Experimental Investigation of Mode Diversity Reception Using an Optical Turbulence Generator and Digital Holography

Experimental Investigation of Mode Diversity Reception Using an Optical Turbulence Generator and Digital Holography

Vincent van Vliet(*), Menno van den Hout, Sjoerd van der Heide, and Chigo Okonkwo

High-Capacity Optical Transmission Laboratory, Electro-Optical Communications Group,
Eindhoven University of Technology, the Netherlands (*) v.v.vliet@student.tue.nl

Abstract *Mode diversity reception is experimentally investigated using an optical turbulence generator, off-axis digital holography, and digital demultiplexing. The results confirm improved fibre coupling efficiency when receiving the optical field using a multi-mode fibre instead of a single-mode fibre under turbulent conditions, specifically beam wander. The coupling loss is reduced by receiving additional modes.*

Introduction

Free-space optical (FSO) communications is considered a promising alternative to radio frequency based communications because of its improved bandwidth, capacity, security against eavesdropping, equipment size, weight, and power consumption. Applications which can benefit from this include backhaul for wireless networks, last mile access, and space communications[1].

The usage of high-quality, commercially available fibre-optic components can catalyse the development of FSO communication systems. However, the plethora of these components is single-mode fibre (SMF)-based. It has been shown that free-space-to-SMF coupling severely suffers from turbulent conditions[2]. The resulting signal fades cause degradation of the link quality. Recently, theoretical models[3],[4], simulations[5],[6], and experiments[5],[7]–[10] have demonstrated the potential of mode diversity reception as a technique to improve the fibre coupling efficiency. Here, additional spatial modes are received using a multi-mode fibre (MMF), after which a de-multiplexer and coherent recombination provide compatibility with SMF-based components. As turbulence induces higher-order aberrations, accommodation of higher-order modes improves the coupling efficiency as compared to single mode. Before-mentioned experiments were performed using either static phase screens or uncharacterised turbulence.

In this work, we evaluate the performance of mode diversity reception using naturally evolving turbulence produced in an optical turbulence generator (OTG), an off-axis digital holography (DH) measurement setup, and digital demultiplexing. The main induced turbulent effect is beam wander. It is shown that the coupling loss statistics are improved when receiving additional modes as compared to only the fundamental mode. The coupling loss is reduced by 1.15 dB for an outage probability of 0.1 % by receiving the first 2 mode groups instead of only the fundamental mode.

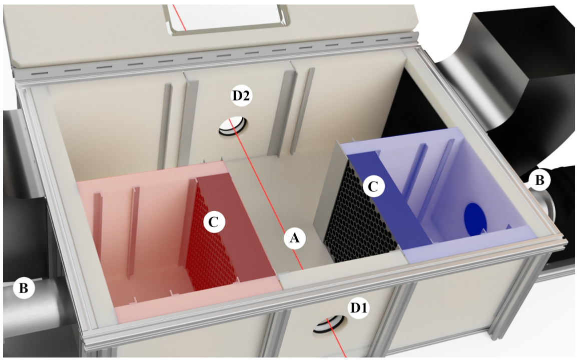

Fig. 1: Design of the OTG used in this work[11]. (A): mixing chamber, (B): (hot-)air blowers, (C): metal mesh to laminarise flow, (D1) and (D2): laser window panels.

Experimental setup

The experimental free-space optical setup is shown in Fig. 2 (left). A signal beam $\mathbf{S_{X\&Y}}$ is propagated through the OTG and captured with a camera operating at 333 fps. The signal is alternated between *x*- and *y*-polarisation every frame using a polarisation switch (PSW). $\mathbf{S_{X\&Y}}$ has a diameter of 0.88 mm after collimation. Using an off-axis DH measurement setup[12],[13], the complete optical field including amplitude and phase is measured for both polarisations. To this end, $\mathbf{S_{X\&Y}}$ is interfered with $\mathbf{R_{X,Y}}$, two orthogonally-polarised reference beams with a flat wavefront. Subsequent digital signal processing (DSP) allows for the extraction of

