PORTUGUESE
QUANTUM COMMUNICATION INFRASTRUCTURE

INSTITUIÇÕES ASSOCIADAS

Free-Space Optical Communication at High Rates

Fernando P. Guiomar

[1]*Instituto de Telecomunicações, 3810-193, Aveiro, Portugal*
guiomar@av.it.pt

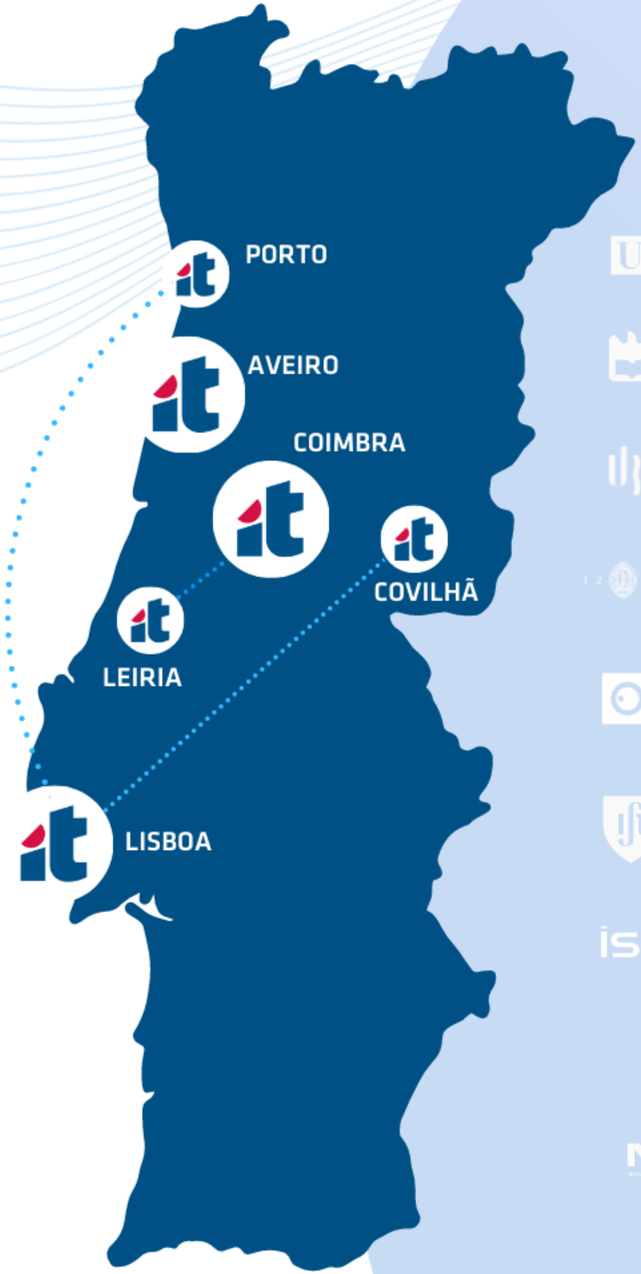
11th September 2024
PTQCI Summer School, Taguspark, Lisbon

Who we are

- Non-profit Organization
- Public Utility (since 1995)
- Associate Laboratory (since 2001)

Mission

- create and disseminate scientific knowledge
- support advanced training
- promote technology transfer
- support public policy



U.PORTO
universidade de aveiro
UNIVERSIDADE BEIRA INTERIOR
UNIVERSIDADE DE COIMBRA
POLITÉCNICO DE LEIRIA
TÉCNICO LISBOA
iscte
altice labs
NOKIA

University of Aveiro Campus

Figures

+15k Students

+1k Professors

+500 researchers

Research Team – Researchers and Senior PhD Students

Paulo Monteiro – Associate Professor
https://www.it.pt/Members/Index/448

Fernando Guiomar – Senior Researcher
https://www.it.pt/Members/Index/4556

Gil Fernandes – Post-Doc Researcher
https://www.it.pt/Members/Index/5475

Beatriz Oliveira – Post-Doc Researcher
https://www.it.pt/Members/Index/27257

Bruno Brandão – PhD Student
https://www.it.pt/Members/Index/27776

Manuel Neves – PhD Student
https://www.it.pt/Members/Index/29937

Pedro Loureiro – PhD Student
https://www.it.pt/Members/Index/31791

Research Team – Junior PhD and MSc Students

Manuel Freitas – PhD Student

Nwanze Nzekwu – PhD Student

Victor Correia – PhD Student

André Campos – PhD Student

Diogo Malheiro – PhD Student

Salma Yahyaoui – PhD Student

Paulo Carvalho – MSc Student

Research Team - Alumni

Marco Fernandes – Post-Doc Researcher
https://www.it.pt/Members/Index/27781

Romil Patel – Post-Doc Researcher

Main Research Activities

fiber optics

- high-capacity coherent links;
- PON;
- radio-over-fiber.

optical wireless

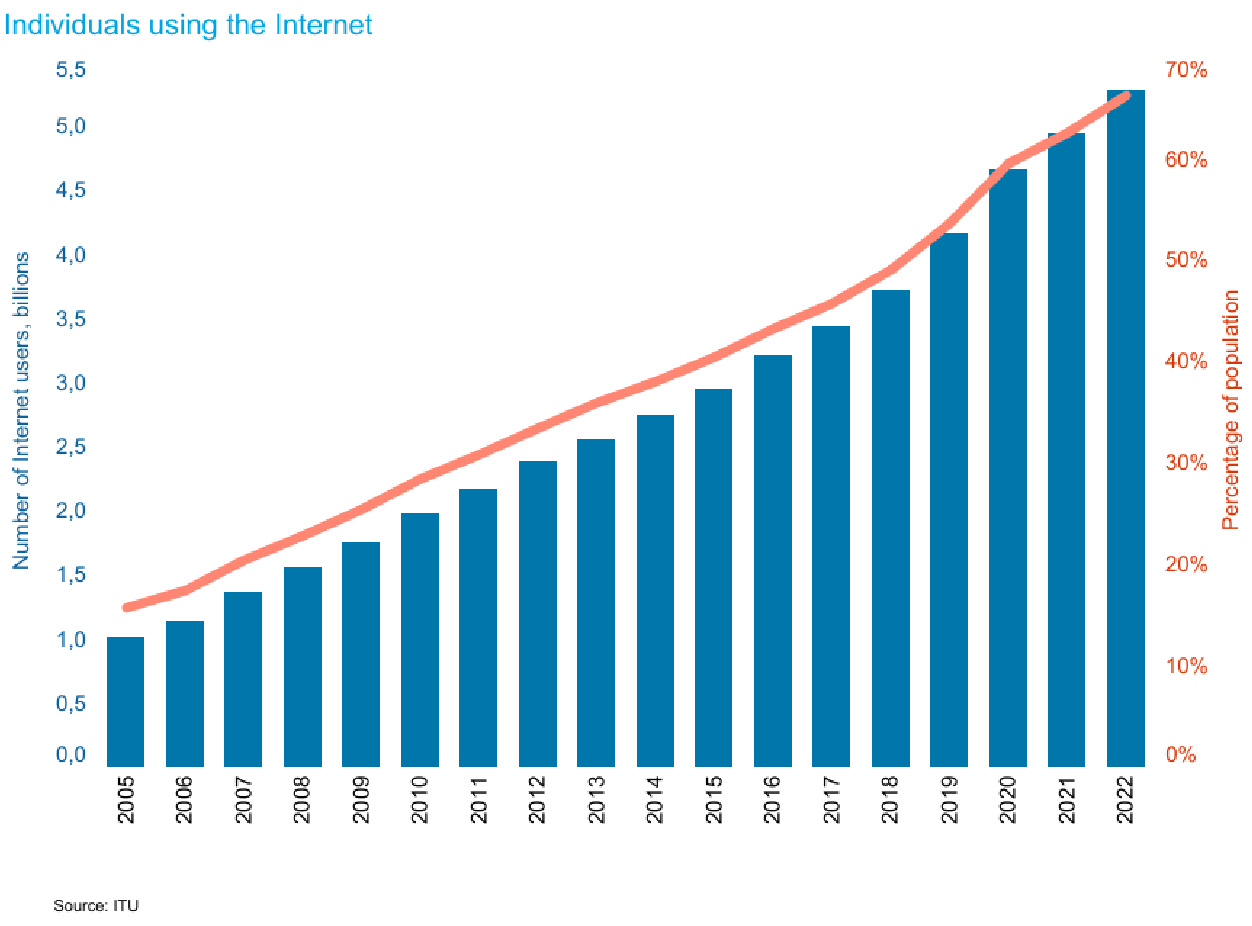
- free-space optics (FSO);
- visible light communications (VLC).

DSP

Outline

- **Introduction and Motivation**
  - Free-Space Optics: What, Why and How?
- **FSO Implementation Challenges**
  - Impact of Pointing Errors;
  - Impact of Atmospheric Turbulence.
- **Enhancing FSO Reliability**
  - Advanced Channel Estimation;
  - Mitigating Atmospheric Turbulence: MIMO-FSO.
- **Enhancing FSO Capacity**
  - Adaptive Modulation for Turbulence Mitigation;
  - Adaptive Modulation for Pointing Error Mitigation.
- **1.8 km WDM-FSO Field Trial**
  - How Many Channels are Enough?
- **Conclusions**

FSO: A High-Capacity Solution for Next-Generation Wireless



- More than 30% of world population still does not have access to internet, with the number being higher considering high-speed transmission.
- Free-Space Optics (FSO) is a solution for providing worldwide high-capacity internet delivery reaching places where fiber cannot go, either with terrestrial or satellite links.

instituto de telecomunicações

Why FSO?

Free S…
to Hit…

STARLINK'S INTER-SATELLITE LASER LINKS ARE SETTING NEW RECORD WITH 42 MILLION GB PER DAY

by: Maya Posch — 44 Comments

February 5, 2024

Alphabet's X tests Fre… Communications in… 700TB across 5km

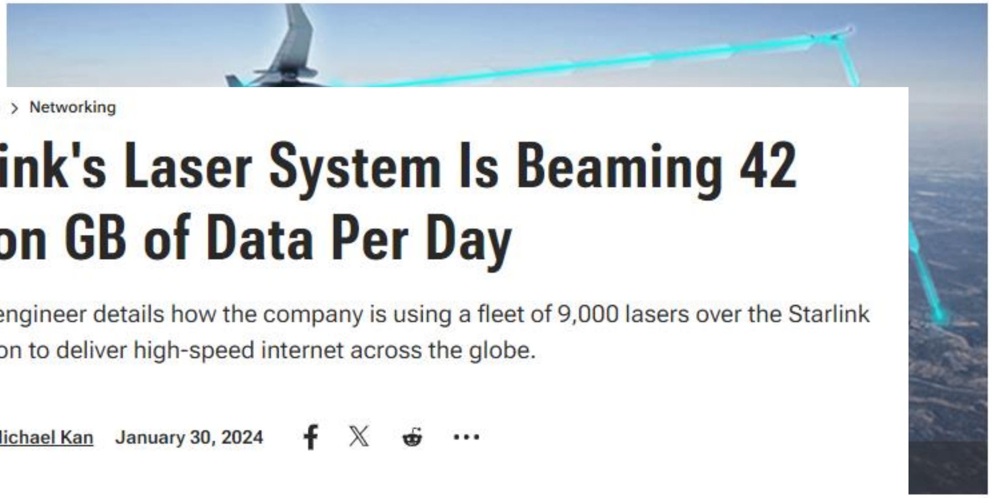
…quid Intelligent Tec…

…Moss Comment

…across 4.8 kilor…
…spun out of the…
…ata in free space…
…0Gbps+ broadb…
…gle sister comp…
…Brazzaville in th…
…Kinshasa in the…
…ngo.

RTX, 2 Other Companies to Help DARPA Develop Airborne Wireless Power Transfer System

by Mary-Louise Hoffman
September 8, 2023, 10:52 am

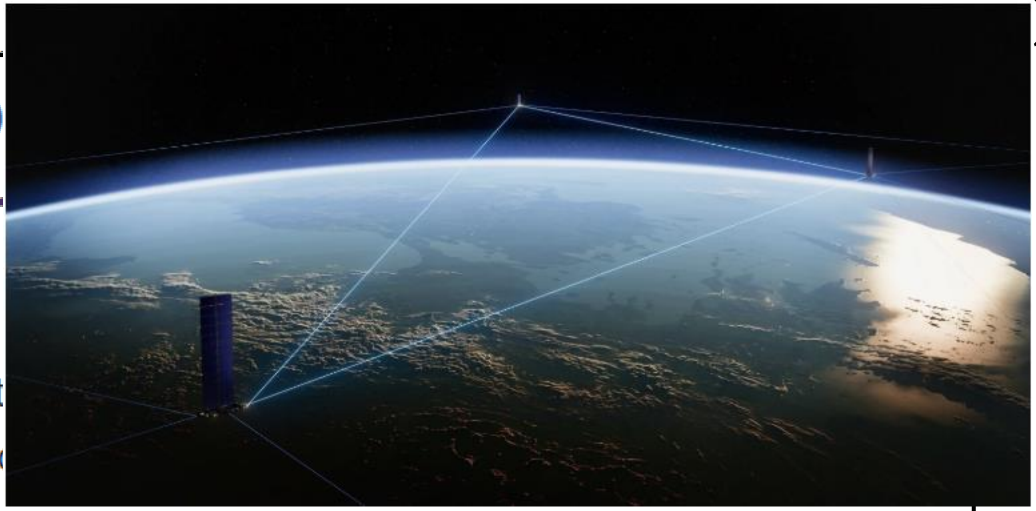


Home › News › Networking

Starlink's Laser System Is Beaming 42 Million GB of Data Per Day

A SpaceX engineer details how the company is using a fleet of 9,000 lasers over the Starlink constellation to deliver high-speed internet across the globe.

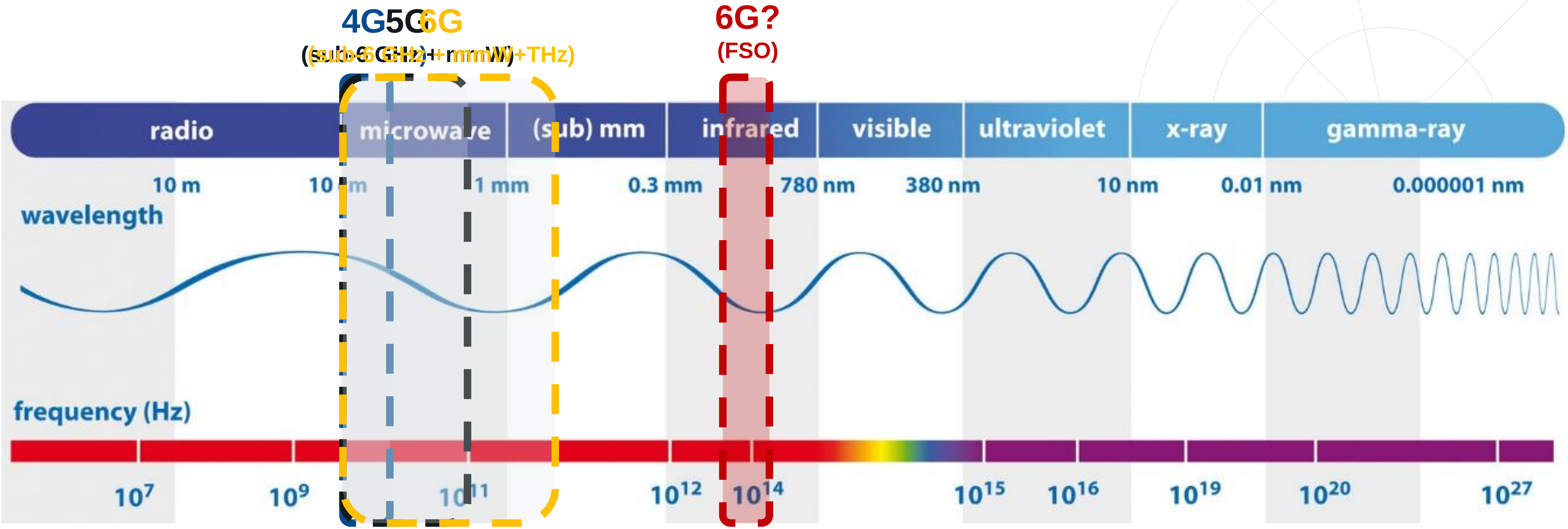
By Michael Kan January 30, 2024



…ce o…
…char…

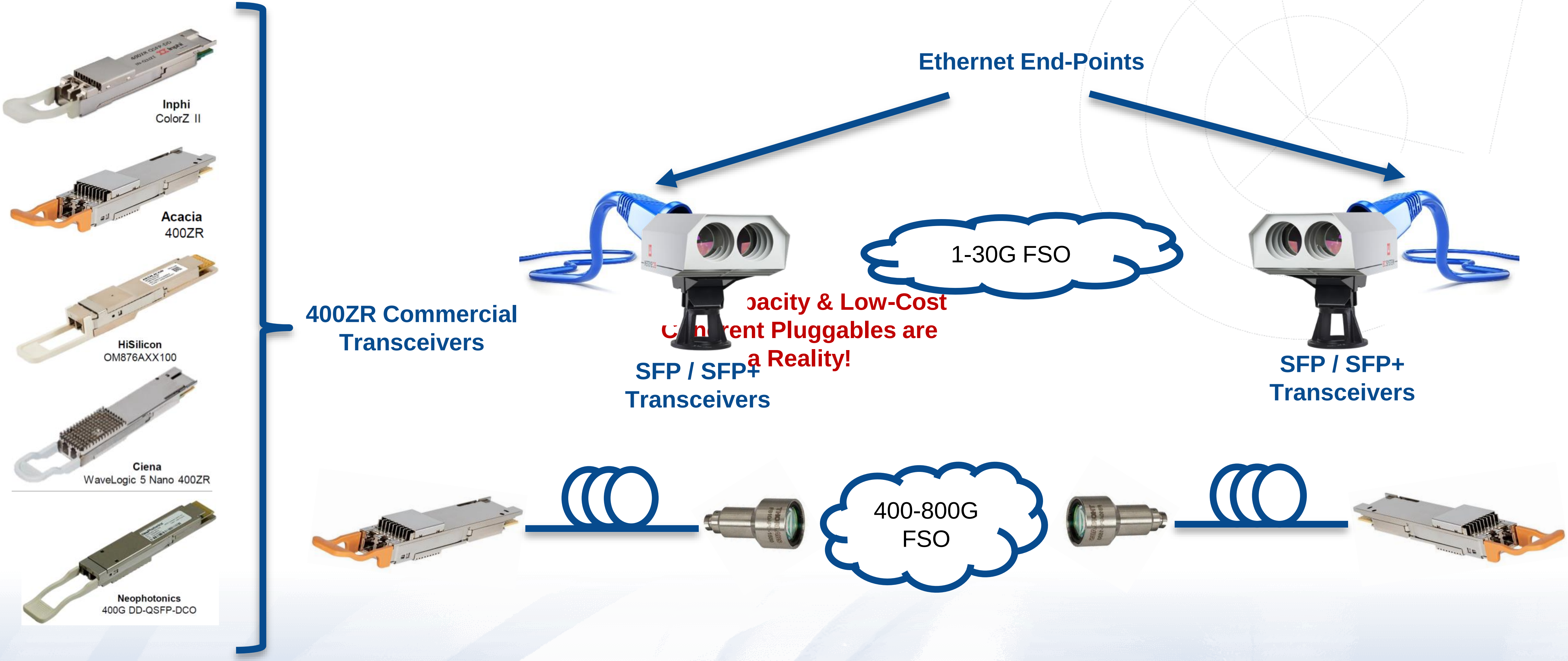
…etween t…
(NYSE) and Nasdaq will soo…
switched on in March.

