Benefits of Mode Multiplexed Free-Space Transmission (Invited Paper)

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***Abstract*—In this invited paper, we review our recent progress on the digital signal processing algorithms for mode-division multiplexed free-space optical transmission systems. The results show enhanced spectral efficiency and turbulence resiliency in free-space transmissions.**

***Index Terms*—free-space optics, mode-division multiplexing, digital signal processing, successive interference cancellation.**

I. Introduction

Free-space optical (FSO) communication systems can provide ultra-high channel capacity, ultra-long transmission distance, inherent security and robustness to electromagnetic interference [1]–[3]. Therefore, it can be employed in a wide range of applications including ground-to-ground and satellite-to-ground wireless links.

In conventional single-input single-output (SISO) FSO transmissions, we only exploit the time diversity of the system, significantly limiting the transmission capacity [2]. To further improve the link capacity, it is also possible to employ the polarization diversity [1], frequency diversity (i.e. dense wavelength-division multiplexing (DWDM)) [4], and spatial diversity (i.e. mode division multiplexing (MDM)) [5], [6].

Atmospheric turbulence is a major negative effect in FSO links [7]. It can be mitigated in both the optical domain and the digital domain. In the optical domain, adaptive optics (AO) may be used to mitigate turbulence effects [8]–[10]. However, a trade-off between the control loop bandwidth and the residual error exists, leading to residual inter-mode crosstalk after AO compensation [10]. Therefore, digital domain compensation should be considered to further mitigate the negative turbulence effects. Different from other approaches, MDM technique can not only increase the link capacity [11], but also mitigate the negative impact of atmospheric turbulence in digital domain [5], [12]. Therefore, it is a promising technique for FSO systems and has been investigated in both academia and industry.

A popular mode basis for MDM transmission is the orbital angular momentum (OAM) modes, which is a strict subset of the complete orthogonal Laguerre-Gaussian mode basis set [13], [14]. Although the OAM mode basis has shown good inter-mode crosstalk resiliency by choosing a suitable spacing between the transmitted modes [8], it will significantly increase the beam divergence when compared with the Laguerre-Gaussian mode basis set. To further improve the link capacity and reduce the size of the receive aperture, it is preferable to employ a complete orthogonal mode basis set such as Laguerre-Gaussian modes.

To achieve a better performance in MDM FSO systems, it is important to introduce suitable multiple-input multiple-output (MIMO) digital signal processing (DSP) algorithms to decode the signal. Conventional DSP algorithms employ minimum mean squared error (MMSE) MIMO decoders, introducing

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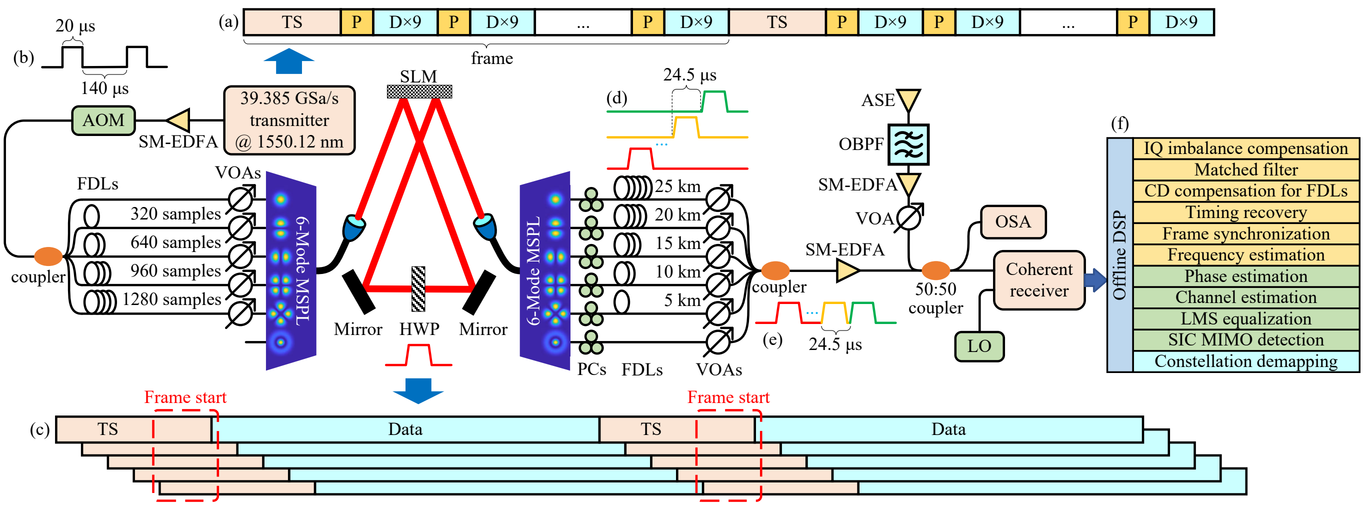