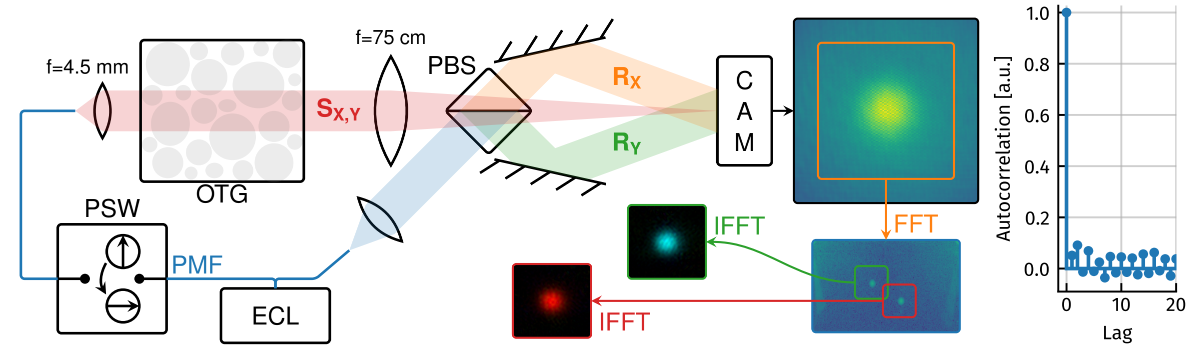

Fig. 2: (left) Experimental setup employing the OTG and optical off-axis DH setup and digital field extraction. $S_{X,Y}$: signal distorted by the OTG, R_X and R_Y: reference beams, ECL: external cavity laser, PMF: polarisation-maintaining fibre, PBS: polarisation beam splitter, (I)FFT: (inverse) fast Fourier transform. Note that $S_{X,Y}$ passes over the PBS. **(right)** Autocorrelation of beam centroid displacement in *x*-direction.

the *x*- and *y*-polarised complex fields from the interference pattern.

$S_{X\&Y}$ is distorted by turbulence in the OTG. This is a device in which turbulence is produced by mixing two air flows in a compact chamber. The temperature difference between the two flows is used to control the strength of the produced turbulence. The design of the OTG is shown in Fig. 1. Using the beam wander variance characterisation technique[14], the device is characterised for a ground-to-satellite link scenario. More information on the OTG and the characterisation process can be found in[11].

The fibre coupling is performed in the digital domain by demultiplexing the measured optical fields into target mode fields of the fibre of interest, here we use a 50 µm core diameter graded-index (GI) MMF[15]. The target modes are calculated using a numerical scalar linearly polarised (LP) mode solver. The measured optical fields are digitally scaled such that the unperturbed transmitted field couples optimally to the LP_{01} mode of the considered fibre. This is the digital equivalent of a beam expander to maximize the coupling efficiency between the LP_{01} mode of the transmitter SMF to the LP_{01} mode of the considered receiver MMF.

It is assumed that every captured frame represents an independent instance of the channel. The autocorrelation function of the beam centroid displacement in the *x*-direction is shown on the right of Fig. 2. Although the frames are not completely uncorrelated, the rapid decrease towards 0 makes our assumption valid.

Results

The complex fields of the distorted signal were measured during 30 seconds for various turbulence strengths, resulting in 10,000 frames

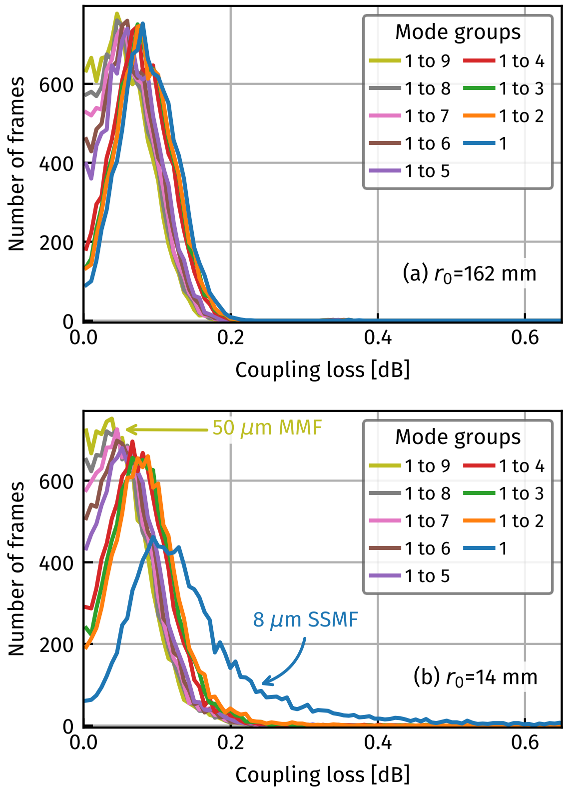

Fig. 3: Histogram of coupling loss over 10,000 frames for (a) r_0 = 162 mm and (b) r_0 = 14 mm

for each measurement. Fig. 3 shows the histogram of the resulting coupling losses after the digital demultiplexing procedure for turbulence conditions with r_0 = 162 mm (Fig. 3a) and r_0 = 14 mm (Fig. 3b), the weakest and strongest turbulence produced in the OTG, respectively. Here, r_0 is the turbulence coherence length, also known as the Fried parameter[16], which is a measure of turbulence strength in an optical path. It can be seen that for weak turbulence conditions the coupling performance of a SMF closely resembles that of a MMF. However, coupling to the SMF worsens after propagation through stronger turbulence. In that case, the

