Tbit/s Single Channel 53 km Free-Space Optical Transmission - Assessing the Feasibility of Optical GEO-Satellite Feeder Links

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Abstract *A 1 Tbit/s 53km single channel free-space optical (FSO) link is demonstrated. High bandwidth, high order modulation formats and advanced adaptive optics are utilized. We show that the absence of a nonlinear-Shannon limit in combination with adaptive optics enables record data-transmission with low link failures. ©2022 The Author(s)*

Introduction

Telecom GEO-satellites are becoming one of the pillars of the telecommunication infrastructure, especially for hard-to-reach and underserved areas. Satellites based on optical feeder links are suitable for this, as their deployment are expected to be less expensive, offering a much larger bandwidth, while the spectrum is less regulated than satellite solutions based on RF counterparts [1-3].

Recently, several outdoor demonstrations showed the viability of high-capacity free space optical (FSO) links at short to medium distances. A single channel employing dual polarized (DP) probabilistically shaped 64QAM and a tip-tilt correction provided a line rate of 920 Gbit/s at 42 m [4] and a line rate of 1 Tbit/s over 3 m [5]. Multiplexing 40 on-off keying (OOK) channels on different wavelengths and a fine-steering mirror (FSM), a 10.45 km 1.72 Tbit/s link, intended to prepare ground to GEO links, was shown under turbulence conditions [1]. By using 54 channels, dual polarized 16QAM and FSM, the line rate of the same 10.45 km link was increased to 13.16Tbit/s [6]. However, to realistically mimic a GEO link, single channel and oblique long-distance transmission at highest capacity is required and the relevant factors enabling high capacity need to be clarified.

In this paper, we demonstrate a single channel FSO link with a capacity of 1 Tbit/s over 53 km between the Jungfraujoch High-Altitude Research Station (HFSJG) at 3700 m above sea-level in the Swiss alps and the Zimmerwald Observatory (ZO) near the city of Bern at 895 m altitude. This location poses particularly challenging channel conditions related to long distance and turbulence conditions on complex terrain, which includes mountains, lakes, and lowlands near Bern. To reach 1 Tbit/s, the link employs a dual polarized 84 GBd 64QAM signal, while atmospheric turbulences is mitigated by adaptive optics (AO). We also show that in a FSO channel, high-order modulation format links might be more advangeous, but AO is essential to ensure a minimum failure below the FEC threshold. To the best of our knowledge, this FSO demonstration is the highest capacity over the longest range on a single wavelength.

Outdoor Demonstration Setup

Fig. 1(a) shows the outdoor demonstration setup and (b) a sitemap of the 53 km FSO link between HFSJG and ZO. The elevation difference between both locations is around 2800 m.

At the Jungfraujoch (HFSJG), the generated digital signals from the transmitter's digital signal processing (Tx DSP) are converted to 4 electrical signals using a 128 GSa/s arbitrary waveform generator (AWG) having a high analog bandwidth of 65 GHz. The Tx DSP only performs a root-raise-cosine pulse shaping. The electrical signals are then amplified by four 55 GHz driver amplifiers (DAs) prior to a 38 GHz dual-polarized IQ-modulator that a C-band tuneable laser source (TLS). The optical signal is then amplified using an EDFA and a bandpass filter. Afterwards, the signal is split for monitoring via an Optical Spectrum Analyzer (OSA). An optical equalizer

This work was supported by the H2020-SPACE-VERTIGO project from the European Union's Horizon 2020 research and innovation program under grant agreement No. 822030. This is the accepted version of an article submitted to an IEEE conference. Posting of accepted versions is permitted under IEEE sharing policies.

