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Single-Wavelength Terabit Multi-Modal Free Space Optical Transmission with Commercial Transponder

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Abstract *We demonstrate a record-high net single-wavelength data rate of 1.1 Tbit/s and spectral efficiency of 28.35 bit/s/Hz over a multi-modal free space optical link with fully independent channels and all key devices used in this work commercially available. ©2022 The Author(s)*

Introduction

Radio frequency has been widely used for point-to-point connections where cabled solutions are challenging. However, the conventional link is facing challenges in the aspects of data rate, security, power consumption, licensed spectrum, etc [1]. To cope with these challenges, optical communication over a free-space optical (FSO) link is emerging as an attractive solution, where mode-division multiplexing (MDM) promises to further boost its capacity. Although orbital angular momentum (OAM) is one of the most popular modal basis sets chosen by many researchers [2], due to the sacrifice of its radial degrees of freedom, for a given aperture size OAM provides lower bandwidth capacity compared to other complete orthogonal basis sets, such as Laguerre-Gaussian modes, Hermite–Gaussian modes, and linearly polarized (LP) modes [3]. Recent demonstrations [4],[5] have achieved an aggregated data rate of 1 Tbit/s over a MDM-FSO link, but are mainly realized by non-commercial devices and based on delayed or partially delayed copies of identical data streams.

In this work, we employ a MDM-FSO system comprising a commercial transponder and commercial mode-selective photonic lanterns (MSPLs) [6] to excite LP modes for MDM transmission. Meanwhile, we design a time-division-multiplexed (TDM) frame structure with fibre delay decorrelation to efficiently emulate a multi-input multi-output (MIMO) MDM-FSO communication system comprising fully independent channels and enabling channelised precoding. By optimizing the MDM-FSO system and leveraging adaptive loading, we demonstrate a net data rate of 1.1 Tbit/s across the 5 lowest order LP modes, and a net spectral efficiency of 28.35 bit/s/Hz. To the best of our knowledge, it is a record-high net data rate and net spectral efficiency achieved by a single-wavelength MDM-FSO communication system using commercial devices.

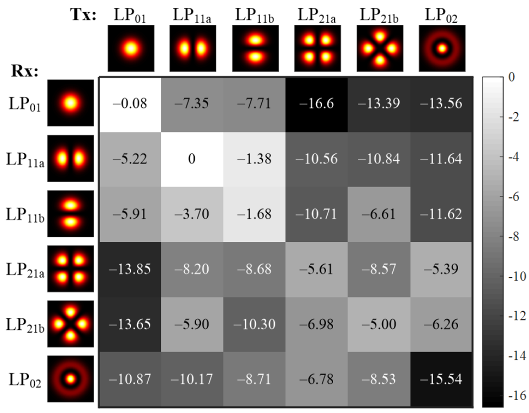

Fig. 1: Normalized crosstalk matrix of MSPLs.

Principle and Experimental Setup

Fig. 1 shows the measured normalized crosstalk matrix of the pair of commercial 6-mode MSPLs (Phoenix Photonics Ltd) used in this work, indicating that they induced relatively strong inter-mode crosstalk, especially for the highest-order mode (LP_{02}). Therefore, we only used the first N modes (N≤5) at the transmitter side for MDM transmission, and used all 6 modes at the receiver side for robust reception [7]. It should be noted from the figure that the overall received power of each transmit mode (column) is different, which can be attributed to the residual mode-dependent loss (MDL) of the MSPLs. Since different crosstalk and MDL result in different signal-to-noise ratios (SNRs) of different channels, Chow's adaptive loading algorithm [8] is employed to maximize the throughput of our system. Multiple independent transmitters and receivers are thus required. To emulate them in a MDM system with only one transmitter and one receiver, we have designed a TDM frame structure in digital signal processing (DSP) with the existing TDM receiver [9] as shown in Fig. 2.

At the transmitter side, a dual-polarization (DP) quadrature amplitude modulation (QAM) optical signal at 1550.12 nm was generated in a commercial line card where the DP-I/Q modulator was driven by the onboard 4-channel 39.385-