Wireless Communications – Past, Present and Future

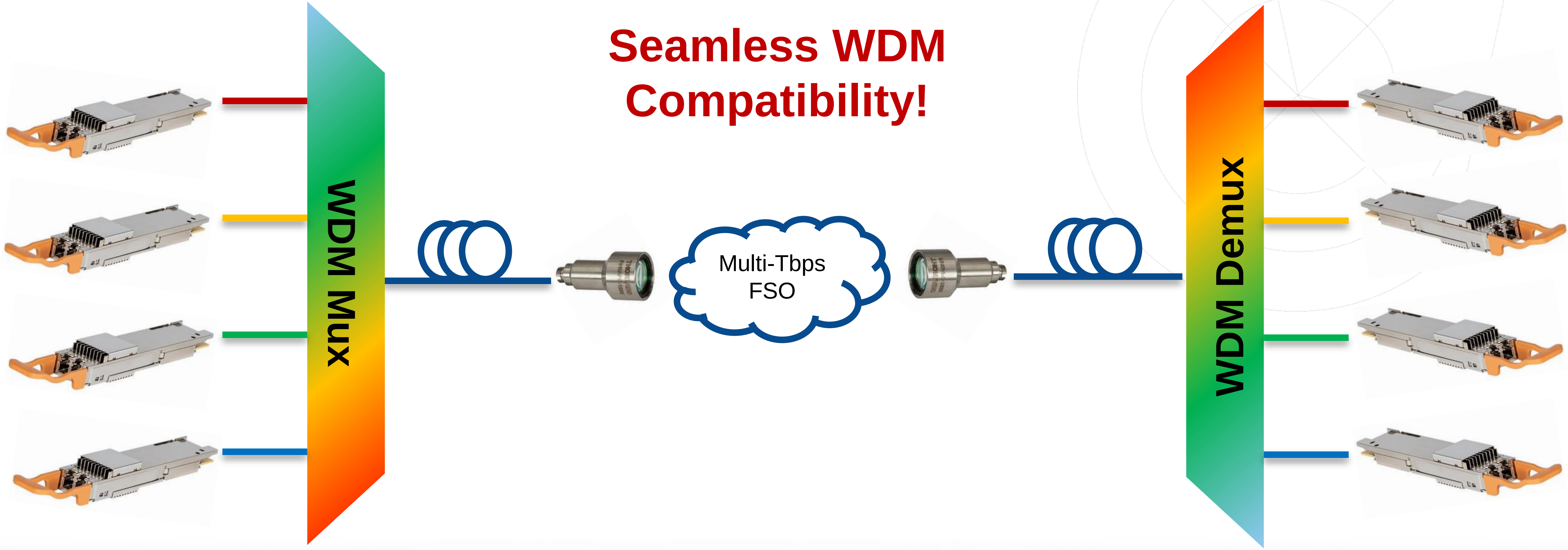


- **5G** extends 4G with **mmW frequencies below 100 GHz**;
- **6G** is expected to **extend mmW and use THz-wave frequencies** (above 300 GHz);
- **Free-space optics** in the infrared region (800 nm – 2000 nm) are an attractive alternative to mmW and THz-wave.

High-Capacity Coherent Pluggables + Seamless Fiber-FSO: A Perfect Match?



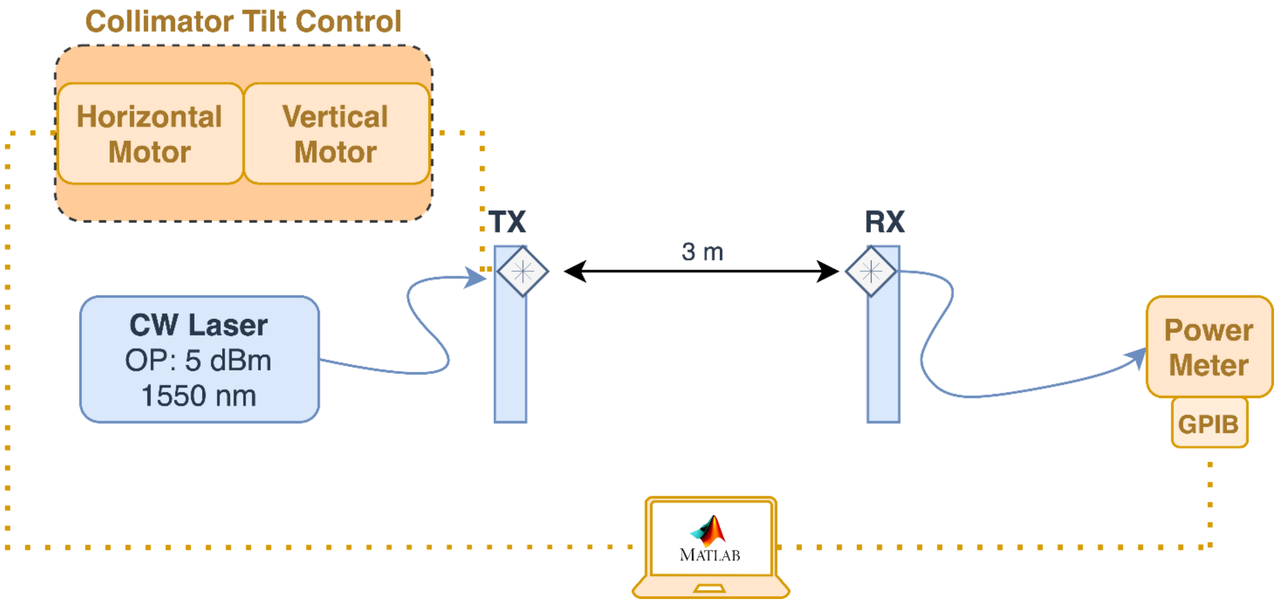
High-Capacity Coherent Pluggables + Seamless Fiber-FSO: A Perfect Match?

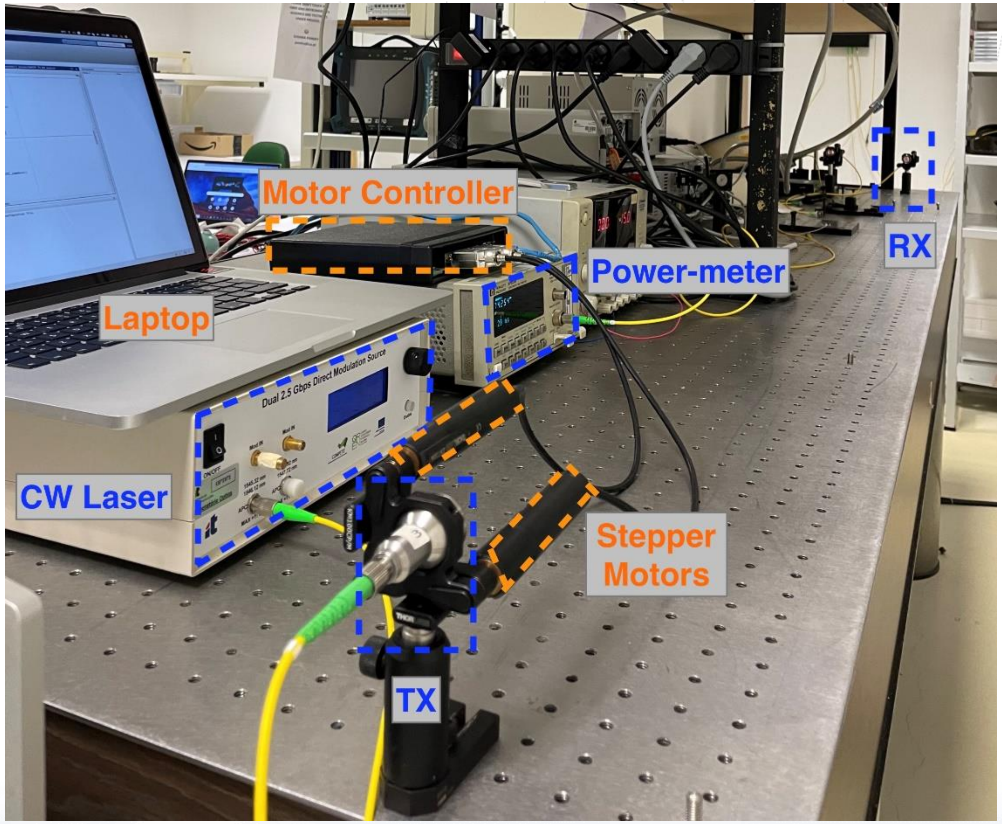


FSO Implementation Challenges

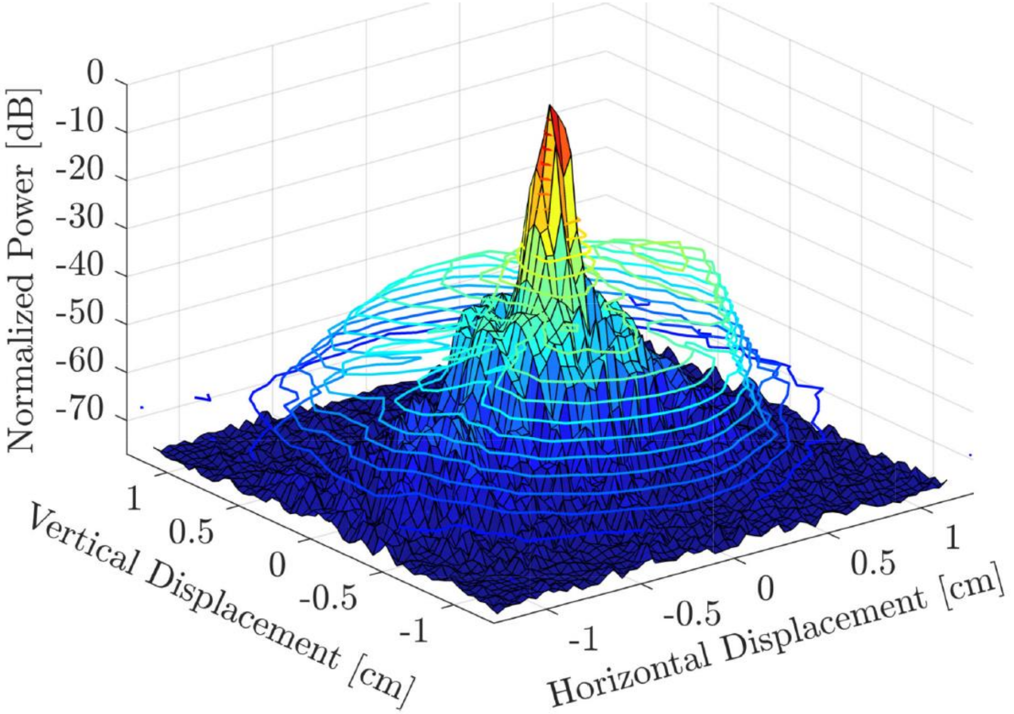
1) Impact of Pointing Errors

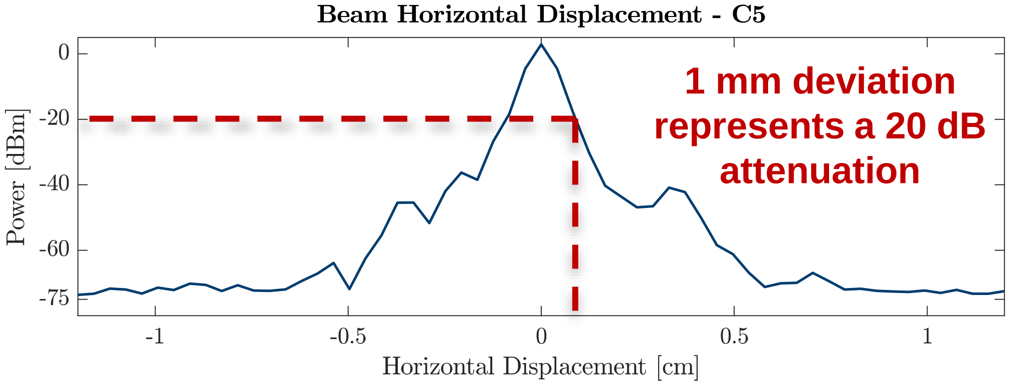
Pointing Errors Tolerance: Seamless Air-to-Fiber

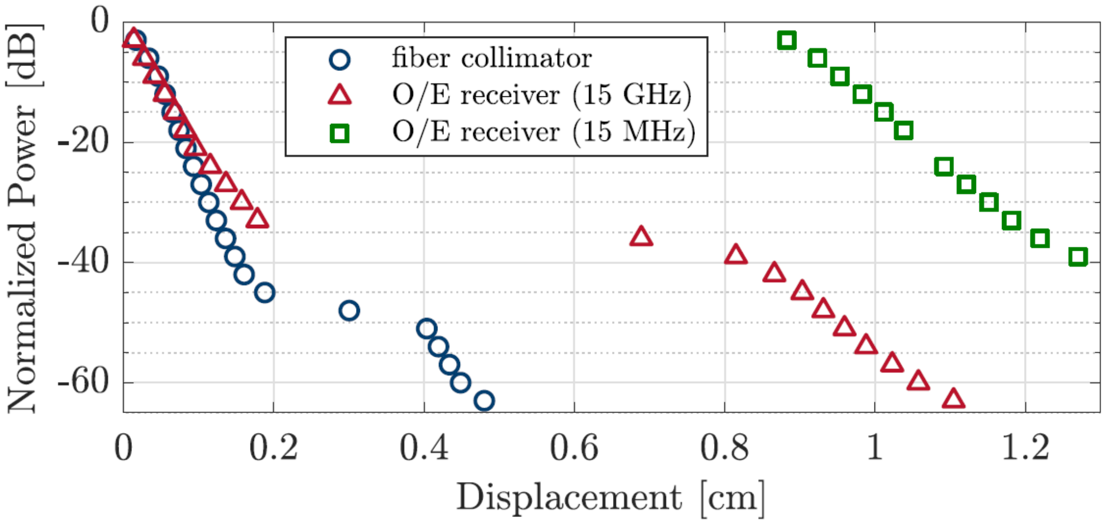




Pointing Errors Tolerance: Seamless Air-to-Fiber

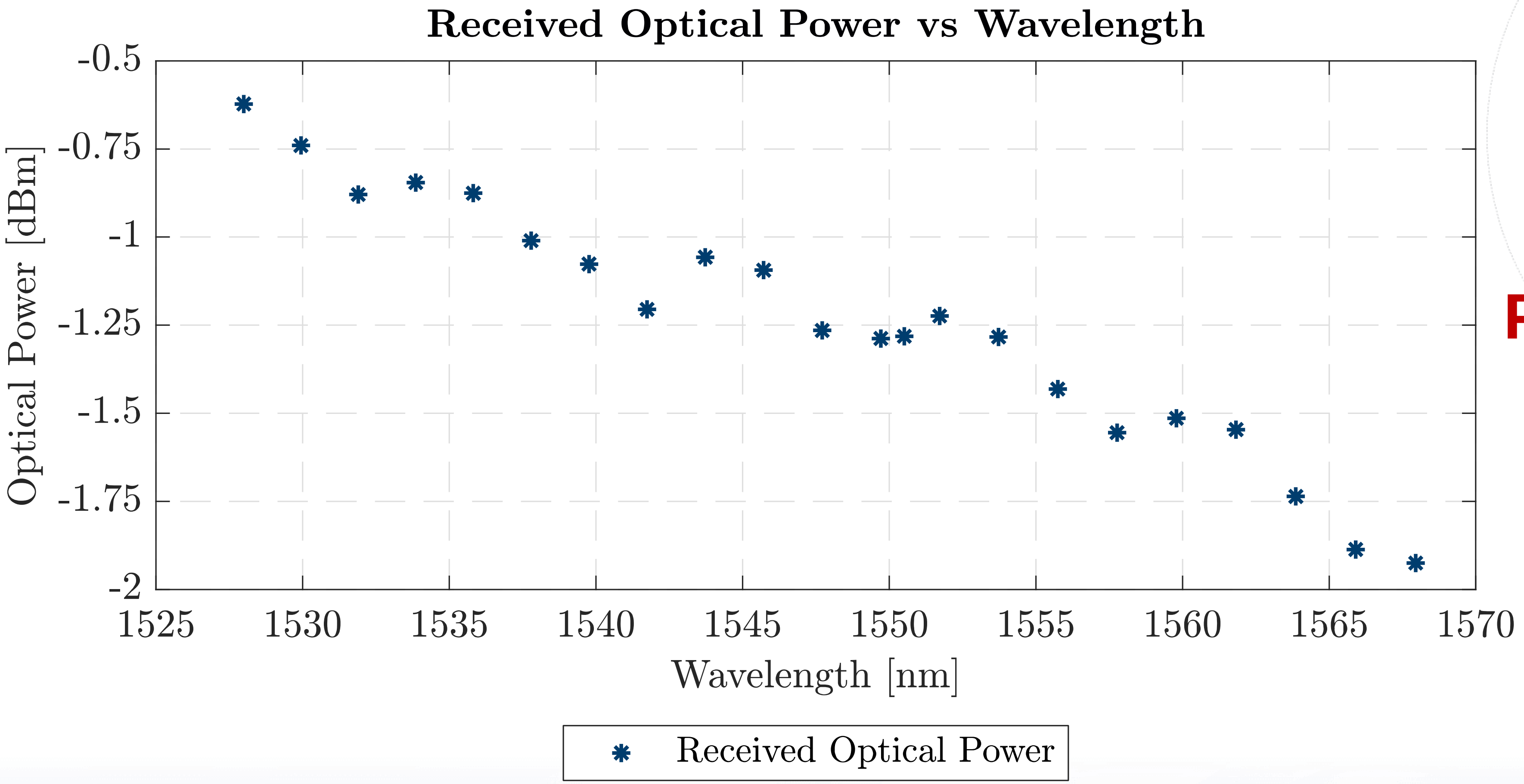






F. P. Guiomar, M. A. Fernandes, J. L. Nascimento, V. A. Rodrigues and P. P. Monteiro, “**Coherent Free-Space Optical Communications: Opportunities and Challenges**,” IEEE Journal of Lightwave Technology, vol. 40, no. 10, pp. 3173-3186, 2022. https://doi.org/10.1109/JLT.2022.3164736

Pointing Errors Tolerance: Seamless Air-to-Fiber



~1.5 dB Optical Power Variation over the Entire C-Band!