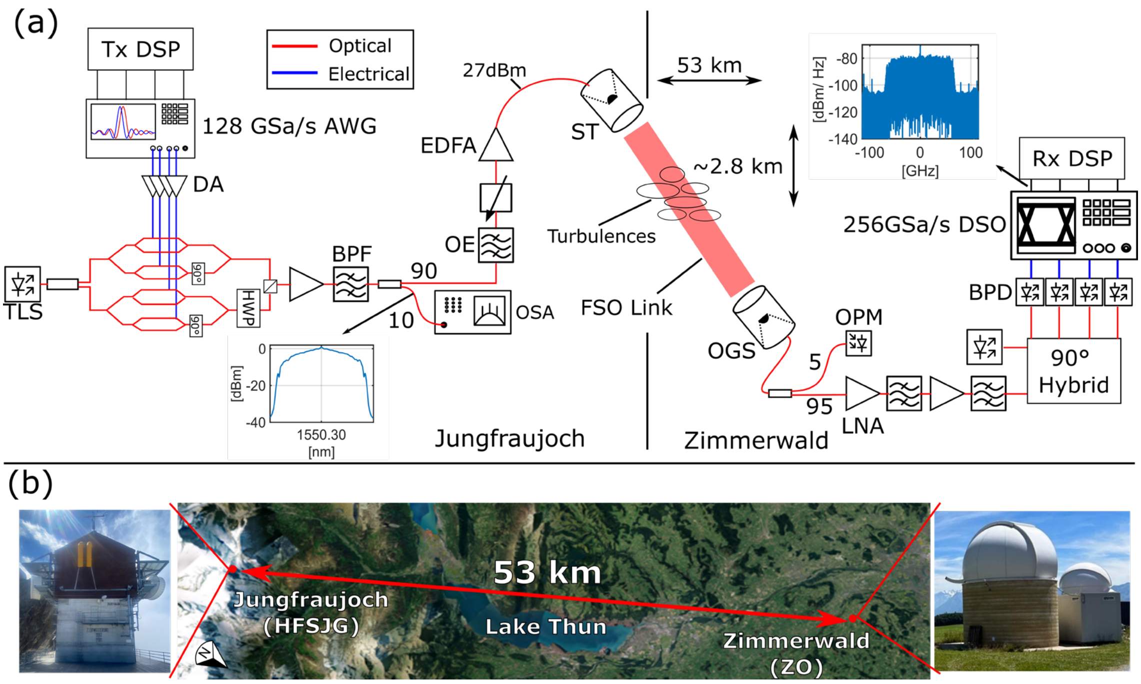

Fig. 1: FSO link with demonstration setup and sitemap. (a) Experimental setup with insets for the optical spectrum and the received spectrum. (b) Map and site plans of the 53 km free space optical link between Jungfraujoch High Altitude Research Station (HFSJG) and Zimmerwald Observatory (ZO). Map taken from map.geo.admin.ch

(OE) is used to compensate for the limited bandwidth of the modulator by flattening the spectrum of the optical signal, see insets of Fig. 1(a). This improves the SNR of the high bandwidth signal by 1 dB. A final amplification boosts the signal to 27 dBm. The high-power signal is then collimated and transmitted through a 4.2 cm diameter sub-aperture of a 20 cm aperture telescope at the space terminal (ST) to the ZO, 53 km away and around 2800 m down from HFSJG.

At the ZO the beam is received using the FEEDELIO optical ground station (OGS) that consists of a 35 cm aperture telescope and an AO system developed for bidirectional optical links [7, 8]. The AO consists of a deformable mirror, an 8x8 sub-apertures Shack-Hartmann wavefront sensor and a real-time controller running at a speed of 1.5 kHz. This is sufficient since the coherent time of the channel is assumed to be a few milliseconds. An optical power meter monitors a small part of the received signal to track the received power over time, while most of the signal goes to a coherent receiver. Prior to the 90°-hybrid, the signal undergoes a 2-stage amplification; one with a low noise amplifier (LNA) and another with an EDFA. After the 90° hybrid, four 70 GHz balanced photodiodes (BPDs) are used to retrieve the 4 electrical signals. They are then digitized using a 256 GSa/s digital storage oscilloscope (DSO) having an analog bandwidth of 110 GHz. The DSO records 16 µs of the waveform where the channel is assumed to be constant. It is then followed by an offline DSP. The offline DSP consists of a matched filter, a timing recovery, a 2x2 polarization demultiplexing filter, a carrier recovery, a phase recovery and finally a T/2-spaced feed forward equalizer.

