Achieving Multi-Terabit FSO Capacity with Coherent WDM Transmission Over a 1.8 km Field Trial

Marco A. Fernandes[1], Gil M. Fernandes[1], Bruno T. Brandão[1], Manuel M. Freitas[1], Nourdin Kaai[2], Alina Tomeeva[2], Bas van Der Wielen[2], John Reid[2], Daniele Raiteri[2], Paulo P. Monteiro[1], Fernando P. Guiomar[1]

[1]Instituto de Telecomunicações and University of Aveiro, Campus Universitário de Santiago, 3810-193, Portugal.
[2]Aircision B.V., HighTech Campus 12, 5656 AE, Eindhoven, Netherlands.
marcofernandes@av.it.pt

Abstract *Using terrestrial optical head prototypes, we experimentally demonstrate 4 Tbps transmission over a field-deployed 1.8 km FSO-link resorting to coherent optics, wavelength multiplexing, optimized coding, and atmospheric turbulence mitigation through optical pre-amplification.*

Introduction

Free-space optics (FSO) have been emerging as a popular solution for next-generation wireless networks, providing advantages over its radio-frequency (RF) counterpart such as unlicensed spectrum, immunity to electromagnetic interference, high directivity and security, virtually unlimited bandwidth, and easy and quick deployment[1]. With the goal of providing fiber-like capacity, we observe a recent trend of merging FSO with coherent optical communications, which is enabled by the use of direct fiber coupling at the optical antennas[2]. Moreover, by avoiding optical-to-electrical conversion in the air-to-fiber transition, capacity-boosting techniques such as wavelength division multiplexing (WDM) can be seamlessly employed in optical wireless systems[3]. However, the use of optical fiber coupling comes at the expense of increased sensitivity to coupling impairments, caused by pointing errors, angle-of-arrival fluctuations, or atmospheric turbulence[4]. Nevertheless, the constant evolution of digital signal processing (DSP) has led to major breakthroughs in communications robustness and flexibility[5]. In this paper, we present the results of a field trial conducted in the municipality of Aveiro, Portugal, connecting two buildings with a 1.8 km FSO-link. Resorting to coherent optics, WDM, and atmospheric turbulence mitigation using dynamic receiver optical gain, we demonstrate 4 Tbps (10×400 Gbps) transmission. Moreover, exploiting the flexibility provided by soft-decision forward error correction (FEC) codes, we analyze the optimum FEC overhead that maximizes the overall throughput.

Experimental Setup and Power Measurements

The conducted field-trial is depicted in Fig. 1. The transmitter was located at Parque de Ciência e Inovação (PCI) - Ílhavo, where a shaped 64 Gbaud signal is generated using probabilistic constellation shaping (PCS) over a 64-QAM template, and a FEC overhead of 20%, yielding a net bit-rate of 400 Gbps. The signal is then pulse-shaped by a root-raised cosine (RRC) filter with 0.1 roll-off, and uploaded to an arbitrary waveform generator (AWG) with 45 GHz bandwidth and 120 Gsps sampling-rate (Keysight M8194A). Afterwards, optical modulation is performed by dual-polarization IQ modulator (35 GHz bandwidth) over a WDM signal generated by coupling multiple lasers. The modulated optical WDM signal is then sent to free-space by a commercial optical head from Aircision, which amplifies the signal and performs fiber-to-air conversion. After travelling over a 1.8 km FSO link, the signal is collected at Instituto de Telecomunicações (IT) - Aveiro, being directly directly coupled into a fiber-core by another Aircision optical head. Then, the optical signal is wavelength demultiplexed by a waveshaper (Finisar WS4000S) and amplified by an Erbium-doped fiber amplifier (EDFA) with automatic power control (APC), *i.e.* with automatic adjustment of the optical gain to flatten the output power. This characteristic of the EDFA is useful to mitigate power fluctuations of the signal due to atmospheric turbulence. Power measurements are performed before and after signal amplification by 2 fast-optical power meters (FOPM) with a sampling-rate of 10 ksps. Finally, the signal is optical-to-electrical converted by a coherent receiver (40 GHz bandwidth), and 4 real-time oscilloscopes (RTO), with 200 Gsps sample-rate and 70 GHz bandwidth, are used to sample and digitize the electrical signal (Tektronix DPO77002SX-R3). Offline DSP techniques are performed, namely IQ imbalance compensation, 2×2 CMA-based adaptive equalization, frequency and phase recovery, 2×2 LMS equalization, bit decoding and normalized generalized mutual information (NGMI) [6] assessment. It is worth emphasizing that the Aircision optical heads perform all the pointing and tracking of the free-space optical beam, considerably minimizing the impact of the pointing errors in the system. The transmitted beam width and power are regu-

