Vector Intensity-Modulation and Channel State Feedback for Multimode Fiber Optic Links

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***Abstract*—Multimode fibers (MMF) are generally used in short and medium haul optical networks owing to the availability of low cost devices and inexpensive packaging solutions. However, the performance of conventional multimode fibers is limited primarily by the presence of high modal dispersion owing to large core diameters. While electronic dispersion compensation methods improve the bandwidth-distance product of MMFs, they do not utilize the fundamental diversity present in the different modes of the multimode fiber. In this paper, we draw from developments in wireless communication theory and signal processing to motivate the use of vector intensity modulation and signal processing to enable high-data rates over MMFs. Further, we discuss the implementation of a closed-loop system with limited channel state feedback to enable the use of precoding at the transmitter, and show that this technique enhances the performance in a 10 Gb/s MMF link, consisting of 3 km of conventional multimode fiber. Experimental results indicate that vector intensity modulation and direct detection with with two modulators and detectors, along with the use of limited feedback results in a 50% increase over the single laser and detector case.**

***Index Terms*—MIMO, OFDM, multimode fiber, dispersion compensation.**

I. INTRODUCTION

OPTICAL fiber technologies have been the primary drivers of very-long distance high-speed communication, and have been able to sustain extremely high data rates. The low loss and extreme scalability provided by optical fibers have been made possible by several technologies developed and refined in the past few decades, including low loss and dispersion controlled fibers, wavelength division multiplexing (WDM), and high quality lasers and detectors. A majority of this long-haul fiber deployment is single-mode fiber (SMF). The usage of SMF over shorter links, however, is extremely limited, as its deployment can prove to be fairly expensive, due to the high cost of SMF components and fiber alignment complexity. Instead, cost-effective multimode fiber (MMF) is typically used in a large number of cases. For example, multimode fiber represents the majority of the fiber currently deployed in data centers, supercomputing applications, office buildings, and as part of the cellular backbone. However, multimode fibers are typically thought to be constrained in terms of data rates and overall performance as compared to their single-mode counterparts.

Dispersion is the primary physical impairment that limits data rates in optical fibers by broadening data pulses as they propagate through the medium. The spreading of the pulse causes symbols embedded into pulses to overlap with each other (referred to as inter-symbol interference), which imposes a fundamental limit on how fast signaling can be sustained over an optical fiber. One such dispersion component is *modal dispersion*, which is increasingly observed with larger diameter multimode fibers. Physically, this results from different solutions to the wave propagation equations, referred to as modes. While some groups of modes are degenerate and possess identical propagation speeds, most non-degenerate modes (and different mode groups) possess different propagation speeds, causing pulse spreading. For this reason, smaller diameter single-mode fibers, which support only a single mode and entirely eliminate modal dispersion [1], [2] are favorable for high data rate communication. However, the small diameter of single-mode fibers necessitates sub-micron alignment during fiber coupling, which complicates packaging significantly, resulting in higher cost. Multimode fibers, on the other hand, do not need as precise alignment and packaging, making them a less-expensive option and thus popular for many application settings. In this work, focus on a simple technique which allows the use of a modulation technique with multiple sources and detectors in a manner similar to that of multiple-input multiple-output (MIMO) communications techniques, which have revolutionized the physical layer in wireless communication [3] and has proven to be useful in an optical communication context as well [4], [5].

Increasing the data rates supported in multimode fibers has been an active research area for several decades, although the focus has been largely on long-haul related applications. The primary technique employed there to boost data rates is the through the use of wavelength division multiplexing (WDM) over single-mode fibers. Recently, it has been demonstrated that further boosts in data rate can be obtained using multiple modes as degrees of freedom. MIMO techniques have been applied in single mode fibers, utilizing polarization modal diversity [6], [7] and orthogonal band multiplexing [8], [9]. There is also a significant new body of work emerging on the application of similar MIMO techniques to modern optical media, specifically multi-core and few-mode fibers. In particular, there have been recent demonstration of several

