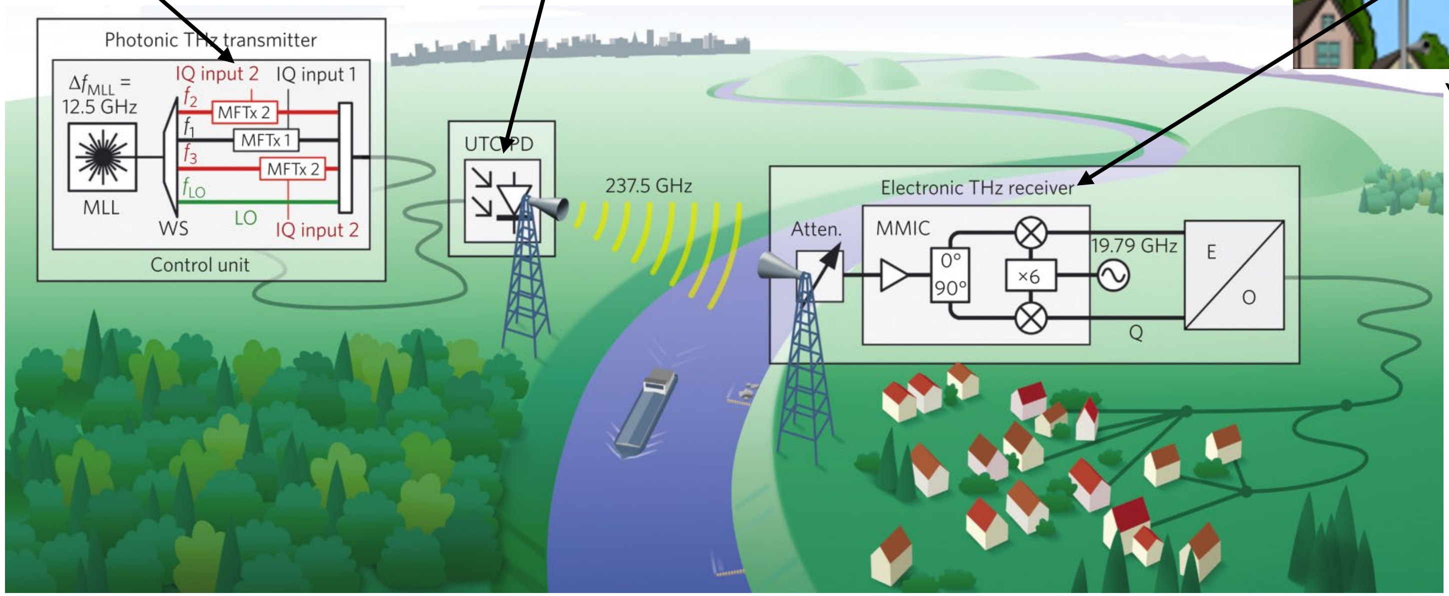
Fast & Efficient Photodiodes

S. Köpfli et al; Science 2023

THz Antenna



Y. Salamin *et al.*, *Nature Photonics, Dec. 2018*



S. Koenig *et al., Nature Photonics, Dec. 2013,*

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- The Institute of Electromagnetic Fields (IEF) at ETH Zurich
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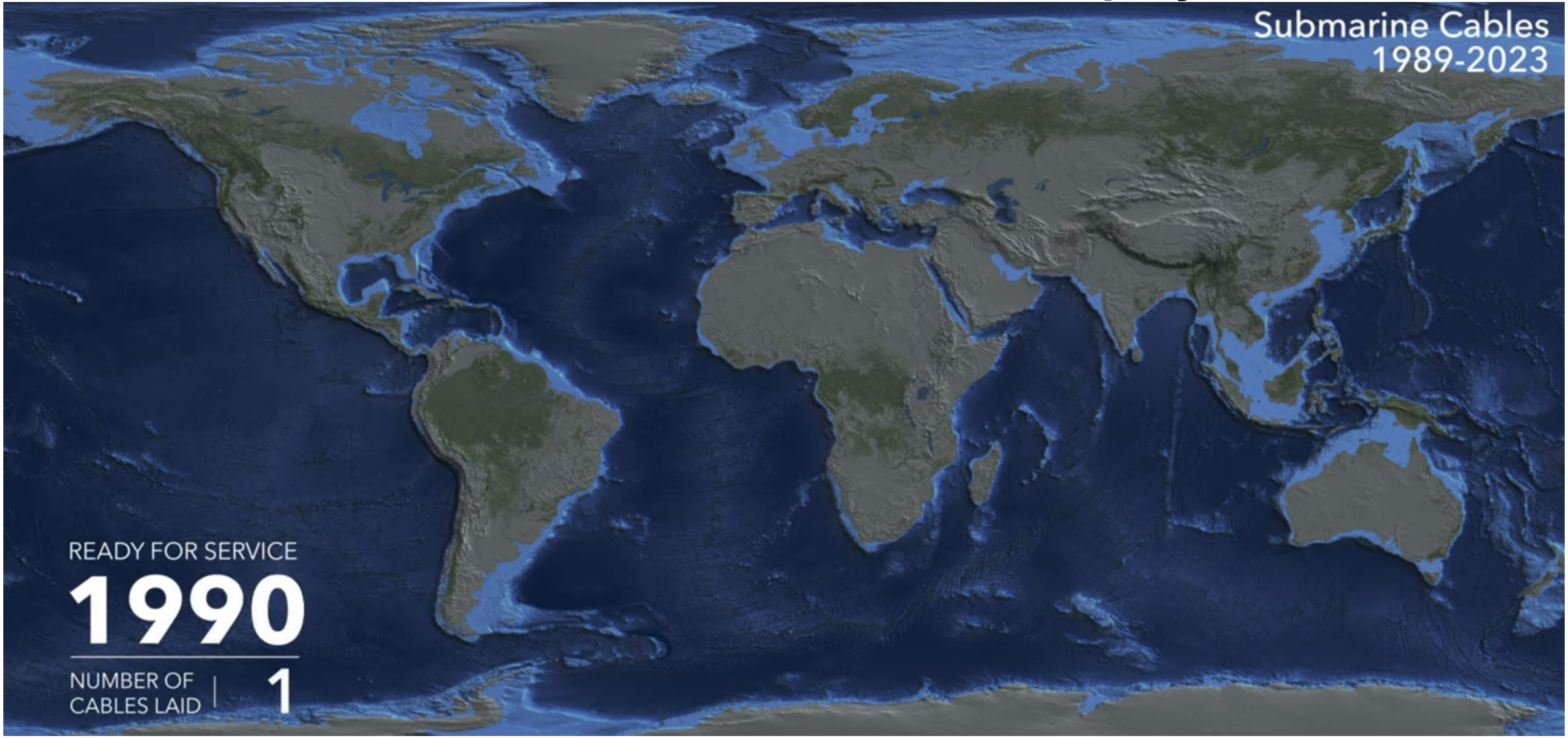
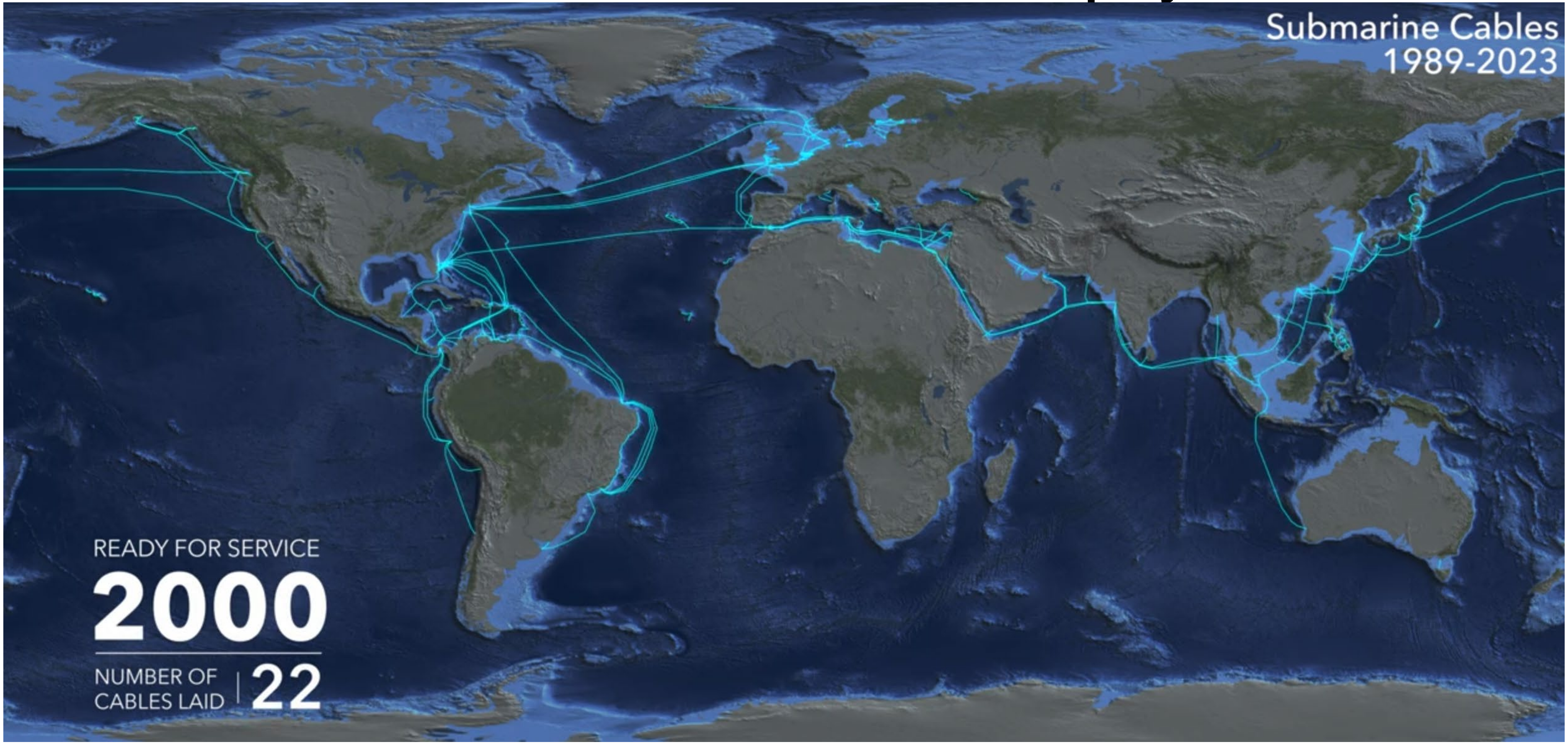
- A Field Trial: Jungfraujoch – Bern
- The 5 Secrets to maximize FSO capacity

