Advanced Modulation and Multiple-Input Multiple-Output for Multimode Fiber Links

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***Abstract*—We evaluate the performance of multiple-input multiple-output (MIMO) concepts and their applicability in increasing data rates achievable in multimode fibers. We draw on several MIMO techniques used commonly in wireless standards, and experimentally evaluate their performance benefits to a 3-km multimode fiber link. Using two transmitters and two detectors in concert, with orthogonal frequency-division multiplexing (OFDM), we achieved a data rate of 12 Gb/s, exceeding the fiber's characteristic bandwidth length product by over 20-fold. It is expected that MIMO strategies can provide significant benefits to local and metropolitan area networks in terms of network cost and complexity, power budget, and data rate.**

***Index Terms*—Frequency-division multiplexing, multiple-input multiple-output (MIMO), optical fiber communication.**

I. Introduction

THE majority of present day optical links are based on single-mode fibers, primarily because they obviate the need to handle modal dispersion present in multimode fibers. Modal dispersion is considered an impairment, since the pulse spreading it causes is more pronounced than that due to chromatic dispersion [1], resulting in significantly lower achievable data rates in multimode fibers, as compared to their single-mode counterparts. However, multimode fibers offer several advantages, for example, in terms of alignment tolerances for fiber-coupling, which reduces packaging costs. Here, we show that using signal processing techniques, dispersion can be compensated to enable data rates beyond the bandwidth-distance product limit of the fiber.

To further augment the data rates, we draw from another technique often used in wireless communication, multiple-input multiple-output (MIMO) [2], wherein multiple antennas are deployed at the transmitter and/or receiver, as shown in Fig. 1. Multiple antennas provide more independent paths between the transmitter and receiver, providing more reliable links, thus enabling higher data rates through the link. It is well known that modal dispersion in multimode fibers [3] achieves a similar effect, and provides us an opportunity to apply similar concepts to utilize the modal diversity offered by the fiber.

Although MIMO for optical links has been considered in the past, there have been several factors limiting its adoption in practice. Signal processing has been shown to be effective for combating dispersion in optical links [4]. Coherent Optical MIMO [5] demonstrations have established that MIMO can improve data rates, but the additional requirement of acquiring the original laser carrier in phase at the receiver adds significant cost and complexity. Conventional modulation methods such as Nonreturn-to-Zero coding have been shown to work with MIMO [6], although the spectral efficiency of such modulation schemes is limited [2]. In our work, we propose a simpler approach based on direct detection, and show that, with Orthogonal Frequency Division Multiplexing (OFDM) signaling and signal processing, MIMO provides significant performance improvements in multimode fiber links. While wavelength division multiplexing (WDM) based approaches are effective at increasing data rates through optical fibers links, the cost and complexity of a WDM deployment hinders its adoption in short-range optical networks. Thus, modulation techniques such as OFDM provide a promising opportunity, with deployments able to scale up to several Gb/s real time [7].

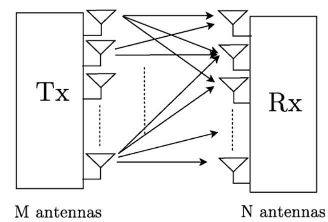

Fig. 1. MIMO: With M transmitters and N receivers.

II. MIMO-OFDM for Multimode Fibers

Wireless links and optical links differ in that they operate in different media and bandwidths, and have several key operational variations. For instance, wireless links are unguided and broadcast in all directions, causing *interference* when multiple links operate at the same frequency in close proximity; this problem is absent in guided media. However, there are some similarities, primarily dispersion in optical fibers and multipath in wireless channels (wherein many copies of the signal reach the receiver at different times).

