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

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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. © 2022 The Author(s)

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[6][7][8][9] 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.

Experimental setup

The experimental free-space optical setup is shown in Fig. 2 (left). A signal beam 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). 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, S_{X&Y} is interfered with R_{X,Y}, two orthogonally-polarised reference beams with a flat wavefront. Subsequent digital signal processing (DSP) allows for the extraction of
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\cite{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\cite{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 $\mu$m core diameter graded-index (GI) MMF\cite{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 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\cite{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
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 $S_{X\&Y}$ 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.

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