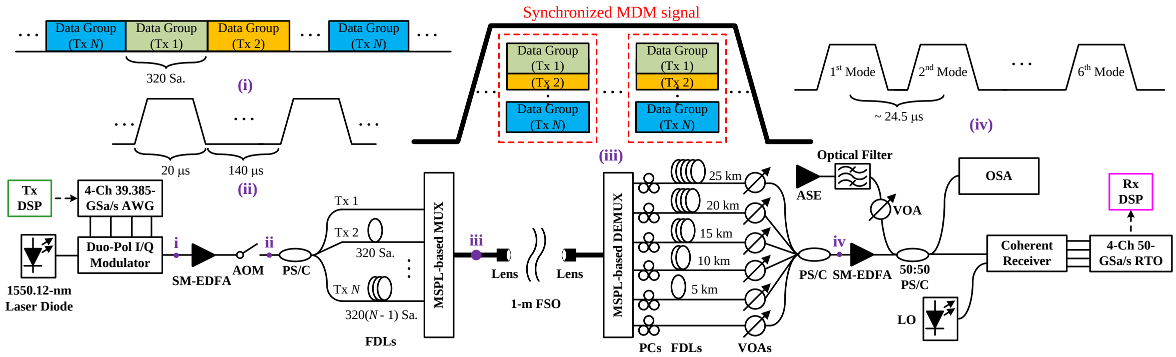

Fig. 2: Proof-of-concept experiment for demonstrating a MIMO MDM-FSO communication system using the TDM frame structure and TDM receiver (ASE: amplified spontaneous emission; LO: local oscillator; OSA: optical spectrum analyzer; RTO: real-time oscilloscope). Insets: (i) Frame structure of the transmitted TDM-SM signal; (ii) Signal bursts after AOM; (iii) Synchronized MDM signal bursts; (iv) Received TDM-SM signal bursts.

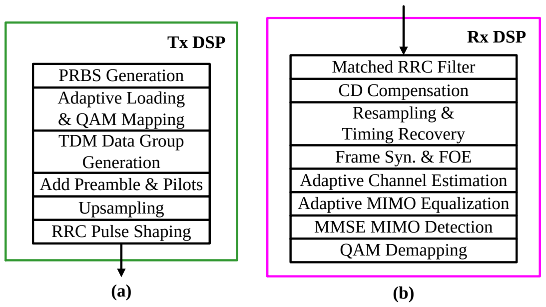

Fig. 3: Block diagrams of the offline DSP at (a) the transmitter side and (b) the receiver side.

GSa/s arbitrary waveform generator (AWG). We can see from Fig. 2(i) that the signal was divided into consecutive TDM data groups, where each data group carried the data allocated to a certain transmitter to be emulated and had a length of 320 samples (~8.1 ns). After amplification by a single-mode (SM) erbium-doped fibre amplifier (EDFA), the signal was sent into an acousto-optic modulator (AOM) set to switch at a period of 160 µs with a duty cycle of 12.5% to generate 20-µs signal bursts (~2,462 data groups) as shown in Fig. 2(ii). A power splitter/coupler (PS/C) was then employed to split the signal bursts into *N* channels. All the channels were decorrelated by an array of variable fibre delay lines (FDLs) before multiplexing via a commercial 6-mode MSPL. As shown in the figure, each FDL had a length of 320(*n*-1) samples, where *n* was the index of transmitters. Besides implementing decorrelation, as shown in Fig. 2(iii), the data groups representing different transmitters can also be synchronized after passing through FDLs and multiplexing to emulate a MDM signal with *N* independent transmitters in practical applications. The MDM signal within a few-mode fibre was then coupled into free space using an achromatic lens for ~1-m FSO transmission.

At the receiver side, another achromatic lens was employed to couple the beam into a few-mode fibre. The MDM signal was then sent into another commercial 6-mode MSPL for demultiplexing, after which the power difference between the two polarization states of the SM signals was minimized by 6 polarization controllers (PCs). 6 independent receivers for the reception of 6 modes can then be emulated by another array of FDLs and PS/C, where the FDLs had a difference in length of ~5 km, delaying the signals by ~24.5 µs as shown in Fig. 2(iv). Before interleaving, an array of variable optical attenuators (VOAs) was employed to balance the received power in different modes. The TDM signal bursts were then amplified by another SM-EDFA before being noise-loaded. The optical signal-to-noise ratio (OSNR) was set by an amplified spontaneous emission noise source with another VOA. After coherent detection by a coherent receiver with a free-running local oscillator, 4 resultant electrical signals were finally acquired by a 4-channel real-time oscilloscope working at 50 GSa/s for the offline DSP.

Fig. 3(a) and Fig. 3(b) show the DSP used at the transmitter side and the receiver side, respectively. At the transmitter side, the generated pseudorandom binary sequence (PRBS) was first mapped onto QAM symbols with adaptive loading based on the prior knowledge of channel state information [8]. The optimized QAM symbols were then used to construct a TDM payload signal as shown in Fig. 2(i). Each frame of the signal consisted of 49×*N* data groups, in which a preamble for frame synchronization and frequency offset estimation (FOE) was inserted as the start of a frame, leading to an overhead of 2% (=1/(49+1)). Pilots (10% overhead) were then added to all groups for the adaptive channel estimation and equalization at the receiver side. Before being sent to the AWG, the signal was up-sampled to 39.385 GSa/s and root-raised cosine (RRC) pulse shaped (0.05 roll-off factor).