F. P. Guiomar, M. A. Fernandes, J. L. Nascimento, V. A. Rodrigues and P. P. Monteiro, "**Coherent Free-Space Optical Communications: Opportunities and Challenges**," IEEE Journal of Lightwave Technology, vol. 40, no. 10, pp. 3173-3186, 2022. https://doi.org/10.1109/JLT.2022.3164736

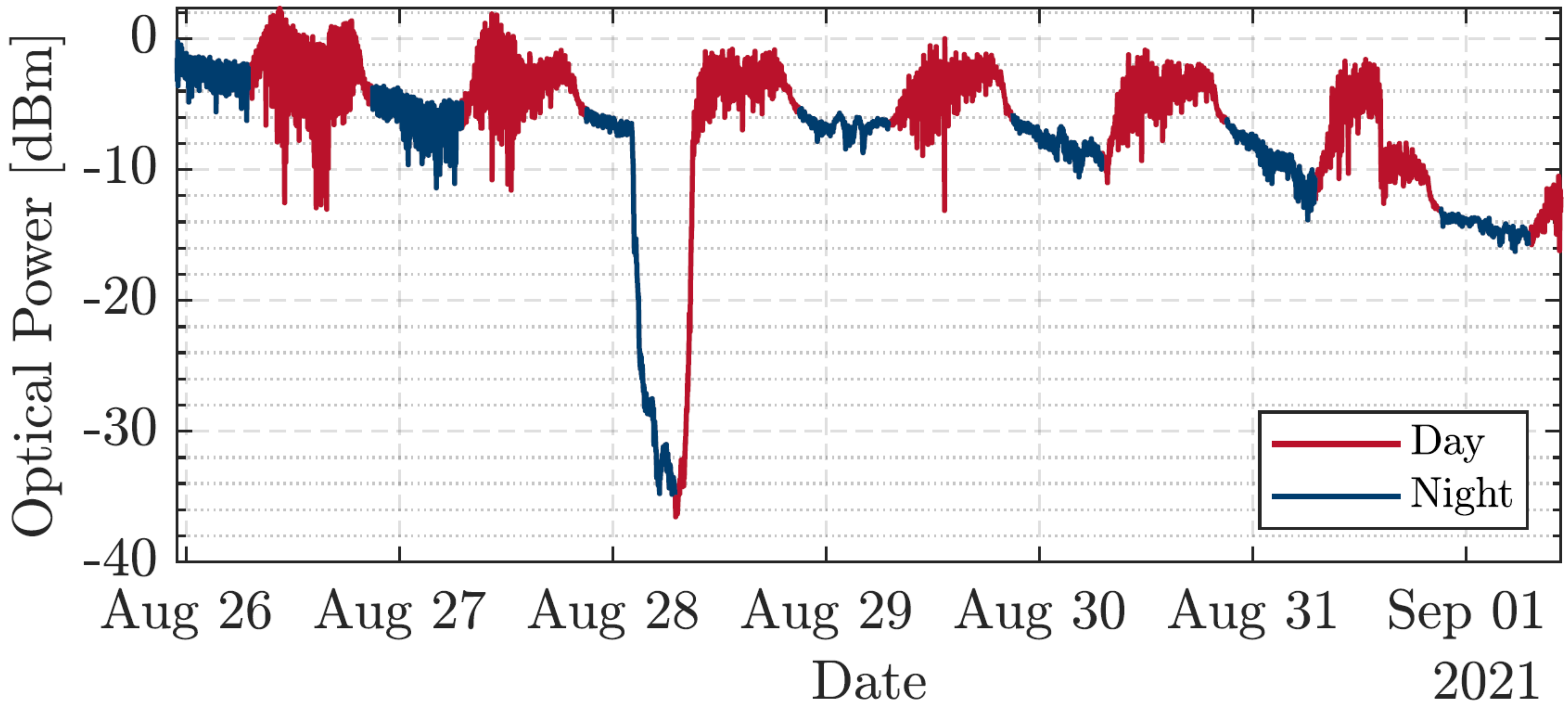
FSO Implementation Challenges

2) Impact of Atmospheric Turbulence

instituto de telecomunicações

Experimental Analysis of Outdoor FSO

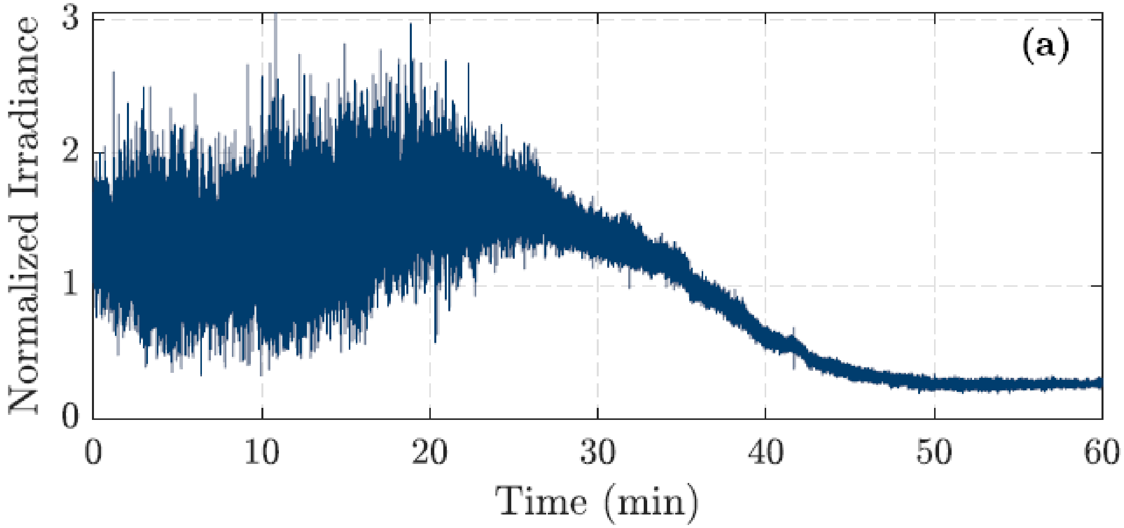
Time-Varying FSO Channel

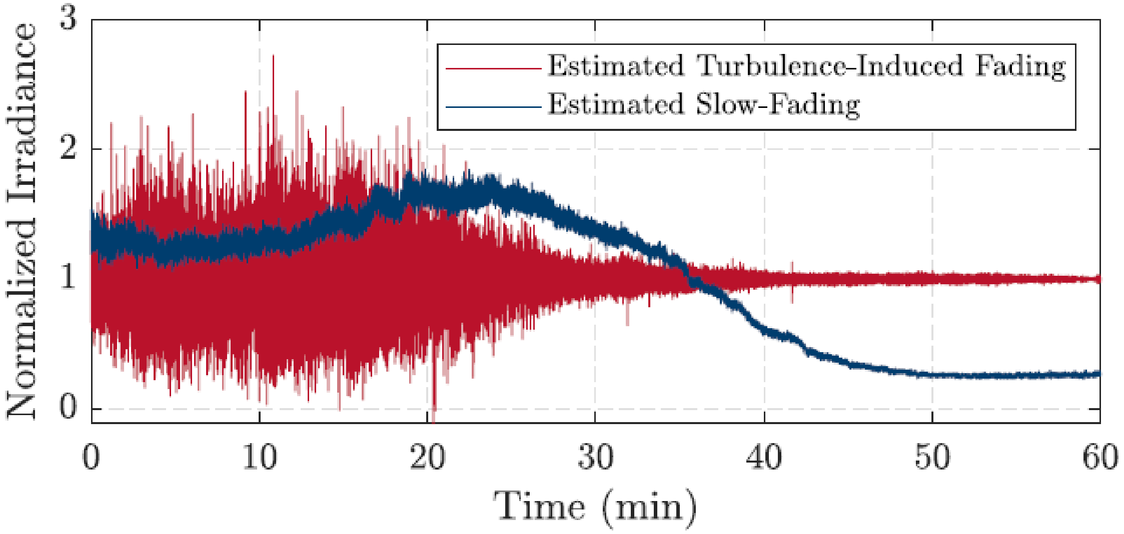


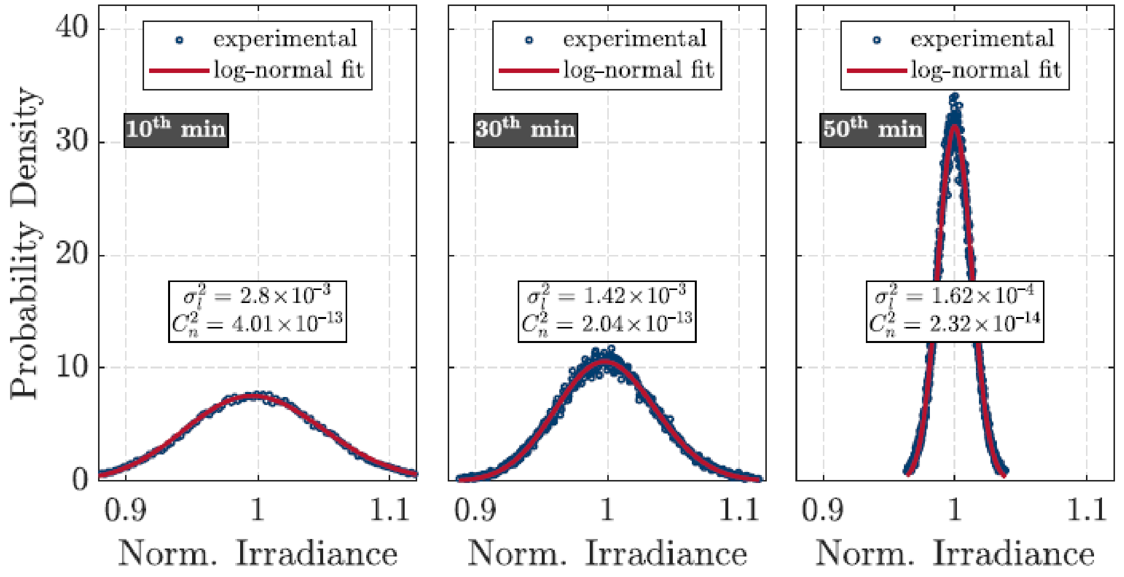
F. P. Guiomar, M. A. Fernandes, J. L. Nascimento, V. A. Rodrigues and P. P. Monteiro, "**Coherent Free-Space Optical Communications: Opportunities and Challenges**," IEEE Journal of Lightwave Technology, vol. 40, no. 10, pp. 3173-3186, 2022. https://doi.org/10.1109/JLT.2022.3164736

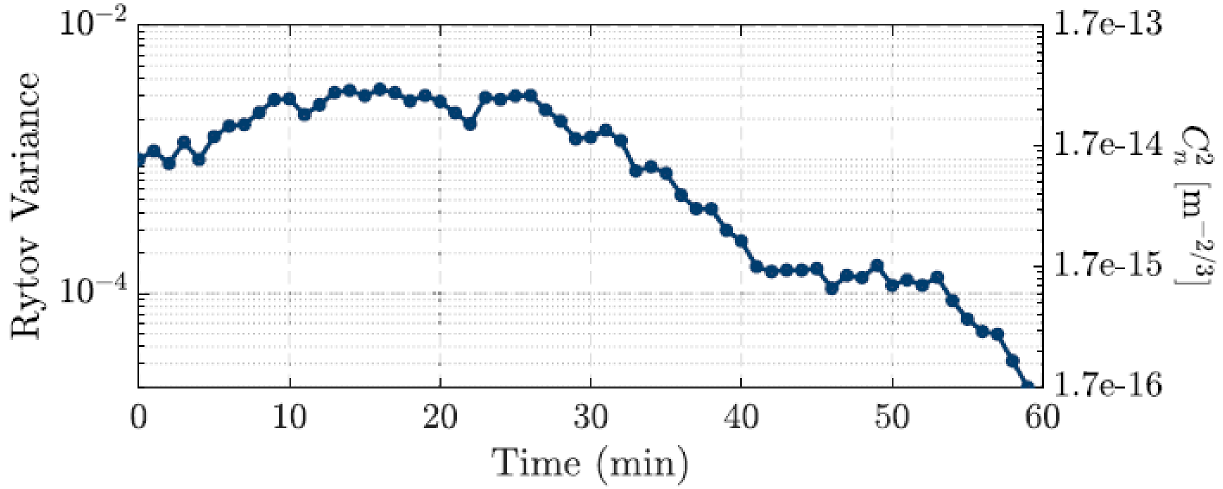
instituto de telecomunicações

Time-Varying FSO Channel









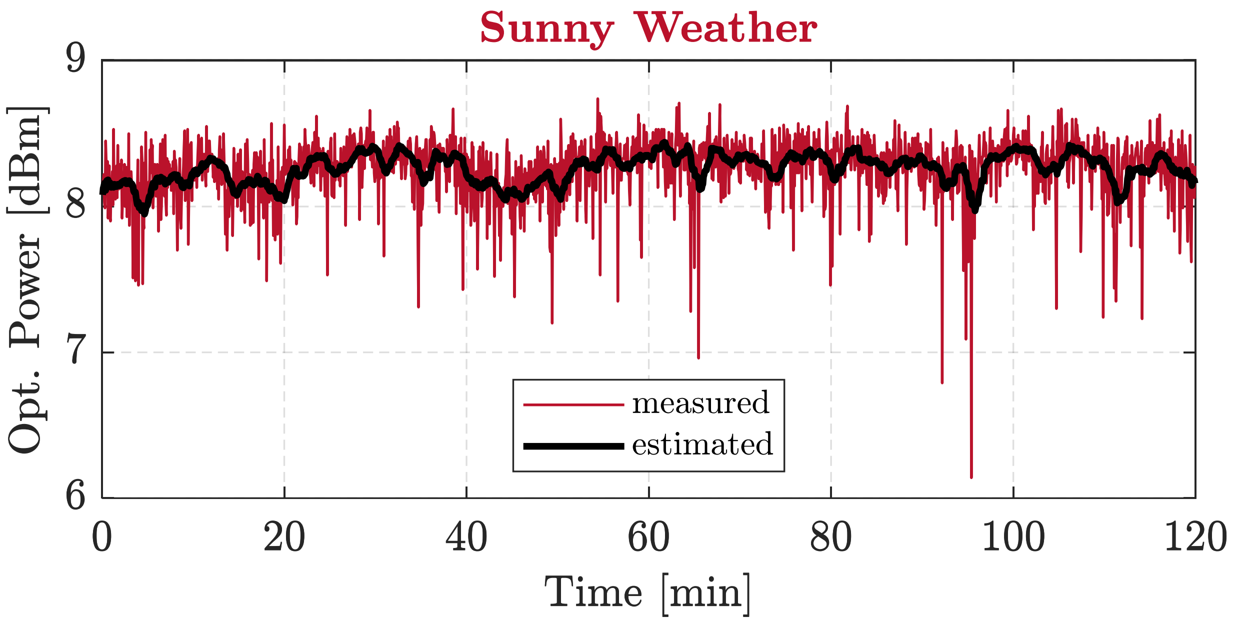
F. P. Guiomar, M. A. Fernandes, J. L. Nascimento, V. A. Rodrigues and P. P. Monteiro, "**Coherent Free-Space Optical Communications: Opportunities and Challenges**," IEEE Journal of Lightwave Technology, vol. 40, no. 10, pp. 3173-3186, 2022. https://doi.org/10.1109/JLT.2022.3164736

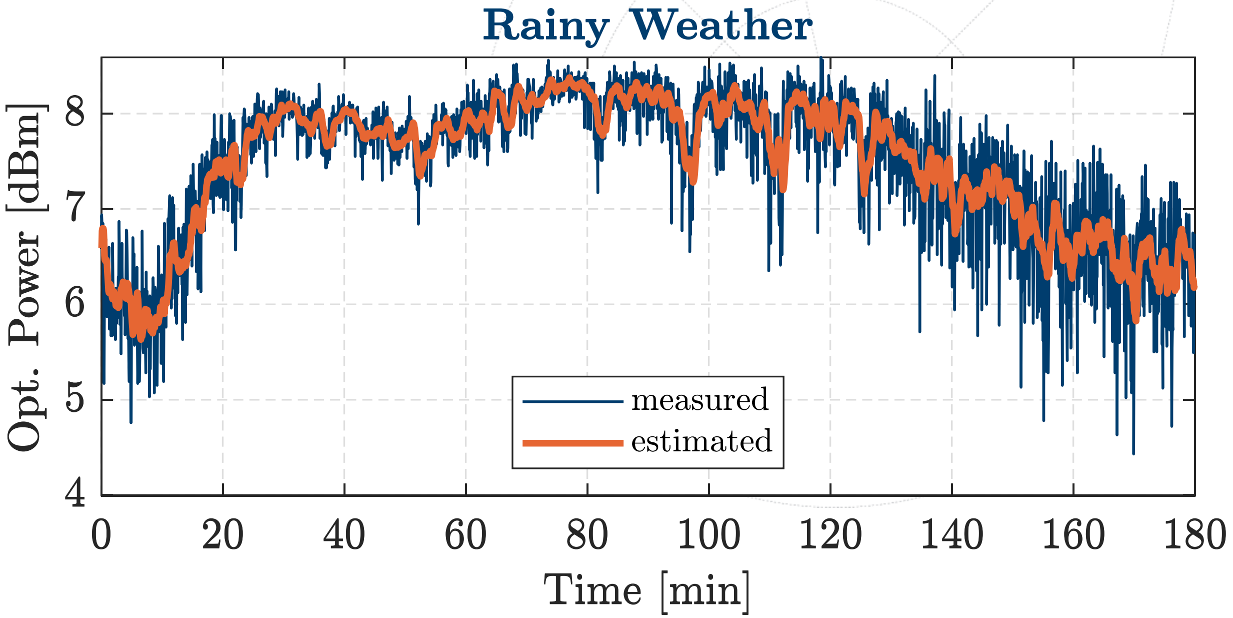
instituto de telecomunicações

Enhancing FSO Reliability

1) Advanced Channel Estimation

FSO Channel Estimation: Low-Complexity Moving Average





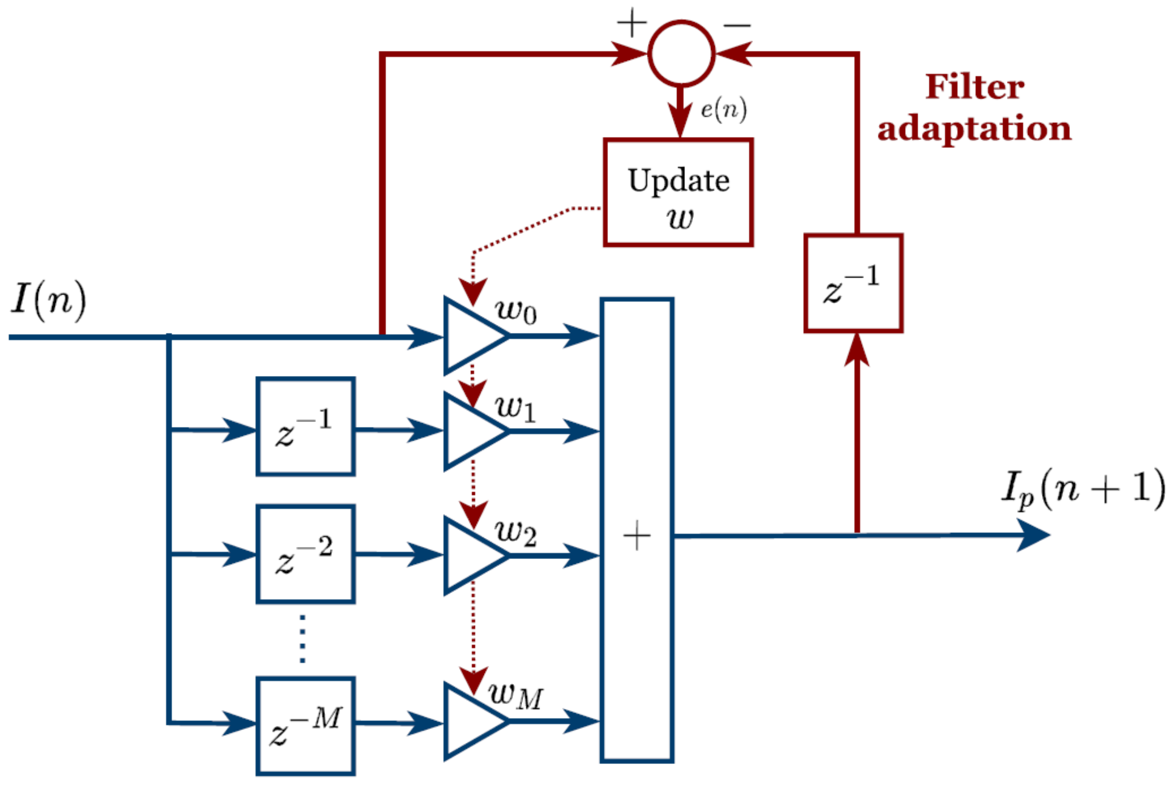
Low-complexity channel estimator:

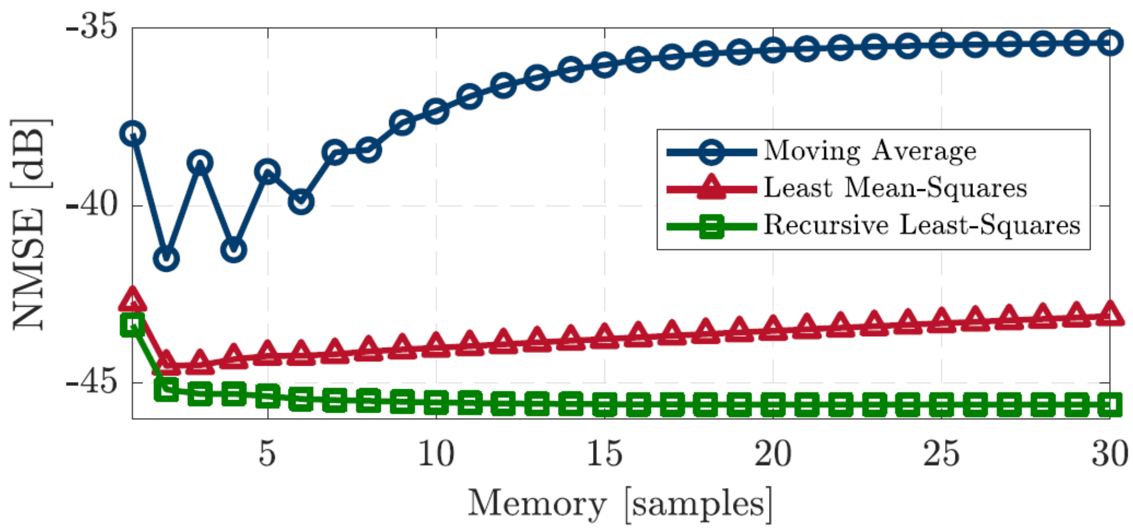
$$P_{\text{est}}(n+1) = \frac{1}{N_{\text{taps}}} \sum_{n-N_{\text{taps}}+1}^{n} P_{\text{meas}}(n),$$

F. P. Guiomar, A. Lorences-Riesgo, D. Ranzal, F. Rocco, A. N. Sousa, M. A. Fernandes, B. T. Brandão, A. Carena, A. L. Teixeira, M. C. R. Medeiros and P. P. Monteiro, "**Adaptive Probabilistic Shaped Modulation for High-Capacity Free-Space Optical Links**," IEEE Journal of Lightw. Tech., vol. 38, no. 23, 2021. https://doi.org/10.1109/JLT.2020.3012737

instituto de telecomunicações

FSO Channel Estimation: Adaptive Algorithms



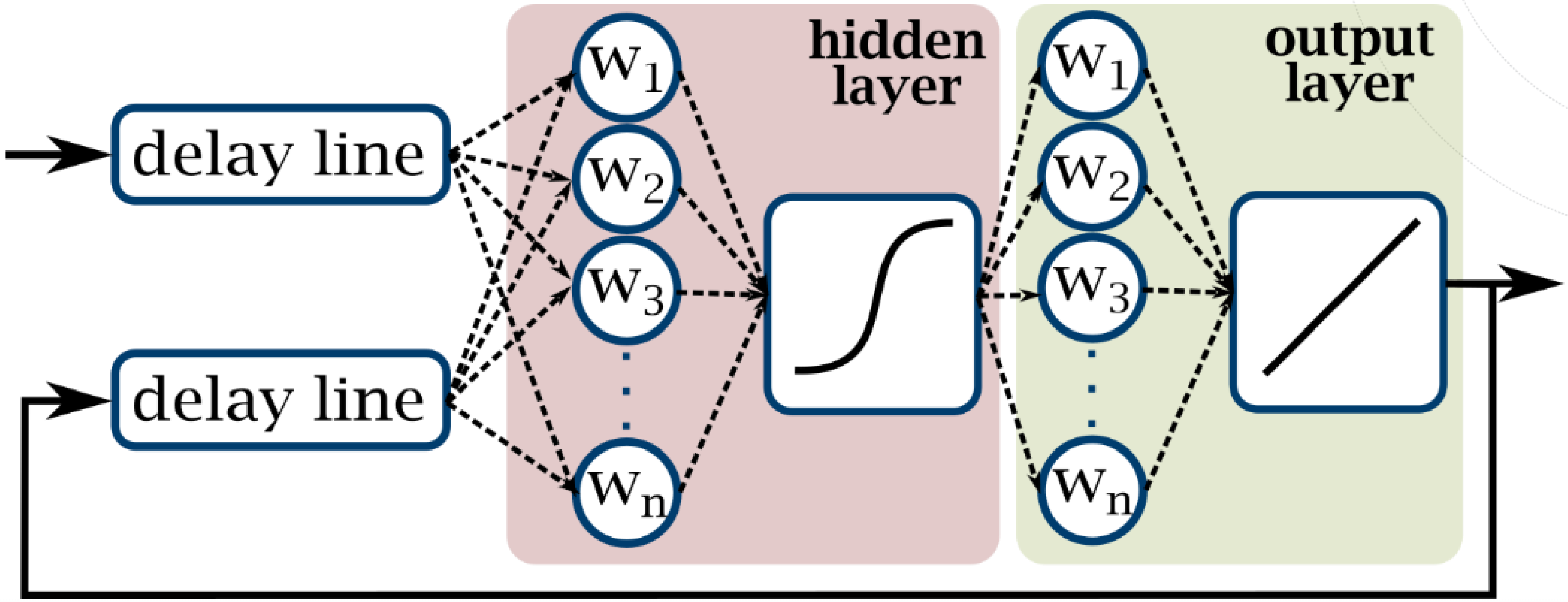


F. P. Guiomar, M. A. Fernandes, J. L. Nascimento, V. A. Rodrigues and P. P. Monteiro, "**Coherent Free-Space Optical Communications: Opportunities and Challenges**," IEEE Journal of Lightwave Technology, vol. 40, no. 10, pp. 3173-3186, 2022. https://doi.org/10.1109/JLT.2022.3164736

FSO Channel Estimation: Advanced Solutions using Machine Learning

Highly Reliable Outdoor 400G FSO Transmission Enabled by ANN Channel Estimation

Marco A. Fernandes, J. Leonardo Nascimento, Paulo P. Monteiro and Fernando P. Guiomar



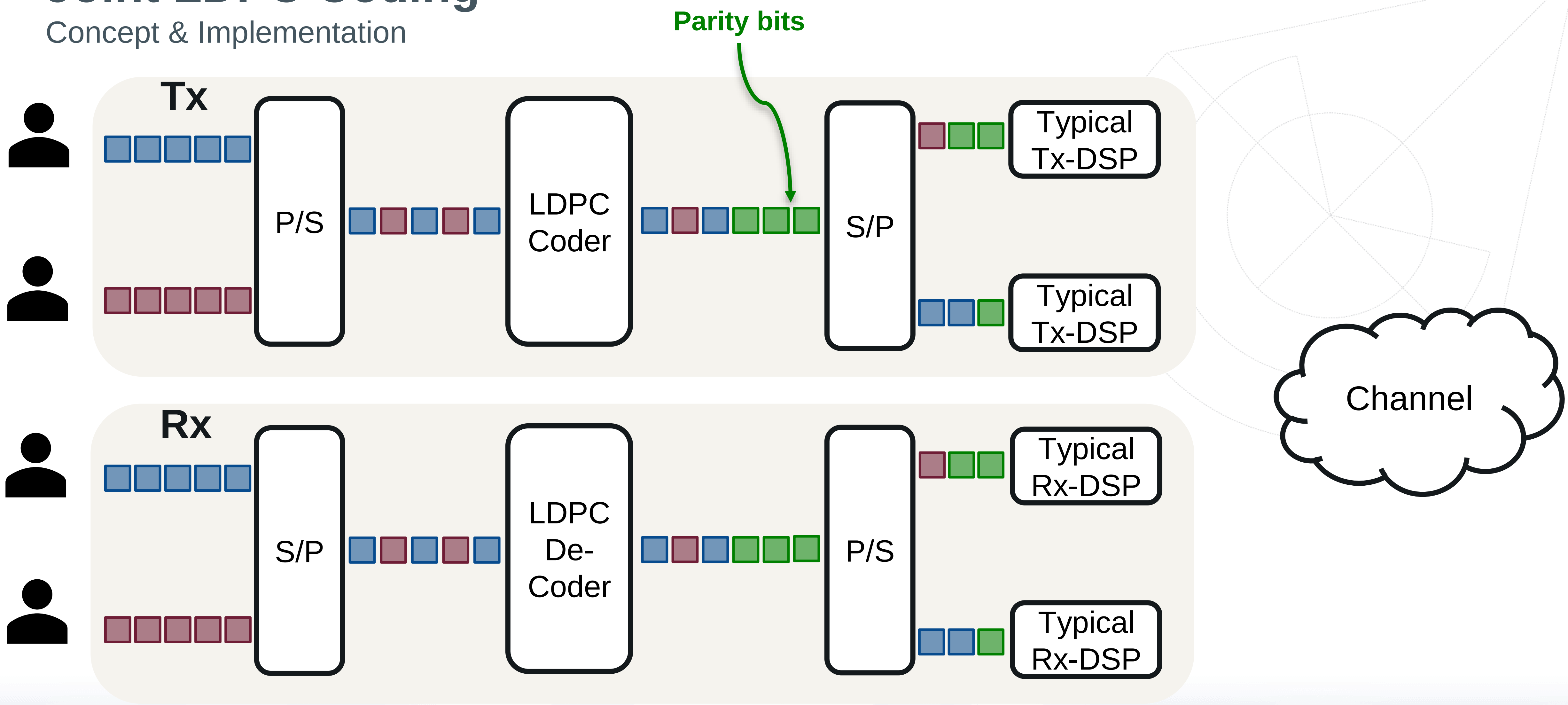
M. A. Fernandes, J. L. Nascimento, P. P. Monteiro and F. P. Guiomar, "**Highly Reliable Outdoor 400G FSO Transmission Enabled by ANN Channel Estimation**," in Proc. OFC, San Diego, USA, 2022. https://doi.org/10.1364/OFC.2022.W3I.4

Enhancing FSO Reliability

2) Mitigating Atmospheric Turbulence: MIMO-FSO

Joint LDPC Coding

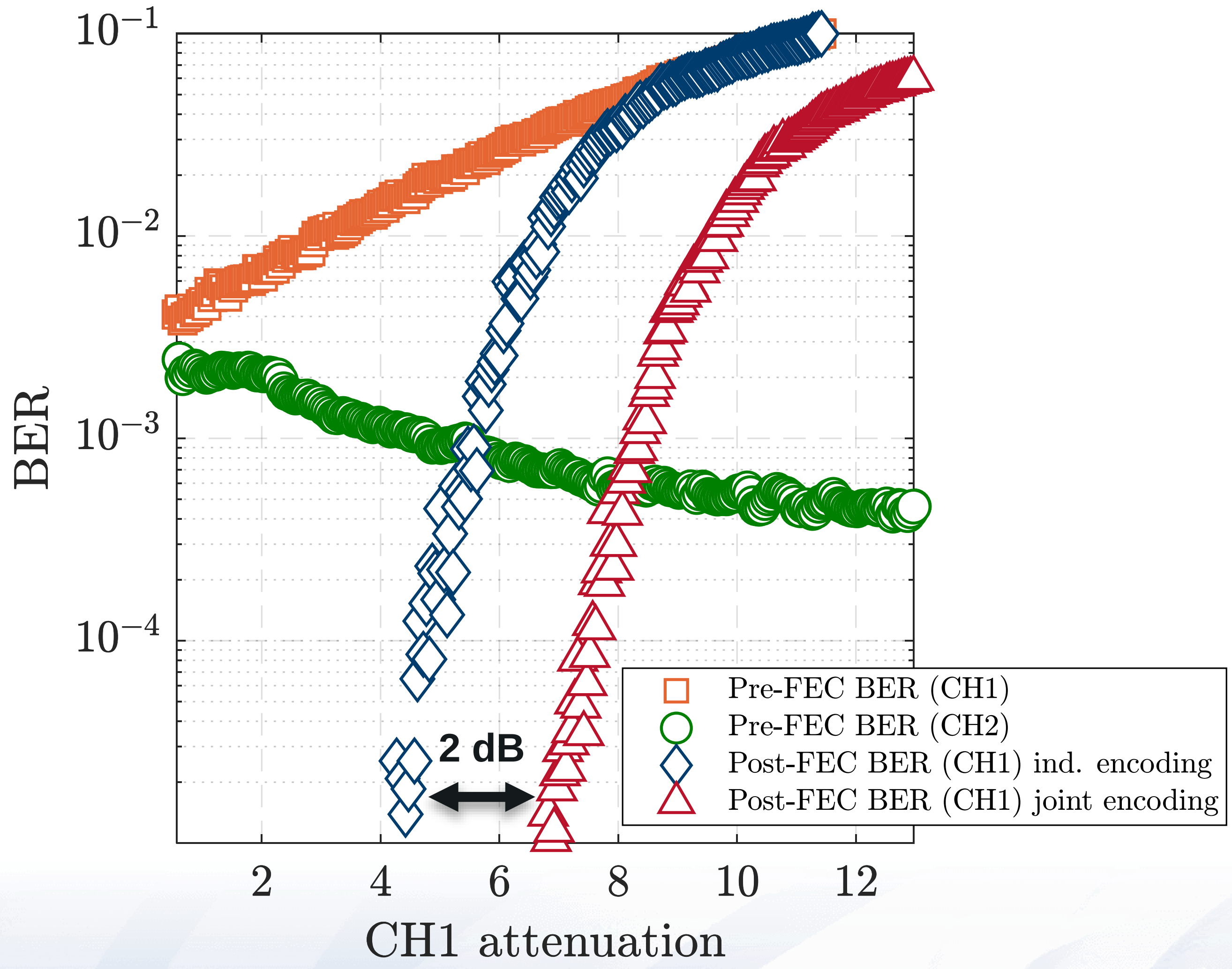
Concept & Implementation



M. A Fernandes, P. P. Monteiro and F. P. Guiomar, "**400G MIMO-FSO Transmission with Enhanced Reliability Enabled by Joint LDPC Coding**," in Proc. 47th European Conf. Optical Communication (ECOC), paper Tu1B.5, Bordeaux, France, 2021. https://doi.org/10.1109/ECOC52684.2021.9605896

Joint LDPC Coding: Experimental Results

Concept validation

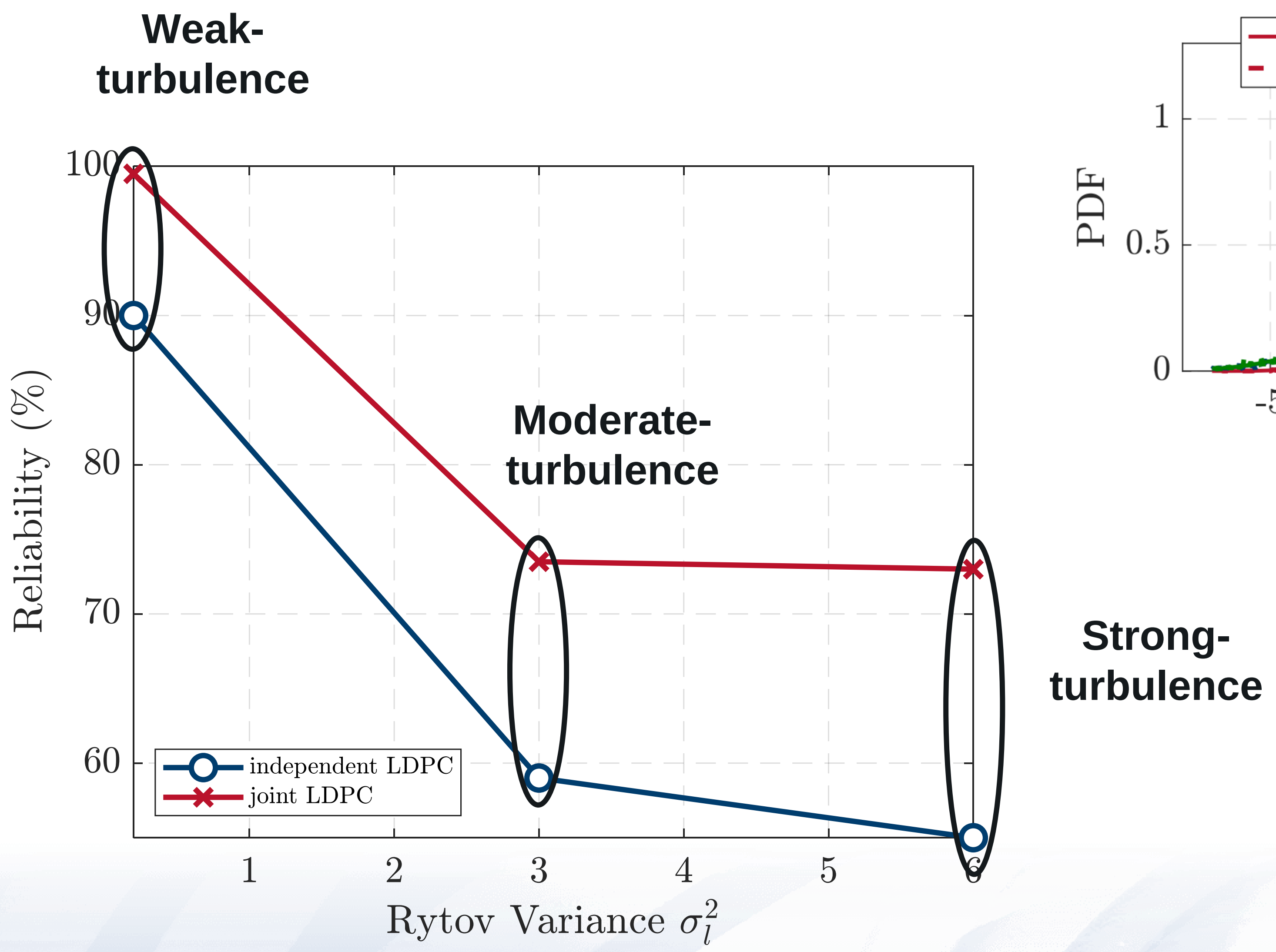


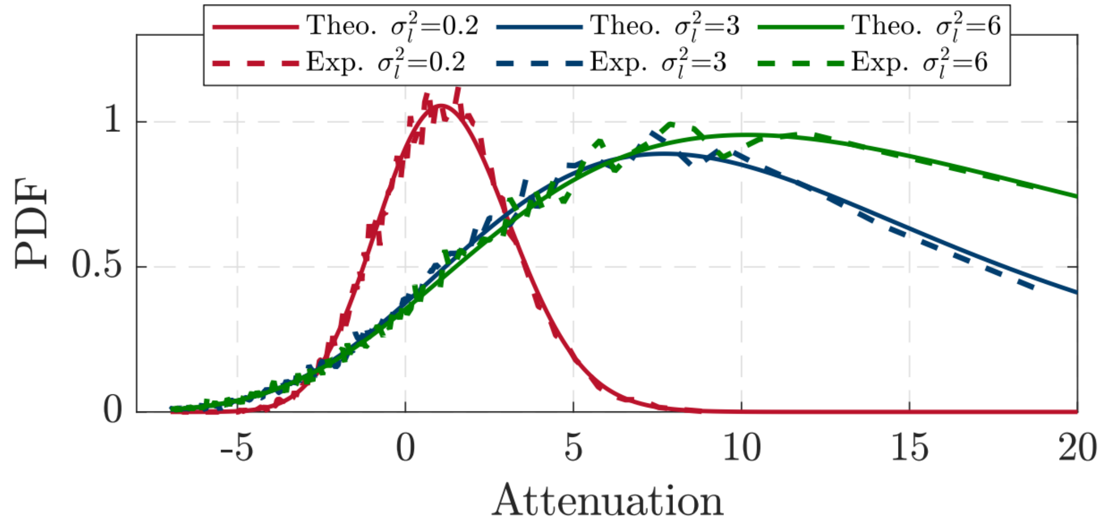
- **The VOA was used to sweep the attenuation of CH1.**
- **Due to having only one receiver, while the CH1 performance degrades, the CH2 performance slightly improves.**
- **In these conditions, only 4 dB of attenuation are supported with individual encoding.**
- **Performing joint encoding present a gain of 2 dB.**