Global Submarine Fiber Network – Cables Deployed within Year

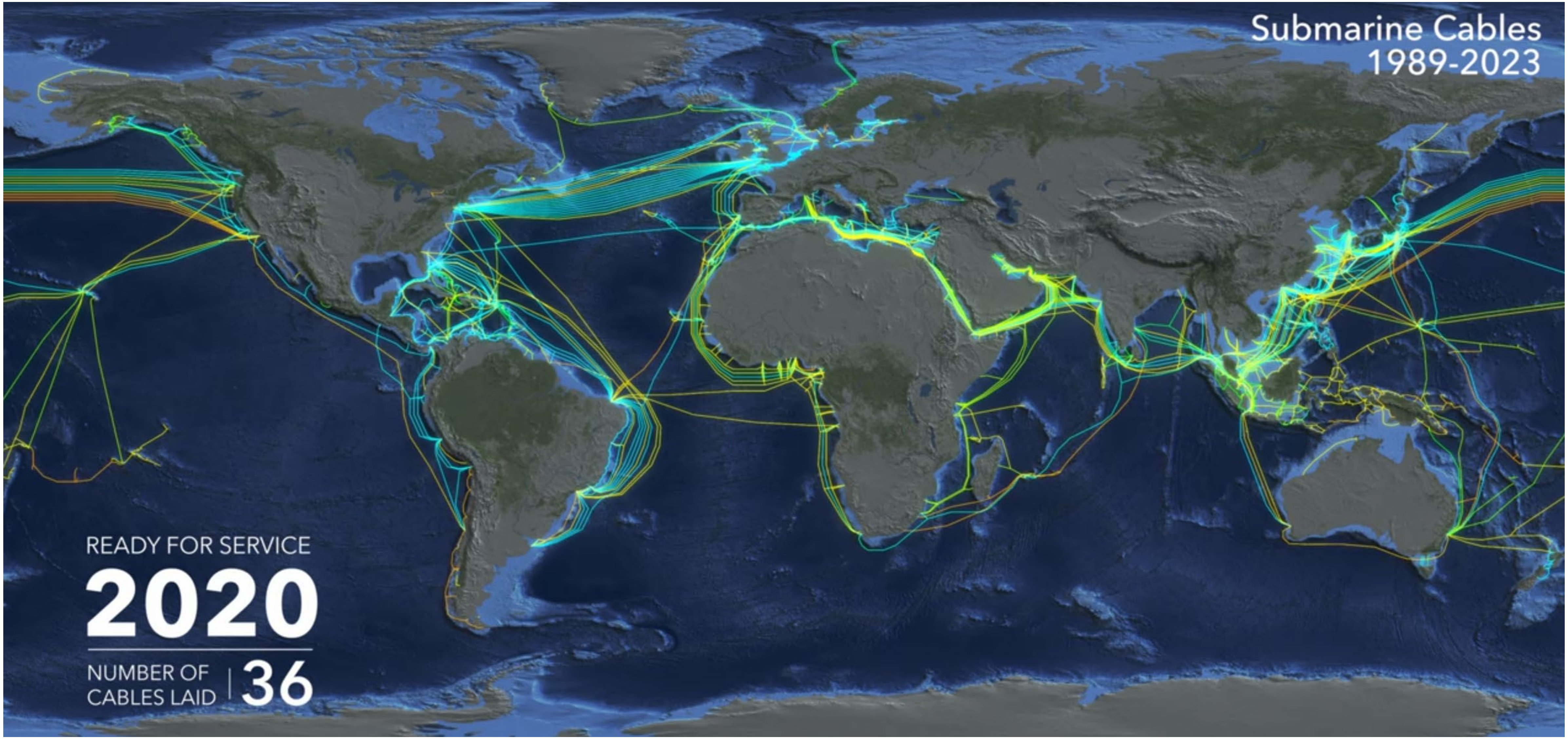


Global Submarine Fiber Network – Cables Deployed within Year



https://www.visualcapitalist.com/wired-world-35-years-of-submarine-cables-in-one-map/

Global Submarine Fiber Network – Cables Deployed within Year



https://www.visualcapitalist.com/wired-world-35-years-of-submarine-cables-in-one-map/

Internet from Space for Homes

Source: CyberHoot

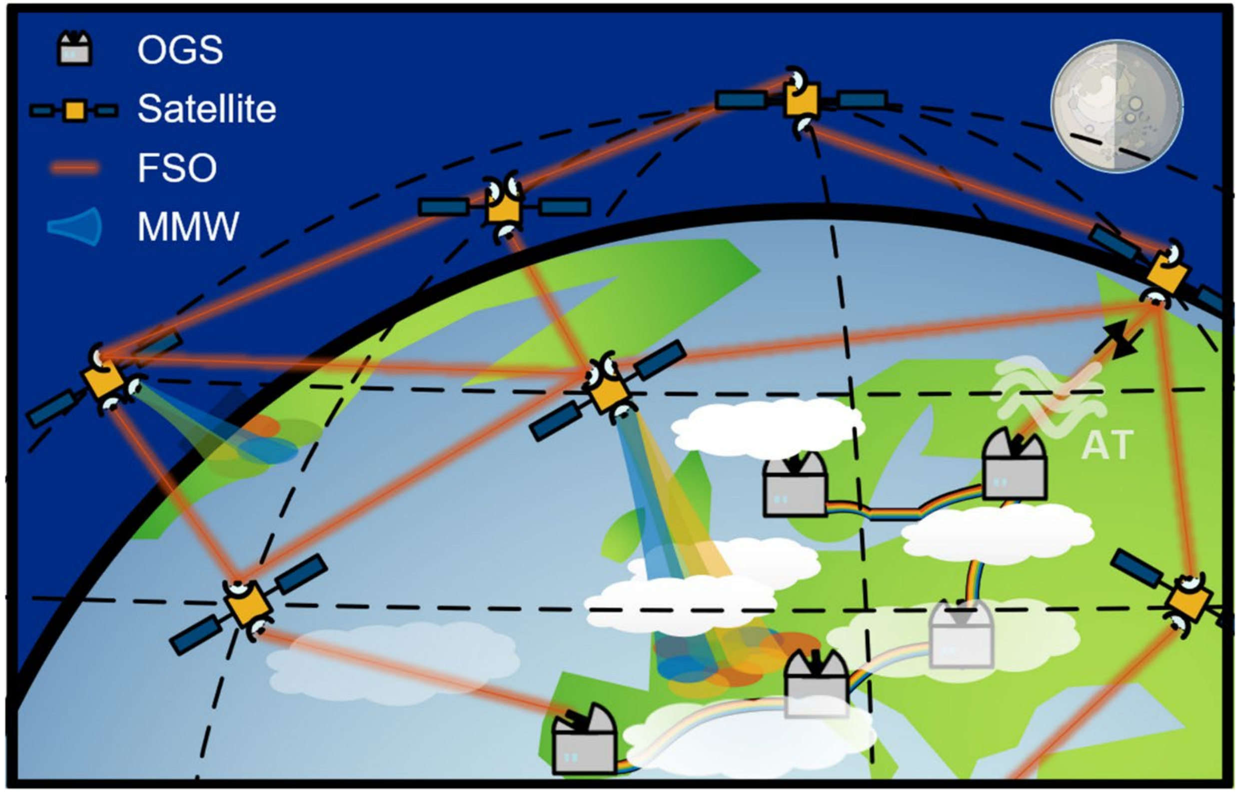
Source: digitec.ch

Starlink

- Company: Space X
- Height: 300 – 600 km (LEO)
- Constellation: ~4500 Satellites (now)
  42'000 (planned)
- Internet via:
  - Starlink Kit (Motor with Phase-Array Antenna, Router, …)
- Operation in Bands between 10 – 30 GHz

Starlink Kit (Switzerland)	
One-time Costs	440,- CHF
Monthly costs	65,- CHF
Download	25 – 220 Mbit/s
Upload	5 – 20 Mbit/s
Latency	25 – 60 ms

Free-Space Optics (FSO) vs. Radio-over-Fiber (RoF)



Critical Challenges for Ground-Space:
Weather conditions
Atmospheric Turbulences

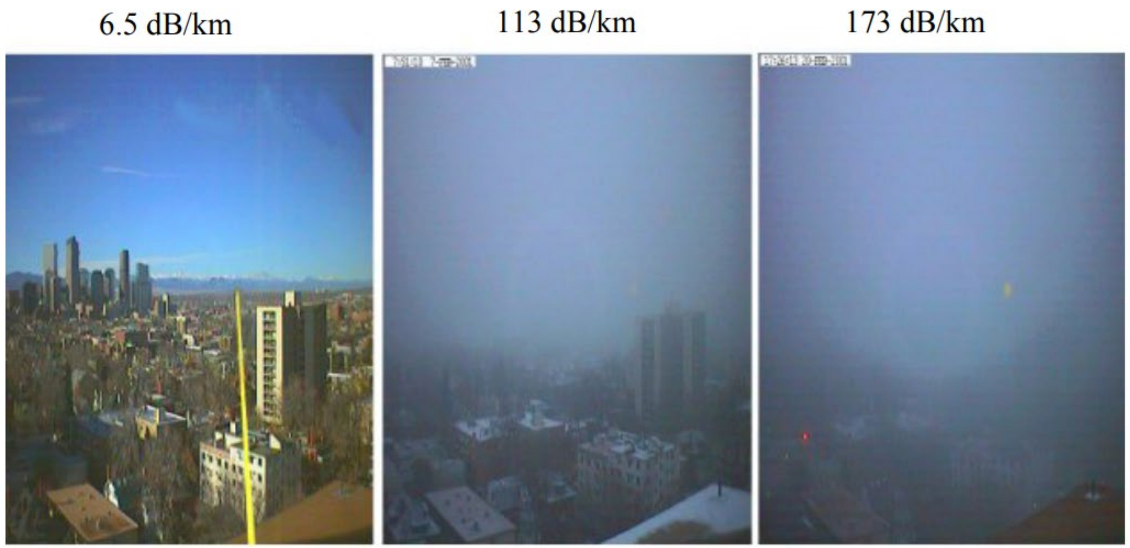
- FSO links for space applications
  - + Low losses in clear weather conditions (0.2 dB/km)
  - + Low divergence
    - High distances (Ground-to-Geo: ~38’000 km)
    - Security
  - + High Throughput
    - Available optical bandwidth (license-free)
    - Multiplexing
    - Reduced number of optical ground gateways
  - + Size, weight and power consumption (SWaP)

Challenges of FSO: Weather

Particle size ↑ →

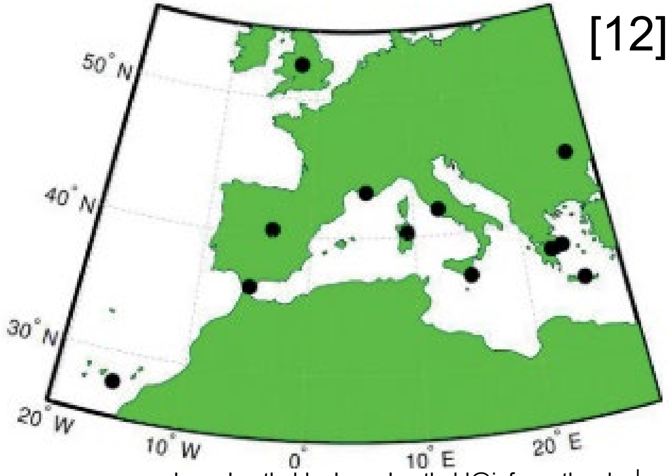
Weather	Clear	Haze / Pollution	Fog / Clouds	Rain	Snow
FSO [dB/km]	0.2 [1,2]	2 – 4 [2]	34 – 340 [2,3,11]	2 – 20 [4]	3 – 43 [1,5]
RoF [dB/km]	0.2 - 3 [6]	0.1 [7]	0.75 – 7.5 [8,11]	4 – 30 [9]	1 – 15 [10]
Visibility [m]	>20’000	4000…2000	500 … 50		

Fog event:



[3]

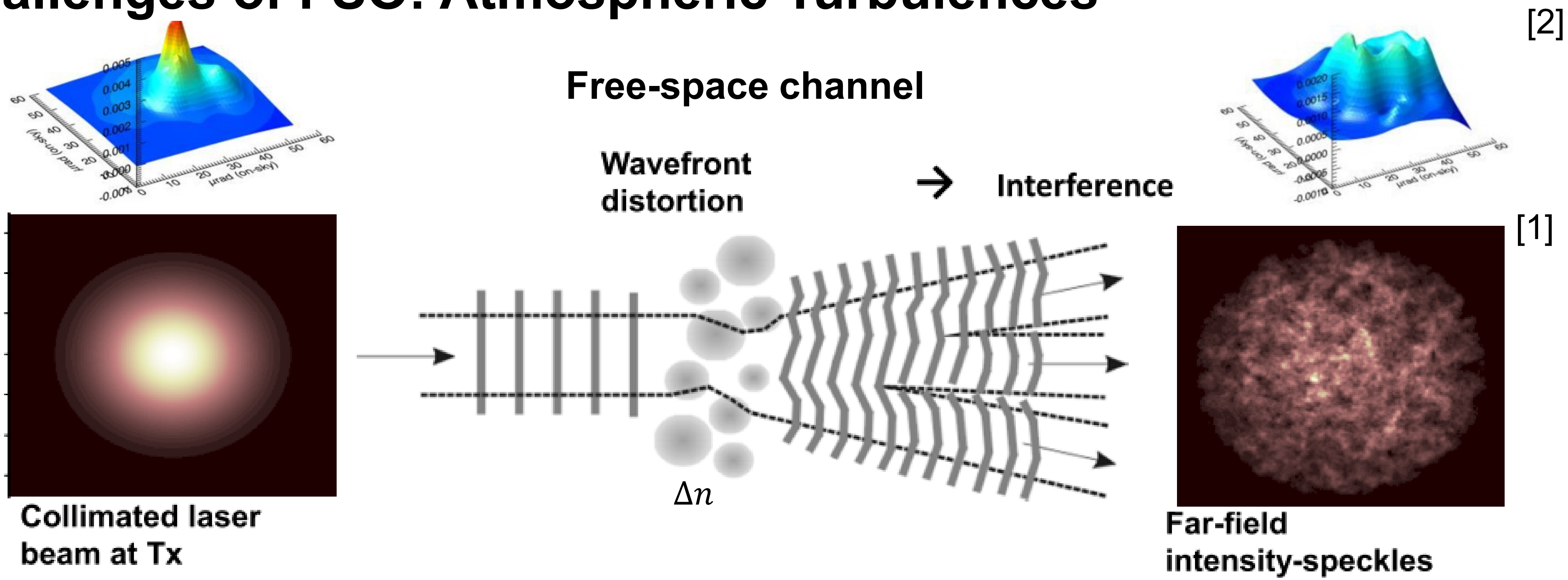
300 m distance to tall building; line is 2.4 km