Fig. 1. The experimental setup. DP-QPSK: dual-polarization quadrature phase shift keying; TS: training sequence; P: pilot; D: data; SM-EDFA: single-mode erbium-doped fiber amplifier; AOM: acousto-optic modulator; FDLs: fibre delay lines; VOAs: variable optical attenuators; MSPL: mode-selective photonic lantern; SLM: spatial light modulator; HWP: half-wave plate; PCs: polarization controllers; ASE: amplified spontaneous emission; OBPF: optical bandpass filter; OSA: optical spectrum analyzer; DSP: digital signal processing; CD: chromatic dispersion; LMS: least mean squares; SIC: successive interference cancellation; MIMO: multiple-input multiple-output. (a) Frame structure generated by Ciena transponder; (b) signal burst after AOM; (c) delayed frame structure after transmitter FDLs; (d) time-division multiplexing (TDM) signal after receiver FDLs; (e) TDM signal after receiver coupler; (f) offline DSP. Adapted with permission from [5] © IEEE.

significant performance degradation and limiting turbulence resiliency [5]. Therefore, it is necessary to investigate the turbulence resilient DSP algorithms for MIMO MDM FSO systems.

In this paper, we review our recent progress on DSP algorithms for MDM FSO transmissions, including adaptive bit and power loading techniques, successive interference cancellation (SIC) MIMO decoders, and redundant receive channels. By introducing these techniques, enhanced transmission data rate, turbulence resiliency, and spectral efficiency are achieved.

II. Experimental Setup

The experimental setup of our MDM FSO system, which is detailed in [5], is also shown in Fig. 1.

At the transmitter side, we used a Ciena WaveLogic 3 transponder to generate a bespoke signal with training sequences and pilots (Fig. 1(a)) for our pilot-aided DSP algorithm. To enable a time division multiplexed (TDM) receiver, an acousto-optical modulator (AOM) was employed after the single-mode erbium-doped fibre amplifier (SM-EDFA) to generate a 20 µs signal burst in every 160 µs period (Fig. 1(b)). The burst signals were then split into 5 copies and delayed by variable fibre delay lines (FDLs) to generate symbol-aligned decorrelated signals for different modes (Fig. 1(c)). Afterwards, 5 variable optical attenuatorss (VOAs) were employed before the mode-selective photonic lantern (MSPL) to compensate for the mode-dependent loss (MDL) in the system. The 6^{th} channel was intentionally left unconnected. The multi-mode signals were then coupled into free space using a collimator.

In the FSO channel, a spatial light modulator (SLM) can be introduced to emulate the turbulence effect. To modulate both polarizations, the FSO beam was passed through the SLM twice. A half-wave plate (HWP) was also located between the first and second passes to swap the two polarization components. For the back-to-back experiments without turbulence, this SLM-based turbulence emulator can be bypassed by either using a factory pre-calibration pattern or directly aligning the transmit collimator to the receiver coupler.

