Reliability Enhancement in FSO Communications Using FMF Assisted by Subcarrier Multiplexing

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Abstract: We exploit the frequency diversity offered by digital subcarrier-multiplexing to overcome the coherent combining challenge associated with the use of FMF in FSO systems. Experimental validation at 200 Gbps in an atmospheric chamber reveals reliability gains of >20% compared with an equivalent single-mode coupling system.

1. Introduction

Free space optical (FSO) communications are a promising wireless solution for a wide range of applications, from optical backhaul for 6G networks up to satellite communications, since it can provide very high unlicensed bandwidth, inherent security, and robustness to electromagnetic interference [1]. However, a significant drawback of FSO communications lies in their susceptibility to atmospheric conditions. In particular, turbulence-induced power fadings can significantly degrade the system performance through effects such as scintillation, beam spread, and beam wander [1]. Several techniques have been developed to mitigate these deleterious effects, including wavefront correction using adaptive optics [2], data-rate adaptation [3], optical pre-amplification [1], forward error correction (FEC) interleaving [4], and spatial diversity [5–7].

A particular kind of spatial diversity, the so-called mode-division multiplexing (MDM), has been used in FSO communications to increase the throughput or to mitigate the impact of turbulence. To take full advantage of mode diversity, the main practical challenge lies on the proper non-interfering combination of the different excited modes at the receiver side. Currently, the proposed solutions require the use of multiple coherent receivers [7], which scales up the required receiver hardware and footprint by a factor of N_{mode}, or tailored combining subsystems to avoid mode interference. To use a single coherent receiver, coherent combining can be done using integrated photonic circuit (PICs) [5], which might be complex, power-inefficient and costly, or digitally by multiple-input multiple-output (MIMO) digital signal processing (DSP) in which spatial redundancy information is introduced by multiple time-division multiplexing copies of the signal, which tends to increase system's latency and DSP complexity [6].

In this paper, we propose a novel concept to overcome intermodal interference in FSO communications supported by coherent receivers and mode diversity. Frequency diversity of digital subcarrier-multiplexing (DSCM) is employed to avoid interference by properly filtering and combining a single subcarrier from each spatial mode. Since the subcarriers carry redundant information, a multiple-input single-output (MISO) algorithm is applied at the coherent receiver for digitally combining all subcarriers. The performance assessment of this technique is evaluated under different turbulent regimes, using an atmospheric chamber, providing reliability gains of >20% when compared with an equivalent single-mode fiber coupling.

2. DSCM-Enabled Non-Interfering Mode Combining

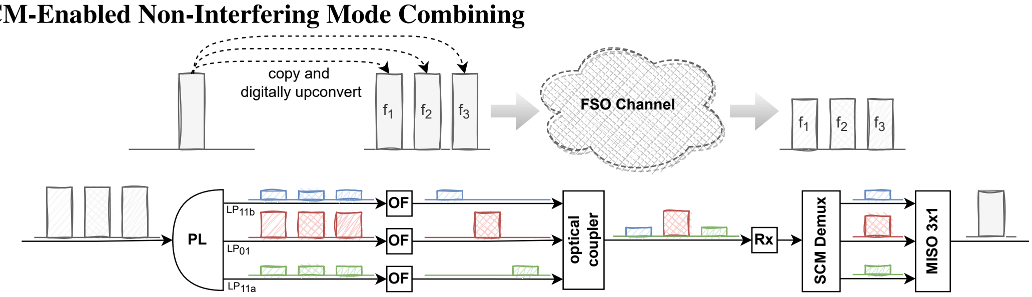

Fig. 1: Concept of non-interfering mode combining for FMF-FSO systems, using DSCM. PL: photonic lantern; OF: optical filter.

