DEMONSTRATION OF A 280-GBIT/S FREE-SPACE SDM COMMUNICATIONS LINK UTILIZING PLANE-WAVE SPATIAL MULTIPLEXING

MARTIN P.J. LAVERY,[1*] HAO HUANG,[2] YONGXIONG REN,[2] GUODONG XIE,[2] AND ALAN E. WILLNER[2]

[1]*School of Engineering, University of Glasgow, Glasgow, UK*
[2]*Dept. of Electrical Engineering, University of Southern California, CA, USA*
**Corresponding author: martin.lavery@glasgow.ac.uk*

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We demonstrate a 280-Gbit/s free-space SDM communications link incorporating a set of independent tilted truncated plane-waves, each generated by a single mode fiber placed at the back-focal plane of a spherical lens. Each of the 7 tilted plane-wave channels are encoded with a 40-Gbit/s 16-QAM signal. Our approach comprises two identical linear fiber-arrays placed approximately 5 m apart. As each fiber array is placed at the back-focal-plane of a spherical lens, each fiber array is effectively placed in a conjugate image plane of the other. A channel crosstalk less than 26 dB is shown, with a bit-error-rate below the FEC threshold of 3.8 × 10−3.

OCIS codes: *(200.2605) Free-space optical communication, (200.4650) Optical interconnects, (060.1660) Coherent communications,(060.4230) Multiplexing, (060.4510) Optical communications*

In recent years the utilization of optical properties beyond the widely implemented wavelength, amplitude and polarization of light to increase the available data capacity of communication links, has become an area of key study. One such area is multiplexing using the spatial degree of freedom of an optical beam [1]. One sub-area of space-division-multiplexing (SDM) is mode-division-multiplexing (MDM), in which multiple modes are efficiently multiplexed and carry independent data channels [1–5].

For a free-space communication link over relatively short distances, like those used for optical interconnects, it has been shown that a transmitter array can be imaged on to a matched receiver array with a particular arrangement of lenses [6,7,8,9]. In 1996, one such system was demonstrated to work over 10 cm link length with a total link capacity of 1.6 Gbit/s [10]. Imaging techniques have also been demonstrated for infrared line-of-sight, and non-line-of-sight links; these receivers are known as Imaging Diversity Receivers [11]. In the case where an emitting point source, such as single mode fiber, is placed at the back-focal plane of a spherical lens a truncated plane-wave is produced [11]. If one varies the spatial locations of the fiber it will result in a plane-wave that is tilted, where this tilt varies directly with the change in spatial location [12]. Hence, using a number of spatially separated fibers, such as linear fiber array, a set of channels can be produced; where each channel produces a plane-wave with a different angular tilt. A second lens placed at the receiver separates these tilted plane-waves in spatial location at its back focal plane with relatively low crosstalk (see Fig.1) [12]. We note that plane-waves in the context of a communications link have been postulated to offer comparable channel capacity to other orthogonal mode sets [12], along with being shown to potentially be more resilient to crosstalk induced by atmospheric turbulence than LG modes [14,15]. Our approach is similar to line-of- sight (LOS) MIMO implemented in RF wireless communications, where an array of spatially separated transmitters and receivers are used. However, our approach does not require the digital signal processing (DSP) commonly required in RF links [16,17,18].

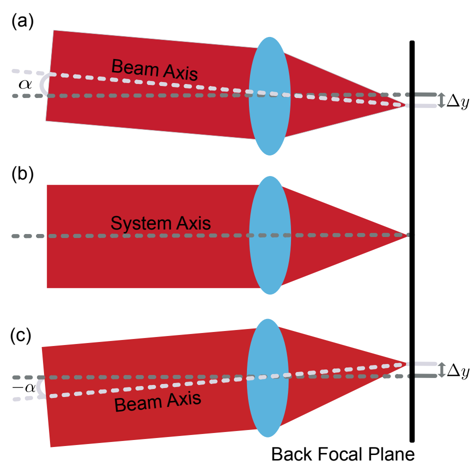

FIG. 1. A spherical lens focuses a collimated incident optical beam to a diffraction-limited point at its back focal plane (a-c). For such an input the propagation direction of the optical beams results in a linear shift, Δy, of the focused spot. This linear shift is directly related to the angular tilt, α, with respect to the system's axis, which is defined by the center of the spherical lens