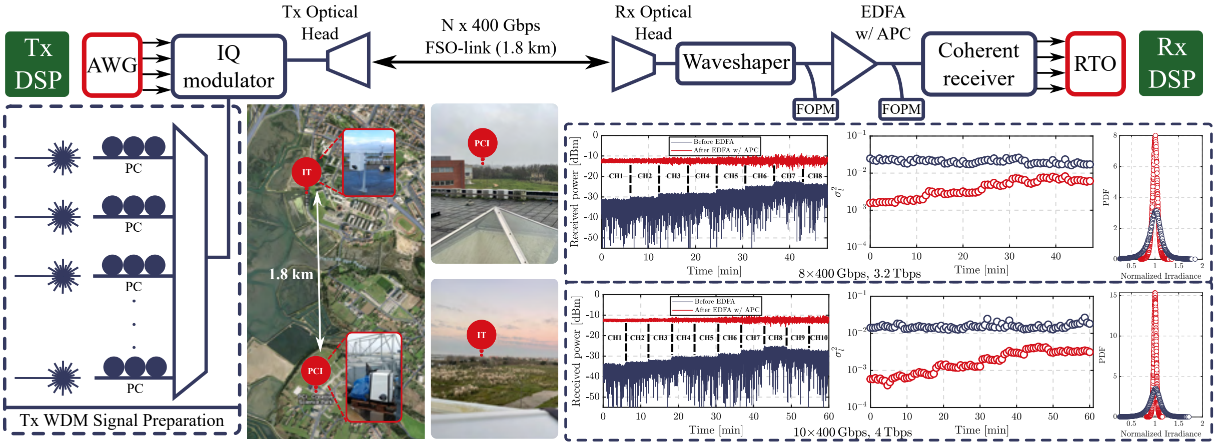

Fig. 1: Field trial of multi-terabit WDM coherent transmission over a 1.8 km FSO link between IT-Aveiro and PCI-Ilhavo, depicted with a Google Maps top-view highlighting the communications terminals. Channel-wise received optical power and turbulence strength are also depicted for 8 and 10 wavelengths.

lated to be eye-safe according to IEC 60825-1[7].

Figure 1 also depicts power measurements taken with 8×400 Gbps and 10×400 Gbps signals. These results show the optical power before and after the EDFA and, since the measurements are taken after the waveshaper, the depicted power relates to a single wavelength; the observed *steps* are due to wavelength-dependent attenuation filters and gain ripple in the FSO heads. From the two figures with received power over time for 8 (top) and 10 (bottom) wavelengths, we can observe that increasing the WDM bandwidth results in a lower power per channel, owing to the fixed launched power. However, the APC of the EDFA leads to a similar power at the coherent receiver in both scenarios. To assess the EDFA with APC capability of atmospheric turbulence mitigation, we took the power measurements and fitted them with a Log-Normal distribution [8], thus obtaining the Rytov variance over time depicted in Figure 1. The results show a considerable gain in performing APC at the EDFA, reducing the Rytov variance by roughly one order of magnitude.

Experimental Performance Assessment

The communications experimental campaign was performed using 8 and 10 wavelengths, each carrying a signal with a net bit-rate of 400 Gbps, adding to a total transmitted net capacity of 3.2 Tbps and 4 Tbps, considering 20% FEC overhead. Figure 2a) shows the optical spectra received before waveshaper filtering for each transmitted signal. The optical filtering imposed by the FSO heads for full-duplex operation is clearly visible, limiting the usable communication bandwidth to about 10 nm. On that note, Fig. 2b) shows the electrical signal-to-noise ratio (SNR) of each channel extracted from the received spectrum, considering 40 measurements per channel. The obtained results with both 8 and 10 wavelengths expose the wavelength dependence of the received signal SNR, which is tightly linked with the optical spectra of Fig. 2a), despite the use of APC pre-amplification. For each individual measurement, the full DSP chain was performed, and the channel quality was assessed by evaluating the signal NGMI. These results are depicted in Fig. 2c), where the performance trends follow the previously analyzed SNR behavior. Owing to the colored SNR characteristic of the system, capacity maximization can be performed by optimizing the allocated FEC overhead. To that end, two alternative approaches can be followed: i) independently optimizing the overhead per channel, or ii) optimizing a single FEC overhead to be shared by all WDM channels. Although higher capacity can be achieved by following i), in this work, we will consider the 2nd option, which follows a more pragmatic practical implementation, providing a lower bound of achievable capacity. Also note that fully independent processing of each wavelength is assumed, even though joint coding and decoding could also enhance the achievable capacity. Following this premise, in Fig. 2d) we show the theoretical relation between net bitrate, FEC overhead and corresponding threshold NGMI, $\mathrm{NGMI_{th}}$, assuming capacity-achieving FEC[9]. Note that the FEC overhead, $\mathrm{OH_{FEC}}$ relates with the coding rate, R_{FEC} as $\mathrm{OH_{FEC}} = 1/R_{\mathrm{FEC}} - 1$, and therefore an FEC overhead of 100% corresponds to a coding rage of 1/2, i.e. 1 parity bit for each information bit. Using this theoretical curve, from Fig. 2c) we determine the number of channels that can be correctly decoded (i.e. that are above the corresponding threshold NGMI), whose results are plotted in Fig. 2e), using solid lines to denote the average NGMI and a shaded area to delimit the region of operation associated with the worst and best-measured NGMIs. Clearly, as the FEC overhead increases, more channels can be correctly decoded as the