At the receiver side, the FSO beam was coupled into a few-mode fiber (FMF) by a second identical FSO coupler and then passed through another MSPL for mode demultiplexing. To enable TDM receiver, the demultiplexed signals were delayed by approximately 24.5 µs between adjacent modes using FDLs (Fig. 1(d)). The polarization controllers (PCs) and the VOAs before and after the FDLs were employed to balance the received power in different polarizations and modes, respectively. The TDM signals were then coupled into one single-mode fibre (Fig. 1(e)) and received by a standard coherent receiver. A standard optical signal-to-noise ratio (OSNR) measuring structure with amplified spontaneous emission (ASE) noise generator and optical spectrum analyzer (OSA) were also included before the coherent receiver to enable OSNR scanning. Finally, the received signals were demodulated by an offline DSP algorithm (Fig. 1(f)).

III. Benefits on Transmission Data Rate

The first benefit of the MDM FSO transmission systems is to improve the transmission data rate. By loading independent signals onto different modes, the spatial degree of freedom can be exploited to maximize multiplexing gain. To compensate for the MDL and maximize the transmission data rate, adaptive bit and power loading techniques were employed in our previous

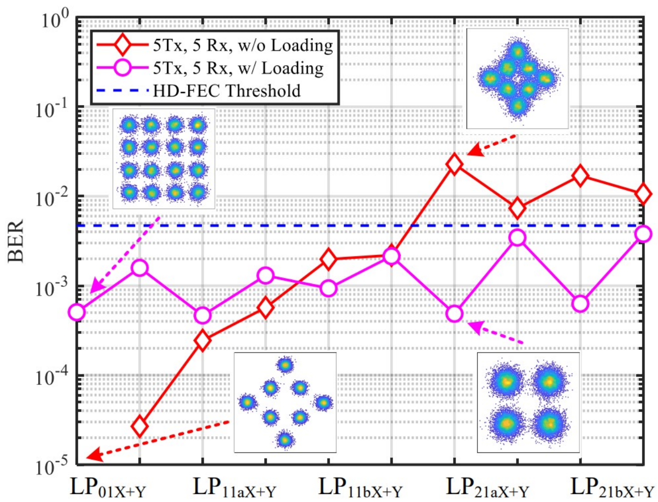

Fig. 2. BER versus channel index for the signals with and without adaptive loading (30 bits, 29.5 Gbaud, average OSNR = 27.04 dB). Reprinted with permission from [11] © The Optical Society.

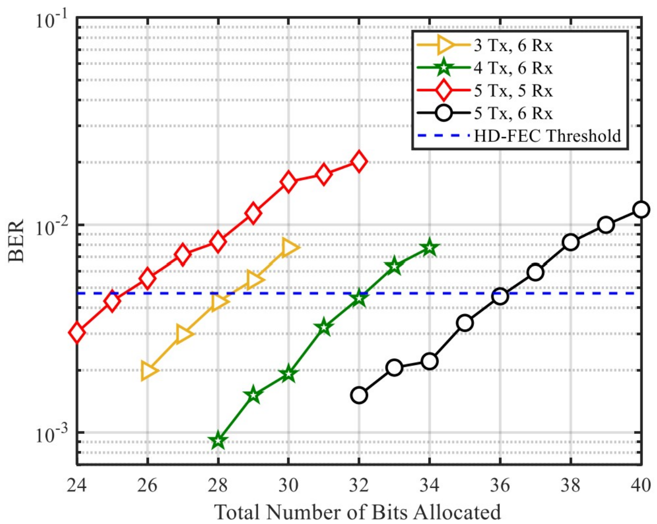

Fig. 3. Throughput maximization with adaptive loading and different schemes (36.9 Gbaud). Reprinted with permission from [11] © The Optical Society.

work [11]. In this section, the turbulence emulator is bypassed to obtain the maximum data rate.