A schematic of the proposed non-interfering mode combining solution is sketched in Fig. 1, considering a few-mode fiber (FMF) supporting 3 modes as an application example. First, the information to be transmitted is replicated over 3 subcarrier multiplexed with central frequencies f_1–f_3 and a small inter-subcarrier guardband of a couple of GHz, making use of the full coherent transceiver bandwidth. After wireless transmission over the turbulent FSO channel, this 3-subcarrier signal is fiber coupled into a 3-FMF and mode-demultiplexed by a photonic lantern (PL) into its respective constituent modes: LP_{01}, LP_{11a} and LP_{11b}. Using standard optical filters, the DSCM signal on each branch is filtered so that only one of the subcarriers is attributed to each LP mode, thus using the frequency dimension to avoid mode-overlap. The 3-DSCM signal is then recovered by simply combining the 3 LP modes with an optical coupler. Finally, after digital processing and demultiplexing at the coherent receiver, the baseband subcarrier components can be fed to a 3×1 MISO equalizer, that will perform the coherent mode combination,

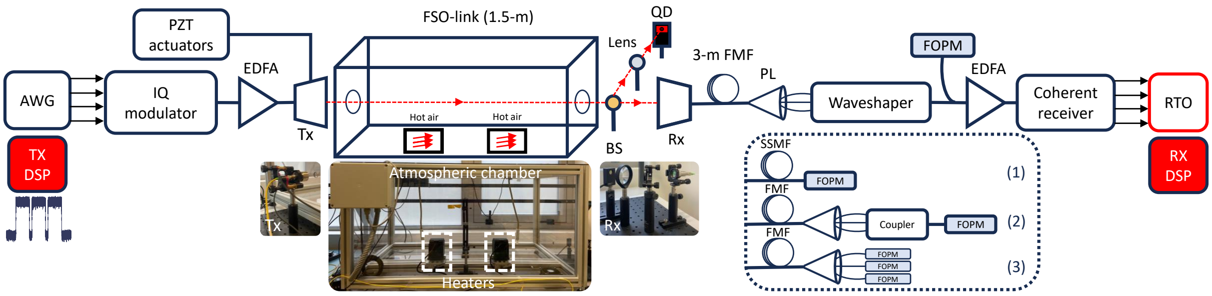

Fig. 2: FSO system experimental setup used for assessing the FMF performance under the turbulent regime.

namely adjusting for residual phase and polarization mismatches between LP-carrying subcarriers. In summary, the proposed DSCM-enabled non-interfering mode combining solution implies a bandwidth-vs-performance tradeoff, resorting only to simple off-the-shelf components (e.g. optical filters and couplers) and thereby avoiding the use of additional complex hardware, such as coherent combining PICs or multiple coherent receivers.

3. FSO System Description

The experimental setup is depicted in Fig. 2. At the transmitter (Tx) side, a DSCM signal is generated with 3 subcarriers spaced by 5 GHz. Each subcarrier is modulated at 25 Gbaud with 64-QAM probabilistic constellation shaping (PCS), and 20% $FEC_{overhead}$, totalizing a net bit-rate of 200 Gbps[1]. Afterwards, the signal is pulse-shaped using a root-raised cosine (RRC) filter with 0.02 roll-off and uploaded into an arbitrary waveform generator (AWG) with 45 GHz bandwidth and 120 Gsps sampling rate (Keysight M8194A). Optical modulation is performed by a dual-polarization IQ modulator (35 GHz bandwidth) over a nano-ITLA laser, outputting 13 dBm optical power at a wavelength of 1550 nm. Before being sent to free space, the signal is amplified by an Erbium-doped fiber amplifier (EDFA) working in automatic power control mode to always ensure 10 dBm launched power at the FSO Tx. The FSO link is composed of two fiber collimators (Thorlabs F810APC-1550), separated by a distance of 1.5 m, and characterized by a lens diameter of 24 mm, a divergence angle of 0.0017° and 0.24 numerical aperture. The auto-alignment of the Tx collimator is performed by two piezoelectric (PZT) actuators (Thorlabs PIAK10), a piezo driver (KIM101), a quadrant detector (QD) (Thorlabs PDQ30C), a beam splitter (BS) (Thorlabs BP108) and a plano-convex lens, enabling the precise alignment of the optical beam position in the horizontal and vertical axis. Turbulence effects are generated by a 1.2 m custom-made atmospheric chamber, consisting of two heaters capable of raising the temperature up to 70 °C, two fans, and two humidity/temperature sensors.