[12]

[1] A. Trichili *et al.*, "Roadmap to free space optics," *J. Opt. Soc. Am. B*, 2020
[2] I. Kim, *et al.*, “Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze…,” *SPIE*, 2001.
[3] S. Bloom *et al.*, " Understanding the performance of free-space optics,“ *Journal of Optical Networking*, 2003
[4] S. A. Al-Gailani, *et al.*, "Enhancement of free space optical link in heavy rain…," *Elsevier*, 2013.
[5] M. S. Awan *et al.*, "Characterization of Fog and Snow Attenuations …," *Journal of Communications*, 2009
[6] I. T. Union “TU Recommendation P.676-9, Attenuation by Atmospheric Gases,” *ITU*, 2021.
[7] Q. Jing *et al.*, "Study on the Scattering Effect of Terahertz Waves in Near-Surface Atmo…," *IEEE Access*, 2018
[8] T. Schneider *et al.*, "Link Budget Analysis for Terahertz Fixed Wireless Links," *IEEE Transactions*, 2012
[9] F. Norouzian *et al.*, "Rain Attenuation at Millimeter Wave and Low-THz Frequencies," *IEEE Transactions*, 2020.
[10] Y. Amarasinghe *et al.*, "Scattering of Terahertz Waves by Snow," *J. of Infrared, Millimeter, and THz Waves*, 2020
[11] S.T. Fiorino, *et al.*, "A first principles atmospheric propagation…," *Atmospheric Propagation of Electromagnetic Waves II*, 2008
[12] D. Giggenbach et al., "A High-Throughput Satellite System … ," in Broadband Coverage in Germany. 9th ITG Symposium. Proceedings, 2015

Challenges of FSO: Atmospheric Turbulences



Atmospheric Turbulence leads:

- Beam wander: pointing & angle of arrival errors
- Phase-distortion
  - Scintillation

➢ Time-varying power fluctuations in the fiber

[1] R. M. Calvo et al., "Optical technologies for very high throughput satellite communications," Free-Space Laser Communications XXXI, San Francisco: SPIE, 2019.
[2] A. Montmerle-Bonnefois et al., "Adaptive optics precompensation .. ," in Applications of Lasers for Sensing and Free Space Communications, 2019: Optical Society of America, p. LTh1B. 3

Challenges of FSO

It is a Signal-to-Noise Ratio (SNR) Challenge

Shannon: $$C = B\log_2(1 + \frac{S}{N})$$

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  Vertigo Project: Thales Alenia Space – Onera – ETH
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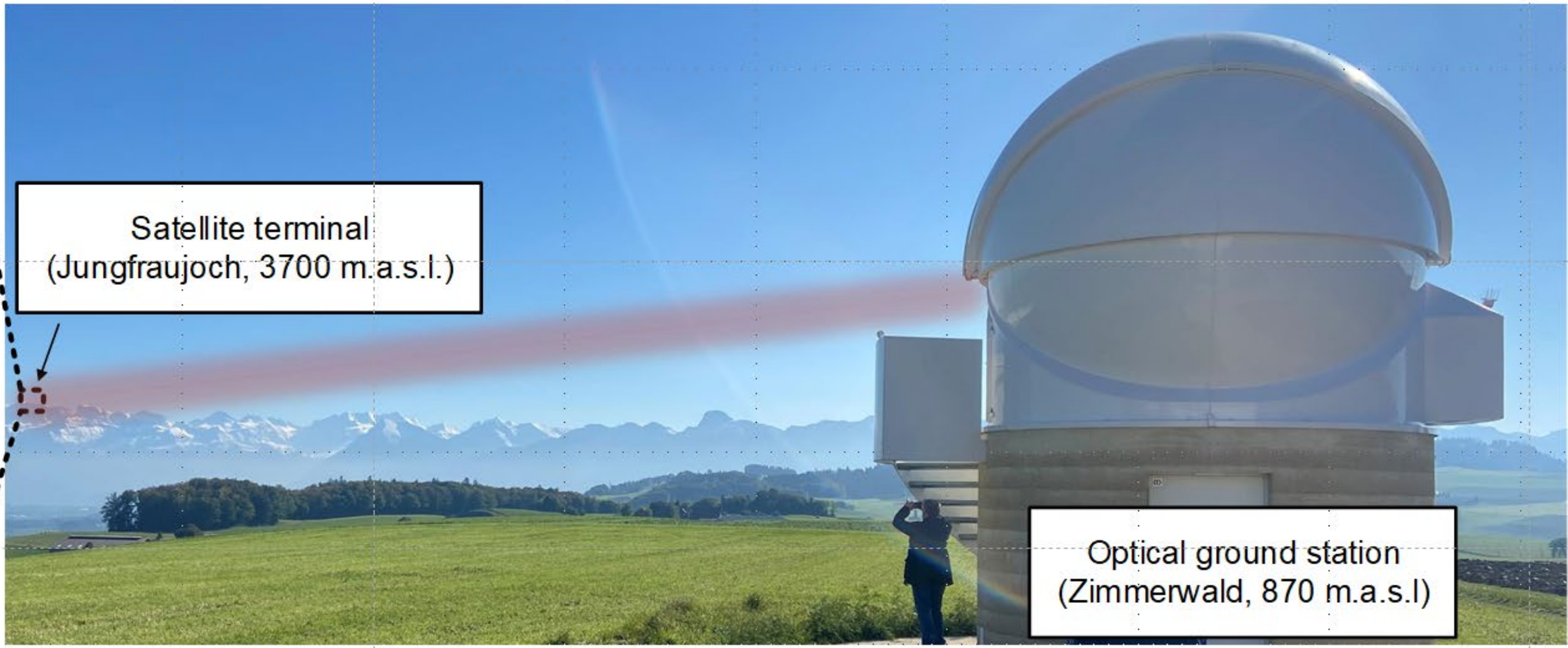
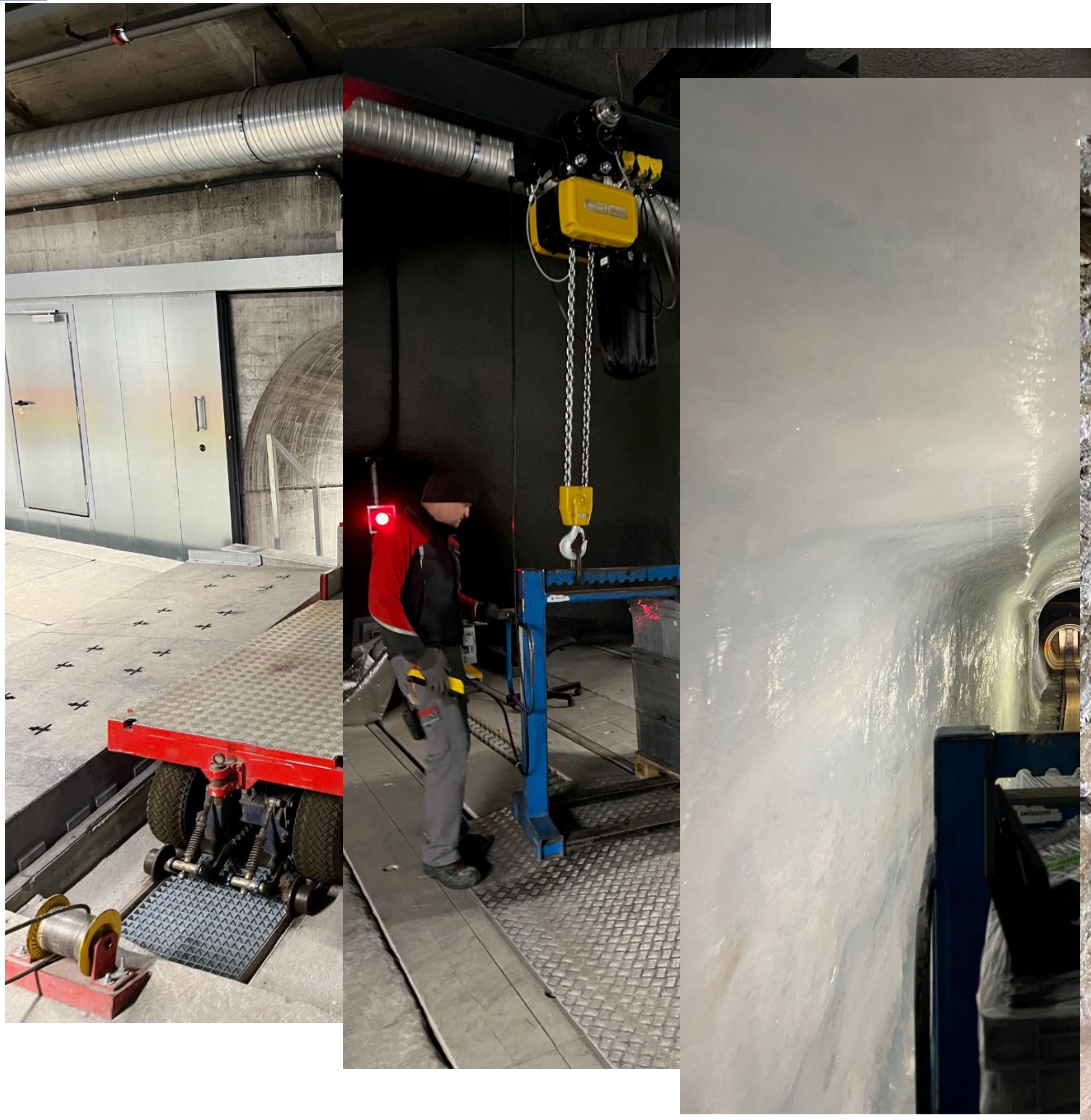
Free Space Optical Link Project: 1 Tb/s over 51 km



51 km link from the Jungfraujoch to Bern

Y. Horst *et al.*, "*Tbit/s line-rate satellite feeder links enabled by coherent modulation and full-adaptive optics,*" *Light: Science & Applications, June 2023*

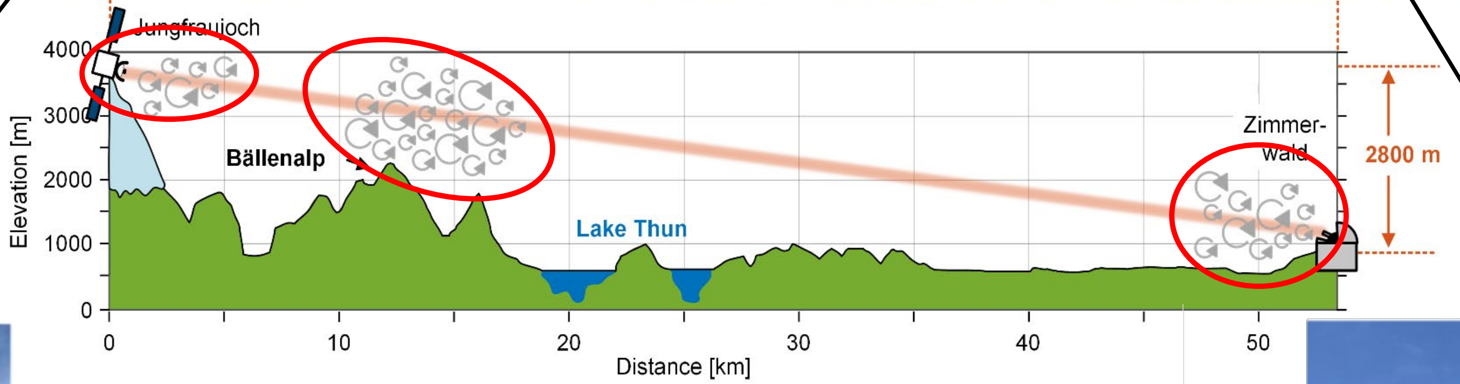


[1] Y. Horst *et al.*, *"Tbit/s line-rate satellite feeder links enabl*
Light: Science & Applications, June 2023