A key requirement for an SDM link is the ability to efficiently separate and detect the multiplexed channels. For the case of plane-waves, the ability to resolve the different plane-wave channels is connected with the diffraction limit of the optical system [12,14]. A tilted plane-wave can described in the z-y plane as,

$$E_n = A\exp(ikz + im\alpha y/k) \quad \textbf{(1)}$$

where z and y are the longitudinal and vertical Cartesian coordinates respectively, k is the wavenumber, m is the channel number and α is

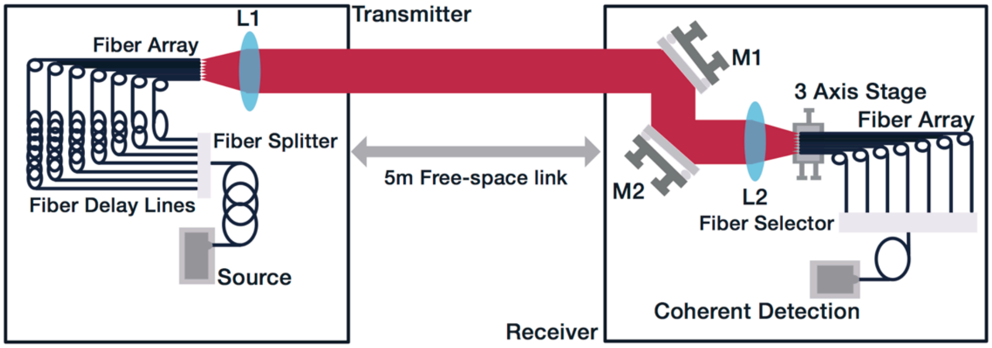

FIG. 2. A 40 Gbit/s 16 QAM signal is modulated onto an optical carrier with a wavelength of 1550 nm. The source signal is split into 7 fiber delay lines of different length. Each delay line is chosen such that the encoded signal on each channel is uncorrelated from all others. These 7 channels are subsequently connected to each of the fibers in the fiber array, where a 200mm focal length lens, L1, collimates the output. After propagation a second 200 mm lens, L2, then collects the beam. Both L1 and L2 are 75 mm in diameter and have a numerical aperture of approximately NA=0.188, which is slightly higher then that of the single-mode fibers, NA=0.13. The collected optical signal is focused to a further fiber array, where two mirrors, M1 and M2, and a 3-axis stage is used to couple the light into the receiver single-mode fibers. A coherent detector independently analyzes each channel.

the angular tilt between any two channels [12,14]. For a given aperture size L, there is a minimum requirement that $\alpha = 2\pi/L$ for the plane-wave states to be orthogonal [14]. Therefore, plane-waves with tilt angles larger than this minimum value of α, could potentially be separated in the far-field with relatively low crosstalk (see Fig. 1).

Generation of these tilted plane-waves can be achieved though the use of an optical device that induces a direction of propagation change to an optical beam; such a device could be a prism, lens, grating, spatial light modulator and MEMS array [19, 20]. In SDM systems, it is important to have efficient methods for the multiplexing (mux) and de-multiplexing (demux) of the independent channels [2, 5]. Hence, efficient and straightforward techniques to mux and demux tilted plane-waves is important in achieving SDM free-space links.

In this paper, we demonstrate a free-space communication link multiplexing 7 tilted plane-waves, with a straightforward mux-demux architecture that operates over a link of ~5 meters in length. The number of resolvable fiber elements in the fiber array determines the number of available channels and a fiber array with seven 40-Gbit/s 16-quadrature-amplitude-modulation (QAM) data channels are used in our demonstration. The measured channel crosstalk is less than 26 dB, with a bit-error-rate (BER) that is below the forward-error-correction (FEC) limit of $3.8 \times 10{-}3$. The demonstrated system capacity is 280 Gbit/s.

The 7-element linear fiber array used in our system are composed of single mode fibers, which are each separated by 127μm. The fiber array is placed in the back focal plane of a 200-mm lens, which has an aperture diameter of 75 mm. The spherical lens in this arrangement approximately performs a Fourier transform of the light emitted by the single mode fiber, as shown in Fig. 1. In the theoretical case that each fiber produced a beam with a spatial profile corresponding to a Dirac-delta function, such a Fourier transforming lens would generate an infinite plane-wave. The direction that plane-wave propagates is determined by the position of the fiber at the back-focal-plane of the Fourier transforming lens [12]. In our experimental realization Dirac-delta functions are difficult to produce; however, single mode fibers provide a diffraction-limited source that can be used in a similar fashion [12]. Our single mode fibers produce a beam with a Gaussian spatial profile that yields a truncated plane-wave when collimated by a lens. The direction of propagation is also determined by the position of the single mode fiber in the back-focal-plane of the collimating lens (L1). Hence, a linear array of fibers will provide a set of multiplexed