M. A Fernandes, P. P. Monteiro and F. P. Guiomar, "**400G MIMO-FSO Transmission with Enhanced Reliability Enabled by Joint LDPC Coding**," in Proc. 47th European Conf. Optical Communication (ECOC), paper Tu1B.5, Bordeaux, France, 2021. https://doi.org/10.1109/ECOC52684.2021.9605896

Joint LDPC Coding: Experimental Results

Reliability measurements





Next Step:

NxN MIMO

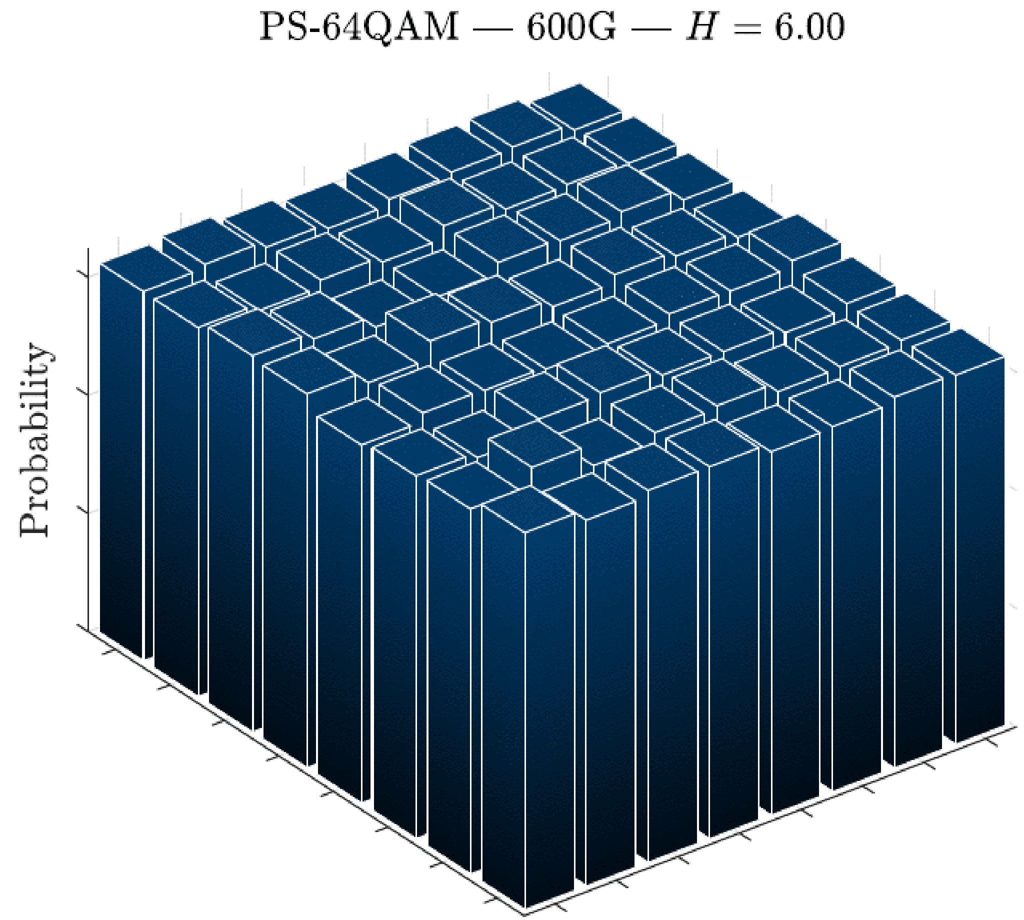
M. A Fernandes, P. P. Monteiro and F. P. Guiomar, "**400G MIMO-FSO Transmission with Enhanced Reliability Enabled by Joint LDPC Coding**," in Proc. 47th European Conf. Optical Communication (ECOC), paper Tu1B.5, Bordeaux, France, 2021. https://doi.org/10.1109/ECOC52684.2021.9605896

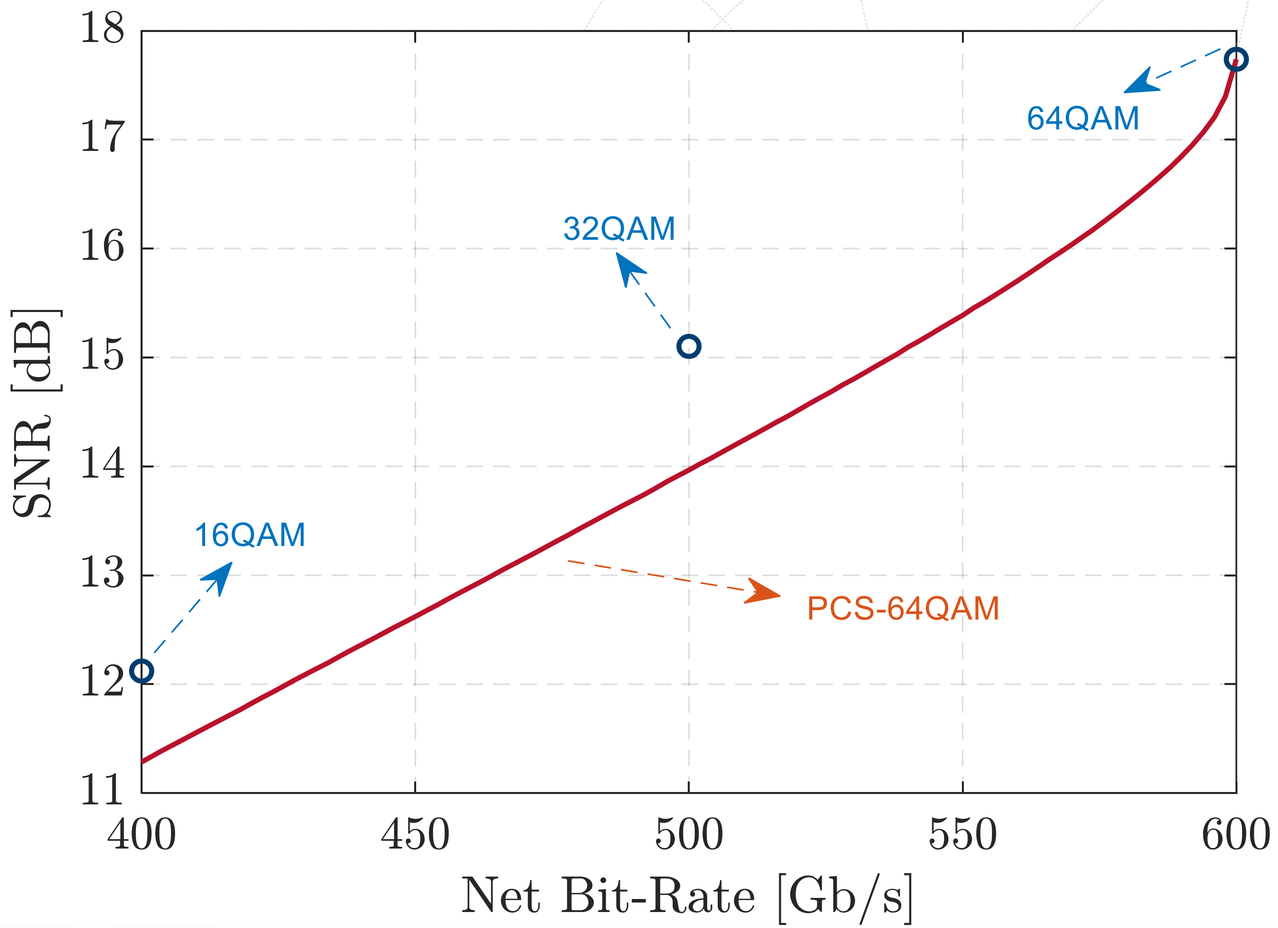
Enhancing FSO Capacity

1) Adaptive Modulation for Turbulence Mitigation

FSO: Indoor Communications Testbed

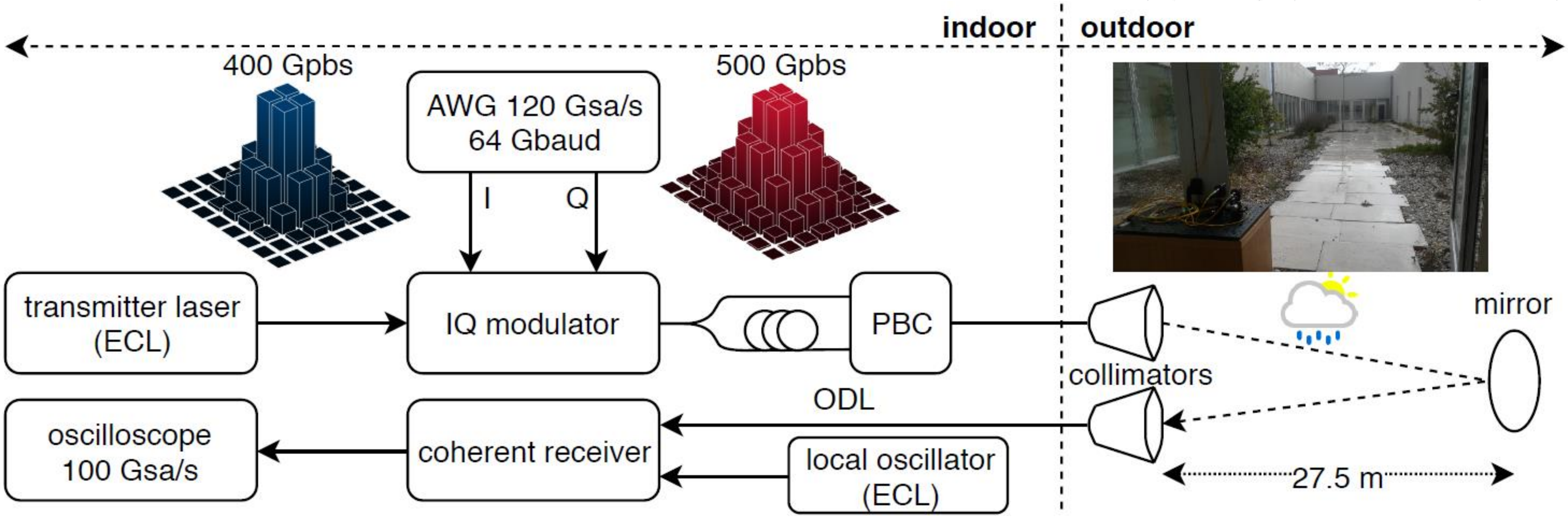
Probabilistic Constellation Shaping for Bit-Rate Flexibility





F. P. Guiomar, A. Lorences-Riesgo, D. Ranzal, F. Rocco, A. N. Sousa, M. A. Fernandes, B. T. Brandão, A. Carena, A. L. Teixeira, M. C. R. Medeiros and P. P. Monteiro, "**Adaptive Probabilistic Shaped Modulation for High-Capacity Free-Space Optical Links**," IEEE Journal of Lightw. Tech., vol. 38, no. 23, 2021. https://doi.org/10.1109/JLT.2020.3012737

FSO: Experimental Setup

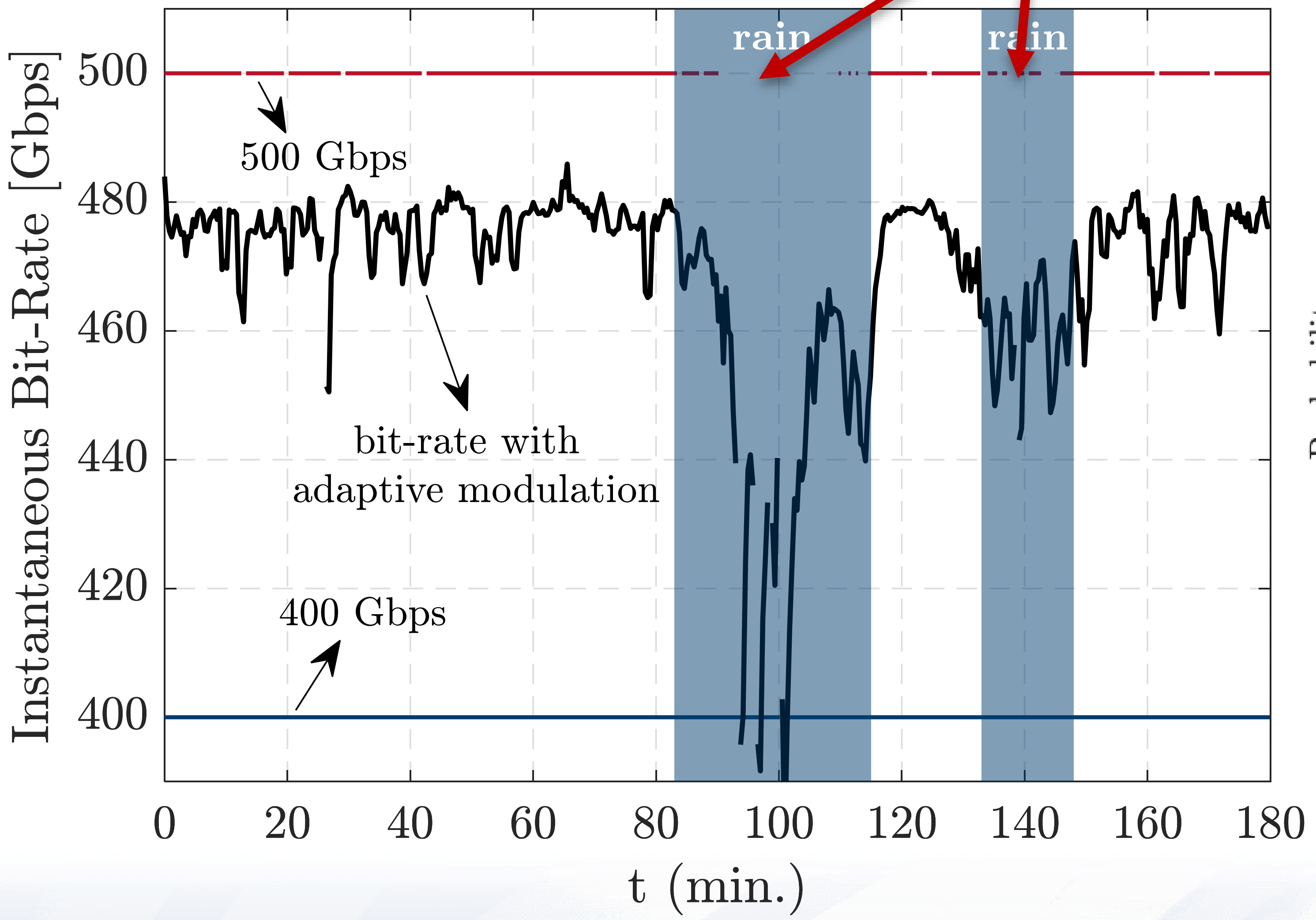


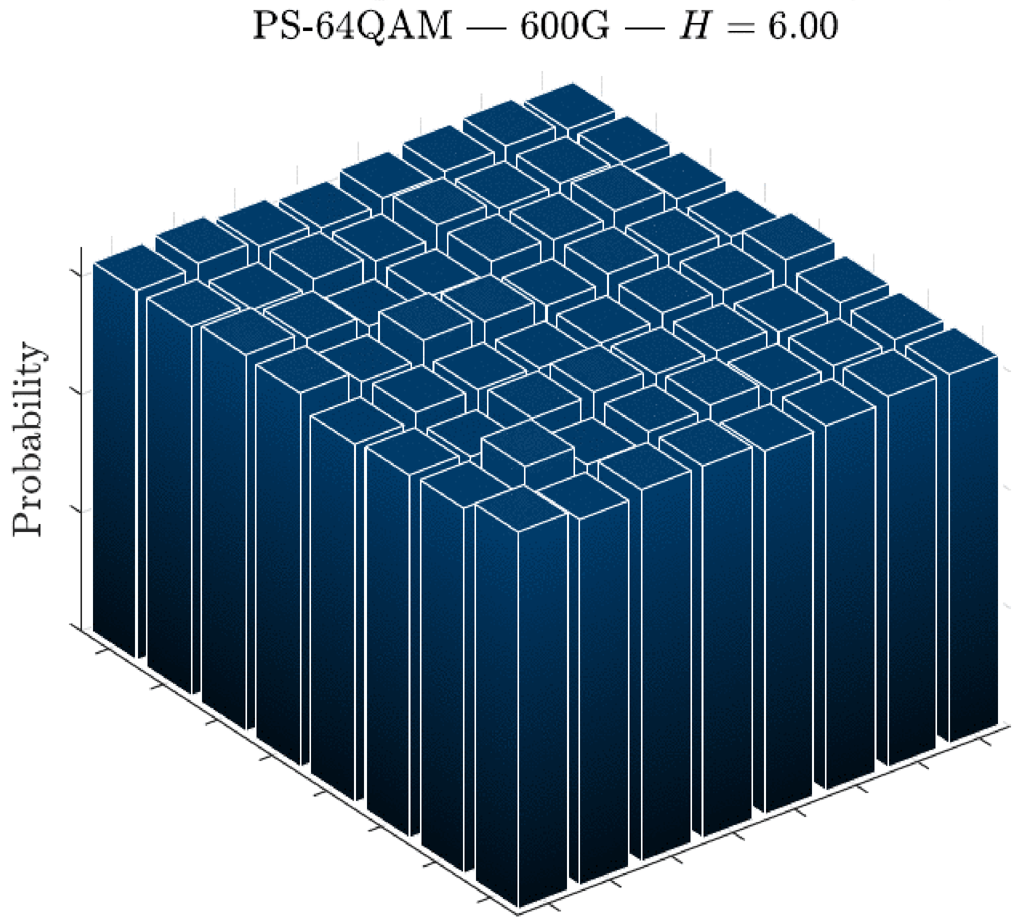
- **64 Gbaud** polarization-multiplexed **PCS-64QAM**;
- **55 meter** outdoor FSO link, with continuous measurement over 3 hours;
- Aim: test resilience against adverse weather conditions (rain showers).

