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# Integrated Mode Multiplexers for Free-Space Optical Communications

Free-space optical (FSO) communications represent a critical framework for high-bandwidth fronthaul link deployment in next-generation 6G wireless networks. However, transitioning from intensity-modulation and direct-detection transmission schemes to high-capacity coherent ones introduces severe link impairments under atmospheric turbulence (AT), which causes random optical path length perturbations that degrade single-mode fiber (SMF) coupling efficiency.

To mitigate these impairments, this work investigates a mode-diverse receiver architecture (see Figure 1) extended with mode-division multiplexing (MDM) to simultaneously optimize system capacity and reliability. We apply the numerical split-step method to generate a suitable channel model and analyze the impact of atmospheric turbulence on the achievable channel capacity. Under a 1% outage capacity constraint in moderate-to-strong turbulence, the implementation of 3×3 and 6×6 MIMO systems enhance the achievable target capacity by factors of 70 and 285, respectively [1].

Further, we validate the numerical model against long-term experimental fading statistics from the 4.6-km-long test link between Eindhoven University of Technology (TU/e) and High Tech Campus. The verified numerical results demonstrate that shifting from single-mode reception to 3-mode and 6-mode few-mode fiber (FMF) configurations can reduce long-term conditional outage probabilities from 0.131 down to  $1.76 \times 10^{-2}$  and  $2.02 \times 10^{-5}$  respectively, yielding a four-orders-of-magnitude reliability improvement [2].

To address the hardware footprint of mode-diverse receiver architectures, we propose a highly compact microstructure Multi-Plane Light Conversion (MPLC) demultiplexer with five phase masks restricted to a  $1 \mu\text{m} \times 1 \mu\text{m}$  pixel size constraint, compressing spatial-mode conversion into a transmissive arrangement under 1 mm in total length. Despite the compact formfactor, this design has shown insertion losses of only 2.5 dB in numerical simulations.

## References

- [1] J. Krimmer und S. Randel, „Outage Capacity of Mode-Division-Multiplexed Free-Space Optical Communications Under Atmospheric Turbulence“, in 2025 European Conference on Optical Communications (ECOC), Copenhagen, Denmark: IEEE, Sep. 2025, W.02.01.156. doi: 10.1109/ECOC66593.2025.11263328.
- [2] J. Krimmer, V. van Vliet, M. van den Hout, E. Tangdionga, C. Okonkwo, und S. Randel, „Mitigating Outages in a 4.6-km FSO Link via Mode-Diverse Reception: An Experimentally Validated Digital Twin Approach“, in 2026 European Conference on Optical Communications (ECOC), Málaga, Spain: IEEE, 2026.

## Figures (with caption)

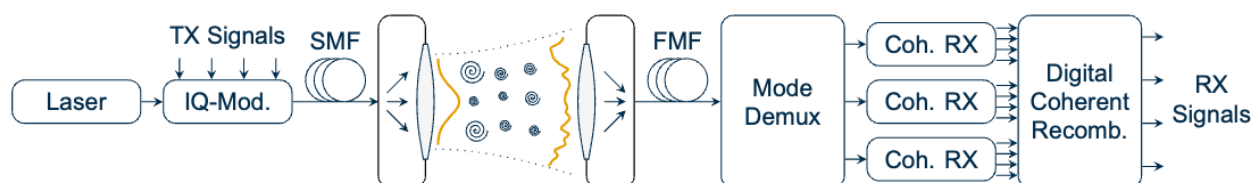


Figure 1: Exemplary setup of a mode-diverse coherent FSO system.