The concept of MIMO is employed heavily in modern wireless systems, where multiple antennas at the transmitter and receiver are essential to mitigate vagaries of the wireless channel and enhance reliability [2]. Conceptually, each antenna added to a single-input single-output (SISO) wireless system provides an independent link, if it is appropriately spaced from other antennas. These independent links provide additional reliability and the ability to send an increased amount of data through wireless links. In a multimode optical fiber, an effect similar to that of multiple antennas can be achieved by coupling signals from multiple modulators and by using multiple detectors. The independence of the channel arises from the fact that different inputs

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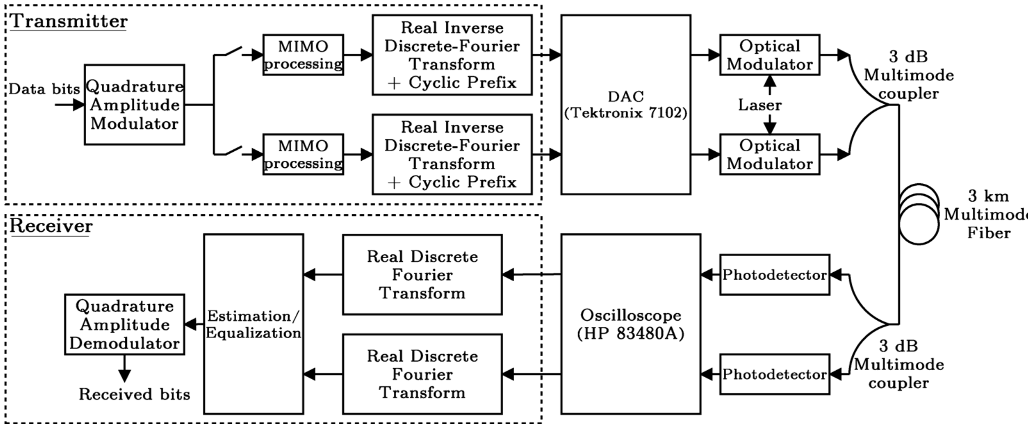

Fig. 2. Schematic of the 2 × 2 MIMO experimental setup: Used for 1 × 2, 2 × 1, and 2 × 2 V-BLAST signaling.

incident at the fiber couple into different fiber modes [3]. This effect, along with intermodal coupling during signal propagation, provides benefits that are similar to wireless MIMO transmission.

OFDM [2] and its variant, discrete multitone modulation (DMT), are the most widely used modulation techniques in both wired and wireless standards today, wherein the data to be transmitted is modulated onto finely spaced frequency bands, called *subcarriers*. The receiver extracts the data from these frequency bands and performs signal processing to compensate for changes which the channel has caused and detects the data. OFDM is the standard modulation technique employed by several communications standards operating at various speeds in different media; ranging from digital subscriber lines (ITU G.992.1) to high-speed wireless standards such as WiMAX and 3GPP Long Term Evolution. This is because of its flexible and robust operation, which simplifies tasks such as estimation and equalization, as well as ease of implementation using the Fast Fourier Transform (FFT). Its widespread deployment, especially in environments where it is useful as a means to combat multipath pulse spreading, suggests that it could also be useful as a tool to combat dispersion in optical fibers [8].

III. System Description

A schematic of the 2 × 1 system setup is given in Fig. 2. We used an optical link, consisting of a conventional distributed feedback (DFB) diode laser operating at ∼1550 nm, connected to two Mach-Zehnder modulators. The signals for the multiple transmit arms were generated as baseband signals, and were fed to the modulators from an arbitrary waveform generator which modulated the intensity of the laser signal. The modulated optical signals were then combined by means of a 3 dB coupler and launched into a 3 km section of conventional 62.5 μm diameter multimode optical fiber, whose bandwidth-length product was rated to be 1 GHz-km. The couplers were conventional off-the-shelf MMF directional couplers that were not specifically designed for the purpose of MMF-MIMO, unlike that in [9]. For a sufficiently high bandwidth-length product, such conventional couplers provide enough spatial diversity for MIMO to be useful. The receiver subsystem consisted of a 1 × 2 splitter, with each output arm connected to a photo detector. An oscilloscope was used to store the received signals, and signal processing and detection was performed offline. The transmit and receive systems were appropriately adapted to support different MIMO configurations (1 × 1, 1 × 2,2 × 1 and 2 × 2; where the two numbers indicate the number of active modulators and photodetectors respectively).

