689 Gbps Single-Wavelength Mode-Division Multiplexing Free-Space Optical Transmission in Strong Turbulence

Yiming Li(1), Zhaozhong Chen(2), David Benton(1), Mohammed Patel(1), Martin Lavery(2), Andrew Ellis(1)

(1) Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, UK,
(2) James Watt School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK,
phyczz@gmail.com

Abstract *By employing successive interference cancellation decoder and redundant receive channels, we achieved a record-high line rate of 689 Gbit/s, channel number of 10, and net spectral efficiency of 13.9 bit/s/Hz in single-wavelength mode-division multiplexing free-space optical transmission under strong turbulence. ©2023 The Authors*

Introduction

Free-space optical (FSO) communications can provide ultra-fast data rate[1], ultra-long link distance[2], robustness to electromagnetic interference[3], and is a promising technology for high-speed wireless transmissions. To further increase the link capacity, different multiplexing technologies have been considered in FSO systems, including polarisation multiplexing[4], dense wavelength-division multiplexing (DWDM)[5], and mode-division multiplexing (MDM)[6]. Unlike the other approaches, the MDM technology can also enhance turbulence resiliency without adaptive optics (AO)[7], making it a promising technology for high-capacity FSO transmissions with a much faster adaption speed for turbulence.

However, the turbulence resiliency of MDM technology was mostly observed in single-input multiple-output (SIMO) systems[7],[8]. In MDM multiple-input multiple-output (MIMO) systems, the AO has been the major approach to combat turbulence[9],[10]. However, a single AO can not fully compensate for strong turbulence, where both phase and amplitude distortion exists, and a considerable amount of power may fall outside the receive aperture. Therefore, previous MDM MIMO transmissions mainly focused on weak turbulence[9], and severe performance degradation has been observed in strong turbulence[10].

In this paper, we demonstrated for the first time a digital signal processing (DSP)-based approach to simultaneously increase transmit data rate and enhance turbulence resiliency in strong turbulent channels. By employing advanced successive interference cancellation (SIC) MIMO decoder and redundant receive channels, we demonstrated an MDM MIMO FSO transmission with a record-high line rate of 689.2 Gbit/s, independent channel number of 10, and net spectral efficiency of 13.9 bit/s/Hz in strong turbulent channels, indicating the feasibility of high-capacity MDM MIMO transmission in long-haul FSO links.

Methods and Experimental Setup

Our experimental setup is shown in Fig. 1. At the transmitter, a Ciena WaveLogic 3 transponder was employed to generate a 34.46 GBaud dual-polarization quadrature phase shift keying (DP-QPSK) signal at 1550.12 nm by using the 39.385 GSa/s onboard arbitrary waveform generator (AWG). The data sequence had a frame length of 20,000 symbols. Each frame had 1,680 symbols as a training sequence and 1 pilot symbol for every 9 data symbols. The training symbols and pilots were generated from random QPSK symbols and the data symbols were generated from a PRBS-15 pseudorandom binary sequence (PRBS). The signals were shaped by a root-raised cosine (RRC) filter with a roll-off factor of 0.1 and then amplified by a booster erbium-doped fibre amplifier (EDFA). To emulate independent receivers, an acousto-optic modulator (AOM) was employed to enable the time-division multiplexing (TDM) receiver[6]. Here a 20 µs signal burst was generated in a period of 160 µs (Fig. 1(a)). To emulate independent transmitters, the burst signals were split into 5 copies and delayed by variable fibre delay lines (FDLs) with lengths of 0, 280, 560, 840, and 1120 symbols to generate decorrelated signals for different modes. The last mode was intentionally left unconnected due to its significantly higher loss. Afterwards, 5 variable optical attenuators (VOAs) were employed to compensate for the mode-dependent loss in the transmitter mode-selective photonic lantern (MSPL). Finally, the MDM signals were coupled into a free-space turbulence emulator.

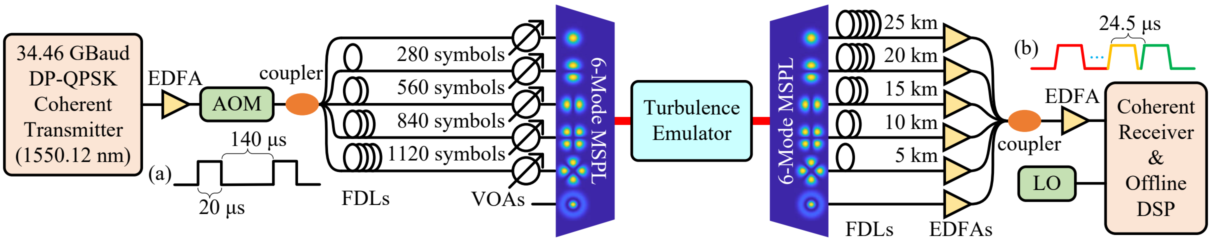

Fig. 1: The experimental setup. DP-QPSK: dual-polarization quadrature phase shift keying; EDFA: erbium-doped fibre amplifier; AOM: acousto-optic modulator; FDLs: fibre delay lines; VOAs: variable optical attenuators; MSPL: mode-selective photonic lantern; LO: local oscillator; DSP: digital signal processing. (a) Signal burst after AOM; (b) TDM signal after receiver coupler.

