Enhancing data rates in graded-index multimode fibers with offset coupling and multiplexing

Kumar Appaiah, Rodolfo Salas, Sriram Vishwanath, Seth R. Bank
Department of Electrical and Computer Engineering
The University of Texas at Austin, Austin, TX - 78712
kumar.a@utexas.edu

Abstract: Offset coupling and DSP based multiplexing techniques are evaluated on silica and plastic multimode fibers of various lengths and operating wavelengths. We demonstrate a $10-28\times$ boost in bandwidth-length product with excellent tolerance to fiber misalignments.

OCIS codes: 060.2310, 060.4510, 060.4230.

1. Introduction

Multimode fibers (MMFs) have been widely deployed over short to medium lengths. While a wide network of legacy MMFs is already in existence, many modern deployments prefer MMFs over single-mode fibers for short links in data centers, supercomputers and even within vehicles, owing to their high tolerance to misalignments. Although data rates through conventional MMFs is limited by modal dispersion, digital signal processing (DSP) and multiple-input multiple-output (MIMO) techniques that leverage spatial mode diversity to increase data rates are a promising path to low energy-per-bit data links [1–3], an essential requirement for future data centers. Mode-group diversity multiplexing is a related technique, although it is limited by fiber dispersion limits [4]. Few-mode fibers and multicore fibers are also gaining relevance for multiplexing in optical fibers [5, 6], but these are specially engineered media that require sub-micron alignment tolerances and coherent detection, making them less suitable for short, inexpensive links. Multiplexing with MIMO, rather than wavelengths in the case of wavelength division multiplexing (WDM), eliminates the need for temperature stabilization of multiple lasers. MIMO in MMFs is implemented using multiple lasers of nominally similar wavelength, and detectors coupled to the fiber facets, possibly with axial offsets, to utilize different spatial modes. In this paper, we characterize incoherent MIMO-MMF links with DSP metrics, and study how launching into, and detecting from the MMF core with an axial offset impacts achievable data rates. The open loop vertical Bell Labs layered space-time code (V-BLAST) and the closed-loop spatial multiplexing techniques were evaluated for silica graded-index MMFs (GI-MMFs) with DFB lasers and VCSELs, and perflourinated plastic GI-MMFs with Fabry Perot (FP) lasers. We observed a bandwidth-length product boost of 10× to 28× over the rated fiber parameters while retaining good tolerance to misalignment, making this an attractive solution to boost data rates over inexpensive short and medium haul MMF links.

2. System description

A schematic of the 4×4 MMF link is shown in Fig. 1. The transmitter consisted of two lasers: 20 dBm 1550 nm distributed feedback lasers or -3 dBm 850 nm VCSELs for the silica case, and 20 dBm 1310 nm FP lasers for the plastic MMF case. Each laser was split as necessary using SMF splitters. For the 4×4 MIMO case at 1550 nm, the four resulting signals were modulated using Mach-Zehnder intensity modulators, whose rf input signals were produced by two arbitrary waveform generators from four quadrature amplitude modulated (QAM) data streams. Mode scramblers were used in the 4×4 case to induce different mode profiles [7] in each arm, and effect modal filtering to differentiate the spatial mode content of each data stream, resulting in improved modal diversity [1, 8]. In the 2×2 VCSEL case, two 850 nm 10 Gb/s VCSELs were directly modulated, and for the 1310 nm 2×2 plastic MMF link, two $LiNbO_3$ intensity modulators were used. For the 2×2 cases, the mode scramblers were bypassed and one optical signal was connected to the offset launch stage while the other went directly to the MMF coupler. After obtaining two signals that were modulated and combined, these signals were further combined by means of an MMF coupler, with one of them directly connected, while the other was connected with an axial offset using a 3-axis nanoprecision fiber alignment stage. For the silica case, the optical signal obtained was then transmitted and received over a 62.5 μm diameter GI-MMF (OM1), whose rated bandwidth-length product was 2 Gb/s-km at 1550 nm and 1 Gb/s-km at 850 nm. The rated