F. P. Guiomar, A. Lorences-Riesgo, D. Ranzal, F. Rocco, A. N. Sousa, M. A. Fernandes, B. T. Brandão, A. Carena, A. L. Teixeira, M. C. R. Medeiros and P. P. Monteiro, "**Adaptive Probabilistic Shaped Modulation for High-Capacity Free-Space Optical Links**," IEEE Journal of Lightw. Tech., vol. 38, no. 23, 2021. https://doi.org/10.1109/JLT.2020.3012737

FSO: Adaptive Modulation

Insufficient SNR -> LoS





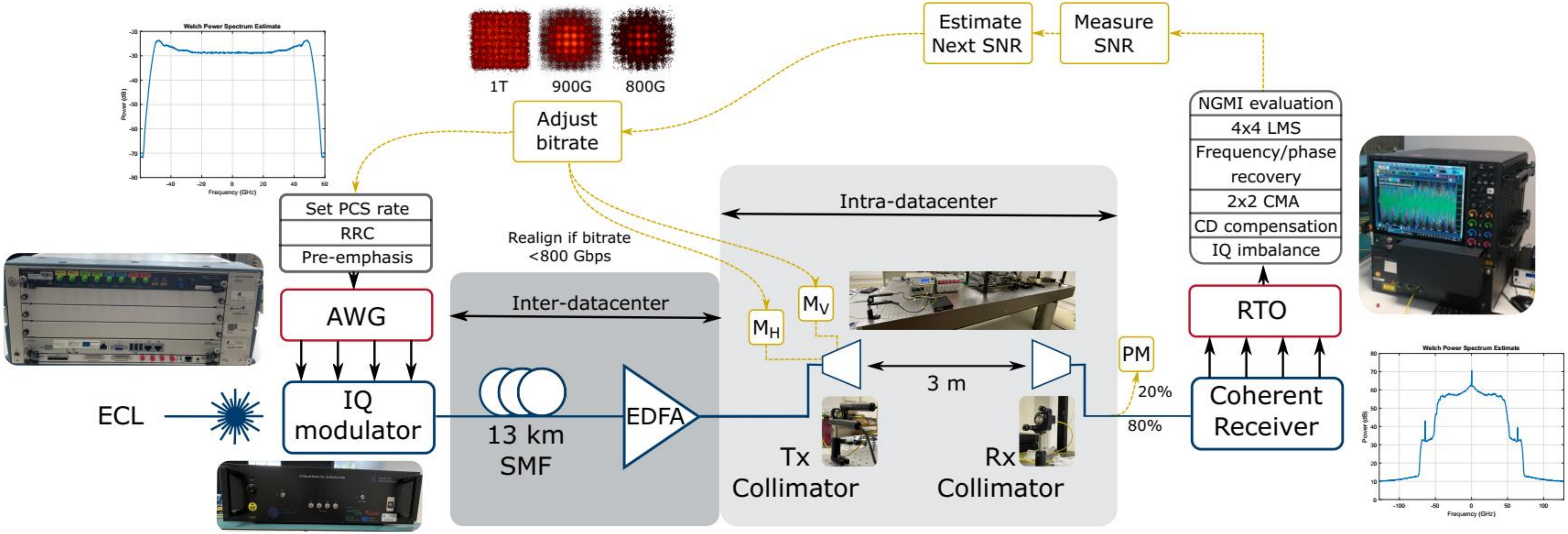
F. P. Guiomar, A. Lorences-Riesgo, D. Ranzal, F. Rocco, A. N. Sousa, M. A. Fernandes, B. T. Brandão, A. Carena, A. L. Teixeira, M. C. R. Medeiros and P. P. Monteiro, “**Adaptive Probabilistic Shaped Modulation for High-Capacity Free-Space Optical Links**,” IEEE Journal of Lightw. Tech., vol. 38, no. 23, 2021. https://doi.org/10.1109/JLT.2020.3012737

instituto de telecomunicações

Enhancing FSO Capacity

2) Adaptive Modulation for Pointing Error Mitigation

Experimental Setup



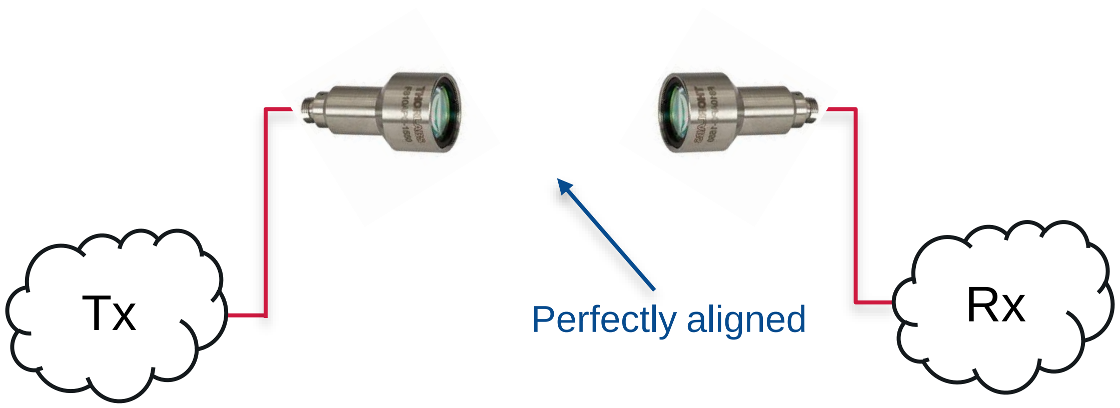
ECL: External Cavity Laser; **RRC**: Root-Raised Cosine; **AWG**: Arbitrary Waveform Generator; **SMF**: Single-Mode Fiber; **PCS**: Probabilistic Constellation Shaping; **EDFA**: Erbium-Doped Fiber Amplifier; $\mathbf{M_H}$: Motor Horizontal; $\mathbf{M_V}$: Motor Vertical; **SNR**: Signal-to-Noise Ratio; **PM**: Power-Meter; **RTO**: Real-Time Oscilloscope; **CD**: Chromatic Dispersion; **CMA**: Constant Modulus Algorithm; **LMS**: Least-Mean Squares; **NGMI**: Normalized General Mutual Information

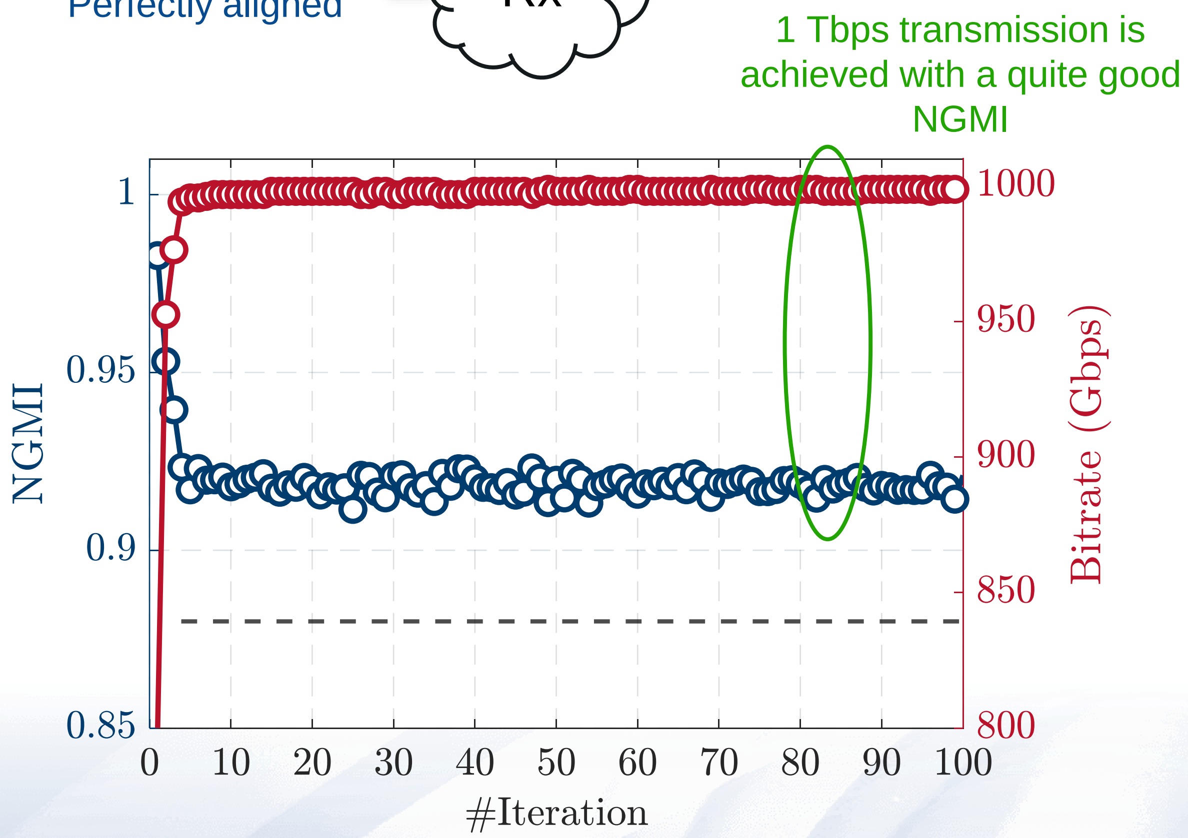
- **64QAM-PCS** signal, with a symbol rate of **100 Gbaud**.
- **Goal:** Use PCS to adjust the bitrate to account for sequential beam misalignment.

instituto de telecomunicações

M. A. Fernandes, P. P. Monteiro and F. P. Guiomar, “**Free-Space Terabit Optical Interconnects**,” IEEE Journal of Lightwave Technology, vol. 40, no. 5, pp. 1519--1526, 2022. https://doi.org/10.1109/JLT.2021.3133070

Ideal Conditions (Baseline Performance)

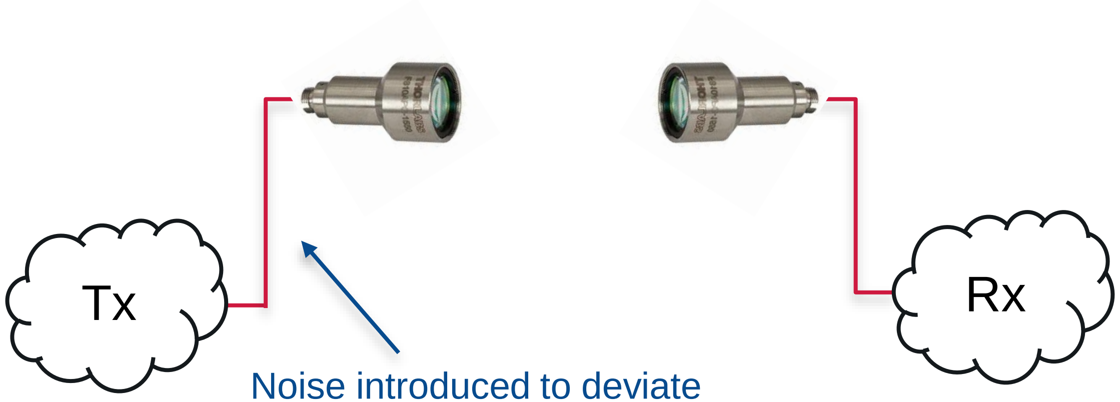




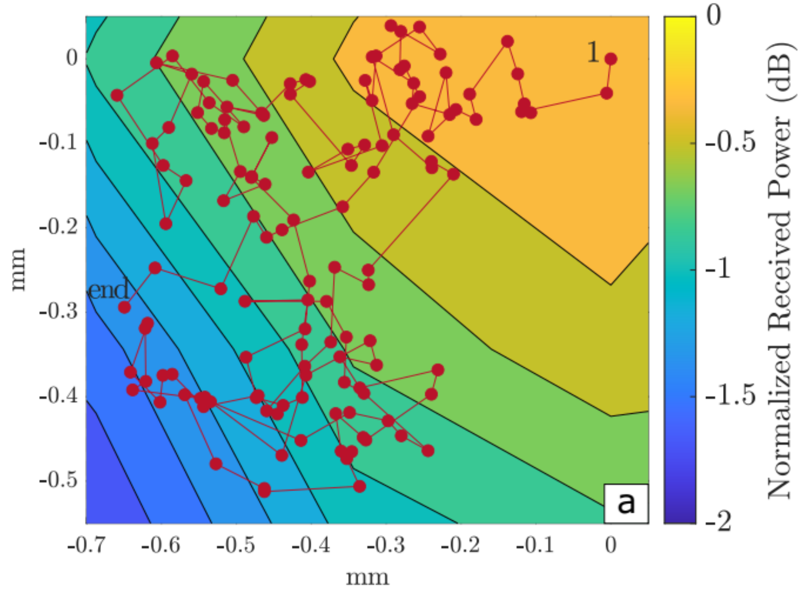
But there are always pointing errors….

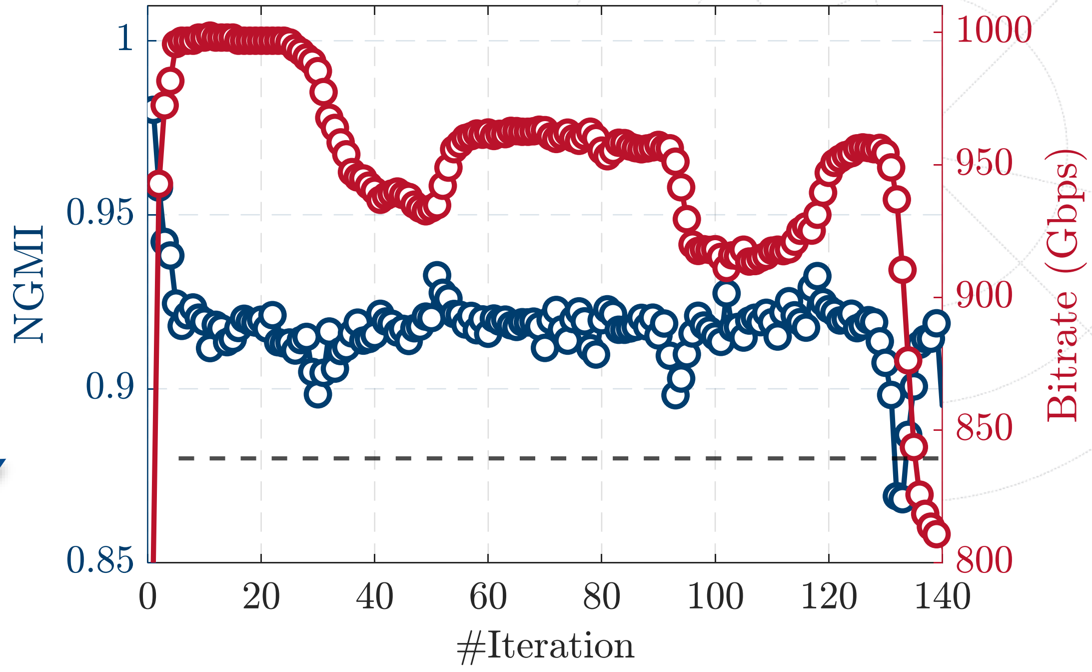
M. A. Fernandes, P. P. Monteiro and F. P. Guiomar, "**Free-Space Terabit Optical Interconnects**," IEEE Journal of Lightwave Technology, vol. 40, no. 5, pp. 1519--1526, 2022. https://doi.org/10.1109/JLT.2021.3133070

Introducing pointing errors



Noise introduced to deviate the beam from the optimal position

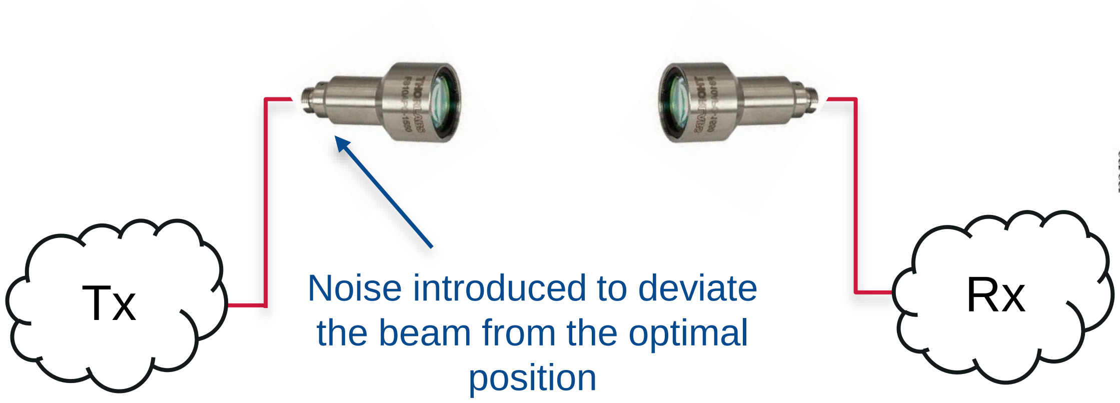


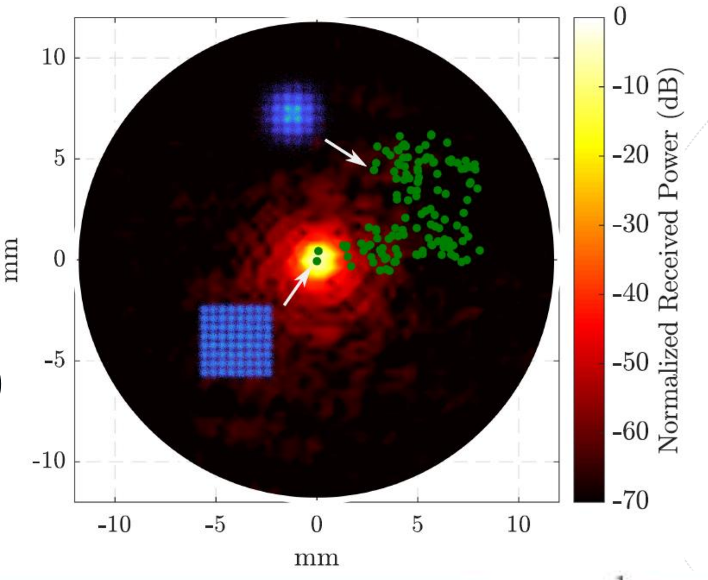


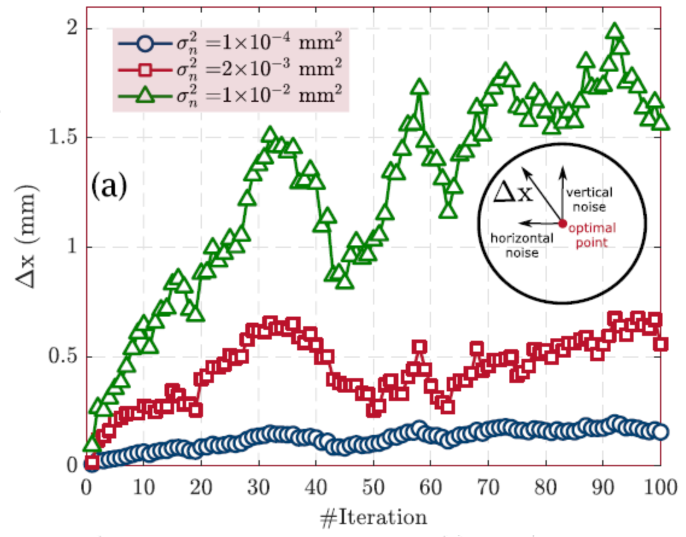
PCS is used to lower the bit-rate and the NGMI is kept constant