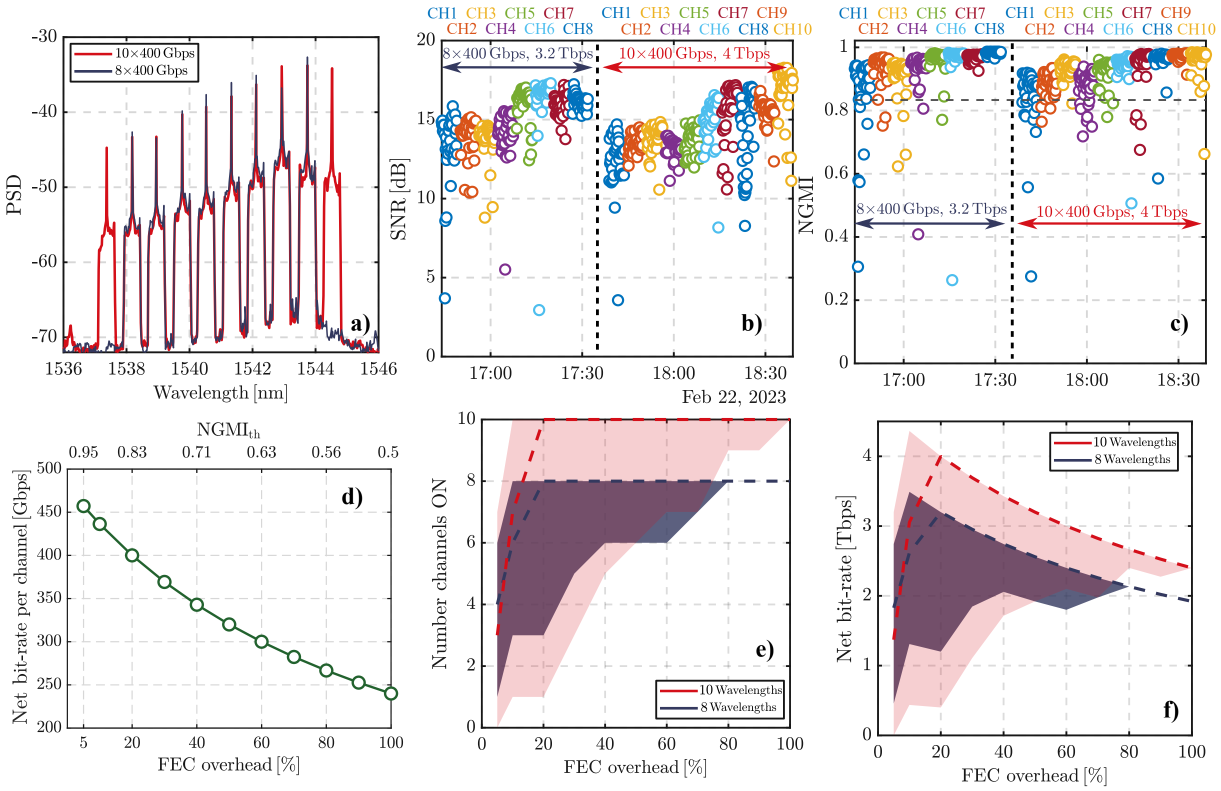

Fig. 2: Results obtained from multi-terabit WDM transmission over a 1.8 km FSO-link: a) received optical spectrum before filtering with 8 and 10 wavelengths; b) measured electrical SNR per channel; c) measured NGMI per channel; d) impact of FEC overhead in the net bit-rate per channel; e) evolution of the number of supported wavelengths versus the FEC overhead; and f) minimum, maximum, and average net capacity obtained by changing the FEC overhead.