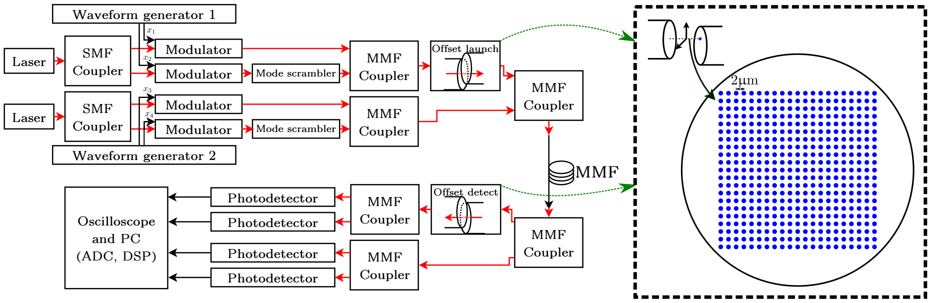
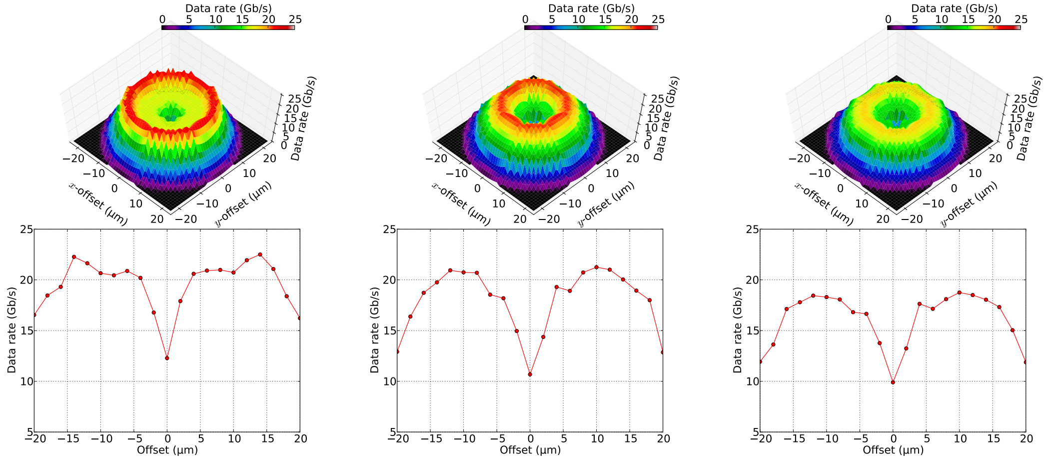


Fig. 1. 4 × 4 MIMO experimental setup. Axial offsets were realized using fiber alignment stages. The MMF couplers were all 2 × 1 couplers. Right inset: Offset positions for the launch and detect stages (square grid of points separated by 2 µm). For the 2 × 2 cases, x_2 and x_4 were left unused.

bandwidth-length of the plastic MMF was 200 Mb/s-km. The receiver consisted of a similar MMF coupler based split, and another nanoprecision fiber alignment stage to facilitate offset coupling to the detector patch cords, connected to 10 Gb/s InGaAs photodetectors, whose outputs were sampled sampled by an oscilloscope. Signal processing was performed offline on a PC. Orthogonal frequency division multiplexing with QAM was used for transmission, and pilot symbols were utilized for channel estimation. Feedback of channel state for spatial multiplexing was realized by using an initial all-pilot symbol to gather channel information tranmitting this estimate to the transmitter.

3. Experimental results

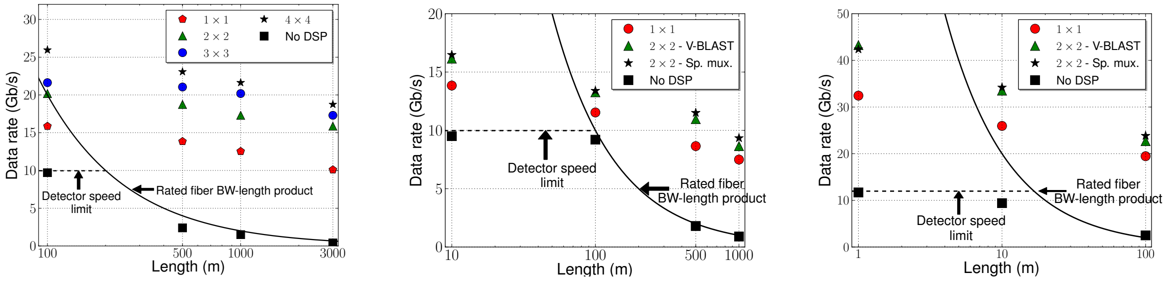


(a) 500 m (b) 1 km (c) 3 km

Fig. 2. Radial variation of achievable rate with detector alignment stage offsets for fixed position of transmitter side alignment stage, in 3-D above and a crossection along a plane below.

Initially, the transmitter side fiber alignment stage (Fig. 1) was fixed to an offset of 15 µm from the fiber axis, and channel parameters were measured by rastering the receiver alignment stage over a grid of positions (shown in inset). The achievable data rate calculated using measured data with the Shannon capacity formula for MIMO channels [1] is plotted in Fig. 2 for 500 m, 1 km and 3 km fiber sections. The maximum data rate falls with increasing fiber length, due to higher losses and dispersion. To achieve 95% or more of the maximum achievable 21 Gb/s for the 500 m case, the misalignment tolerance was ±4 µm, while for the 18.7 Gb/s in the 3 km case, it was ±6 µm.