[1] Y. Horst *et al.*, *"Tbit/s line-rate satellite feeder links enabled by coherent modulation and full-adaptive optics," Light: Science & Applications, June 2023*

VERTIGO Outdoor Demonstration: Location

[1]



Ostgrat

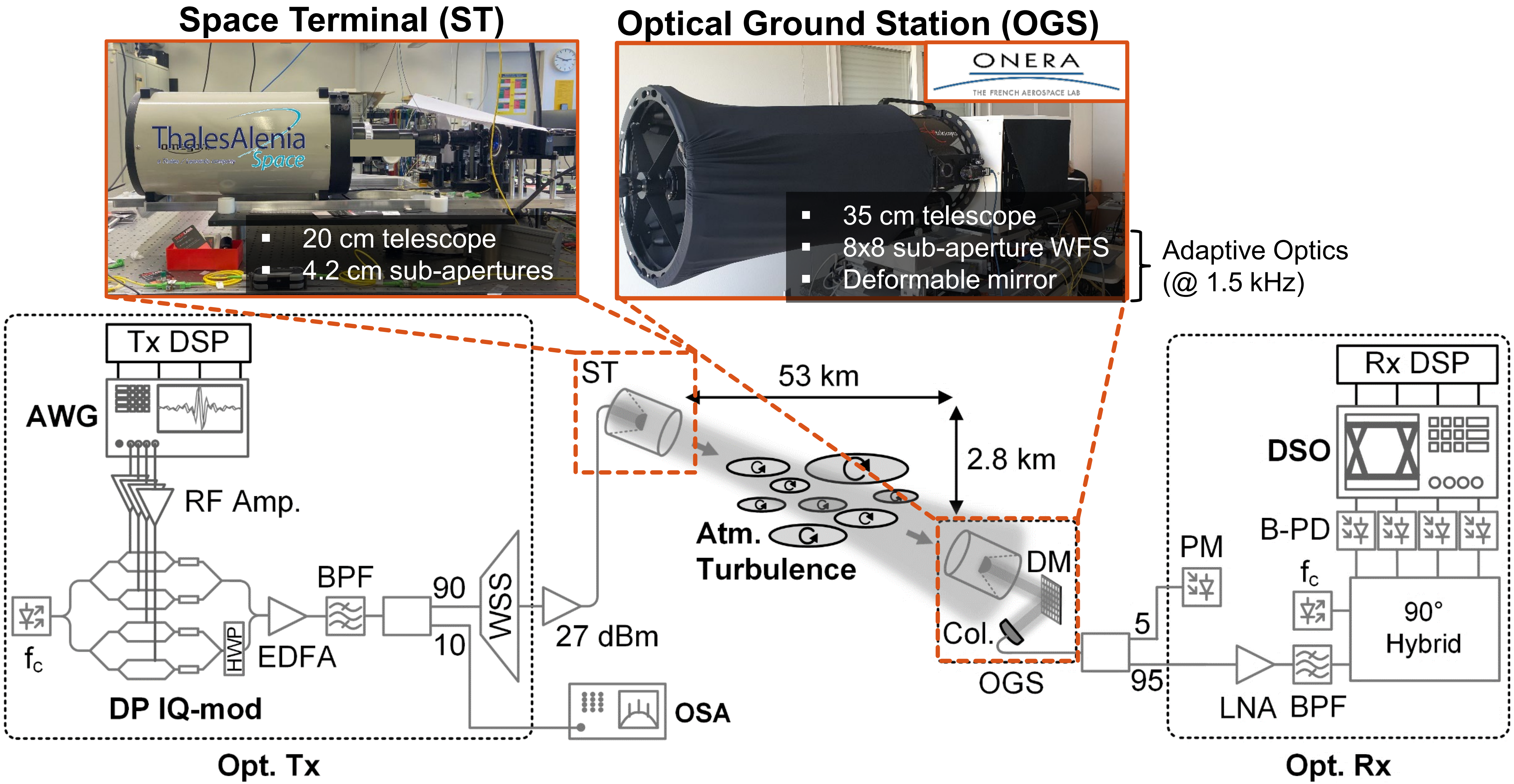
Old radio relay station

- operating until 2013

swisscom

[1] Horst, Y., Bitachon, B.I., Kulmer, L. *et al.* Tbit/s line-rate satellite feeder links enabled by coherent modulation and full-adaptive optics. *Light Sci Appl* (2023)

Outdoor Demonstration: Experimental Configuration



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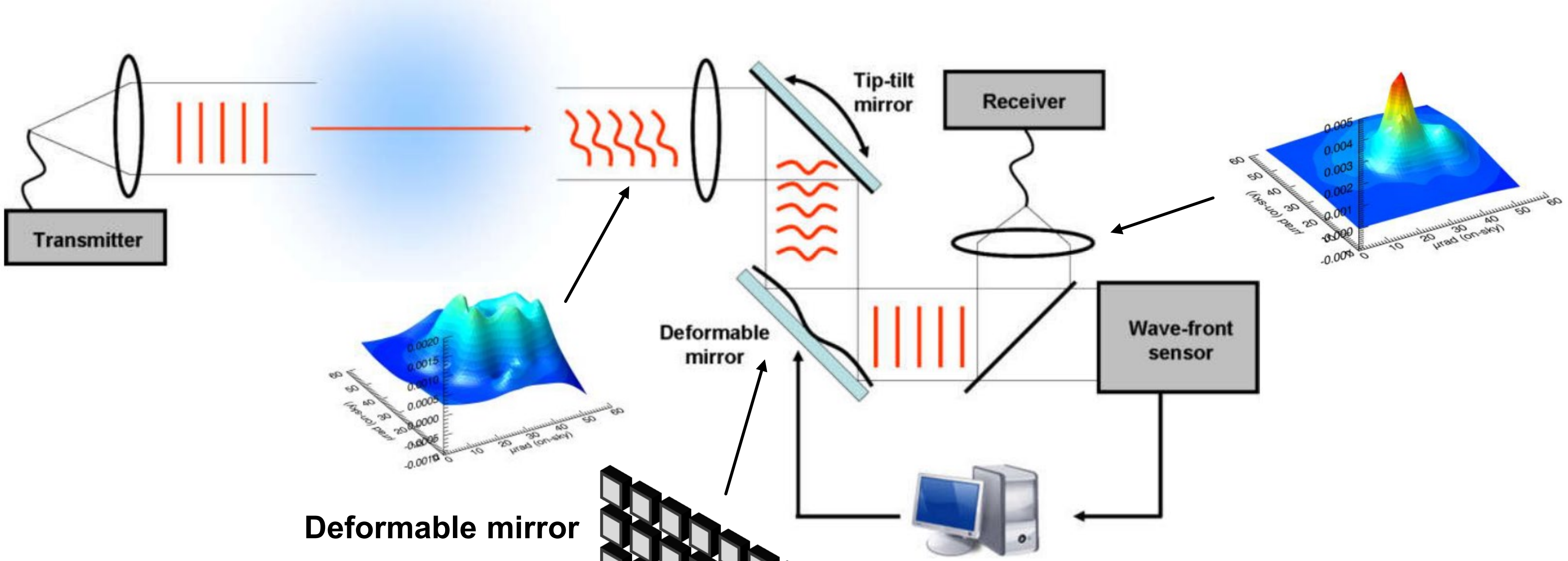
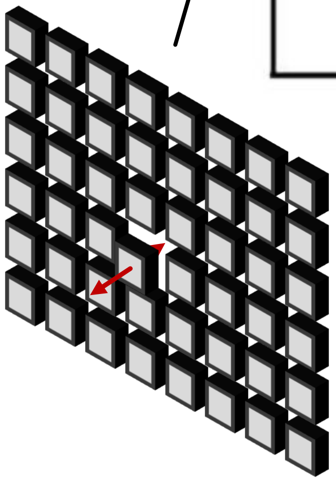
Solution 1: Turbulence Mitigation Technique: Adaptive Optics

[1]



Deformable mirror

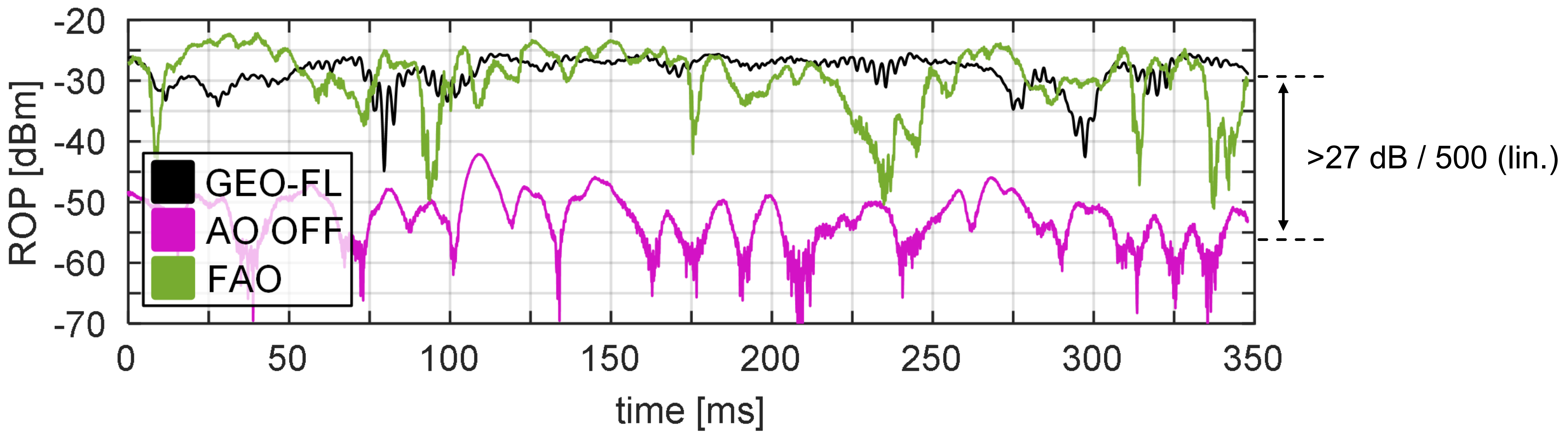


Key components:

- Wave-front sensor w/. 8x8 sub-aperture camera
  - Investigation of the phase wavefront
- Deformable mirror w/. MxN controllable mirrors
  - Correction of the phase wave front

[1] R. M. Calvo *et al.*, "Optical technologies for very high throughput satellite communications," *Free-Space Laser Communications XXXI, San Francisco: SPIE, 2019.*

Solution 1: Turbulence Mitigation Technique: Adaptive Optics (Role of Adaptive Optics (AO) for 1 Tbit/s Transmission)

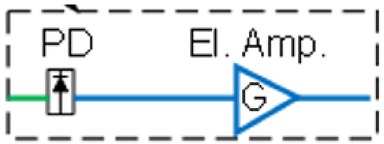


GEO = Simulation of a ground earth communication link.
AO Off = Adaptive Optics Off
FAO = Full Adaptive Opitcs

[1] Horst, Y., Bitachon, B.I., Kulmer, L. *et al.* Tbit/s line-rate satellite feeder links enabled by coherent modulation and full-adaptive optics. *Light Sci Appl* (2023)