Results and Discussion

Fig. 2 shows the line rate (dashed lines) and highest achievable net rate (solid lines) as a function of symbol rate and modulation format. Line rates of 1 Tb/s are achieved for both 16 and 64QAM. However, the 64QAM have higher net rates of 941 Gb/s. The line rates are obtained by multiplication of the symbol-rate and $\log_2 M$, where M is the number of symbols within the modulation format, while the net rates are calculated with generalized mutual information (GMI).

The results in Fig. 2 summarize the best results from the demonstration. The best results

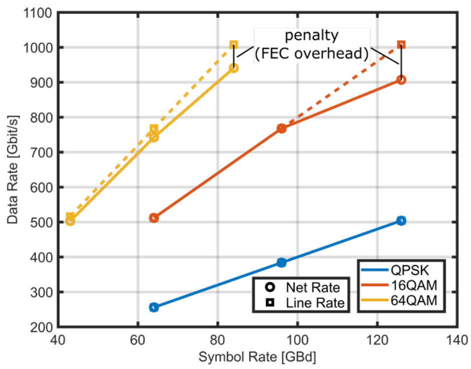

Fig. 2: Line rate (dashed) and net-rate (solid) as a function of symbol rate and modulation format

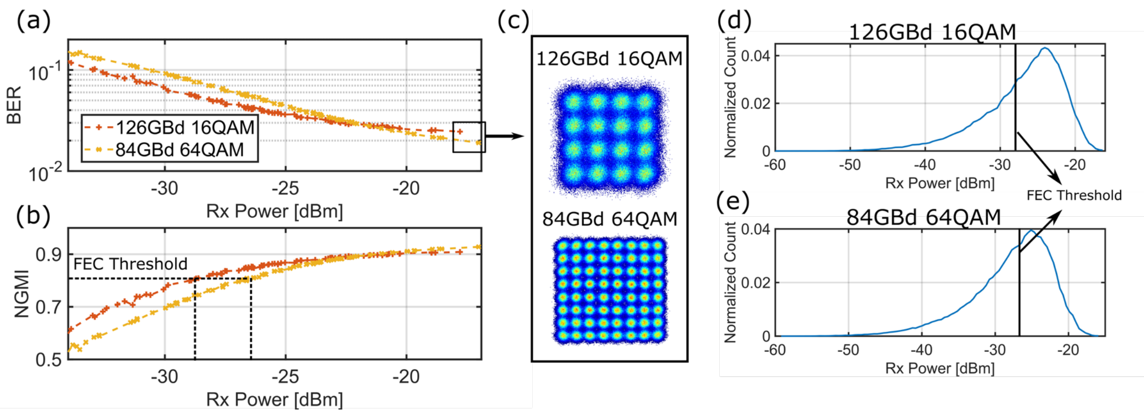

Fig. 3: (a) Average BER and (b) Average NGMI as a function of received power for DP 126 GBd 16QAM and DP 84 GBd 64QAM. (c) Best constellation diagram for one of the polarizations of both 126 GBd 16QAM and 84GBd 64QAM. Received power distribution for (d) 126 GBd 16QAM and (e) 84 GBd 64QAM.

have been obtained with high received powers. The 64QAM signal outperforms the 16QAM signal because the latter is limited at high-speed by the 38 GHz IQ-modulator. Unlike in fiber transmission, where high powers are penalized by the nonlinear Shannon limit, the FSO link can accommodate high power.