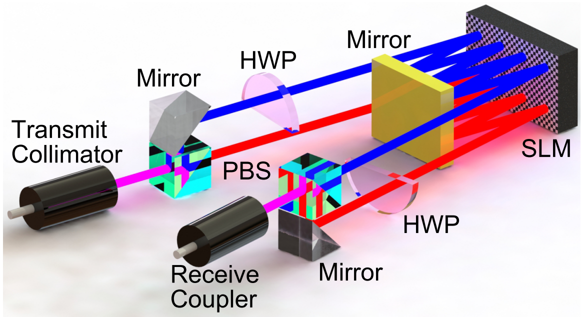

Fig. 2: Turbulence emulator based on polarisation multiplexed multi-plane light conversion. PBS: polarising beam splitter; HWP: half-wave plate; SLM: spatial light modulator.

The details of the turbulence emulator in Fig. 1 are shown in Fig. 2. Here we employed the polarisation multiplexed multi-plane light conversion (MPLC) technology to emulate distributed strong turbulent channels which can not be accurately described by a single phase plate[11],[12]. In this emulator, the MDM signals were coupled from a few-mode fibre (FMF) into free-space by using a transmit collimator with a focal length of 10 mm. A polarising beam splitter (PBS) was placed after the collimator to split both polarisations of the beam, the upper beam was reflected by a mirror and passed through a D-shaped half-wave plate (HWP), rotating the polarisation by $90°$ for the polarisation-sensitive spatial light modulator (SLM). Both the upper and lower beams were reflected four times on the 1920×1200 SLM by employing a square mirror. Here turbulence patterns were generated from the von Kármán spectrum, mapped onto the SLM using the MPLC method[13], and duplicated for the upper and the lower beam, respectively. Afterwards, the lower beam was rotated by $90°$ by another D-shaped HWP and then reflected by another mirror. The upper and lower beams were then composed by another PBS and coupled into a receive coupler with a focal length of 10 mm.

To illustrate the polarisation insensitivity of our proposed turbulence emulator, Fig. 3 depicts a typical beam profile after the turbulence emulator for (a) the upper beam, (b) the lower beam, and

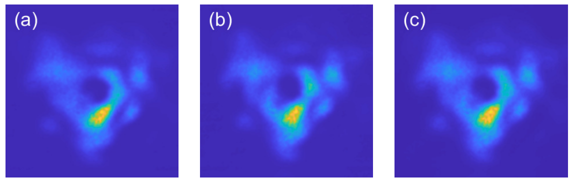

Fig. 3: A typical beam profile after the turbulence emulator. (a) The upper beam; (b) the lower beam; (c) both beams.

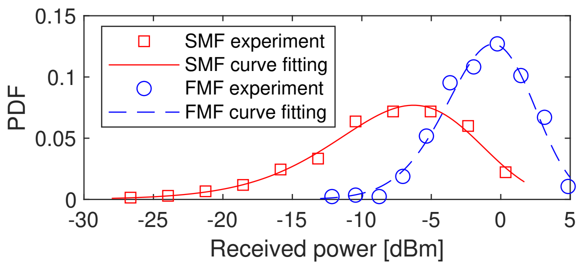

Fig. 4: Received power distribution after the turbulence emulator. The Gamma-Gamma model was employed in curve fitting. PDF: probability density function.

(c) both beams with a Gaussian beam coupled into the transmit collimator and using a phosphor-coating beam-profiling camera in place of the receive coupler. By blocking the beam paths with an opaque card, all the beam profiles can be seen to show good similarity.

We also tested the statistical distribution of the received power after the turbulence emulator. To compare the received power difference using different kinds of fibres, we connected a single-mode fibre (SMF) and an FMF to the receive coupler, respectively. To obtain a fair comparison, an SMF was always connected to the transmit collimator. As shown in Fig. 4, both setups were well-fitted with the curve-fitting results using the Gamma-Gamma model. When compared with the SMF setup, the FMF setup provided a larger effective aperture and a larger number of supported modes[14]. Therefore, it showed a significant improvement in both the average received power (increased from -5.00 dBm to -0.02 dBm) and the Rytov variance (σ_R^2 reduced from 9.01 to 1.45, both setups were associated with strong turbulence). These results also indicated the potential to exploit diversity gain by employing MDM.