threshold NGMI for error-free decoding is lowered. However, on the other hand, the net bit-rate per channel also decreases with increasing overhead, as shown in Fig. 2d), and therefore, the optimum capacity has to ponder these two opposing effects adequately. This is exactly what is shown in Fig. 2f), where the overall achievable capacity for the entire WDM signal is depicted, again with shaded areas delimiting the lower and upper bounds corresponding to the best and worst measurements. From these final results, a set of key conclusions can be withdrawn:

i) while at low FEC overhead (below 20%) the FSO system benefits from a lower WDM bandwidth, at high FEC overhead the achievable capacity seems to be primarily limited by the number of WDM channels. This exposes the need to properly adequate the coding overhead to the utilized WDM bandwidth to avoid a significant loss of capacity;
ii) an intrinsic benefit of using stronger FEC lies in the enhanced reliability of the FSO system, even if at the cost of lower capacity, which is clearly shown by the narrowing of the shaded area towards larger FEC overheads in Fig. 2f). Therefore, depending on the application scenario, and whether overall capacity or reliability are to be prioritized, different coding options should be considered;
iii) interestingly, the maximum achieved capacity of 4 Tbps for the considered field-trial deployment is found at FEC overheads that are compatible with the current generation of coherent optical transceivers, i.e. at roughly 20% overhead, which highlights the potential of this technology to be exploited in high-capacity FSO systems.

Conclusion

Resorting to coherent optics and WDM transmission we demonstrate multi-Terabit FSO transmission over a field-deployed 1.8 km FSO-link. Exploiting automatic optical gain adjustment at the receiver side to mitigate atmospheric turbulence, we show a reduction of one order of magnitude in the measured Rytov variance. Finally, we analyze the trade-off between the number of transmitted channels and the net bit-rate per channel by changing the FEC overhead, resulting in a maximum net capacity of 4 Tbps, obtained with the transmission of 10 WDM channels supporting 400 Gbps each.

Acknowledgements

This work was partially supported by FCT/MCTES through project OptWire (PTDC/EEI-TEL/2697/2021) and by H2020-EU.1.3 program through project DIOR (GA ID: 101008280). Fernando P. Guiomar acknowledges a fellowship from "la Caixa" Foundation (ID 100010434), code LCF/BQ/PR20/11770015. Marco A. Fernandes and Bruno T. Brandão acknowledge Ph.D. fellowships from FCT, codes 2020.07521.BD and 2021.05867.BD, respectively. Gil M. Fernandes acknowledges funding by FCT through the individual scientific employment program contract (2022.07168.CEECIND).

References

[1] M. A. Khalighi and M. Uysal, “Survey on free space optical communication: A communication theory perspective”, *IEEE Communications Surveys Tutorials*, vol. 16, no. 4, pp. 2231–2258, 2014. DOI: 10.1109/COMST.2014.2329501.

[2] M. A. Fernandes, P. P. Monteiro, and F. P. Guiomar, “Free-space terabit optical interconnects”, *Journal of Lightwave Technology*, vol. 40, no. 5, pp. 1519–1526, 2022. DOI: 10.1109/JLT.2021.3133070.

[3] K. M. M. Binkai, S. Koshikawa, T. Yoshida, H. Sano, Y. Konishi, and N. Suzuki, “Field demonstration of real-time 14 tb/s 220 m fso transmission with class 1 eye-safe 9-aperture transmitter”, in *2021 Optical Fiber Conference (OFC)*, IEEE, Jun. 2021.

[4] F. P. Guiomar, M. A. Fernandes, J. L. Nascimento, V. A. Moreira Rodrigues, and P. P. Monteiro, “Coherent free-space optical communications: Opportunities and challenges”, *Journal of Lightwave Technology*, pp. 1–1, 2022. DOI: 10.1109/JLT.2022.3164736.

[5] S. L. Jansen, D. van den Borne, and M. Kuschnerov, “Advances in modulation formats for fiber-optic transmission systems”, in *CLEO: 2011 - Laser Science to Photonic Applications*, 2011, pp. 1–2. DOI: 10.1364/CLEO_SI.2011.CWJ1.

[6] A. Alvarado, T. Fehenberger, B. Chen, and F. M. J. Willems, “Achievable information rates for fiber optics: Applications and computations”, *Journal of Lightwave Technology*, vol. 36, no. 2, pp. 424–439, 2018. DOI: 10.1109/JLT.2017.2786351.

[7] IEC, “IEC 60825-1:2014, Safety of laser products - Part 1: Equipment classification and requirements”, International Electrotechnical Commission, Tech. Rep.

[8] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical wireless communications: system and channel modelling with Matlab®*. CRC press, 2019.

[9] J. Cho, L. Schmalen, and P. J. Winzer, “Normalized generalized mutual information as a forward error correction threshold for probabilistically shaped qam”, in *2017 European Conference on Optical Communication (ECOC)*, 2017, pp. 1–3. DOI: 10.1109/ECOC.2017.8345872.