To elaborate further, the average BER and average normalized GMI (NGMI) of the 126 GBd 16QAM signal and 84GBd 64QAM signals are plotted in Fig. 3(a) and (b). The average of both polarizations for the same measurement points are taken. At low powers, the noise of the system is the main limitation so that 16QAM is better. As the received power increases, the relatively small bandwidth of the system becomes a limiting factor and due to lower bandwidth requirements, the 64QAM signal outperforms the 16QAM signal. In Fig. 3(b) we also mark the NGMI threshold for the FEC code-rate of 0.7519. It shows the FEC rate for a concatenated tail-biting SC-LDPC code and a BCH code [9]. Based on the power threshold and received power distribution in Fig. 3(d) and (e), 45.1% of the received power is above the power threshold for the 64QAM signal while it is 69.47% for the 16QAM signal. Therefore, the 126 GBd 16QAM signal is more robust to power fluctuations of a FSO channel. To increase the robustness of the link, one can adapt the rate by changing both the symbol rate and modulation format during transmission depending on the channel condition [10]. It should be noted that this demonstration represents a worst-case FSO channel scenario for GEO satellite applications since the oblique line of sight always remains close to ground [11].

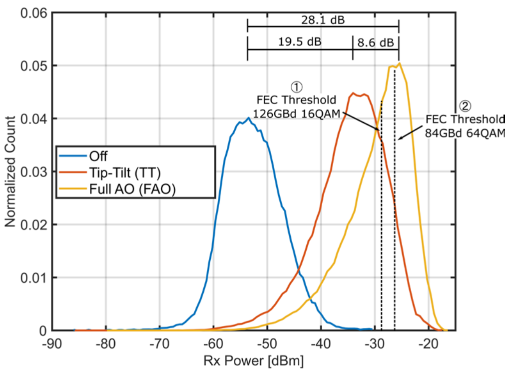

Fig. 4: Comparison of the received power distribution for 3 different modes namely, Off, tip-tilt correction (TT) and full adaptive optics correction (FAO)

Finally, we discuss the impact of AO onto the link. Fig. 4 shows the received power distribution for different AO configurations, namely without correction (Off), with tip-and-tilt correction (TT), and with full AO correction (FAO). The measurements were performed at other times than those taken in Fig. 3, but under similar atmospheric turbulence conditions. We show that the received power distribution improves by 19.5 dB when TT is used while it increases by 28.1 dB when FAO is used instead. We also mark the FEC threshold for 126 GBd 16QAM ① and 84 GBd 64QAM ② in Fig. 4. It is shown that no power value is above FEC-thresholds when the AO is off. In contrast, 19.15% of the received powers are above ① and 7.22% are above ② when TT is used while 54.38% are above ① and 35.53% are above ② when FW is used. Therefore, full wavefront correction is required to achieve a line rate of 1 Tbit/s with minimal failure.

Conclusion

In this work, we demonstrate for the first time a 53 km FSO link at a record line rate of 1 Tb/s. The link employs a dual polarized 84 GBd 64QAM and an adaptive optics system on the receiver side.

Acknowledgements

We thank Jungfrau Railways, HFSJG, AIUB, skw logistics, G. Tamburello, & M. Eppenberger for support. We thank ESA for FEEDELIO (N°4000120300/17/NL/PS). The project is funded by the H2020 EU Project VERTIGO (822030).

References

[1] J. Poliak, R. M. Calvo, and F. Rein, "Demonstration of 1.72 Tbit/s Optical Data Transmission Under Worst-Case Turbulence Conditions for Ground-to-Geostationary Satellite Communications," *IEEE Communications Letters,* vol. 22, no. 9, pp. 1818-1821, 2018, doi:https://doi.org/10.1109/LCOMM.2018.2847628.

[2] A. Le Kernec, L. Canuet, A. Maho, M. Sotom, D. Matter, L. Francou, J. Edmunds, M. Welch, E. Kehayas, N. Perlot, M. Krzyzek, P. Anagnostis, J. Leuthold, Y. Horst, J. Bourderionnet, A. Brignon, E. Lallier, V. Billault, L. Leviandier, J. M. Conan, N. Védrenne, C. B. Lim, A. Montmerle-Bonnefois, C. Petit, L. Stampoulidis, M. Fehrenz, and T. Lehnigk-Emden, "The H2020 VERTIGO project towards tbit/s optical feeder links," in *Proc.SPIE*, 2021, vol. 11852, p. 1185217, doi:https://doi.org/10.1117/12.2599229.