At the receiver, another MSPL was employed

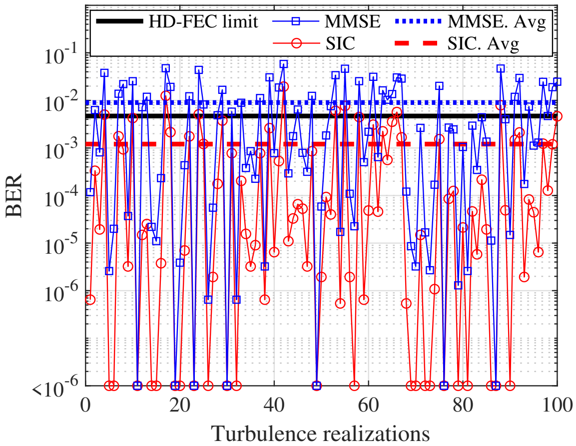

Fig. 5: The BER performance of the 10×12 MIMO system under 100 independent strong turbulence realizations. Avg: average BER.

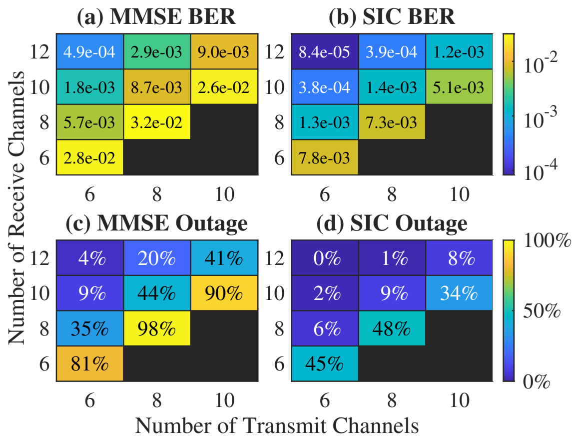

Fig. 6: The average BER and outage probability of MIMO systems with different numbers of transmit and receive channels under 100 independent strong turbulence realizations. (a) Average BER with MMSE decoder; (b) average BER with SIC decoder; (c) outage probability with MMSE decoder; (d) outage probability with SIC decoder.

to decompose the received MDM signal from the turbulence emulator. Afterwards, the 6 decomposed signals were delayed by the 25 km, 20 km, 15 km, 10 km, 5 km, and 0 km FDLs, generating ˜24.5 µs delay between adjacent modes, which was slightly longer than the signal burst, to enable the TDM receiver[6]. The TDM signals were amplified by 6 independent EDFAs, coupled into one SMF, and amplified by another EDFA (Fig. 1(b)). Finally, the TDM signals were received by a coherent receiver with a 23 GHz, 50 GSa/s oscilloscope and demodulated by an offline DSP.

Experimental results

As shown in Fig. 5, We tested 100 independent strong turbulence realizations to compare the performance of different MIMO decoding algorithms in an MDM FSO system. Here all 10 transmit channels (5 modes $\times$ 2 polarisations) and 12 receive channels (6 modes $\times$ 2 polarisations) in Fig. 1 were exploited. In this test, the conventional minimum mean square error (MMSE) MIMO decoder had an average bit error rate (BER) performance of 9.01×10^{-3}. To further improve the BER, we tested the SIC MIMO decoder[15], obtaining a BER of 1.21×10^{-3}, well below the 6.25% hard-decision forward error correction (HD-FEC) limit of 4.7×10^{-3}[16]. If we consider an outage when the BER is larger than the HD-FEC limit, the outage probability was reduced from 41% (the MMSE decoder) to 8% (the SIC decoder), indicating a significantly better strong turbulence resiliency by employing the SIC decoder.

To validate the BER and outage performance improvement by employing redundant receive channels, Fig. 6 depicts the average BER and outage probability of MIMO systems with different numbers of transmit channels (N_t) and receive channels (N_r). This was realized by only connecting the lowest $N_t/2$ transmit modes and the lowest $N_r/2$ receive modes. As shown in Fig. 6, the BER and outage performance can be improved by either increasing N_r or decreasing N_t. Moreover, the SIC decoder always outperformed the MMSE decoder in the same system setup.

Conclusions

In this paper, we have shown that the SIC MIMO decoder and redundant receive channels can provide enhanced resiliency to strong turbulence, leading to a better BER and outage performance. By employing such DSP technologies, we achieved a record-high line rate of 689.2 Gbit/s and independent channel number of 10 in single-wavelength MDM MIMO FSO communications with strong turbulence, which was emulated by an MPLC-based turbulence emulator. Considering the 8.4% training sequence, 10% pilot rate, 6.25% HD-FEC cost, and 0.1 roll-off factor, a record-high net spectral efficiency of 13.9 bit/s/Hz was achieved in strong turbulent links. These results indicate the feasibility of employing the MDM technology for high-capacity long-haul FSO transmissions in strong turbulent links.