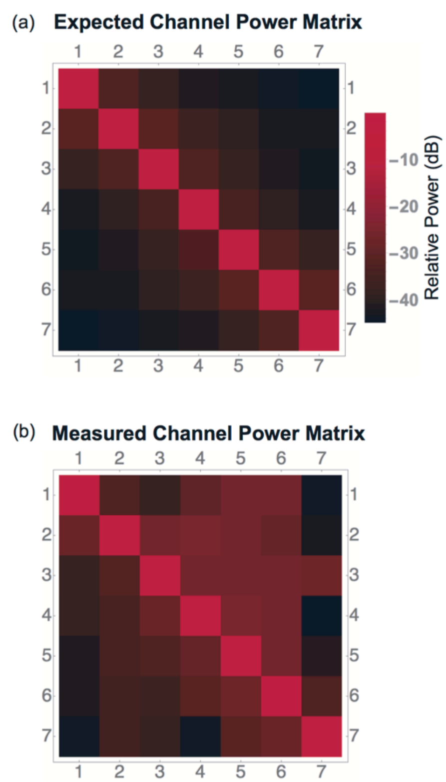

FIG. 3. (a) A numerical simulation of the optical system gives the expected channel crosstalk for the free-space link. (b A measurement of the power in all 7 channels is made for each of the 7 input channels, yielding the experimentally measured power matrix.

truncated plane-waves, in which each are tilted slightly with respect to all others as a function of the fiber separation, Fig. 2.

In the case of our fiber array with a fiber spacing of 127 μm, the tilt between each truncated plane-wave channel is $\alpha \approx 62\pi/L$, where L=75 mm. Therefore, our demonstration generates plane-waves with an angular tilt separation great than the minimum requirement. It should be noted our experimental realization produces truncated plane-

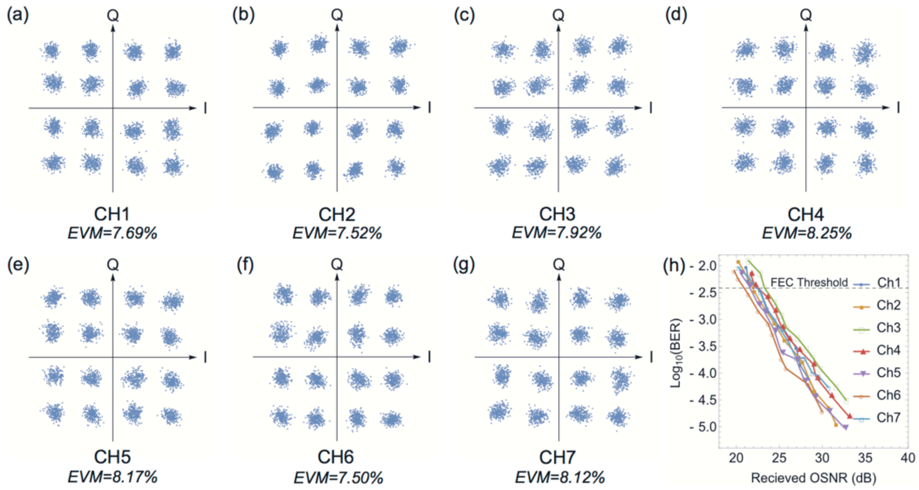

FIG. 4. A 40 Gbit/s 16 QAM signal is encoded on to each of the 7 tilted-plane-wave states used in the free-space link. The constellation plots for each of the 7 received 40 Gbit/s 16 QAM signals were measured along with an error vector magnitude (EVM) as shown below each constellation (a-g). The mean signal-to-noise ratio was 19.5 dB.

waves, which are not strictly orthogonal but yet can still produce relatively low crosstalk.

The channels are propagated over a ~5m free-space link. The 7 channels are de-multiplexed by a receiver-side further spherical lens (L2), focusing the power corresponding to each channel to an independent spatial location based on the tilt angle of the incident truncated plane-wave, Fig. 2. A second fiber-array is placed in the back-focal-plane of L2, collecting the power associated with each channel into an independent single–mode fiber. To recover the data carried on each of the 7 channels, the fiber array is connected to a fiber selector, allowing a coherent detector to individually analyze each channel.