[3] M. Yasushi, F. Tetsuharu, K.-o. Toshihiro, K. Hiroo, R. K. Dimitar, C.-C. Alberto, T. Hideki, S. Yoshihiko, T. Phuc Viet, S. Kenji, K. Yoshisada, and T. Morio, "Design status of the development for a GEO-to-ground optical feeder link, HICALI," in *Proc.SPIE*, 2018, vol. 10524, p. 105240F, doi:https://doi.org/10.1117/12.2291881.

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

[5] M. A. Fernandes, P. P. Monteiro, and F. P. Guiomar, "Single-Wavelength Terabit FSO Channel for Datacenter Interconnects Enabled by Adaptive PCS," in *Optical Fiber Communication Conference (OFC) 2021*, 2021, p. Th5E.3, doi:https://doi.org/10.1364/OFC.2021.Th5E.3.

[6] A. Dochhan, J. Poliak, J. Surof, M. Richerzhagen, H. F. Kelemu, and R. M. Calvo, "13.16 Tbit/s Free-space Optical Transmission over 10.45 km for Geostationary Satellite Feeder-links," in *Photonic Networks; 20th ITG-Symposium*, 2019, pp. 1-3.

[7] A. Montmerle Bonnefois, J.-M. Conan, C. Petit, C. Lim, V. Michau, S. Meimon, P. Perrault, F. Mendez, B. Fleury, J. Montri, and N. Védrenne, "Adaptive optics pre-compensation for GEO feeder links: the FEEDELIO experiment," Proc. SPIE 11180, *International Conference on Space Optics*, 2018, 2019, doi:https://doi.org/10.1117/12.2536003.

[8] N. Védrenne, A. Montmerle Bonnefois, C. B. Lim, C. Petit, J. F. Sauvage, S. Meimon, P. Perrault, F. Mendez, B. Fleury, J. Montri, J.-M. Conan, V. Michau, Z. Sodnik, and C. Voland, "First Experimental Demonstration of Adaptive Optics Pre-Compensation for GEO Feeder Links in a Relevant Environment," in *2019 IEEE International Conference on Space Optical Systems and Applications*, 2019, pp. 1-5, doi:https://doi.org/10.1109/ICSOS45490.2019.8978970.

[9] Q. Hu, R. Borkowski, Y. Lefevre, J. Cho, F. Buchali, R. Bonk, K. Schuh, E. D. Leo, P. Habegger, M. Destraz, N. D. Medico, H. Duran, V. Tedaldi, C. Funck, Y. Fedoryshyn, J. Leuthold, W. Heni, B. Baeuerle, and C. Hoessbacher, "Ultrahigh-Net-Bitrate 363 Gbit/s PAM-8 and 279 Gbit/s Polybinary Optical Transmission Using Plasmonic Mach-Zehnder Modulator," *Journal of Lightwave Technology,* vol. 40, no. 10, pp. 3338-3346, 2022, doi:https://doi.org/10.1109/JLT.2022.3172246.

[10] Y. Tang, M. Brandt-Pearce, and S. G. Wilson, "Link Adaptation for Throughput Optimization of Parallel Channels with Application to Hybrid FSO/RF Systems," *IEEE Transactions on Communications,* vol. 60, no. 9, pp. 2723-2732, 2012, doi:https://doi.org/10.1109/TCOMM.2012.061412.100460.

[11] S. Basu, J. Osborn, P. He, and A. W. DeMarco, "Mesoscale modelling of optical turbulence in the atmosphere: the need for ultrahigh vertical grid resolution," *Monthly Notices of the Royal Astronomical Society,* vol. 497, no. 2, pp. 2302-2308, 2020, doi:https://doi.org/10.1093/mnras/staa2010.