Acknowledgements

This research was supported by EPSRC (Grants EP/T009047/1, EP/T009012/1, and EP/S016171/1), H2020 Marie Skłodowska-Curie Actions (713694), and H2020 Future and Emerging Technologies Open grant agreement (829116). We thank Ciena and Dr Charles Laperle for kindly providing the WaveLogic 3 transponder used in our experiments.

References

[1] 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.

[2] R. Lange, B. Smutny, B. Wandernoth, R. Czichy, and D. Giggenbach, "142 km, 5.625 Gbps free-space optical link based on homodyne BPSK modulation", in *Free-Space Laser Communication Technologies XVIII*, San Jose, USA, 2006, 61050A. DOI: 10.1117/12.673749.

[3] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: a communication theory perspective", *IEEE Communications Surveys & Tutorials*, vol. 16, pp. 2231–2258, 4 2014, ISSN: 1553-877X. DOI: 10.1109/COMST.2014.2329501.

[4] N. Cvijetic, D. Qian, J. Yu, Y.-K. Huang, and T. Wang, "Polarization-multiplexed optical wireless transmission with coherent detection", *Journal of Lightwave Technology*, vol. 28, no. 8, pp. 1218–1227, 2010. DOI: 10.1109/JLT.2010.2044017.

[5] 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: 10.1109/LCOMM.2018.2847628.

[6] Y. Li, Z. Chen, Z. Hu, *et al.*, "Enhanced Atmospheric Turbulence Resiliency With Successive Interference Cancellation DSP in Mode Division Multiplexing Free-Space Optical Links", *Journal of Lightwave Technology*, vol. 40, no. 24, pp. 7769–7778, 2022. DOI: 10.1109/JLT.2022.3209092.

[7] N. K. Fontaine, R. Ryf, Y. Zhang, *et al.*, "Digital turbulence compensation of free space optical link with multimode optical amplifier", in *45th European Conference on Optical Communication (ECOC 2019)*, IET, Dublin, Ireland, 2019, pp. 1–4. DOI: 10.1049/cp.2019.1015.

[8] R. Zhang, N. Hu, H. Zhou, *et al.*, "Turbulence-resilient pilot-assisted self-coherent free-space optical communications using automatic optoelectronic mixing of many modes", *Nature Photonics*, vol. 15, no. 10, pp. 743–750, 2021. DOI: 10.1038/s41566-021-00877-w.

[9] N. Hu, H. Song, R. Zhang, *et al.*, "Demonstration of turbulence mitigation in a 200-Gbit/s orbital-angular-momentum multiplexed free-space optical link using simple power measurements for determining the modal crosstalk matrix", *Optics Letters*, vol. 47, no. 14, pp. 3539–3542, 2022. DOI: 10.1364/OL.464217.

[10] Z. Qu and I. B. Djordjevic, "500 Gb/s free-space optical transmission over strong atmospheric turbulence channels", *Optics Letters*, vol. 41, no. 14, pp. 3285–3288, 2016. DOI: 10.1364/OL.41.003285.

[11] N. K. Fontaine, R. Ryf, H. Chen, D. T. Neilson, K. Kim, and J. Carpenter, "Laguerre-Gaussian mode sorter", *Nature communications*, vol. 10, no. 1, p. 1865, 2019. DOI: 10.1038/s41467-019-09840-4.

[12] M. P. Lavery, "Vortex instability in turbulent free-space propagation", *New Journal of Physics*, vol. 20, no. 4, p. 043 023, 2018. DOI: 10.1088/1367-2630/aaae9e.

[13] R. Alsaigh, N. Fontaine, and M. P. Lavery, "Bulk optical turbulence mitigation using dynamic multiple plane light conversion", in *Complex Light and Optical Forces XVII*, SPIE, San Francisco, United States, 2023, PC124360H. DOI: 10.1117/12.2668730.

[14] D. M. Benton, A. D. Ellis, Y. Li, and Z. Hu, "Emulating atmospheric turbulence effects on a micro-mirror array: assessing the DMD for use with free-space-to-fibre optical connections", *Engineering Research Express*, vol. 4, no. 4, p. 045 004, 2022. DOI: 10.1088/2631-8695/ac7d49.

[15] D. Tse and P. Viswanath, *Fundamentals of wireless communication*. New York, USA: Cambridge University Press, 2005. DOI: 10.1017/CBO9780511807213.

[16] L. M. Zhang and F. R. Kschischang, "Staircase codes with 6% to 33% overhead", *Journal of Lightwave Technology*, vol. 32, no. 10, pp. 1999–2002, 2014. DOI: 10.1109/JLT.2014.2316732.