As shown in Fig. 2, the adaptive loading algorithm suppressed the bit error rate (BER) fluctuation among different channels by allocating different modulation formats and power to different channels. As the average BER of the system is dominated by the worst-case channels, the adaptive loading can also reduce the average BER from 6.28×10^{-3} to 1.56×10^{-3}, well below the hard-decision forward error correction (HD-FEC) limit of 4.7×10^{-3}.

By employing the adaptive loading algorithm in systems with different numbers of transmit and receive modes, the throughput of the system can also be maximized. As shown in Fig. 3, we successfully achieved a maximum line rate of ˜1.33 Tbit/s (≈ 36 bits × 36.9 Gbaud) by employing all the

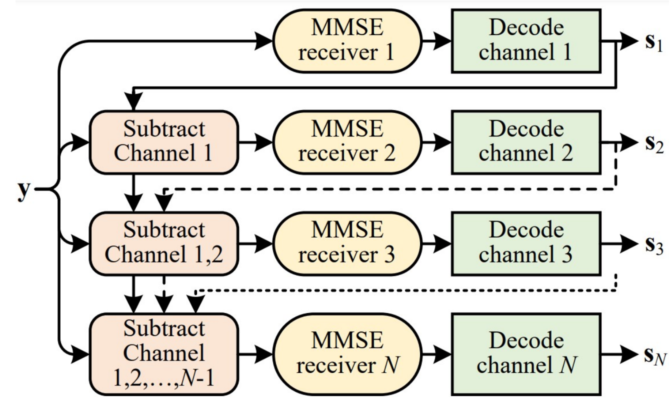

Fig. 4. Schematic diagram for the SIC algorithm. Adapted with permission from [5] © IEEE.

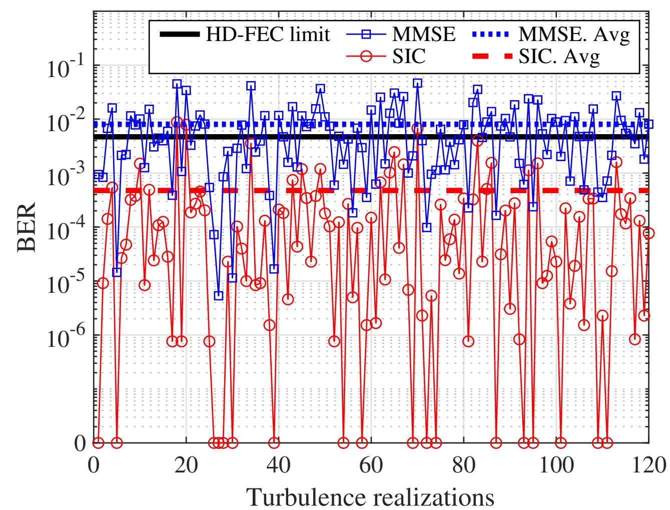

Fig. 5. The BER performance of the 5×6 MIMO system under 120 independent turbulence realizations (34.46 GBaud). Reprinted with permission from [5] © IEEE.

5 transmit modes and 6 receive modes for data transmission. Considering the 2% training sequence, 10% pilot rate, 6.25% HD-FEC cost, and 0.05 rolloff factor, a net spectral efficiency of 28.35 bit/s/Hz was achieved in turbulence-free channels.

IV. Benefits on Turbulence Resiliency

To improve the atmospheric turbulence resiliency of an MDM FSO system, we experimentally verified two methods in our previous work [5], including SIC MIMO decoder and redundant receive modes.

