100 Gb/s Per-Channel Free-Space Optical Transmission with Coherent Detection and MIMO Processing

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Abstract *We experimentally demonstrate the first 100 Gb/s per-channel free-space optical transmission using polarization-multiplexed QPSK, coherent detection, and MIMO processing. This is the highest per-channel FSO rate yet reported, highly-suitable for short-distance 100 Gb/s fiber backhaul.*

Introduction

Free-space optical (FSO) transmission continues to emerge as an unlicensed, highly secure, and rapidly-deployable solution for point-to-point, high-capacity (multi-Gb/s) access in next generation networks[1]. Ultra high-speed fiber backhaul in urban areas is a particularly attractive application of FSO[1, 2]. However, poor atmospheric and weather conditions and building sway cause stochastic received power fluctuations that tend to dominate FSO performance[1]. Consequently, to increase data rates and approach 100 Gb/s per-channel transmission envisioned in next-generation fiber systems, advanced modulation and coherent detection are also of great interest for the FSO channel. Legacy FSO systems have exploited binary intensity modulation with direct detection (IM/DD), in conjunction with wavelength division multiplexing (WDM), to exhibit impressively high total transmission capacity. For example, 32 x 40 Gb/s transmission over 420 m was shown in [2], while 8 x 10Gb/s over 3.4 km was demonstrated in[3]. However, advanced modulation, such as orthogonal frequency division multiplexing (OFDM) with baseband QPSK modulation and DD, was shown to outperform on-off keying (OOK) [4], while the benefits of coherent detection in FSO channels have been shown to be as large as 10 dB [5, 6]. In this paper, we propose polarization-multiplexed (POLMUX) QPSK and coherent detection with multiple input multiple output (MIMO) processing to significantly increase the FSO per-channel rate. We experimentally demonstrate the effectiveness of the proposed solution on a 112 Gb/s POLMUX-QPSK FSO system, achieving the highest per-channel FSO data rate yet reported for variable power loss equivalent to a 1-1.5 km distance. The presented results indicate that FSO is promising for short-distance urban fiber backhaul in next-generation 100 G-based systems.

Experimental Setup

The experimental setup for this work is shown in Fig. 1. The POLMUX-RZ-QPSK transmitter is formed by two cascaded Mach-Zehnder modulators (MZM1 and MZM2), separated by a phase modulator (PM1) and a polarization-maintaining EDFA, with the output of MZM2 followed by a polarization-multiplexer. MZM1 is biased using an external cavity laser (ECL) and both MZM1 and PM1 are driven by independent 28 Gb/s data streams to provide 0/π and 0/0.5π phase modulation, respectively. The 28 Gb/s data sequence is obtained by time-division-multiplexing four 7 Gb/s PRBS signals, each having a pattern length of 2^{11}-1. To carve out 50%-duty-cycle RZ pulses, MZM2 is driven by a 28 GHz clock. The two 28 Gb/s data signals are de-correlated by a differential bit delay, and electrically multiplexed such that the resulting pattern length of the 28 Gbaud/s signal is 2^{13}-4. Polarization multiplexing is achieved by dividing the 28 Gbaud/s RZ-QPSK signal into two orthogonal polarizations, offsetting them with a 322 symbol delay, and recombining the two branches with a polarization beam combiner. The data rate per polarization is thus 28 Gbaud/s x 2 bits/symbol = 56 Gb/s, yielding a total rate of 112 Gb/s for the POLMUX-QPSK signal. An EDFA was used to adjust the output optical power to 0 dBm. To produce a parallel FSO beam, a fiber pig-tailed collimator with a 4 mrad output divergence angle was used, while the FSO power attenuation was controlled via a

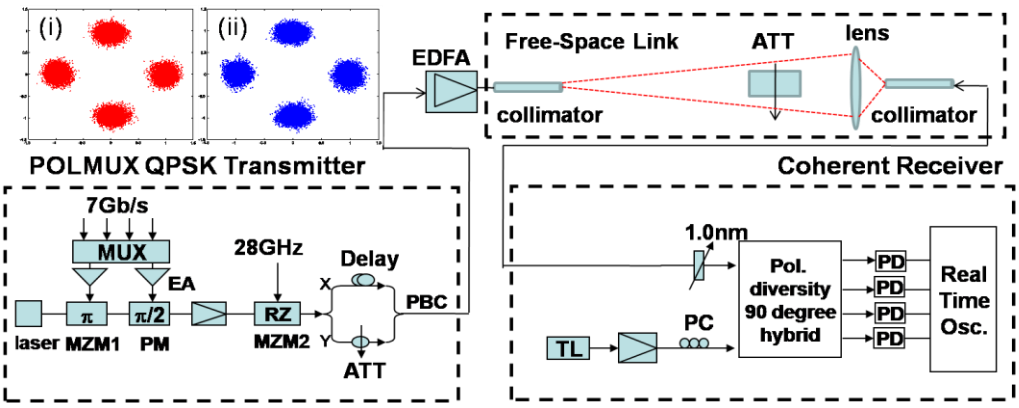

Fig. 2: Experimental setup with measured QPSK constellations in (i) polarization X and (ii) polarization Y. (TL: tunable laser, ATT: attenuator, EA: electrical amplifier)