At the receiver side, matched RRC filtering, chromatic dispersion (CD) compensation,

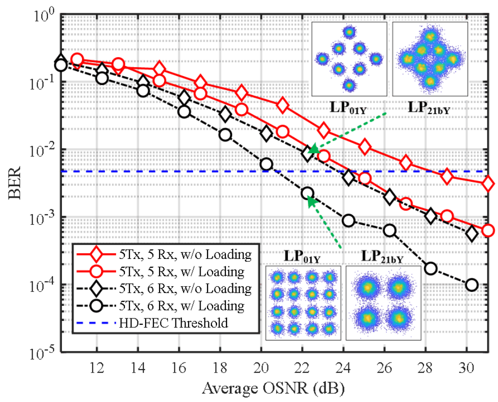

Fig. 4: Transmission performance of different signals at the same data rate (30 bits, 29.5 Gbaud).

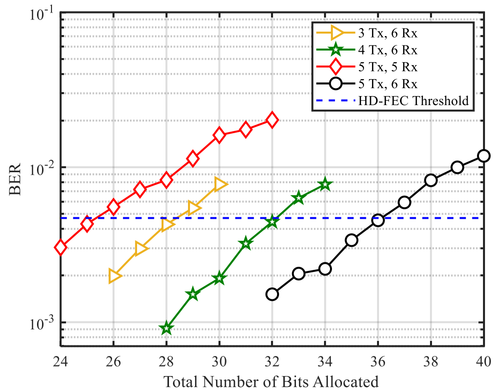

Fig. 5: Throughput maximization with adaptive loading and different schemes (36.9 Gbaud).

resampling and timing recovery were applied to the received signal before performing frame synchronization and FOE. The transfer matrices of the MIMO channel were then adaptively estimated via pilots, which were then used for the subsequent adaptive MIMO equalization and minimum mean square error (MMSE) MIMO detection. After MIMO detection and the subsequent QAM demapping, the transmission performance was finally evaluated.

Experimental Results and Discussion

We first compare the transmission performance of the MDM signals with and without adaptive loading as shown in Fig. 4. For a fair comparison, the data rate of all signals was fixed at 885 Gbit/s by allocating 30 bits to all 10 channels (2 polarizations $\times$ 5 modes) and setting the symbol rate to 29.5 Gbaud. To verify the feasibility of the robust reception using all 6 receivers, we also evaluated the performance of the MDM-FSO system with only the first 5 receivers. We can see from the figure that the adaptive loading can bring on performance improvement for both cases, i.e., ~4-dB OSNR sensitivity improvement when using only 5 receivers and ~3.5-dB OSNR sensitivity improvement when using all 6 receivers, at the hard-decision forward error correction (HD-FEC) threshold of 4.7×10^{-3} [10]. Moreover, we can see from Fig. 4 that one more receiver can provide more power as well as more information for detection, leading to ~4-dB OSNR sensitivity improvement. The performance improvement from adaptive loading can be explained by the insets of Fig. 4. The channels in our MDM-FSO system show relatively large differences in SNR mainly due to the crosstalk and MDL induced by the commercial MSPLs and FSO transmission. However, this problem can be effectively solved by allocating different modulation formats and power to different channels based on the SNR estimated before transmission [8]. Specifically, for the signal detected by 6 receivers and at an OSNR of 22.25 dB, the average bit error rate (BER) is reduced from 8.60×10^{-3} to 2.24×10^{-3}, meeting the requirement of HD-FEC.

We finally maximized the throughput of our MDM-FSO system by leveraging adaptive loading as shown in Fig. 5. Herein, we varied the number of transmitters and the total number of bits allocated. The number of receivers was fixed at 6 except for the benchmark using 5 transmitters and 5 receivers. The symbol rate was set to 36.9 Gbaud for all cases. We can see from the figure that by enabling the first 5 modes for carrying data, we successfully achieved a maximum line rate of ~1.33 Tbit/s (≈36 bits $\times$ 36.9 Gbaud). After considering the 0.05 roll-off factor and the overhead of preamble (2%), pilots (10%) and HD-FEC (6.25%), the net data rate and the net spectral efficiency achieved in this work are ~1.1 Tbit/s and 28.35 bit/s/Hz, respectively.

Conclusions

In this work, we have demonstrated a TDM frame structure for emulating multiple independent transmitters in a MDM system. With this scheme and the conventional TDM receiver, we applied adaptive loading to a MDM-FSO system suffering from relatively strong crosstalk, and have successfully achieved a record high net single-wavelength data rate of 1.1 Tbit/s and spectral efficiency of 28.35 bit/s/Hz using commercial transponder and MSPLs. These results verify the effectiveness of the scheme and the potential of leveraging the complete modal basis in MDM-FSO systems for ultra-high-speed transmission.

Acknowledgements

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