As shown in Fig. 4, the SIC algorithm successively cancelled out the interference from the already-decoded channels. By doing so, the inter-channel interference can be better suppressed than conventional MMSE MIMO decoders. To illustrate the performance improvement of the SIC algorithm, we tested 120 independent turbulence patterns in our system with 5 transmit modes and 6 receive modes, achieving a line rate of 689.23 Gbit/s (≈ 20 bits × 34.46 Gbaud). Considering the 8.4% training sequence, 10% pilot rate, 6.25% HD-

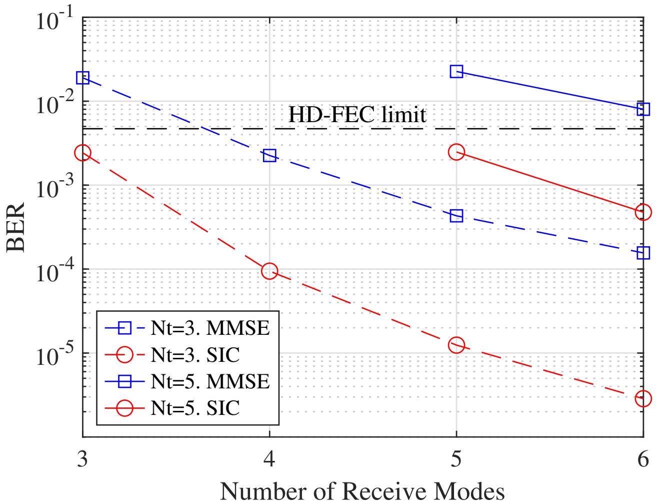

Fig. 6. The average BER performance of different MIMO systems under 120 independent turbulence realizations (34.46 GBaud). Adapted with permission from [5] © IEEE.

FEC cost, and 0.1 rolloff factor, a net spectral efficiency of 13.9 bit/s/Hz was achieved in turbulent channels. As shown in Fig. 5, the BER of the SIC MIMO decoder was consistently lower than the MMSE MIMO decoder. The average BER was also decreased from 8.02×10^{-3} (MMSE) to 4.76×10^{-4} (SIC), well below the HD-FEC limit of 4.7×10^{-3}.

Employing redundant receive modes can also improve turbulence resiliency in MDM systems. Due to the turbulence effect, a certain portion of power will leak from the desired mode to the other modes. By collecting the optical beam from redundant receive modes, information in these modes can be exploited to obtain a better decoding performance. As shown in Fig. 6, for a fixed number of transmit modes (N_t), the average BER decreased when the number of receive modes increased. It is also worth noting that the SIC decoder always worked better than the MMSE decoder.

V. Conclusions

This invited paper has introduced our recent progress on DSP algorithms for MDM FSO transmissions. In turbulence-free links, the adaptive bit and power loading algorithm was employed to maximize the transmission data rate. In emulated turbulence links, the SIC decoder and redundant receive channels were employed to improve turbulence resiliency in the digital domain. In single-wavelength MDM transmissions, we achieved record-high line rates of 1.33 Tbit/s without turbulence and 689.23 Gbit/s with turbulence. Compared with the conventional SISO transmissions, the MDM MIMO transmissions obtained a much higher net spectral efficiency of 28.35 bit/s/Hz without turbulence and 13.9 bit/s/Hz with turbulence, showcasing the significant benefits of utilizing spatial diversity in FSO systems.

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References

[1] B. I. Bitachon, Y. Horst, L. Kulmer, T. Blatter, K. Keller, A. M. Bonnefois, J.-M. Conan, C. Lim, J. Montri, P. Perrault, C. Petit, B. Sorrente, N. Vedrenne, and D. Matter, "Tbit/s single channel 53 km free-space optical transmission - assessing the feasibility of optical GEO-satellite feeder links," in *European Conference on Optical Communication (ECOC)*, 2022.

[2] R. Lange, B. Smutny, B. Wandernoth, R. Czichy, and D. Giggenbach, "142 km, 5.625 Gbps free-space optical link based on homodyne BPSK modulation," in *Free-space laser communication technologies XVIII*, vol. 6105. SPIE, 2006, p. 61050A.

[3] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE communications surveys & tutorials*, vol. 16, no. 4, pp. 2231–2258, 2014.