Next, for each fiber section, the positions of the alignment stages at the transmit and receive ends were rastered across a grid, as shown in Fig. 1. For the offset locations where the best channel quality was obtained, the data rate was evaluated for a BER of 10^{-9} and plotted in Fig. 3. Fig. 3(a) shows the data rates obtained with spatial multiplexing for the DFB laser case over silica MMF. Using 4×4 MIMO with signal processing boosts the bandwidth-length product 28× over the rated fiber parameters. In the VCSEL case, shown in Fig. 3(b), since the lasers possessed large beam sizes, lesser control of modal excitation was possible with offset coupling, and this limited the bandwidth-length product boost to 9×. Fig. 3(c) shows the data rates over plastic MMFs with 1310 nm FP lasers. Here, the performance benefits diminish with increasing lengths, indicating that the multiplexing capabilities of plastic MMFs are poor in comparison to the silica MMFs. This is due to heavy intermodal coupling over relatively short lengths of plastic MMF, consistent with earlier observations of this phenomenon [9, 10]. Thus, the bandwidth-length boost over the rated 200 Mb/s-km is largely due to dispersion compensation rather than multiplexing, and is restricted to about 4× at 1 m and 11× at 100 m in the 2×2 case, while the 1×1 already achieves 2.9× and 10× boosts at these respective lengths.



(a) With DFB lasers

(b) With VCSELs

(c) With Plastic MMF

Fig. 3. The data rate achieved for a BER of 10^{-9} for various media. "Sp. mux." refers to spatial multiplexing with channel state feedback.

4. Conclusion

We evaluated MIMO-MMF channels with silica and plastic GI-MMFs of various lengths and obtained a signal processing based characterization of channel parameters. These characterizations were used to boost the bandwidth-length product of the fibers by up to 28× over the rated fiber parameters using DSP based multiplexing. Future work would consider the use of lasers and detector arrays, and their impact on the design of high-speed MIMO-MMF links.

References

[1] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge Univ Press, 2005.

[2] M. Greenberg, M. Nazarathy, and M. Orenstein, "Data Parallelization by Optical MIMO Transmission over Multimode Fiber with Intermodal Coupling," *J. Lightw. Technol.*, vol. 25, no. 6, pp. 1503–1514, 2007.

[3] K. Appaiah, S. Vishwanath, and S. Bank, "Advanced Modulation and Multiple-Input Multiple-Output for Multimode Fiber Links," *IEEE Photon. Technol. Lett.*, vol. 23, no. 20, pp. 1424–1426, 2011.

[4] C. Tsekrekos, A. Martinez, F. Huijskens, and A. Koonen, "Mode Group Diversity Multiplexing Transceiver Design for Graded-Index Multimode Fibres," in *ECOC 2005*, vol. 3. IET, 2005, pp. 727–728.

[5] M. Salsi, C. Koebele, D. Sperti, P. Tran, P. Brindel, H. Mardoyan, S. Bigo, A. Boutin, F. Verluise, P. Sillard *et al.*, "Transmission at 2x100Gb/s, over Two Modes of 40km-long Prototype Few-Mode Fiber, using LCOS based Mode Multiplexer and Demultiplexer," in *NFOEC 2011*. Optical Society of America, 2011.

[6] B. Zhu, T. Taunay, M. Fishteyn, X. Liu, S. Chandrasekhar, M. Yan, J. Fini, E. Monberg, and F. Dimarcello, "Space-, Wavelength-, Polarization-Division Multiplexed Transmission of 56-Tb/s over a 76.8-km Seven-Core Fiber," in *OFC 2011*. Optical Society of America, 2011.

[7] Z. Haas and M. Santoro, "A mode-filtering scheme for improvement of the bandwidth-distance product in multimode fiber systems," *J. Lightw. Technol.*, vol. 11, no. 7, pp. 1125–1131, 1993.

[8] H. Stuart, "Dispersive multiplexing in multimode optical fiber," *Science*, vol. 289, no. 5477, pp. 281–283, 2000.

[9] S. Golowich, W. White, W. Reed, and E. Knudsen, "Quantitative estimates of mode coupling and differential modal attenuation in perfluorinated graded-index plastic optical fiber," *J. Lightw. Technol.*, vol. 21, no. 1, pp. 111–121, 2003.

[10] X. Quan, L. Blyler, and W. White, "Plastic Optical Fibers: Pipe-Dream or Reality?" in *ACS Symposium Series*, vol. 795. ACS Publications, 2001, pp. 25–34.