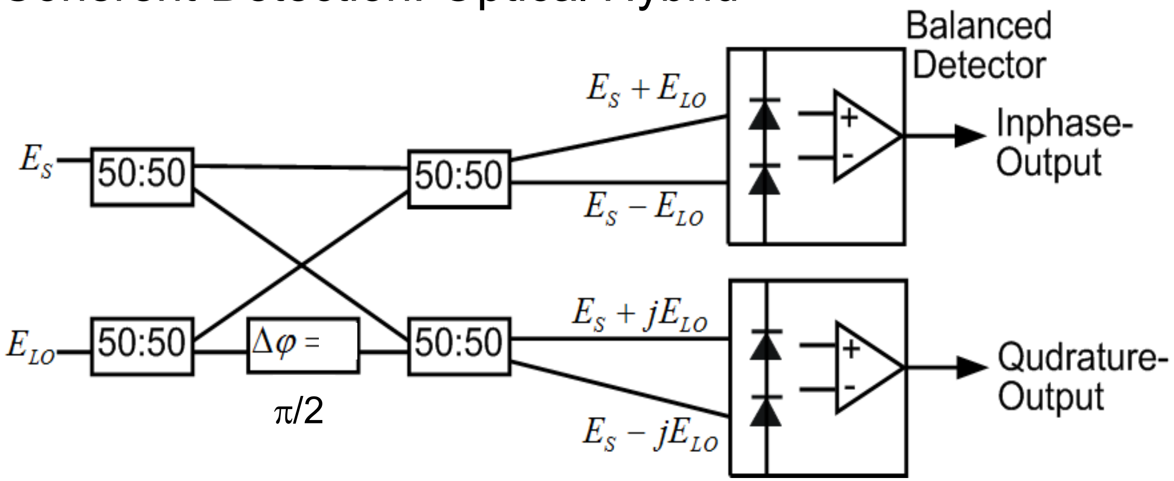
Solution 2: Coherent Transmission Techniques

Direct Detection: Single Photodiode



$$\frac{1}{2}\overline{|E_S|^2} \rightarrow I = \Re\, P_S$$

Coherent Detection: Optical Hybrid



$$I = \mathcal{R} \cdot 2\sqrt{P_S P_{LO}} \cos([\omega_S - \omega_{LO}]t + [\varphi_S - \varphi_{LO}])$$

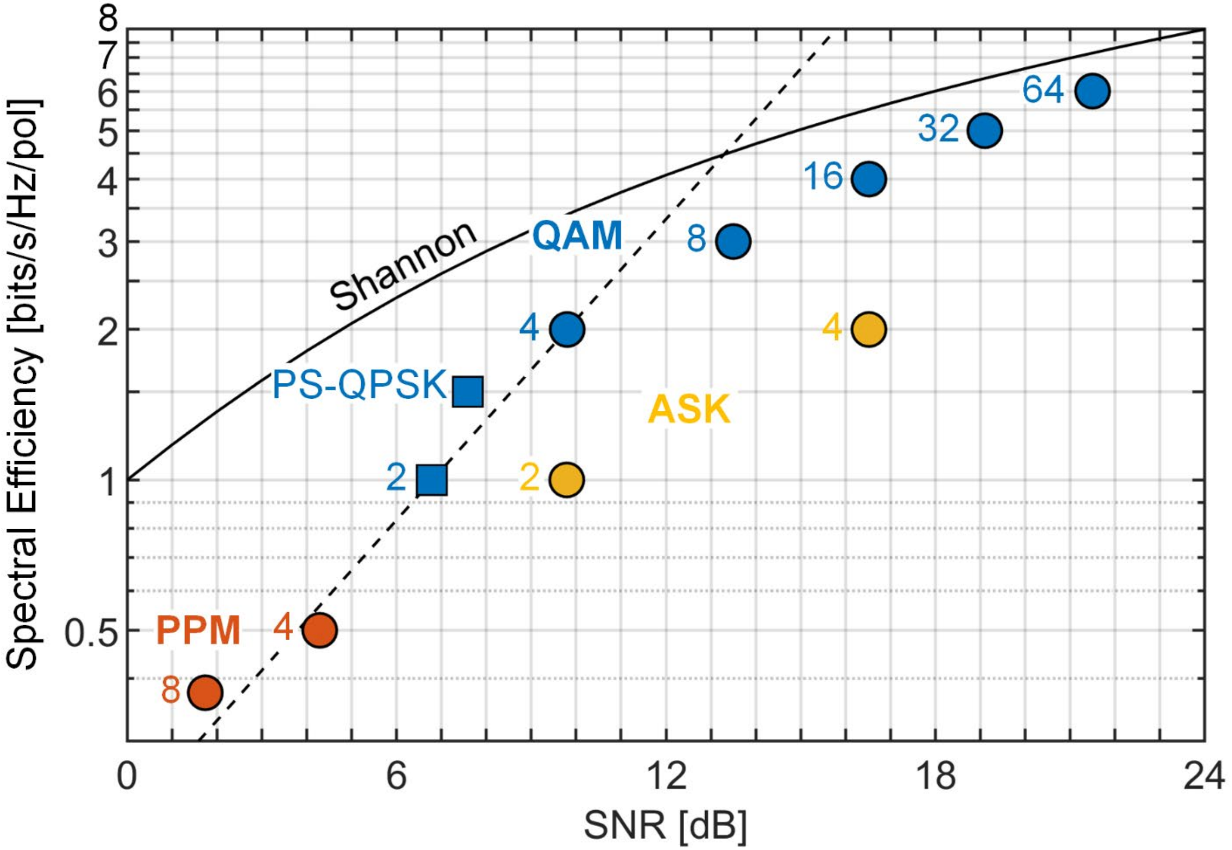
$$Q = \mathcal{R} \cdot 2\sqrt{P_S P_{LO}} \sin([\omega_S - \omega_{LO}]t + [\varphi_S - \varphi_{LO}])$$

There is a factor 4 of SNR Advantage of Coherent over Direct Detection!

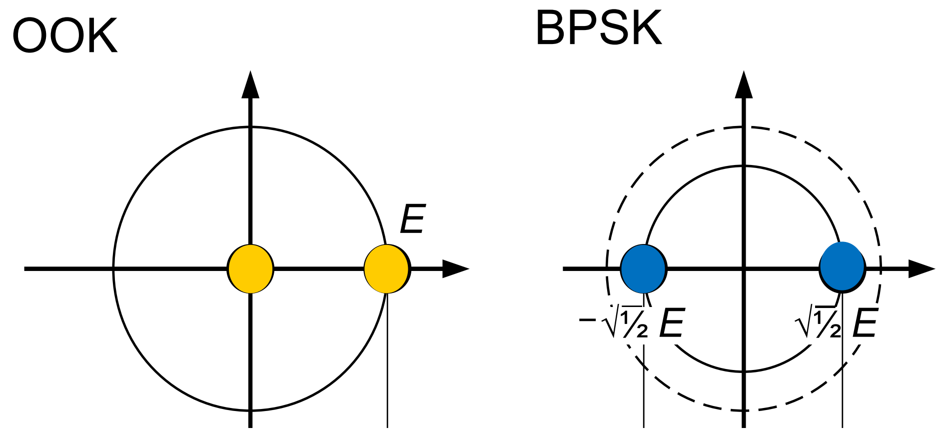
(6 dB)

Solution 3: Novel Modulation Formats for FSO - Links

Required SNR for a $1 \cdot 10^{-3}$ error!



As an example:
Should one encode as OOK or BPSK?



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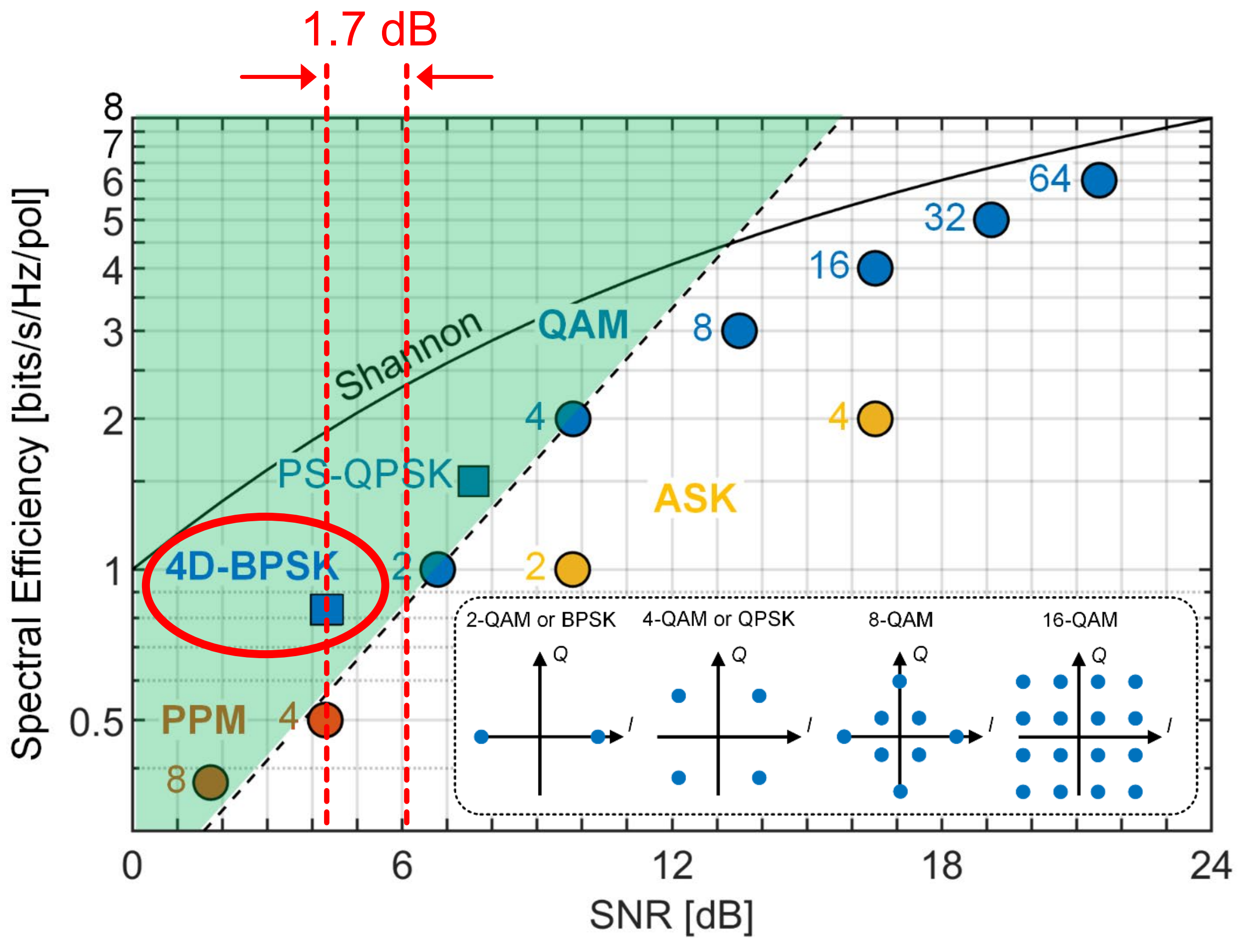


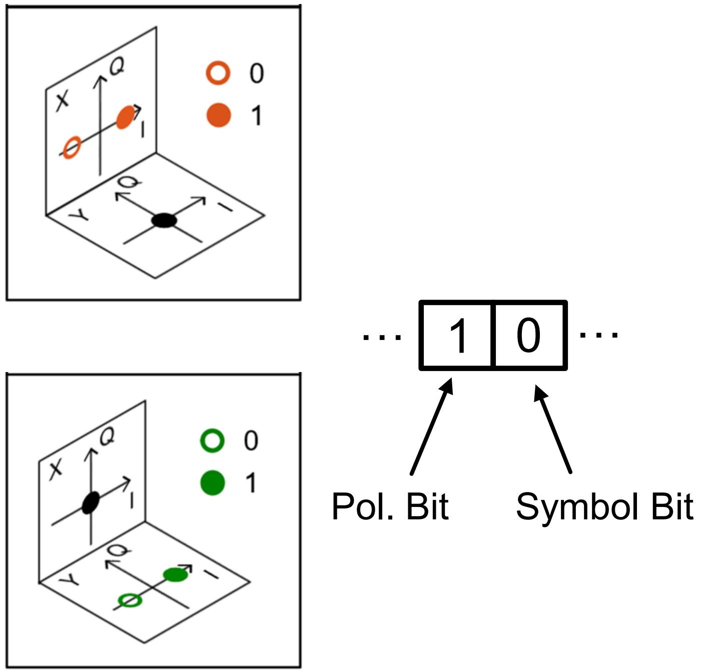
Constellation Modulation 4D-BPSK [1]:

- SE = 0.83 bit/symbol
- +1.7 dB advantage over QPSK

[1] S. S. Dash *et al.*, "Constellation modulation - an approach to increase spectral efficiency," Optics Express, 2017

Constellation Modulation - 4D-BPSK

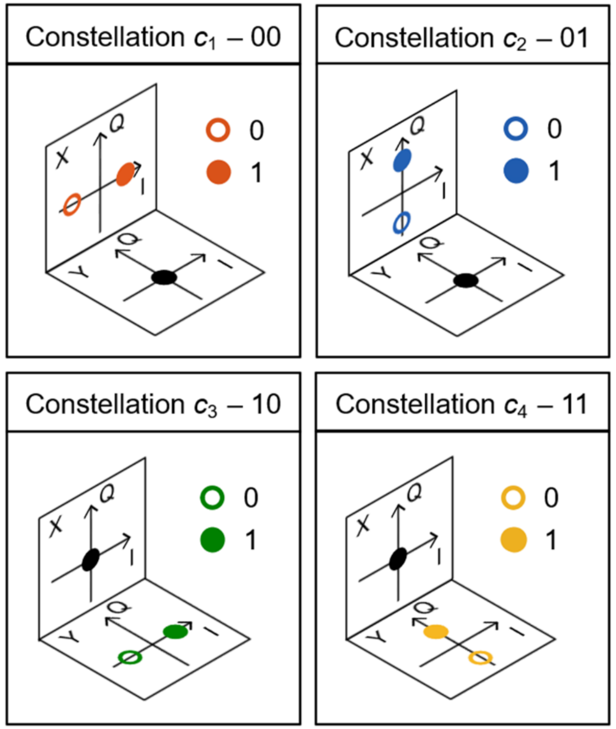
4D-BPSK

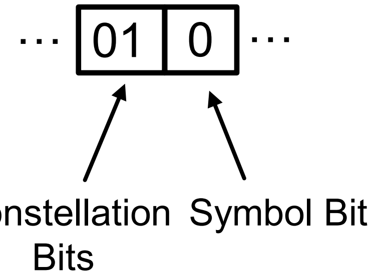


[1] Horst, Y., Bitachon, B.I., Kulmer, L. *et al.* Tbit/s line-rate satellite feeder links enabled by coherent modulation and full-adaptive optics. *Light Sci Appl* (2023)

Constellation Modulation - 4D-BPSK

4D-BPSK





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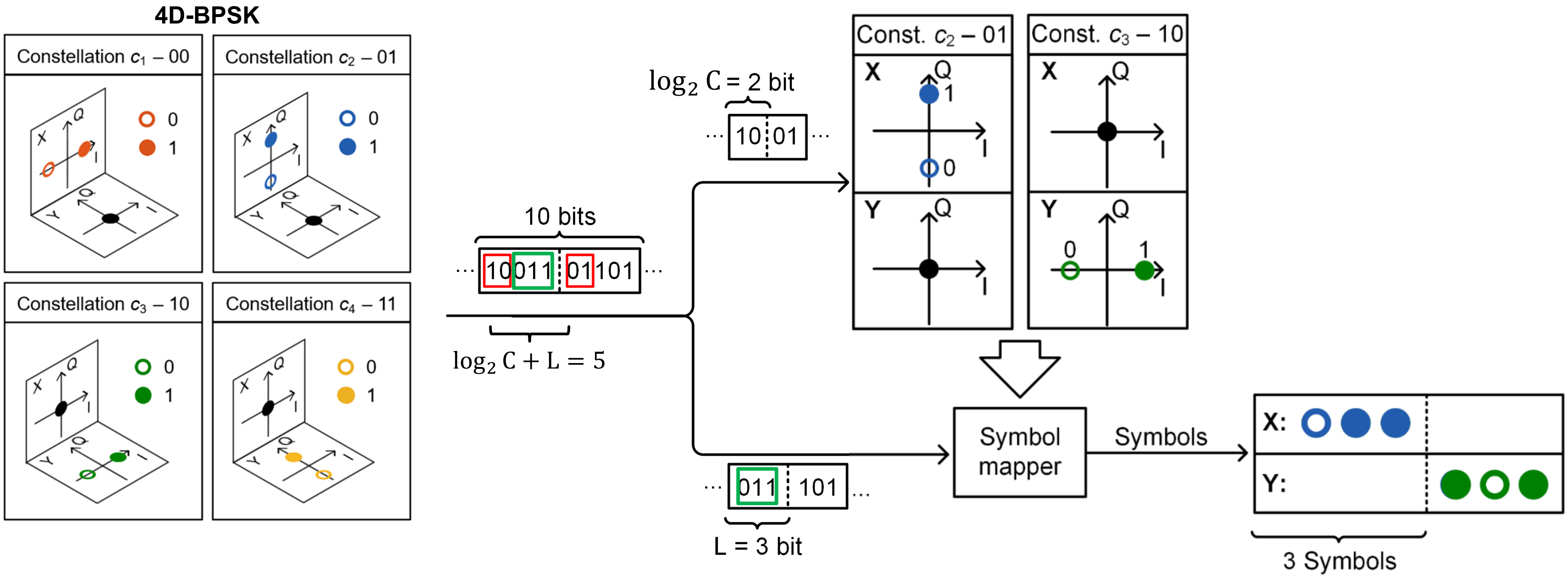
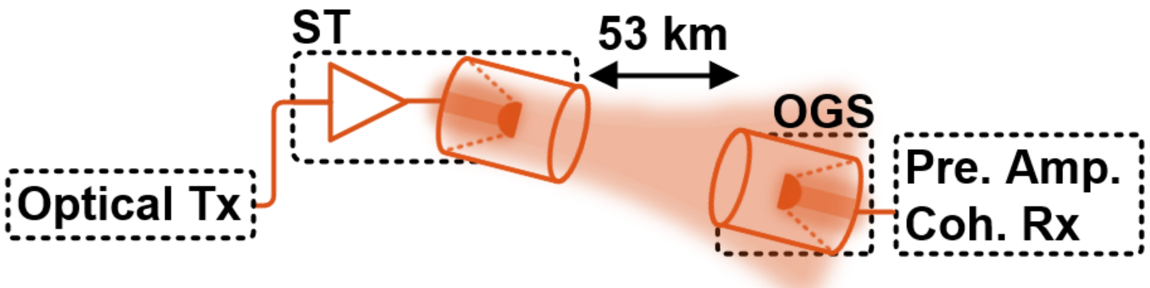
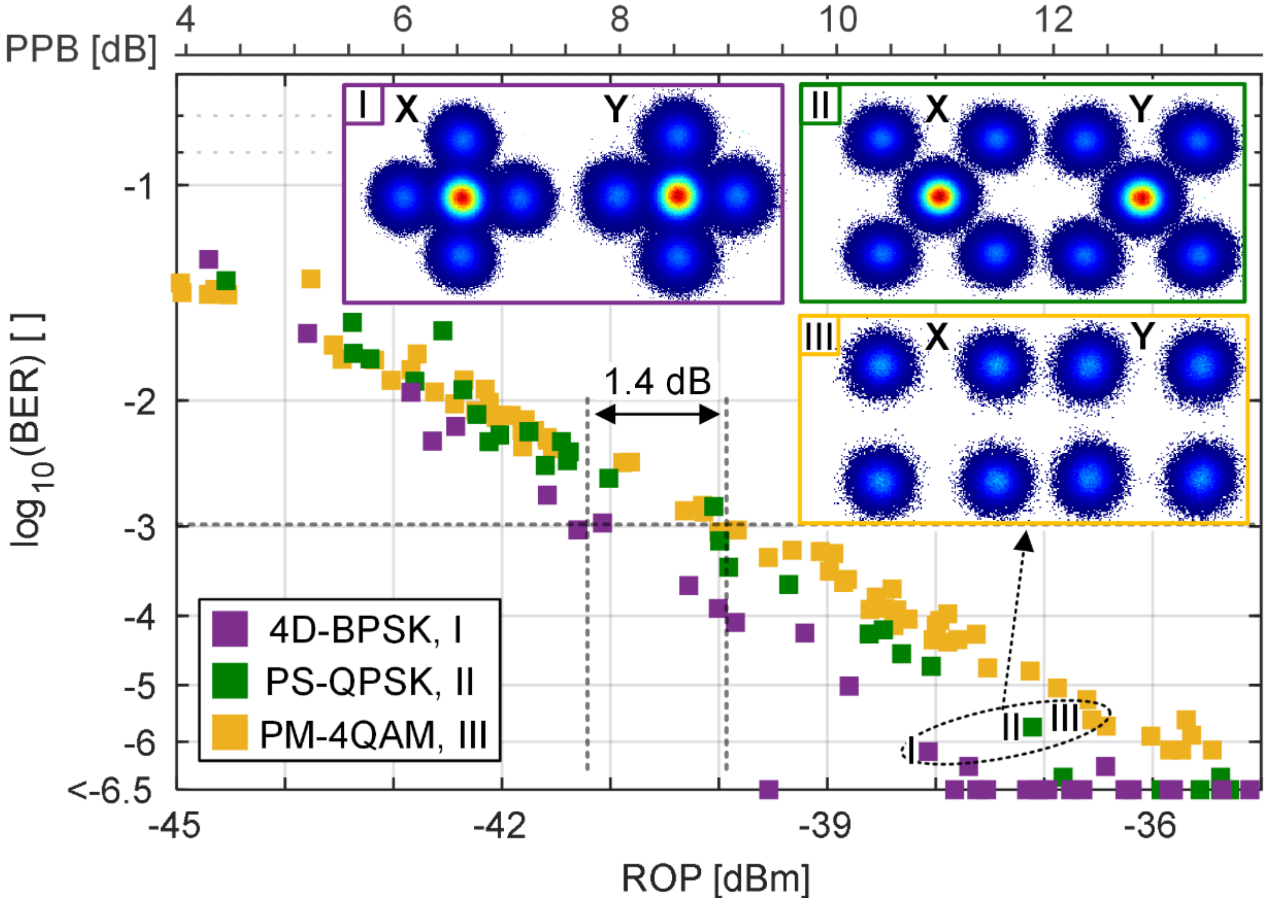


Spectral Efficiency $SE = \left[\frac{\log_2 C}{L} + \log_2 M\right] \cdot \frac{1}{P}$ [bit/symbol/Pol]

[1] Horst, Y., Bitachon, B.I., Kulmer, L. *et al.* Tbit/s line-rate satellite feeder links enabled by coherent modulation and full-adaptive optics. *Light Sci Appl* (2023)

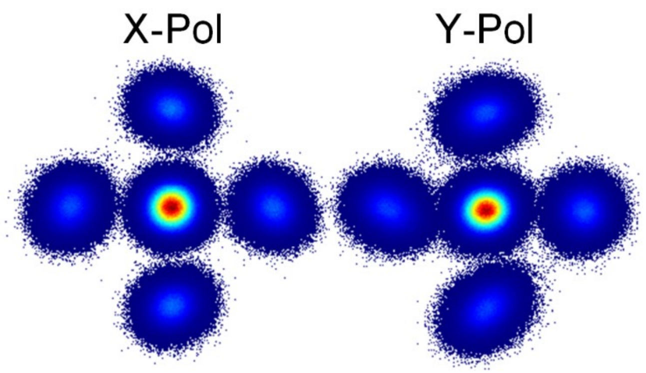
100 Gbps FSO Transmission over 53 km Turbulent Channel