At the receiver (Rx) side, the optical signal is coupled into a 3-mode FMF, which is connected to a PL for mode demultiplexing. Afterwards, a waveshaper (Finisar WS4000S) is used to filter a unique digital subcarrier per mode and combines the optical signals. Following, an EDFA amplifies the signal to ensure the optimal power at the coherent receiver. Power measurements are performed before signal amplification by a fast-optical power meter (FOPM) with a sampling-rate of 10 ksps. Finally, the optical signal is converted to the electrical domain by a coherent receiver (40 GHz bandwidth) and digitized/quantized by 4 real-time oscilloscopes (RTO, Tektronix DPO77002SXR3) with 70 GHz bandwidth operating at 200 Gsps. The signal is digitally post-processed, which includes IQ imbalance compensation, 2×2 CMA-based adaptive equalization (11 taps), frequency and phase recovery, 2×2 LMS equalization (75 taps), 3×1 MISO equalization (101 taps), bit decoding and normalized generalized mutual information (NGMI) [8] assessment (in the single carrier scenario the MISO filter is removed).

4. Results and Discussion

In this section, turbulence is generated by varying the heat inside the atmospheric chamber. The received optical power is analyzed using either an SSMF or an FMF attached to Rx collimator, see insets in Fig. 2. For a 15 min test, the turbulence-induced fading highly affects the SSMF resulting in power fluctuations up to 40 dB, as shown in Fig. 3a. In contrast, due to its larger core diameter (14 μm) and higher number of modes, the FMF is expected to provide enhanced resilience towards turbulence. Indeed, Figs. 3b and 3c show that FMF can take advantage of its inherent modal diversity to reduce the impact of power fadings in a wide range of turbulence regimes. In Fig. 3b, we measure the optical power directly by combining the optical output of the PL with a coupler, as depicted in Fig. 2 inset (2). However, the lack of proper coherent combining among the 3-FMF modes results in an interferometer-like effect with recurrent destructive interference patterns, see Fig 3b. On the other hand, as an upper bound for mode combining performance, we perform the digital combination of the optical power waveforms measured on each LP mode, see inset (3). As shown in Fig. 3c, if the interference-induced beating is avoided, the full potential of FMF-based optical coupling can be unleashed, significantly outperforming SSMF-coupled receivers.

In order to assess the improved FMF-based optical coupling in an actual FSO communication scenario, let us now proceed with the experimental validation of the proposed DSCM-enabled FMF-mode combining technique. The performance of the proposed technique is evaluated with and without MISO at the post-processing stage and compared against an equivalent single-mode approach, in which only the central subcarrier is transmitted through the FSO channel, i.e. the LP_{11a} and LP_{11b} modes are suppressed. The obtained NGMI performance is shown in Fig.

[1] in the single carrier scenario, only one carrier is generated with the same parameters

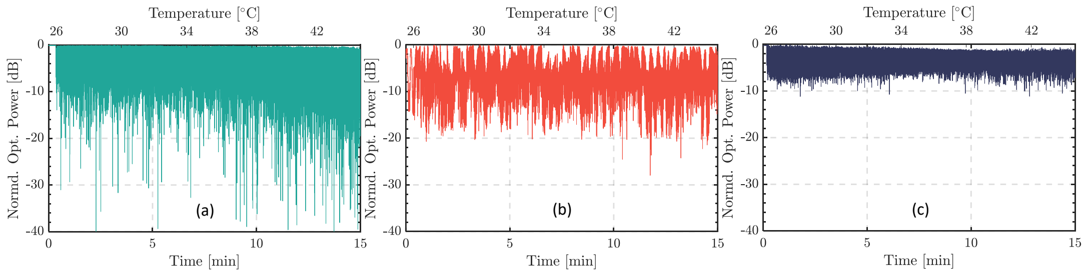

Fig. 3: Comparison of the evolution of the received optical power for different turbulence-induced fadings. (a) SSMF-coupled; (b) FMF-coupled with non-coherent combining; (c) FMF-coupled with ideal power combining.