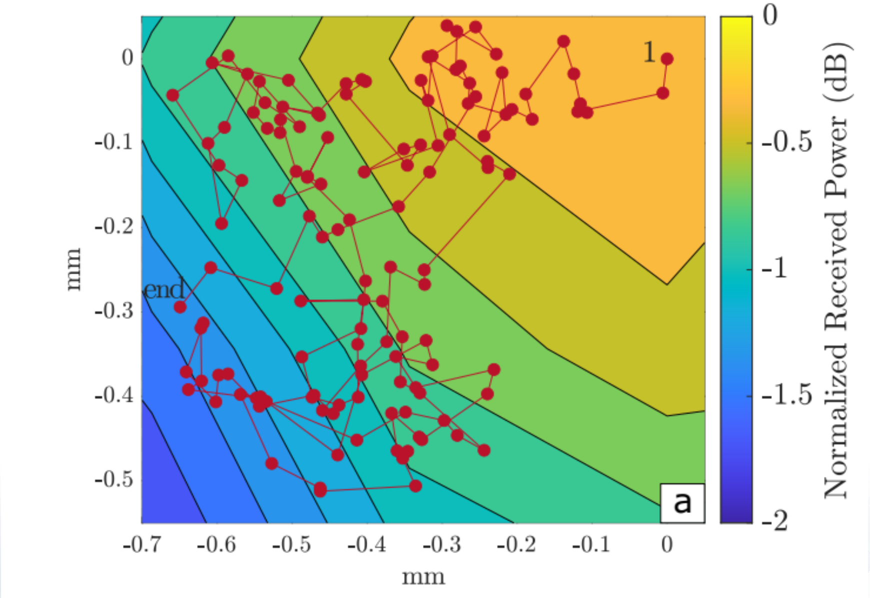
M. A. Fernandes, P. P. Monteiro and F. P. Guiomar, “**Free-Space Terabit Optical Interconnects**,” IEEE Journal of Lightwave Technology, vol. 40, no. 5, pp. 1519--1526, 2022. https://doi.org/10.1109/JLT.2021.3133070

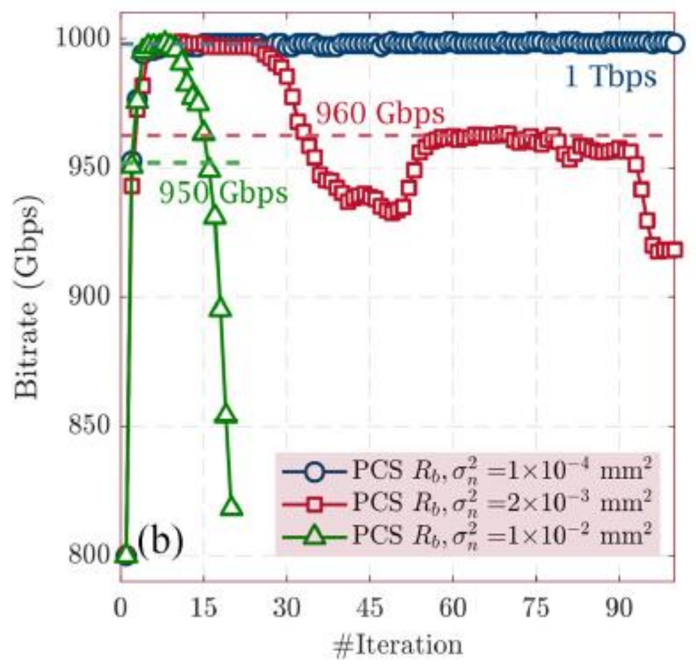
Introducing pointing errors

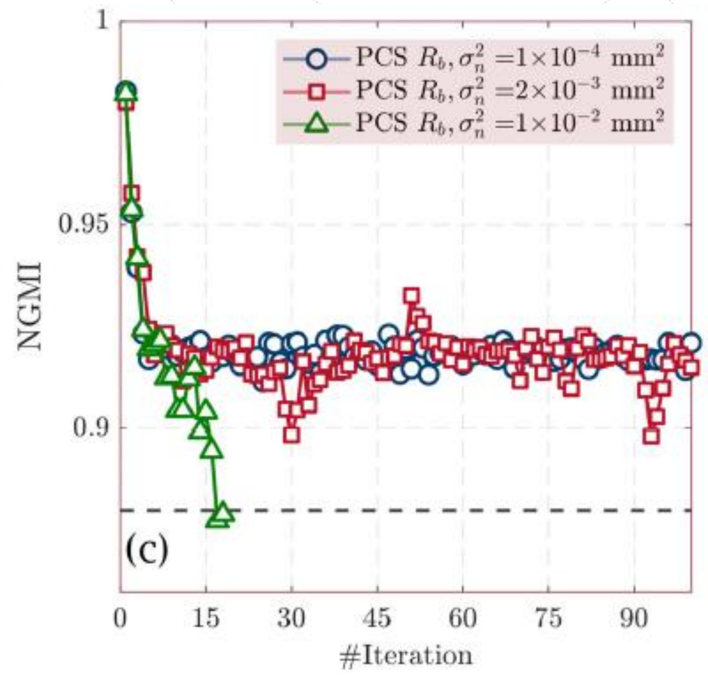












M. A. Fernandes, P. P. Monteiro and F. P. Guiomar, "**Free-Space Terabit Optical Interconnects**," IEEE Journal of Lightwave Technology, vol. 40, no. 5, pp. 1519--1526, 2022. https://doi.org/10.1109/JLT.2021.3133070

1.8 km WDM-FSO Field Trial

How many channels are enough?

instituto de telecomunicações

Achievable bit-rate

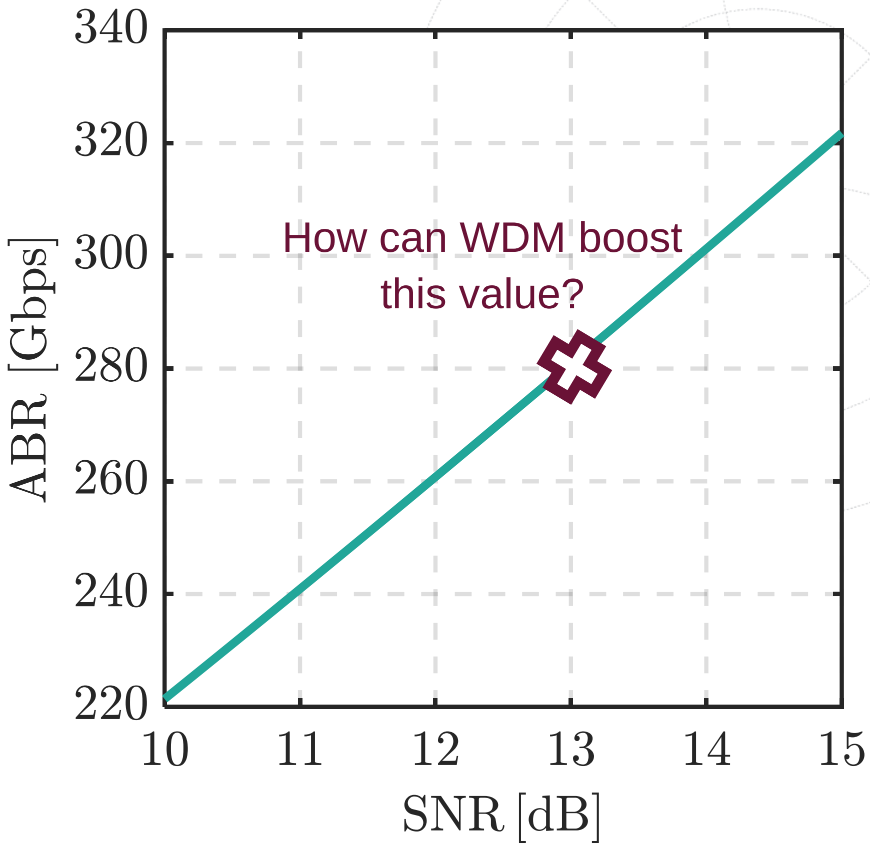
Single-wavelength Shannon capacity

Transceiver Parameters (200G COTS-like)**:**

- B = 32 Gbaud

Shannon Capacity (dual-pol)**:**

- $ABR = 2 \times B \times log_2(1 + SNR)$



M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Achievable bit-rate

WDM Shannon capacity (infinite power)

Transceiver Parameters (200G COTS-like)**:**

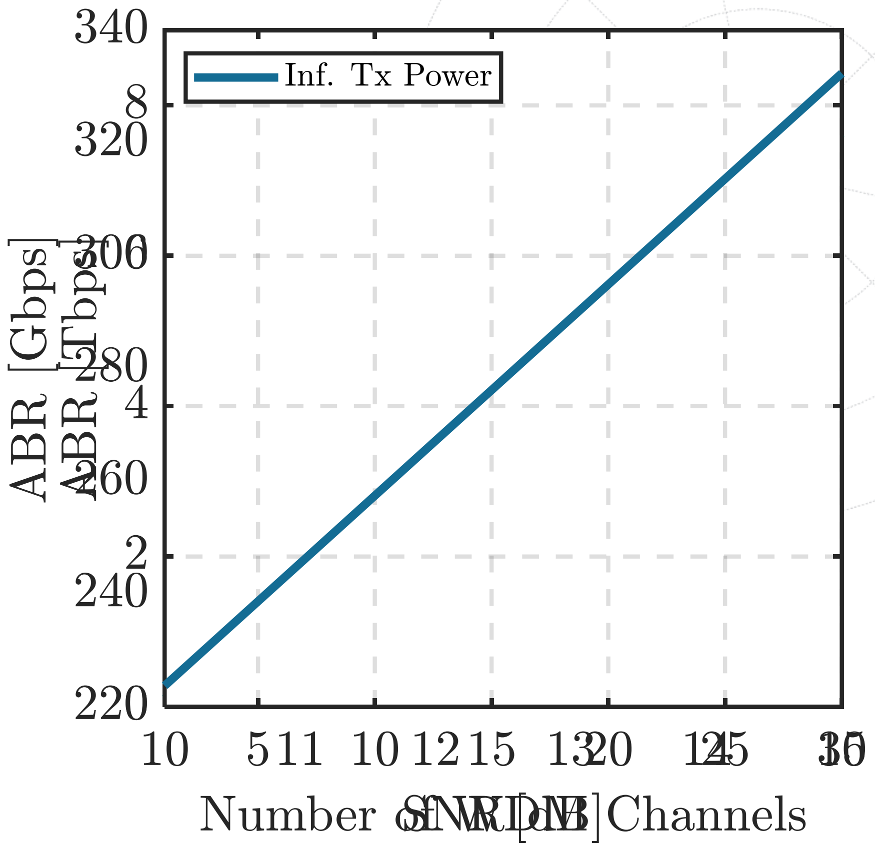
- B = 32 Gbaud

Shannon Capacity (dual-pol)**:**

- $ABR = 2 \times B \times log_2(1 + SNR)$

Shannon Capacity (dual-pol, WDM)**:**

- $ABR = 2 \times B \times nCh \times log_2(1 + SNR)$



M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Achievable bit-rate

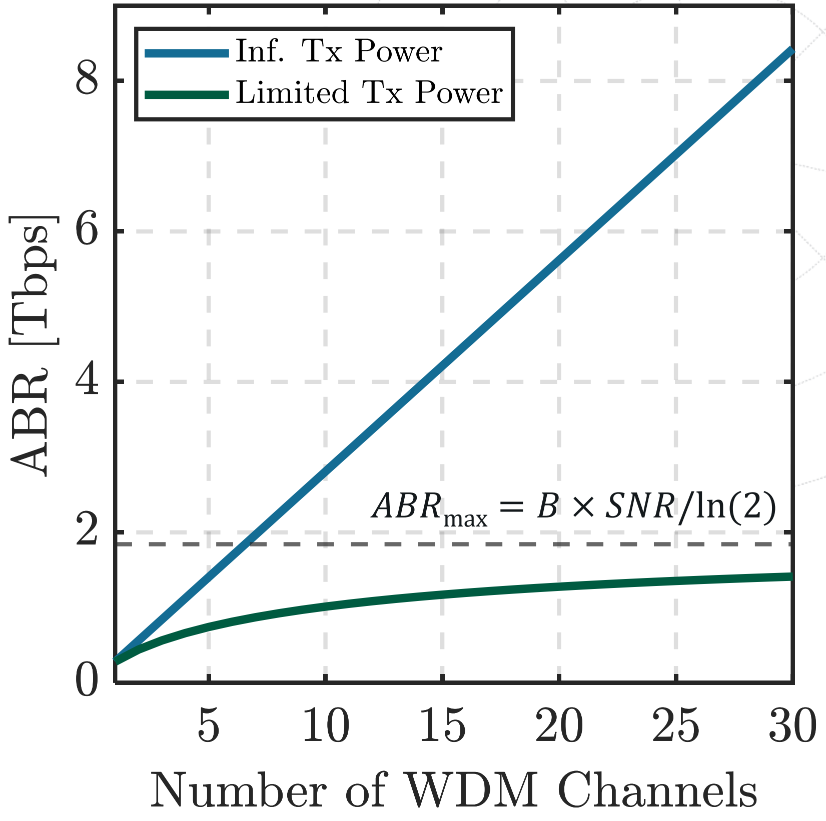
WDM Shannon capacity (limited power)

Transceiver Parameters (200G COTS-like)**:**
- B = 32 Gbaud

Shannon Capacity (dual-pol)**:**
- $ABR = 2 \times B \times log_2(1 + SNR)$

Shannon Capacity (dual-pol, WDM)**:**
- $ABR = 2 \times B \times nCh \times log_2(1 + SNR)$

Shannon Capacity (dual-pol, WDM, lim. power)**:**
- $ABR = 2 \times B \times nCh \times log_2(1 + SNR/nCh)$



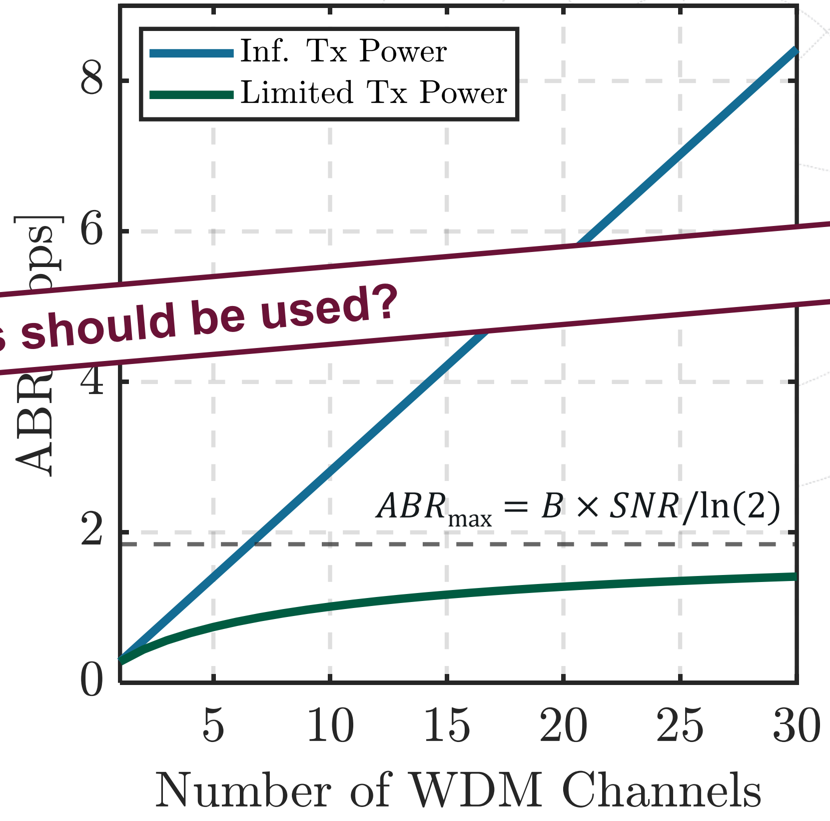
M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Achievable bit-rate

WDM Shannon capacity (limited power)

- The capacity gain of increasing the number of WDM channels considerably decreases
- Considering simple Tx-power as a limitati… saturates…
- If additional constraints are considered (filtering / wavelength-dependent losses) **increasing** the number of channels can **degrade** the global ABR.

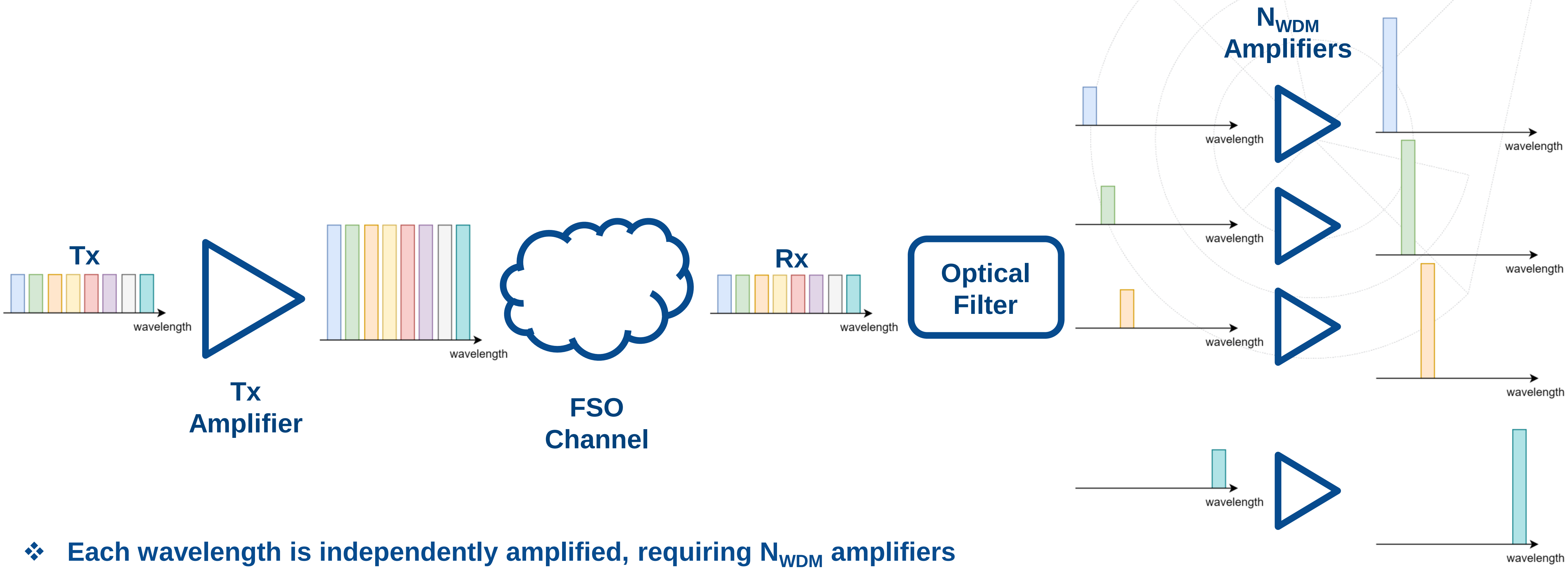
Question 1: How many channels should be used?



M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Receiver amplification architecture

Dedicated amplification.