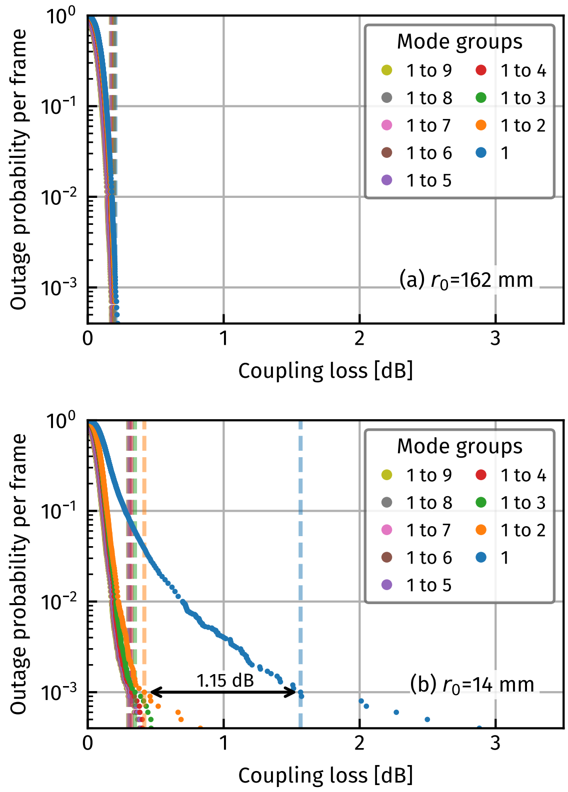

Fig. 4: Outage probability statistics from 10000 frames for (a) r_0 = 162 mm and (b) r_0 = 14 mm. The vertical lines indicate the threshold loss corresponding to an outage probability of 0.1 %.

coupling efficiency improves when the receiving fibre supports a higher number of modes.

Fig. 4 displays the corresponding outage probabilities. No performance difference can be distinguished for the weakest turbulence condition (Fig. 4a). However, a clear distinction is observed for the stronger turbulence condition (Fig. 4b). In that case, for an outage probability of 0.1 % the coupling loss is reduced by 1.15 dB when coupling into a fibre supporting three modes, as compared to the SMF.

Because the beam diameter of $\mathbf{S_{X\&Y}}$ is much smaller than r_0, the main effect induced by the turbulence is beam wander. This turbulent effect is represented by the LP_{11a} and LP_{11b} modes. Accordingly, the results show that incorporation of the second mode group clearly improves the coupling efficiency. However, consideration of the higher-order modes does not provide significant advantage because of the lack of higher-order aberrations in the optical field. It is expected that receiving higher-order modes is advantageous when these aberrations are present.

Conclusions

The coupling loss statistics of free-space-to-fibre coupling are investigated experimentally using an optical turbulence generator, off-axis digital holography, and digital demultiplexing. It was shown that mode diversity reception improves the coupling efficiency after propagation through turbulent atmosphere. Considering three modes instead of only the fundamental mode results in a reduction in coupling loss of 1.15 dB for an outage probability per frame of 0.1 %.

Future steps include the characterisation of the OTG turbulence for satellite-to-ground and horizontal FSO links and extension to a deployed field link for long-term testing in a realistic scenario. Furthermore, measurements with an increased beam diameter will provide information on the fibre coupling efficiency for fields with turbulence-induced higher-order aberrations.

Acknowledgements

Funding received from KPN-TU/e Smart Two Program, the Dutch NWO Gravitation Program (Grant Number 024.002.033) and NWO Perspectief project Optical Wireless Superhighways: Free photons.

References

[1] H. Kaushal and G. Kaddoum, ‘Optical Communication in Space: Challenges and Mitigation Techniques’, *IEEE Communications Surveys Tutorials*, vol. 19, no. 1, pp. 57–96, 2017. DOI: 10.1109/COMST.2016.2603518.

[2] Y. Dikmelik and F. M. Davidson, ‘Fiber-coupling efficiency for free-space optical communication through atmospheric turbulence’, *Appl. Opt.*, vol. 44, no. 23, pp. 4946–4952, Aug. 2005. DOI: 10.1364/AO.44.004946.

[3] X. Fan, D. Wang, J. Cheng, J. Yang, and J. Ma, ‘Few-Mode Fiber Coupling Efficiency for Free-Space Optical Communication’, *Journal of Lightwave Technology*, vol. 39, no. 6, pp. 1823–1829, 2021. DOI: 10.1109/JLT.2020.3041865.

[4] A. Fardoost, H. Wen, H. Liu, F. G. Vanani, and G. Li, ‘Optimizing free space to few-mode fiber coupling efficiency’, *Appl. Opt.*, vol. 58, no. 13, pp. D34–D38, May 2019. DOI: 10.1364/AO.58.000D34.