We used a MIMO-OFDM-based modulation approach, as discussed in Section II, with signal processing at the receiver to compensate for dispersion and to coherently combine copies of data obtained at different receivers. Coded OFDM with a cyclic-prefix is a robust and widely used technique, which, along with signal processing, significantly simplifies the task of coherently combining delayed copies of signals obtained in wireless systems due to the multipath propagation effect. In addition, the same signal processing techniques extend themselves in a very simple way for the MIMO case. In our system we use a "pilot-based" estimation and equalization approach, which is used in most wireless standards.

Using the aforementioned setup, we evaluated the performance of MIMO-OFDM in the intensity-modulation and direct-detection based optical link by transmitting and receiving several OFDM symbols and evaluating the bit-error rate (BER). We used a 128-point Discrete Fourier Transform (DFT) with a 5 symbol cyclic prefix, and utilized four equally spaced symbols as pilot symbols dedicated to channel estimation. In order to have real baseband transmit signals, we duplicated and conjugated the data on half of the subcarriers onto the other half, so that the Inverse-DFT operation produced a real output. Bits were generated and modulated to a Quadrature Amplitude(QAM) constellation. These symbols were split into two copies for the purpose of multiple transmitters for MIMO. The two copies were each individually preprocessed and sent out to one of the channels of the arbitrary waveform generator, operating at 10 GS/s. The waveform was generated with an up sampling factor of 2, to facilitate easy recovery at the receiver, with tolerance for timing errors. The collected symbols were then post processed. Pilots were used to estimate all independent channel responses, and this estimate was used to perform equalization to compensate for dispersive effects. Finally, the symbols were decoded and the BER was evaluated.

We performed the experiment in the following configurations to compare performance over a baseline 1 × 1 system:

- A single modulator was activated and two detectors were used, to have a 1 × 2 system. In the two detectors, the pilots were used to estimate the two channel responses, and

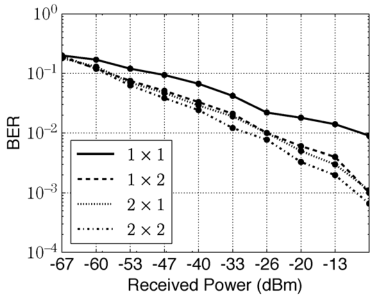

Fig. 3. Measured BER versus SNR for MIMO configurations.

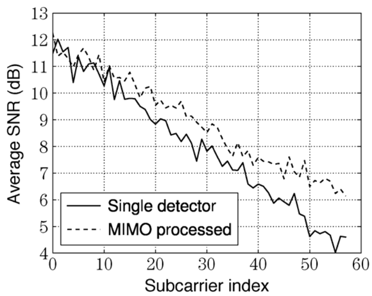

Fig. 4. Processed SNR: With and without MIMO (1 × 2 case).

maximum ratio combining (MRC) [2] was used to combine the two received signals for diversity benefit.

- In the second configuration, both modulators were activated but only one detector was used, to have a 2 × 1 system. Here, in addition to pilots, another layer of complex coding of the symbols with the Alamouti code [2] was used to harness the diversity benefit.
- Finally, both modulators and detectors were activated, to get a 2 × 2 system. Signaling was done in two ways: (1) an Alamouti code was used, much like a 2 × 1 system, and (2) V-BLAST [2] was employed to send two streams of data simultaneously.

For each case, we characterized the modulation scheme with optimal performance for that configuration. For all experiments, of the available 64 subcarriers, 58 are modulated with QAM symbols, the rest being nulled or dedicated to pilots. Reed-Solomon codes of different rates for forward error correction (FEC) were employed to achieve a BER of 10^{-9}.

IV. Results

We first verified that using multiple transmit and/or receive devices provides a lower bit-error rate than the SISO case. For this, we employ a QAM-16 constellation and vary the input power and observe the BER. The observations in Fig. 3, shown for the 1 × 2, 2 × 1 and 2 × 2 cases, show that modal diversity indeed improves performance, though the incremental improvement in the 2 × 2 case is probably due to correlated paths. A sample instantaneous 2 × 2 matrix was observed to be $[0.73+0.31j, 0.34+0.21j; 0.13+0.39j, 0.82+0.08j]$. In addition, viewing the effective average SNR across subcarriers, we are able to observe the improvement in performance with and without MIMO. Fig. 4 shows this benefit for the 1 × 2 case.