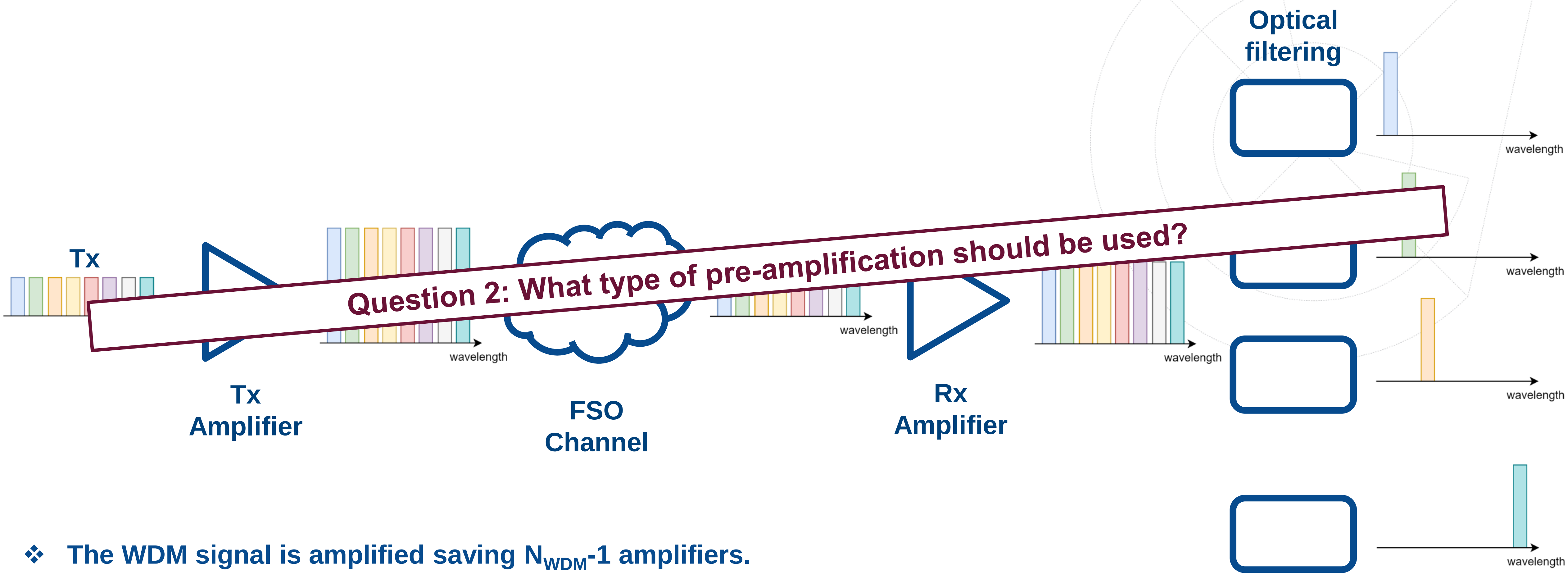
❖ **Each wavelength is independently amplified, requiring N_{WDM} amplifiers**

M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

instituto de telecomunicações

Receiver amplification architecture

Global amplification.



❖ **The WDM signal is amplified saving N_{WDM}-1 amplifiers.**

M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Field trial:

Experimental Setup

AIRCISION

AIRCISION

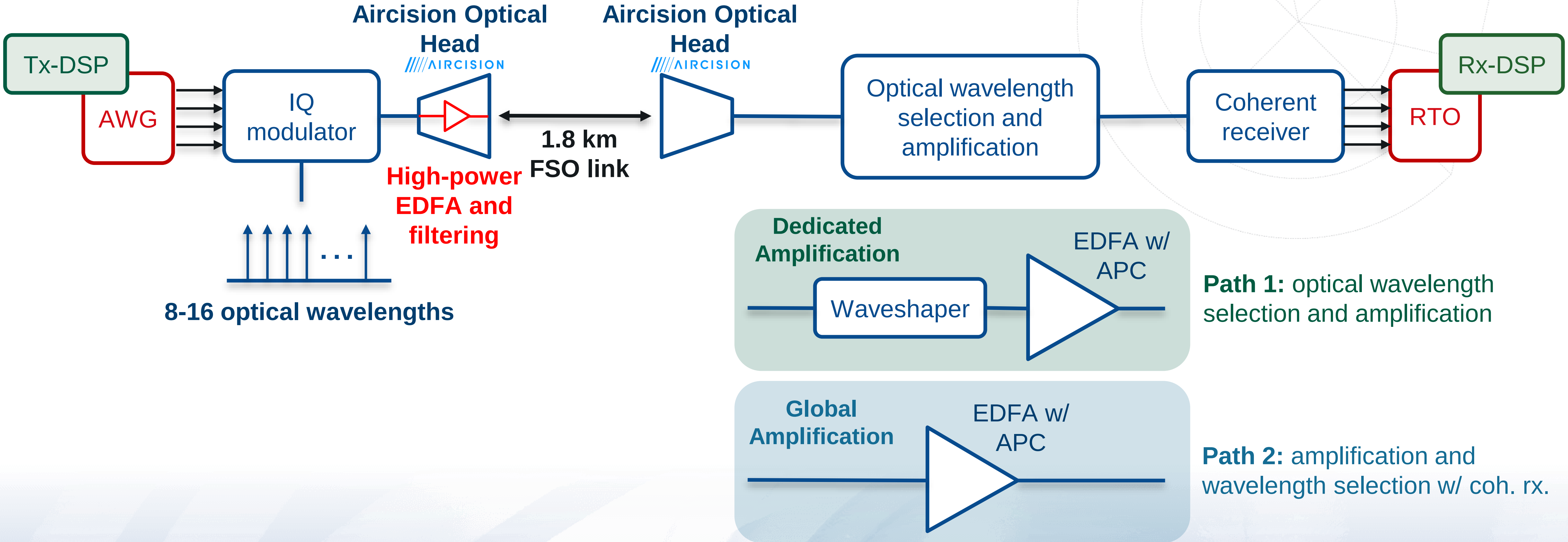
M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, “**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?” in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Field trial:

Experimental Setup

Single channel parameters:

- 32 Gbaud, 16 QAM
- 200 Gbps



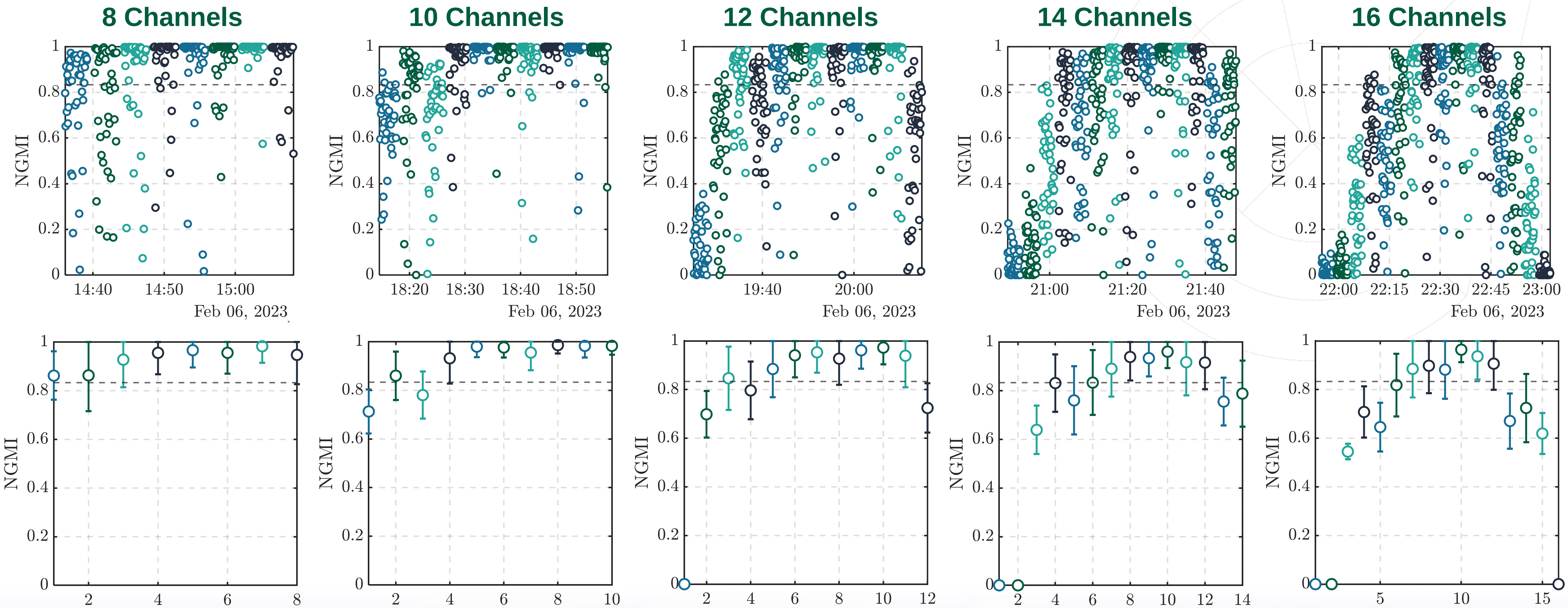
Path 1: optical wavelength selection and amplification

Path 2: amplification and wavelength selection w/ coh. rx.

M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Field trial:

NGMI results (path 1: channel-wise amplification)



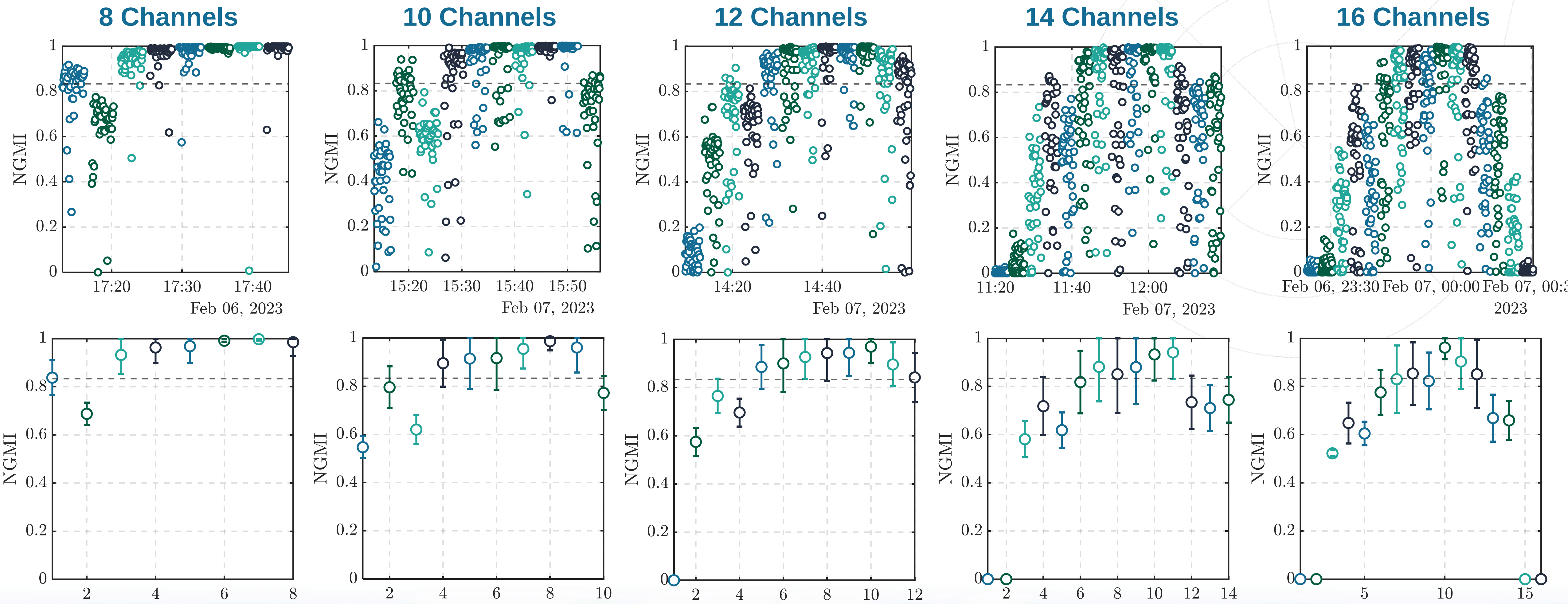
❖ Despite channel-wise amplification, increasing the number of channels tends to degrade the global performance due to optical filtering in the optical heads.

instituto de telecomunicações

M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Field trial:

NGMI results (path 2: global amplification)



❖ Amplifying the full WDM signal together, exposes more significantly the limitations imposed by the transmitted power and optical filtering.

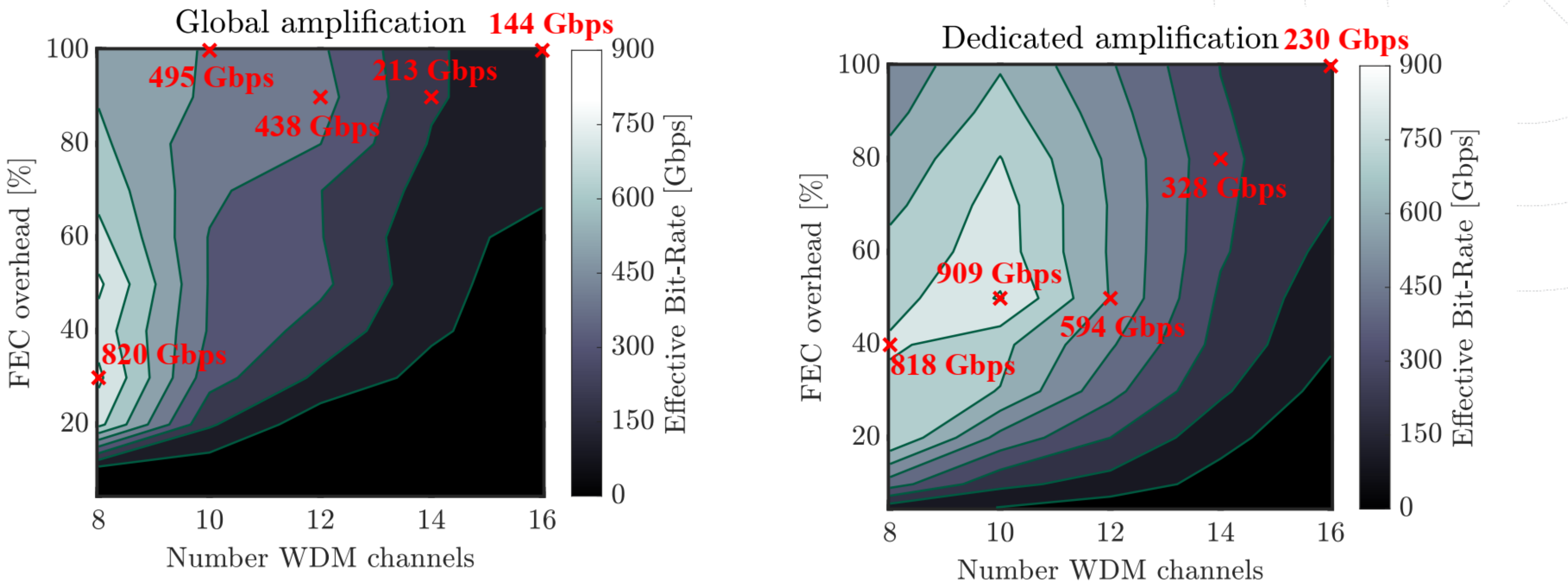
instituto de telecomunicações

M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, “**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?” in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Field trial:

Achievable capacity (vs number of channels and FEC overhead)

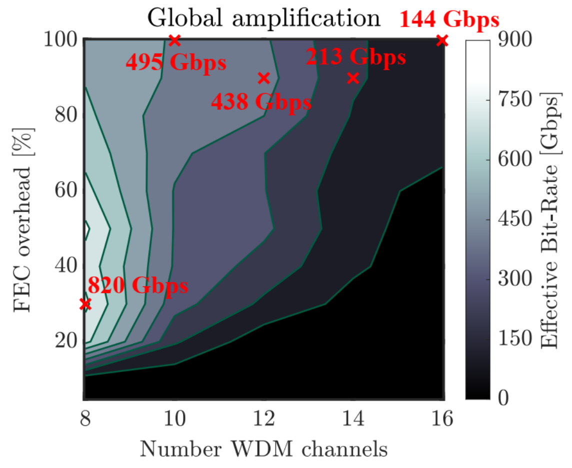
- The chosen number of WDM channels significantly impacts the achievable capacity / reliability.
- We have previously demonstrated that optimizing the FEC overhead, can considerably increase the achievable effective bit-rate (https://ieeexplore.ieee.org/document/10414049)

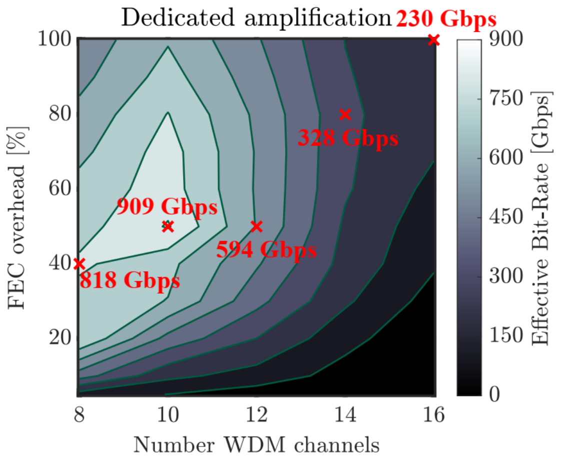


M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

instituto de telecomunicações

Conclusion:





- Contrarily from the expected power-constrained Shannon capacity, the overall system capacity **does not monotonically increase** with the number of WDM channels:
  - Limited optical bandwidth.
  - Limited gain provided by the receiver EDFA.

- If maximum capacity is required, channel-wise dedicated amplification is required **achieving 909 Gbps**; however, global amplification still reaches **820 Gbps** while **saving N_{WDM}-1** amplifiers**.**

- The presented results are very constrained by limited optical bandwidth, in different scenarios (longer distances / no optical filtering), the **benefits of dedicated amplification can be higher.** The optimal solution can be resorting to **group amplification**.

- We have presented a **field-trial (1.8 km)** addressing critical signal design optics for terabit WDM-FSO, showing the high impact of number of channels and the FEC overhead, achieving a maximum **effective bit-rate of 909 Gbps**.

M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro and F. P. Guiomar, "**Eye-Safe Terabit-Class WDM Optical Wireless: How Many Channels are Enough**?" in Proc. Optical Fiber Conference (OFC), paper Th3C.7, San Diego, USA, March 2024. https://doi.org/10.1364/OFC.2024.Th3C.7

Conclusions

instituto de telecomunicações

Conclusions

- **Coherent technology + FSO: high-capacity fiber-compatible optical wireless!**
  - Commercial off-the-shelf 400G+ coherent transceivers are available;
  - Optical collimators perform seamless fiber-to-air conversion;
    - No need for E/O and O/E conversion;
    - Full fiber bandwidth is preserved;
    - Compatible with WDM.
- **Reliability challenges: Pointing errors and atmospheric turbulence;**
  - Channel estimation and adaptive modulation are key ingredients to enable robust FSO transmission;
- **High-capacity FSO demonstrations:**
  - 400G+ outdoor FSO transmission with adverse weather conditions;
  - 1 Tbps indoor FSO transmission with enhanced resilience towards pointing errors;
  - Multi-Terabit field trial over 1.8 km, enabled by optimized WDM-FSO transmission.

ORCIP

optical radio convergence infrastructure for communications and power delivering

instituto de telecomunicações

Thank You!

Questions?