[4] A. Dochhan, J. Poliak, J. Surof, M. Richerzhagen, H. F. Kelemu, and R. M. Calvo, "13.16 Tbit/s free-space optical transmission over 10.45 km for geostationary satellite feeder-links," in *Photonic Networks; 20th ITG-Symposium*. VDE, 2019, pp. 1–3.

[5] Y. Li, Z. Chen, Z. Hu, D. M. Benton, A. A. Ali, M. Patel, M. P. Lavery, and A. D. Ellis, "Enhanced Atmospheric Turbulence Resiliency With Successive Interference Cancellation DSP in Mode Division Multiplexing Free-Space Optical Links," *Journal of Lightwave Technology*, vol. 40, no. 24, pp. 7769–7778, 2022.

[6] Y. Li, Z. Hu, D. M. Benton, A. Ali, M. Patel, and A. D. Ellis, "Demonstration of 10-channel mode- and polarization-division multiplexed free-space optical transmission with successive interference cancellation DSP," *Optics Letters*, vol. 47, pp. 2742–2745, 6 2022.

[7] L. C. Andrews and R. L. Phillips, *Laser Beam Propagation through Random Media, Second Edition*. SPIE Press, 2005.

[8] Y. Ren, G. Xie, H. Huang, N. Ahmed, Y. Yan, L. Li, C. Bao, M. P. Lavery, M. Tur, M. A. Neifeld *et al.*, "Adaptive-optics-based simultaneous pre-and post-turbulence compensation of multiple orbital-angular-momentum beams in a bidirectional free-space optical link," *Optica*, vol. 1, no. 6, pp. 376–382, 2014.

[9] S. Chen, S. Li, Y. Zhao, J. Liu, L. Zhu, A. Wang, J. Du, L. Shen, and J. Wang, "Demonstration of 20-Gbit/s high-speed Bessel beam encoding/decoding link with adaptive turbulence compensation," *Optics letters*, vol. 41, no. 20, pp. 4680–4683, 2016.

[10] T. Weyrauch, M. A. Vorontsov, T. G. Bifano, J. A. Hammer, M. Cohen, and G. Cauwenberghs, "Microscale adaptive optics: wave-front control with a μ-mirror array and a VLSI stochastic gradient descent controller," *Applied Optics*, vol. 40, no. 24, pp. 4243–4253, 2001.

[11] Z. Hu, Y. Li, D. M. Benton, A. A. I. Ali, M. Patel, and A. D. Ellis, "Single-wavelength transmission at 1.1-Tbit/s net data rate over a multimodal free-space optical link using commercial devices," *Optics Letters*, vol. 47, pp. 3495–3498, 7 2022.

[12] N. Fontaine, R. Ryf, Y. Zhang, J. Alvarado-Zacarias, S. van der Heide, M. Mazur, H. Huang, H. Chen, R. Amezcua-Correa, G. Li, M. Capuzzo, R. Kopf, A. Tate, H. Safar, C. Bolle, D. Neilson, E. Burrows, K. Kim, M. Bigot-Astruc, F. Achten, P. Sillard, A. Amezcua-Correa, and J. Carpenter, "Digital turbulence compensation of free space optical link with multimode optical amplifier," in *45th European Conference on Optical Communication (ECOC 2019)*, 2019, p. 4.

[13] L. Allen, M. W. Beijersbergen, R. Spreeuw, and J. Woerdman, "Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes," *Physical review A*, vol. 45, no. 11, p. 8185, 1992.

[14] A. E. Willner, Z. Zhao, C. Liu, R. Zhang, H. Song, K. Pang, K. Manukyan, H. Song, X. Su, G. Xie *et al.*, "Perspectives on advances in high-capacity, free-space communications using multiplexing of orbital-angular-momentum beams," *APL Photonics*, vol. 6, no. 3, p. 030901, 2021.