An experimental measurement of the channel crosstalk is achieved by measuring the power coupled into each of the independent fiber channels (Fig.3 (b)). The experimentally measured results achieved nearest neighbor crosstalk between -26 and -33 dB, depending on the particular channel, Fig. 3 (b). We believe that the increased crosstalk arises partly from physical aberrations in the optical components; however the crosstalk is adequate for digital modulation formats such as high order QAM. The optical surface quality of the lenses used within the system could be a source of aberration. We postulate that improving the quality of the lenses used in the optical setup could reduce the measured channel crosstalk.

To assess the quality of the free-space optical link, a 40-Gbit/s 16-QAM signal is encoded on each of the 7 tilted plane-wave channels. The 16-QAM electrical data signal, carrying a pseudo random bit sequence, is created using an arbitrary waveform generator (AWG) and then modulated on the 1550nm optical carrier using a QAM modulator. Since 7 independently multiplexed channels were required, the optical signal was split between the 7 channels and a relative delay was introduced in order to achieve each to give uncorrelated channels. The delay was introduced by varying the fiber optical path length of each channel Fig. 2. After propagation over the free-space channel, the plane-waves channels are de-multiplexed and a coherent detector is used to analyze the signals. To analyze the system performance constellation plots and error vector magnitudes for all 7 16-QAM channels are acquired with a mean signal-to-noise ratio of 19.5 dB, Fig. 4 (a-g). A measurement of the BER of the system in relation to the optical signal-to-noise-ratio (OSNR) finds that all channels achieved a BER below an FEC limit of 3.8×10−3, Fig.4 (h).

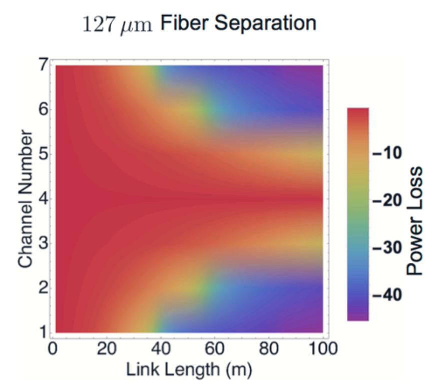

FIG. 5. Modeled channel-dependent loss for up to a propagation distance of 100 m for a set of 7 plane-waves generated by a fiber array with 127μm spacing. Through the adjustment of the fiber separation one can reduce the modal-dependent loss in the system to tune it for a particular operational distance.

Over our 5m link the optical power loss from transmitter to receiver was approximately 11 dB, with a variation of approximately ±1 dB between each channel. We believe that these losses arise partly from the non-ideal single mode fiber coupling, as there is a mismatch between the numerical aperture (NA) of the coupling lens (NA = 0.19) and that of the optical fiber (NA = 0.13). Further sources of power loss could be optical alignment and system aberrations.

Although we used a 5 m link length, a longer length could potentially be implemented. However, as each tilted plane-wave channel is propagating in a slightly different direction, one would likely experience channel dependent power loss. This channel dependent power loss will increase with propagation length, as our truncated plane-waves slowly propagate away from one another and will no longer be fully captured by the receiver aperture. For the system specification given above, a numerical simulation of the channel dependent loss is shown in Fig. 5 for a link length of up to 100 meters;

for the fiber separation of our array, the loss becomes significant beyond 40 meters. A method to potentially mitigate this channel dependent loss is to reduce the separation between the fibers in the array, or alternatively through the addition of further demagnification optics that would reduce the effective separation between the fibers in a conjugate image plane. In doing so, one could engineer an array to suit to a desired link length. However, fibers that are too close together would produce beams that would be difficult to resolve with low crosstalk [12].

The ability to scale the number of channels is an important consideration in assessing a multiplexing technique. The number of supported plane waves could be larger by increasing the numerical aperture of the optical system. Moreover, two-dimensional fiber-arrays could be implemented in an optical system similar to that presented here. Additionally, if fibers can be placed closer together, then longer distances than 5 meters can be achieved. We note that in any free-space optical link atmospheric turbulence issues are a concern, where turbulence could place limitations on the link capacity [9]. The correction of optical aberration arising from turbulence is a common challenge facing astronomical observations, where certain approaches might be applied for correction in free-space optical communications links [20,21,22]. In addition to increasing the number of spatially multiplexed channels one could, with use of suitably achromatic lens at the sender and receiver, implement wavelength based multiplexing schemes [24]. An important consideration when developing systems for free-space communication is the choice of wavelength, as atmospheric conditions could limit the functional range of such a system. In our experimental realization we choose to use 1550 nm as light at this wavelength experiences minimal absorption by water, and lower loses due to Mie-scattering than other commonly used optical communications frequencies [25].