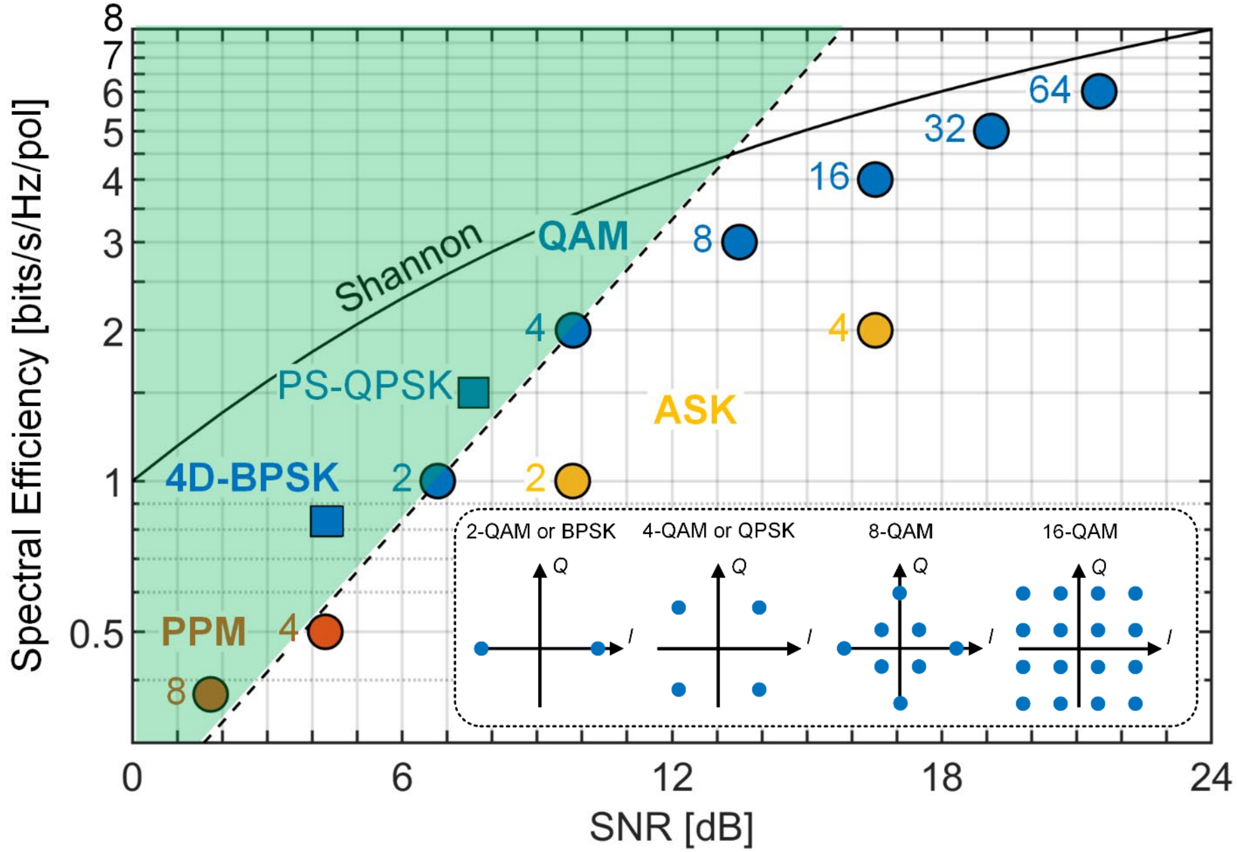
Experimental Results:

- ROP/SNR advantage of
  - 1.4 dB over QPSK (1.7 dB Sim.)
- Reliable Communication (BER $\leq 10^{-3}$)
  - 100 Gbps: ROP ≥ -41.2 dBm (5.8 PPB)
- High-Capacity
  - Data rate: > 200 Gbit/s (Limited by Equip.)



Solution 4: Go for Highest Speed and Simplest Modulation Format

Required SNR for a $1 \cdot 10^{-3}$ error!

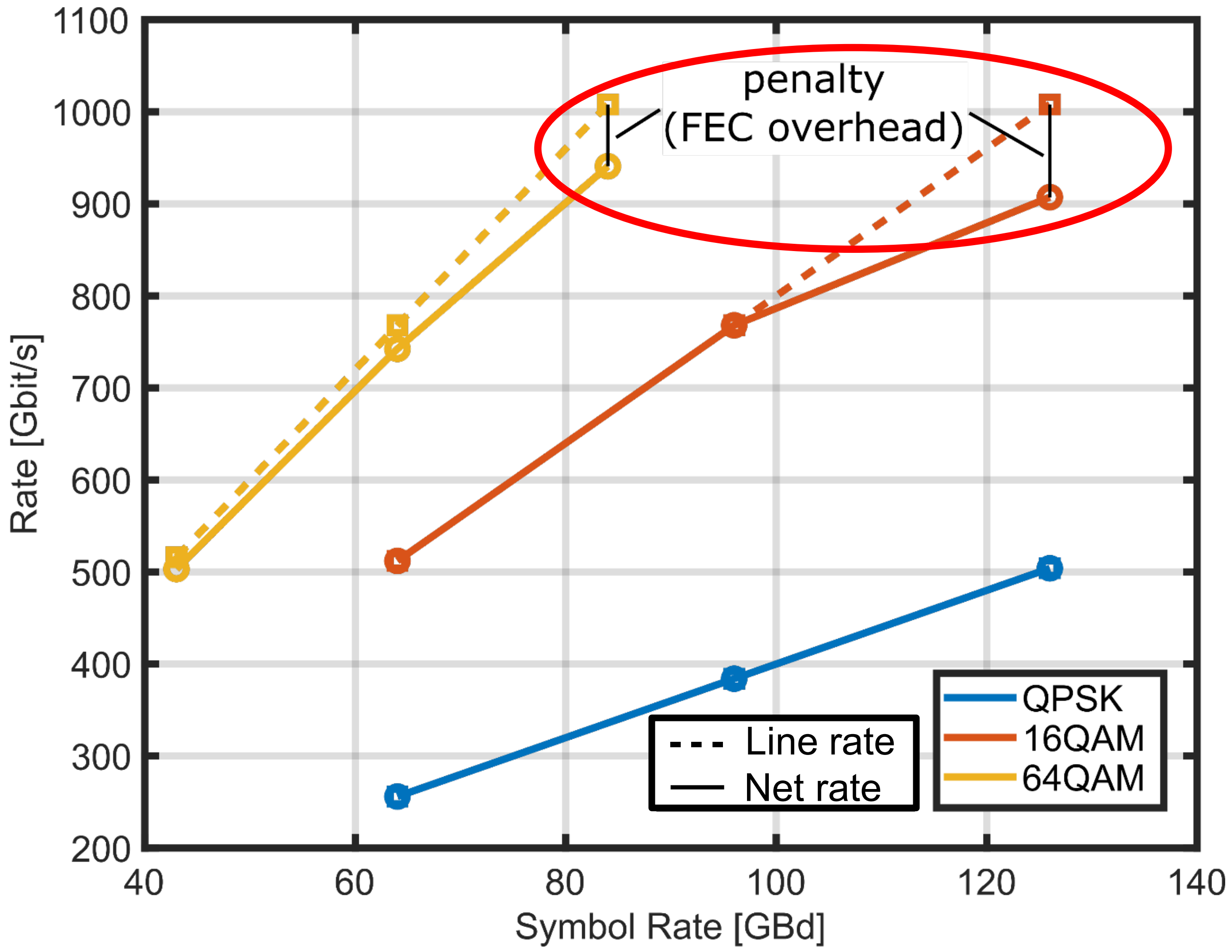


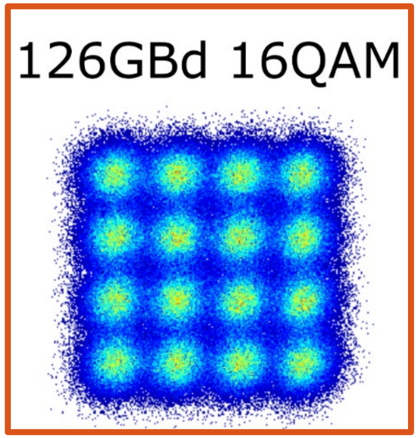
How to get 3 dB higher capacity?

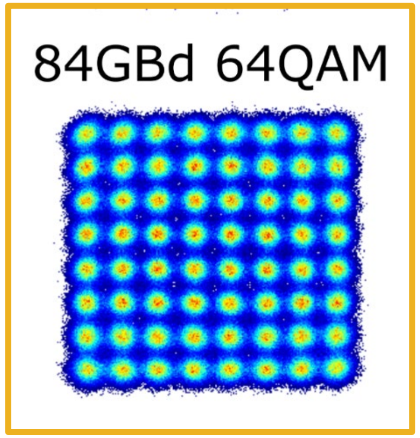
By increasing symbols
- 2 symbols → 1 bit → 0 dB
- 4 symbols → 2 bits → 3 dB
- 16 symbols → 4 bit → 10 dB
- …..

By doubling speed
- factor 2 → 3 dB for every factor 2!

Achieved Maximum Line Rate – 1 Tbit/s





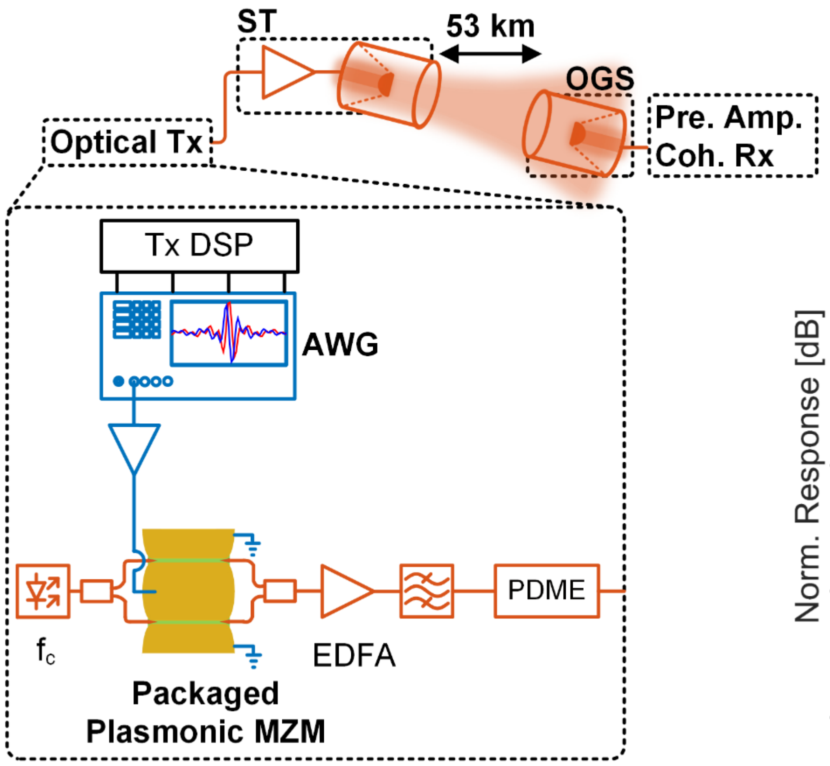


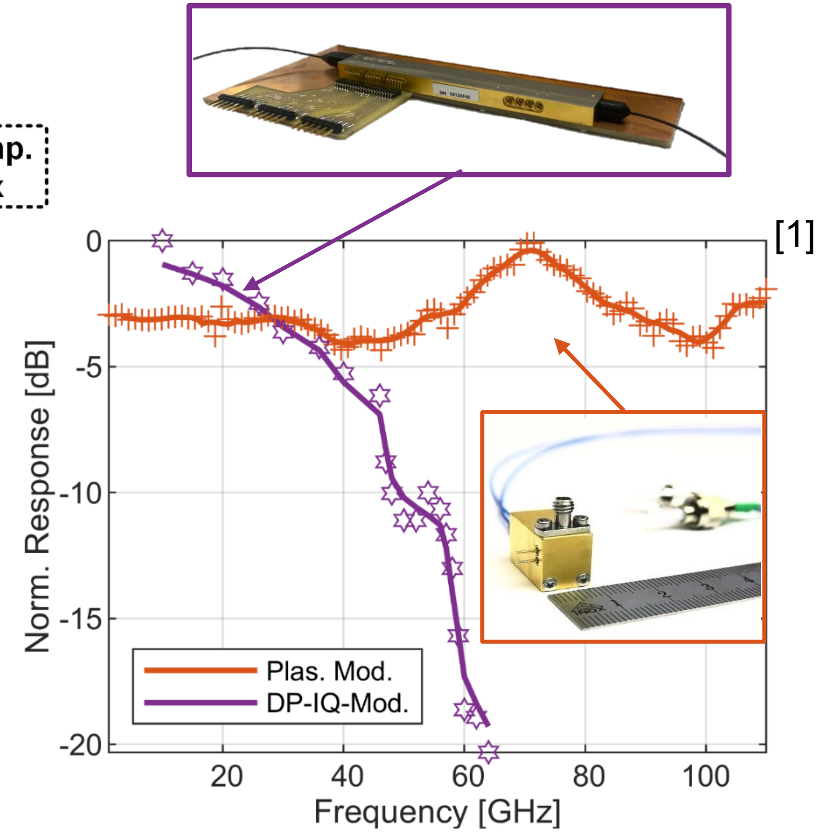
Results:

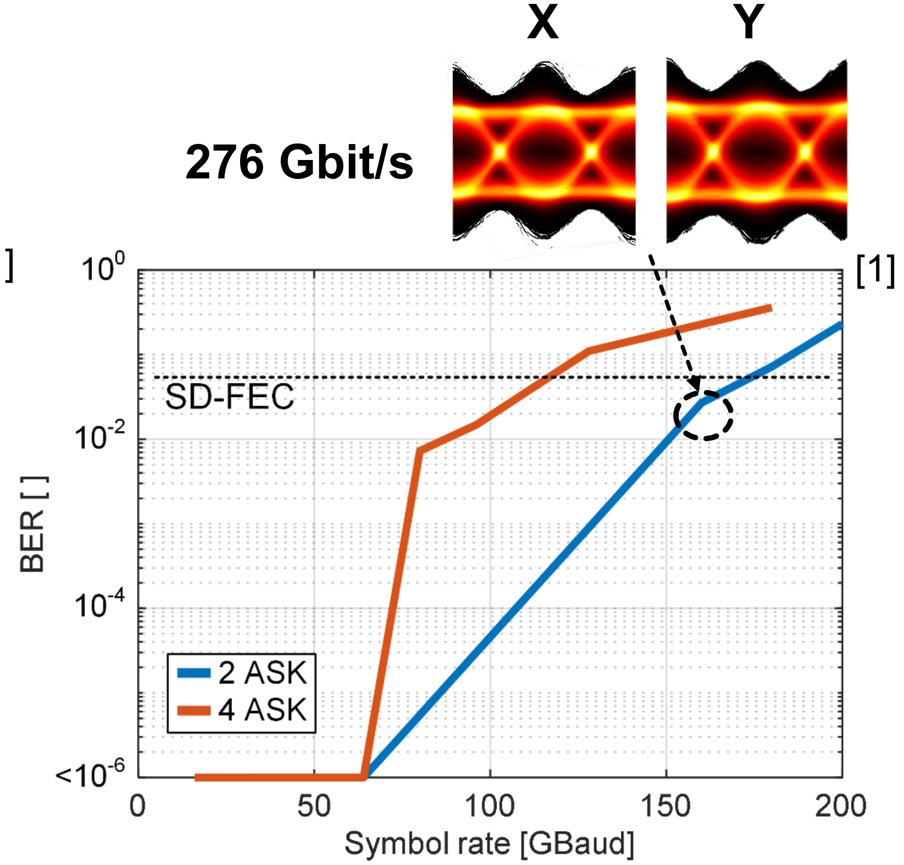
- High symbol rates:
  126 Gbaud for QPSK & 16QAM
- High line rates:
  1 Tbit/s for 16QAM & 64QAM
  - ➢ 64QAM performs better than 16QAM due to BW limitations of IQ Modulator

[1] Horst, Y., Bitachon, B.I., Kulmer, L. *et al.* Tbit/s line-rate satellite feeder links enabled by coherent modulation and full-adaptive optics. *Light Sci Appl* (2023)

Plasmonic Modulators for Highest-Speed FSO communications



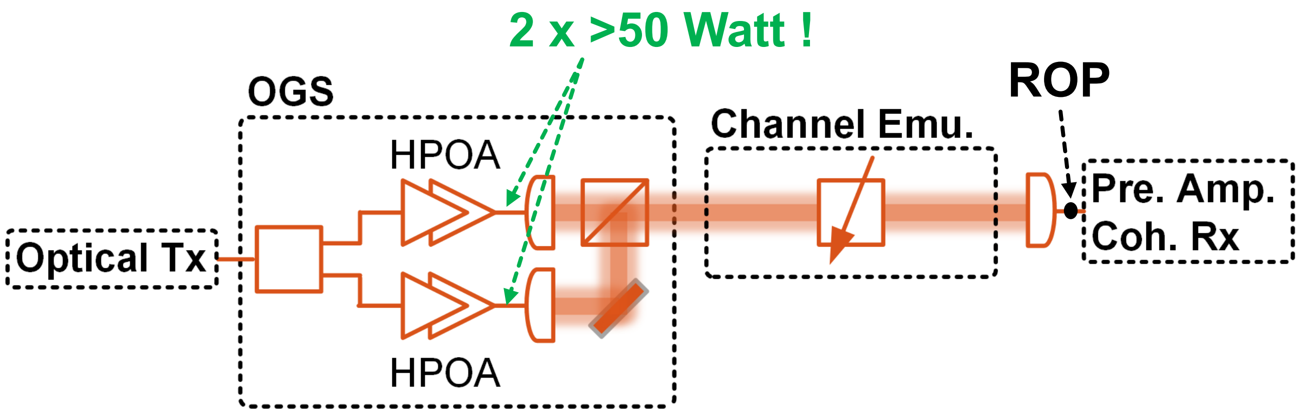


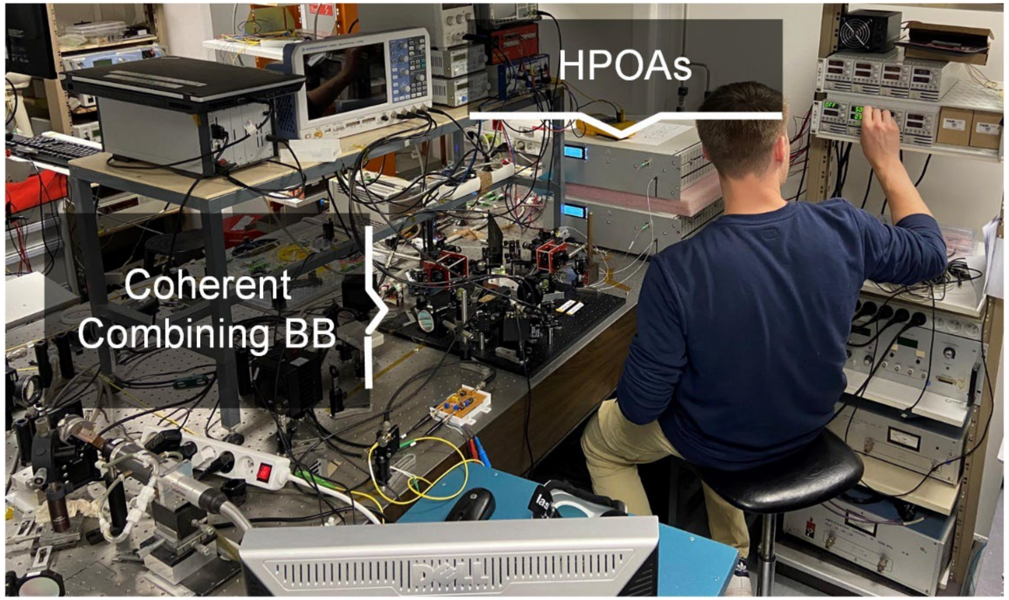


Unpackaged Plasmonic Mod from Polariton.: > 500 GHz BW [2]

[1] L. Kulmer *et al.*, "Plasmonic Modulators for Future Highest-Speed Free Space Optical Communications," Optical Fiber Communication (OFC) Conference, 2023, (W3I.1).
[2] M. Burla *et al.*, "500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics," *APL Photonics*, 2019

Solution 5: Increase Signal-Power - 100 Watt Optical Amplifiers





Ground-Satellite Links:

- 1000 – 40’000 km
- FSPL ∝ d^2 (d = distance)

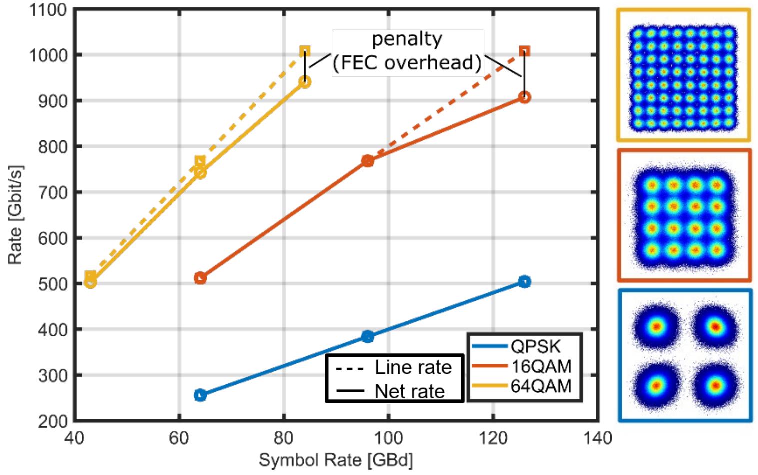
→ High power optical amplifiers (HPOA) [1]

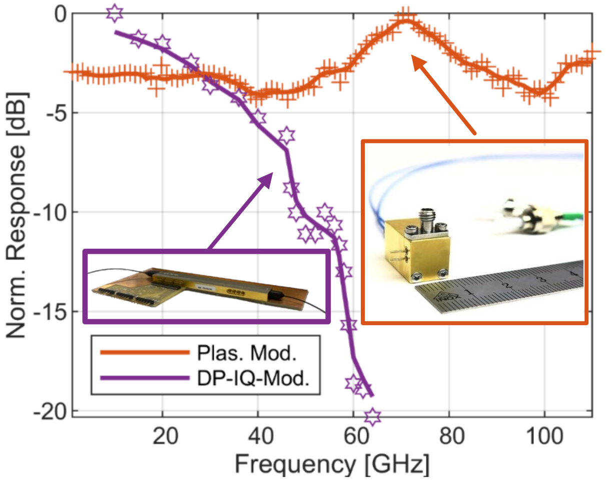
Investigation of:

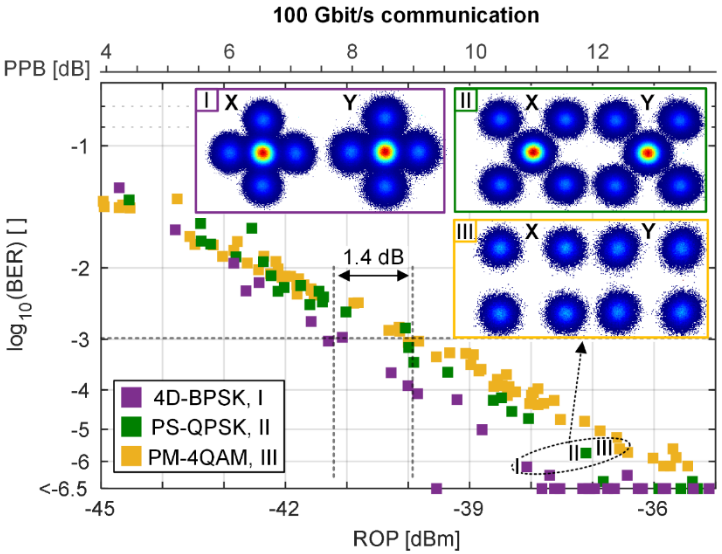
- Different modulation formats
- Different symbol rates
- FS-Channel emulation: different ROP

[1]: Vincent Billault, *et al.* "Optical coherent combining of high-power optical amplifiers for free-space optical communications," Opt. Lett. (2023)

Summary - Ground-to-Satellite Link







Key Achievements

- Distance: > 53 km FS w/. 2800 m elevation
- Line-Rate: up to 1 Tbit/s
- Sensitivity: 100 Gbit/s with ROP = 0.1 μW
- Atmospheric Turbulence Mitigation: + 28.1 dB (AO off)

Secrets to success:

- Adaptive Optics
- Coherent Communications
- Advanced Modulation Formats
  - e.g. 4D-BPSK
- Highest-Speed enabled by Plasmonic MZM
- High power amplifiers

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