4a. Note that the experiments are carried out for similar turbulent conditions, see the Rytov variance over time in the inset of Fig. 4a. When the temperature inside the chamber exceeds 45 °C, the induced turbulence leads to an overall NGMI degradation in the three system configurations under test, as Fig. 4a depicts. Nevertheless, the MISO-assisted DSCM provides lower NGMI fluctuations, owing to its full exploitation of the mode diversity feature offered by the FMF. Considering typical FEC algorithms employed in coherent optical transceivers, in Fig. 4b we assess the system reliability for a threshold NGMI, NGMI_{th}, of 0.88. According to the observed NGMI variations in Fig. 4a, higher reliability is found in the initial minutes when the turbulence is weak. Nevertheless, when MISO is applied the obtained reliability is constantly $>80\%$, showing a consistent gain compared to the other systems. The absence of MISO processing results in increasingly performance degradation, even for lower power fadings, since all power spared to the adjacent subcarriers and coupled into higher modes in unused. In turn, the equivalent single-mode approach (all Tx power allocated to the central subcarrier and suppressed LP_{11} modes) is especially impaired when the turbulence is increased, justifying the use of the proposed DSCM-MISO technique for these scenarios.

With the aim of devising general rules of achievable gains through the use of FMF-FSO with DSCM, in Fig. 4c we show the reliability for different NGMI_{th} (i.e. different FEC coding gain) and the corresponding improvement is highlighted when comparing with the single-mode system. As the FEC threshold increases, particularly after $\text{NGMI}_{th} = 0.9$, the trend demonstrated by the DSCM-MISO system is to progressively rise its reliability gains. It therefore becomes apparent that the proposed mode-combining technique can be particularly relevant for turbulence-impaired FSO systems with low FEC complexity.

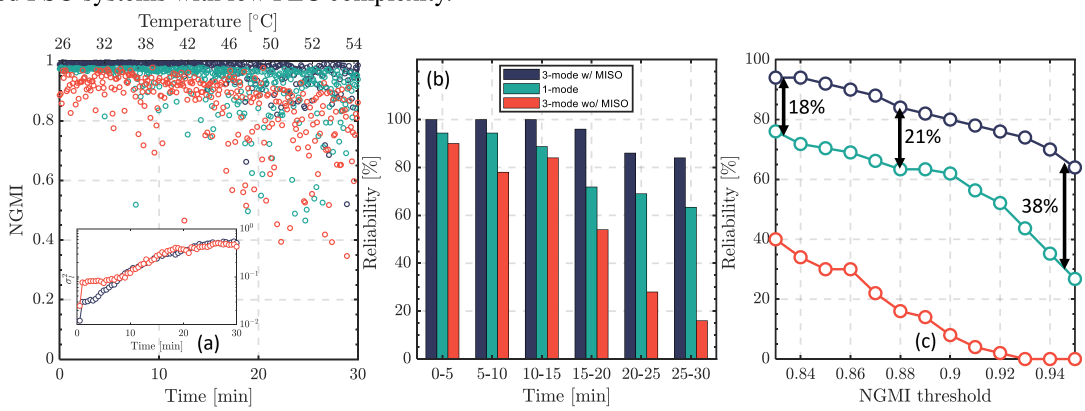

Fig. 4: Transmission performance results under the impact of turbulence. (a) Evolution of the measured NGMI over time with the respective Rytov variance; (b) Reliability over time for $\text{NGMI}_{th} = 0.88$; (c) Impact of NGMI_{th} on the system reliability.

5. Conclusions

Exploiting the use of frequency-diversity in DSCM signals, we have proposed a novel technique for non-interfering mode combining in FMF-coupled FSO systems, whose working principle leverages on a bandwidth-vs-performance tradeoff, thus requiring no additional receiver hardware. Experimental validation at 200 Gbps in realistic turbulent channels has revealed reliability gains in the range of ∼20–40%, depending on the considered FEC threshold.

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