Following diversity verification, we performed data transmission experiments with a target BER, and employed FEC with MIMO to meet this target. The transmit laser power was held constant at 25 mW. The summary of the performance results for each MIMO configuration a represented as follows:

- 1 × 1: An uncoded data rate of 8.72 Gb/s is obtained with QAM-16 with BER 1.2×10^{-6}. A coding overhead of 7% yielded an effective data rate of 10^{-9} at 8.11 Gb/s.
- 1 × 2: A QAM-64 constellation yielded an uncoded data rate of 13.082 Gb/s BER of 10^{-5}. 13% FEC was needed to reduce the BER to acceptable levels of 10^{-9} and achieve an effective data rate of 11.38 Gb/s.
- 2 × 1: With Alamouti coding shows a similar BER performance as the 1 × 2 situation, though the requirement of additional pilots along with FEC overheads allowed a lower effective data rate of 10.98 Gb/s for a BER of 10^{-9}.
- 2 × 2: With an Alamouti code and QAM-64, we were able get an effective data rate of 12 Gb/s at a BER of 10^{-9}, since the coding overhead reduces to 8%. With V-BLAST, we were able to send two data streams, one at 8.1 Gb/s, and the other at 2 Gb/s at a BER of 10^{-9} each. The incremental improvement over the previous cases indicates that modal coupling does not provide four completely independent paths, and the correlation among the paths could limit the improvements obtained by increasing transmitters and receivers.

We were able to operate at an effective bandwidth-length product of 22.5 GHz-km; well in excess of the rated fiber characteristic bandwidth-length product of 1 GHz-km [10].

V. Conclusion

We have demonstrated the operation of a MIMO-OFDM based optical communication system, which uses simple direct detection along with signal processing techniques to compensate for modal dispersion. Accounting for (small) overheads incurred due to forward error correction, the effective data rate achieved is 12 Gb/s. Thus, MIMO and signal processing can facilitate reliable communication over multimode fibers, with the operating point well exceeding the rated bandwidth-length product of the fiber by over 20-fold.

References

[1] G. P. Agrawal, *Fiber-Optic Communication Systems*. Hoboken, NJ: Wiley, 1997.
[2] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge, U.K.: Cambridge Univ. Press, 2005.
[3] H. R. Stuart, “Dispersive multiplexing in multimode optical fiber,” *Science*, vol. 289, no. 5477, p. 281, 2000.
[4] B. Schmidt, A. Lowery, and J. Armstrong, “Experimental demonstrations of electronic dispersion compensation for long-haul transmission using direct-detection optical OFDM,” *J. Lightw. Technol.*, vol. 26, no. 1, pp. 196–203, Jan. 1, 2008.
[5] A. R. Shah, R. C. J. Hsu, A. Tarighat, A. H. Sayed, and B. Jalali, “Coherent optical MIMO (COMIMO),” *J. Lightw. Technol.*, vol. 23, no. 8, pp. 2410–2419, Aug. 2005.
[6] B. Thomsen, “MIMO enabled 40 Gb/s transmission using mode division multiplexing in multimode fiber,” in *Proc. Optical Fiber Communication Conf.*, San Diego, CA, 2010, Optical Society of America.
[7] Q. Yang, S. Chen, Y. Ma, and W. Shieh, “Real-time reception of multigigabit coherent optical OFDM signals,” *Opt. Express*, vol. 17, no. 10, pp. 7985–7992, 2009.
[8] W. Shieh, X. Yi, Y. Ma, and Q. Yang, “Coherent optical OFDM: Has its time come?,” *J. Opt. Netw.*, vol. 7, no. 3, pp. 234–255, 2008.
[9] B. Franz, D. Suikat, R. Dischler, F. Buchali, and H. Buelow, “High speed OFDM data transmission over 5 km GI-multimode fiber using spatial multiplexing with 2 × 4 MIMO processing,” in *Proc. IEEE 36th Eur. Conf. and Exhibition Optical Communication*, 2010, pp. 1–3.
[10] Thorlabs Inc., GIF625-1000—0.275 NA Graded-Index 62.5 μm Multimode Fiber.