[5] D. Zheng, Y. Li, E. Chen, B. Li, D. Kong, W. Li, and J. Wu, ‘Free-space to few-mode-fiber coupling under atmospheric turbulence’, *Opt. Express*, vol. 24, no. 16, pp. 18 739–18 744, Oct. 2016. DOI: 10.1364/OE.24.018739.

[6] J. Krimmer, C. Füllner, W. Freude, C. Koos, and S. Randel, ‘Statistical Analysis of Free-Space-to-Fiber Coupling Under Atmospheric Turbulence’, in *OSA Advanced Photonics Congress (AP) 2020 (IPR, NP, NOMA, Networks, PVLED, PSC, SPPCom, SOF)*, Optica Publishing Group, 2020, NeM4B.3. DOI: 10.1364/NETWORKS.2020.NeM4B.3.

[7] N. K. Fontaine, R. Ryf, Y. Zhang, J. C. Alvarado-Zacarias, S. van der Heide, M. Mazur, H. Huang, H. Chen, R. Amezcua-Correa, G. Li, M. Capuzzo, R. Kopf, A. Tate, H. Safar, C. Bolle, D. T. Neilson, E. Burrows, K. Kim, M. Bigot-Astruc, F. Achten, P. Sillard, A. Amezcua-Correa, and J. Carpenter, 'Digital turbulence compensation of free space optical link with multimode optical amplifier', *IET Conference Publications*, no. CP765, pp. 4–7, 2019. DOI: 10.1049/cp.2019.1015.

[8] M. Arikawa, 'Application of Optical Fiber Communication Technologies to Free-Space Optical Communications Under Atmospheric Turbulence', in *OSA Advanced Photonics Congress (AP) 2020 (IPR, NP, NOMA, Networks, PVLED, PSC, SPPCom, SOF)*, Optica Publishing Group, 2020, NeM4B.2. DOI: 10.1364/NETWORKS.2020.NeM4B.2.

[9] D. J. Geisler, T. M. Yarnall, M. L. Stevens, C. M. Schieler, B. S. Robinson, and S. A. Hamilton, 'Multi-aperture digital coherent combining for free-space optical communication receivers', *Optics Express*, vol. 24, no. 12, p. 12661, 2016. DOI: 10.1364/oe.24.012661.

[10] Y. Huang, H. Huang, H. Chen, J. C. Alvarado, N. K. Fontaine, M. Mazur, Q. Zhang, R. Ryf, R. Amezcua-Correa, Y. Song, Y. Li, and W. Min, 'Free-Space Optics Communications Employing Elliptical-Aperture Multimode Diversity Reception Under Anisotropic Turbulence', *Journal of Lightwave Technology*, vol. 40, no. 5, pp. 1502–1508, 2022. DOI: 10.1109/JLT.2021.3130250.

[11] V. van Vliet, 'Optical Turbulence Generator for Lab-based Experimental Studies of Atmospheric Turbulence in Vertical Optical Communication Links', 2022, MSc. thesis.

[12] S. van der Heide, B. van Esch, M. van den Hout, T. Bradley, A. M. Velazquez-Benitez, N. K. Fontaine, R. Ryf, H. Chen, M. Mazur, J. E. Antonio-López, J. C. Alvarado-Zacarias, R. Amezcua-Correa, and C. Okonkwo, 'Optical Field Characterization using Off-axis Digital Holography', in *Optical Fiber Communication Conference (OFC) 2022*, Optica Publishing Group, 2022, M3Z.6. DOI: 10.1364/OFC.2022.M3Z.6.

[13] S. van der Heide, 'Space-division Multiplexed Optical Transmission enabled by Advanced Digital Signal Processing', Ph.D. dissertation, Electrical Engineering, Apr. 2022, ch. 3, ISBN: 978-90-386-5491-1. DOI: 10.6100/2d04a1e9-15e1-40fb-8e6d-7b22444397bc.

[14] H. Kaushal *et al.*, 'Experimental study on beam wander under varying atmospheric turbulence conditions', *IEEE Photonics Technology Letters*, vol. 23, no. 22, pp. 1691–1693, 2011. DOI: 10.1109/LPT.2011.2166113.

[15] P. Sillard, D. Molin, M. Bigot-Astruc, A. Amezcua-Correa, K. de Jongh, and F. Achten, '50 µm Multimode Fibers for Mode Division Multiplexing', *J. Lightwave Technol.*, vol. 34, no. 8, pp. 1672–1677, Mar. 2016. DOI: 10.1109/JLT.2015.2507442.

[16] D. L. Fried, 'Optical Resolution Through a Randomly Inhomogeneous Medium for Very Long and Very Short Exposures', *J. Opt. Soc. Am.*, vol. 56, no. 10, pp. 1372–1379, Oct. 1966. DOI: 10.1364/JOSA.56.001372.