continuous neutral density filter with optical density range 0-2.0. Free-space power attenuation was varied between 3-20 dB, corresponding to measured data for 1-1.5 km links where atmospheric conditions vary from clear sky to wind and/or rain[3]. At the receiver, following the collecting aperture, a second fiber pig-tailed collimator coupled the received signal into a 1.0 nm optical filter and onto a polarization-and phase-diverse coherent receiver composed of a 90-degree hybrid, a tunable ECL local oscillator (LO) with 100 kHz linewidth, and four single-ended photoreceivers. Signal distortion from square law (direct) detection was mitigated by using a relatively high local oscillator (LO)-to-received-signal power ratio, with an EDFA used to set the LO power P_{LO} = 8 dBm. For all measurements, the LO was tuned within 1 GHz of the transmitter laser. Since the input signal polarization state was not controlled, DSP multiple input multiple output (MIMO) processing was applied to reconstruct POLMUX data; DSP procedure details are given in[7]. The sampling and digitization (A/D) function for the off-line electronic post-processing was done by a 4-channel digital storage scope with 50 Gsamples/s sample rate and electrical bandwidth B = 16 GHz. Errors were counted over 20×50,000 symbols (20 data sets consisting of 50,000 symbols each), such that the average BER for the 112Gb/s POLMUX-RZ-QPSK signal is based on 4M bits.

Results and Discussion

Figure 2 plots experimental BER values versus received optical signal power, P_s, for the 100 Gb/s

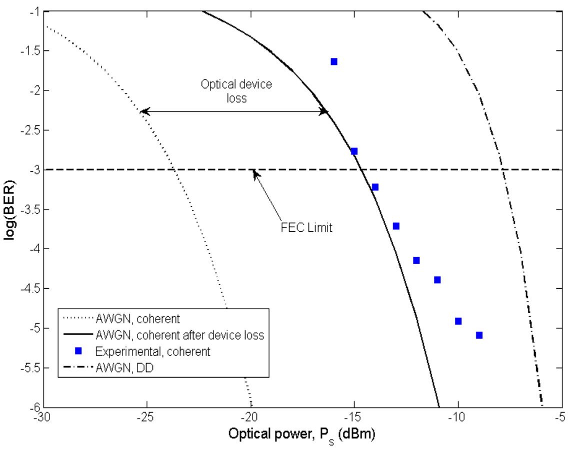

Fig. 2: BER versus received optical signal power, P_s.

FSO POLMUX-QPSK system with coherent detection. For reference, Fig. 2 also plots the theoretical BER curves for QPSK in additive white Gaussian noise (AWGN), the commonly-accepted model for terrestrial FSO links dominated by thermal noise in the absence of stochastic turbulence[5,6]. For the theoretical curves, P_{LO} = 8 dBm, B = 16 GHz and the noise power spectral density N_0 = -31 dBm/Hz (experimentally measured.) Since the optical power P_s measurements were made at the input of the 90 degree hybrid (Fig. 1), a second theoretical coherent detection curve is plotted in Fig. 2 to account for the 9 dB optical coupler loss and 0.75 A/W photodetector responsitivity. As shown by Fig. 2, once device losses are accounted for, at the FEC limit (BER = 10^{-3}), the experimental coherent detection data meets its AWGN limit, indicating that frequency offset and/or phase noise do not exert a significant performance penalty on the coherent FSO system. Moreover, a comparison of the experimental coherent detection BER with the theoretical AWGN direct detection (DD) result reveals that, at the FEC limit, coherent detection yields a 7 dB improvement. Finally, as shown by Fig. 2, comparison of the theoretical and experimental coherent detection curves at lower BER indicates that the experimental performance degrades with increased received optical power. This effect may be directly attributed to the fact that for a fixed P_{LO}, an increase in P_S reduces the effective power ratio between them, such that the distortion from square-law photo-detection becomes increasingly prominent. Specifically, as the P_{LO}/P_s ratio decreases, the MIMO post-processing algorithm used to recover data in each polarization operates in an increasingly unfavorable range. Recently, a promising new approach that addresses this effect in fiber systems was demonstrated[8]. It is conjectured that an analogous method may be adopted for coherent FSO receivers as well.

Conclusions

We have presented the first experimental demonstration of 100 Gb/s per-chanel free-space optical transmission, the highest single-channel FSO data rate yet reported. The demonstrated result was achieved using POLMUX-QPSK and coherent detection with MIMO processing, in the presence of power attenuation equivalent to 1-1.5 km terrestrial links. The proposed approach could thus be an effective solution for next generation FSO systems that support short-distance backhaul of 100G-based fiber transmission. The authors would like to thank Dr. X. Zhou of AT&T Labs-Research, Middletown, NJ, for valuable technical collaboration on this project.

References

1 D. Kedar et al., IEEE Commun. Mag., **42**, 5,(2004).
2 E. Ciaramella et al., Proc. OFC'09, OMN7 (2009).
3 M.-C. Jeung et al., IEEE Photon. Technol. Lett., **15**, 171-173, (2003).
4 N. Cvijetic et al., Proc. OFC'08, OThD2 (2008).
5 N. Cvijetic et al., Proc. IEEE GLOBECOM 2006.
6 E. Ip et al., Proc. ECOC '08, Tu 3.E.7. (2008).
7 X. Zhou et al, Proc. OFC'08, PDP 1 (2008).
8. X. Zhou et al, Proc. ECOC '08, Mo.4.D.2. (2008).