In summary, we demonstrated a 5-meter free-space SDM optical link in which independent channels are transmitted as truncated plane-waves. The system demonstrated 7 channels with a link capacity of 280 Gbit/s. All channels were measured to have a BER below a limit of $3.8\times10{-3}$.

Funding. U.S. National Science Foundation
Royal Academy of Engineering Research Fellowship
EPSRC Doctoral Prize Fellowship

References

1. D. J. Richardson, J. M. Fini, and L. E. Nelson, *Nature Photon.* **7**, 354 (2013).
2. G. Gibson, J. Courtial, M. J. Padgett, M. V. Vasnetsov, V. A. Pas'ko, S. M. Barnett, and S. Franke-Arnold, *Opt. Express* **12**, 22, 5448 (2004).
3. J. Wang, J.-Y. Yang, I. M. Fazal, N. Ahmed, Y. Yan, H. Huang, Y. Ren, Y. Yue, S. Dolinar, M. Tur, and A. E. Willner, *Nature Photon*. **6**, 488 (2012).
4. Y. Yan, G. Xie, M. P. J. Lavery, H. Huang, and N. Ahmed, *Nat. Commun*. **5**, 4876 (2014).
5. R. Ryf, N. K. Fontaine, and R.-J. Essiambre, *IEEE Trans. Commun. Technol.* **24**, 1973 (2012).
6. F. A. P. Tooley, *Proceedings of MPPOI*, 138 (1996) .
7. L J. Camp, R. Sharma, and M. R.Feldman, *Appl. Opt.* ***33***, 26, 6168 (1994).
8. R.K. Kostuk , S. Kemme, and R. Boye, *Proceedings of MPPOI*, 108 (1997).
9. Fengguang Luo, Mingcui Cao, Jun Xu, Anjun Wan, Xinjun Zhou, Xiaoyan Hu, and Tie Wang, Optical Interconnects for Telecommunication and Data Communications, *Proc. SPIE* **4225**, 280 (2000).
10. S. Araki, M. Kajita, K. Kasahara, K. Kubota, K. Kurihara, I. Redmond, E. Schenfeld, and T. Suzaki, *Appl. Opt.* **35**, 8 (1996).
11. J. M. Kahn, R. You, P. Djahani, A.G. Weisbin, B.K. Teik, and A. Tang, *IEEE Commun. Mag.* ***36***, 12, 88 (1998).
12. M. Born and E. Wolf, "Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light", Cambridge University Press, 7th edition 1999.
13. M. Andersson, E. Berglind, and G. Björk, *New J. Phys.* **17**, 4, 1 (2015).
14. R. W. Boyd, B. Rodenburg, M. Mirhosseini, and S. M. Barnett, *Opt. Express* **19**, 19, 18310 (2011).
15. M. Mirhosseini, B. Rodenburg, M. Malik and Robert W. Boyd, *J. Mod. Opt.* **61**, 1, 43 (2014).
16. P.F. Driessen and G.J. Foschini, *IEEE Trans. Commun.* **47**, 2, 173 (1999).
17. I. Sarris and A.R. Nix, IEEE CCSP, 1236 (2005).
18. F. Bøhagen, P. Orten, and G. E. Øien*, IEEE Wirel. Commun.* **6**, 4, 1420 (2007).
19. J. Leach, K. Wulff, G. Sinclair, P. Jordan, J. Courtial, L. Thomson, G. Gibson, K. Karunwi, J. Cooper, Z. J. Laczik, and M. J. Padgett, *Appl. Opt.* **45**, 5, 879 (2006).
20. A. Tuantranont, V. M. Bright, J. Zhang, W. Zhang, J. A. Neff, and Y. C. Lee, Sensors and Actuators A: Physical, vol. 91, pp. 363–372, July 2001.
21. J. M. Beckers, Annual Review Astronomy and Astrophysics, 31, 13 (1993).
22. V. I. Tatarski, Wave Propogation in a Turbulent Medium, McGraw-Hill, 1961.
23. D. L. Fried, *J. Opt. Soc. Am.* **55**, 1427 (1965).
24. C.A. Brackett, *IEEE J. Sel. Area. Comm.* **8**, 6, 948 (1990).
25. E. Leitgeb, M. Gebhart, and U. Birnbacher, *J. Opt. Fiber. Comm. Rep.* **2,** 56 (2005).