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Gb/s to Tb/s data rates achieved over few-mode and multicore fibers. [10]–[14]. The fundamental distinction between these and our work is that these approaches involve MIMO techniques using a coherent communication framework, on new media specifically designed for multiplexing many data streams in order to improve data rate, with a focus on long-haul and ultra long-haul reach. Moreover, there is a large existing deployment of legacy MMF in $\sim$100 m to $\sim$5 km range that can benefit from advanced modulation and multiplexing techniques, such as those considered here [15], [16]. Coarse WDM (CWDM) approaches for increasing MMF data rates have also been considered [17], [18], though they require lasers for each wavelength and corresponding detectors with wavelength selective filtering. However, CWDM and MIMO are technologies that can be used simultaneously, since MIMO for multiplexing utilizes the spatial modes of the fiber over a single wavelength, and can be used for each wavelength employed [19], [20]. MIMO techniques can, therefore, be employed in uncooled CWDM links to further enhance data rates. The use of spatial multiplexing in conventional MMF based links was first considered in [21], where a nominal speed of 50 Mb/s was achieved in a proof-of-concept 2×2 MIMO-MMF link. Subsequently, coherent approaches to MIMO in MMFs have been demonstrated [4], where advanced modulation and detection enabled a data rate of 800 Mb/s. However, this method requires the recovery of the laser carrier and phase at the receiver, making the deployment an expensive and complex proposition for short, inexpensive links. The use of incoherent techniques for multiplexing include mode group diversity multiplexing [22]–[24], square law detection approaches [25], although these approaches are spectrally limited due to their restriction to binary modulation. Theoretical considerations concerning device properties for MIMO on MMFs have been also been studied [26]. In this work, we explore a low-complexity approach to improving data rates over conventional MMFs. We thus restrict ourselves to an incoherent approach using a vector of intensity modulated signals and direct detection for a 3 km MMF link. In addition, by utilizing the fact that channel variations are temporally slow in comparison to data speeds, we experimentally evaluate the utility of feedback for preprocessing the data for improved performance.

The paper is organized as follows: the following section summarizes background material on multimode fibers and signal processing techniques. Section III presents our signal processing methodology for advanced modulation and compensation for modal dispersion and coupling on multimode fiber links. Section IV presents experimental results and Section VI concludes the paper.

II. MULTIPLEXING IN MULTIMODE FIBERS

The large number of orthogonal modes present in a multimode fiber allow for a diversity of spatial paths to propagate in the fiber. However, these modes propagate with different group velocities, which causes pulse spreading which severely limits data rates through these fibers [1]. Owing to the predominant interest in applications involving short or medium haul links, solutions such as WDM impose higher complexities and costs, which are not desirable. Thus, the electronic dispersion compensation is an attractive proposition for multimode fibers. Until recently, advanced signal processing techniques were deemed too slow to match the speeds required for high data-rate optical communication. With recent developments in signal processing hardware and software, such techniques are much more tractable at high data rates [27], [28]. While optical methods of dispersion compensation have been shown to be effective [29], digital signal processing allows for inexpensive and reliable implementation of algorithms and techniques which offer excellent scalability and performance.

Further, research in wireless signal processing, such as MIMO, has matured to a great degree in recent years [3]. In wireless MIMO, relative statistical independence of signal paths between appropriately spaced antennas has been shown to significantly increase the reliability and capacity of the channels. This has enabled several strategies and algorithms to exploit the increased signaling capability by means of efficient signal processing algorithms. The constraints imposed by wireless communication are somewhat different than those of their optical counterparts. For instance, the wireless medium is an unguided medium with strict bandwidth and signaling constraints, and interference from other users that share the same medium. This has motivated the usage of several advanced bandwidth-efficient communication techniques, with several modulation and access techniques such as code-division multiple access (CDMA), orthogonal frequency division multiplexing (OFDM) etc. [3]. The advent of multi-antenna wireless communication has brought with it techniques that harness these gains, such as maximum ratio combining, spatial multiplexing, Alamouti coding and several other space-time coding techniques that aim to improve the robustness of wireless links as well as increase data rates [3]. Recent research on modulation and coding techniques for multimode fibers have also shown the value in exploiting new modulation formats [30], [31] to approach channel capacity and exploit diversity [32], [33] in multimode fiber links.

Advanced signal processing has traditionally not been considered a viable option for optical systems due to low processor speeds, but is quickly becoming attractive owing to reduced costs and increasing speed of processors. In particular, in recent years, Gigabit Ethernet solutions for optical systems have recently been developed based entirely on DSPs [34]. These improvements in speed and cost-effectiveness motivates the development of more advanced signal processing solutions for optical links.

To effectively develop and implement digital signal processing (DSP) algorithms for a vector intensity modulation links, it is essential to arrive at an abstraction of the multimode-fiber in the current context, for modeling all the effects which need to be taken into consideration in order to communicate successfully. In this section, we first present a channel model to describe and encapsulate the pulse spreading caused by the multimode fiber, and extend it to the case where there are multiple transmitters (lasers) and detectors. This assumption is justified since the photodetector facets employed in our systems are of comparable size to the fiber core, thus avoiding the time-variance which is predicted by speckle theory [26]. In our models, we assume that the length of the fiber is sufficiently long so that phases of the pulse arriving at different

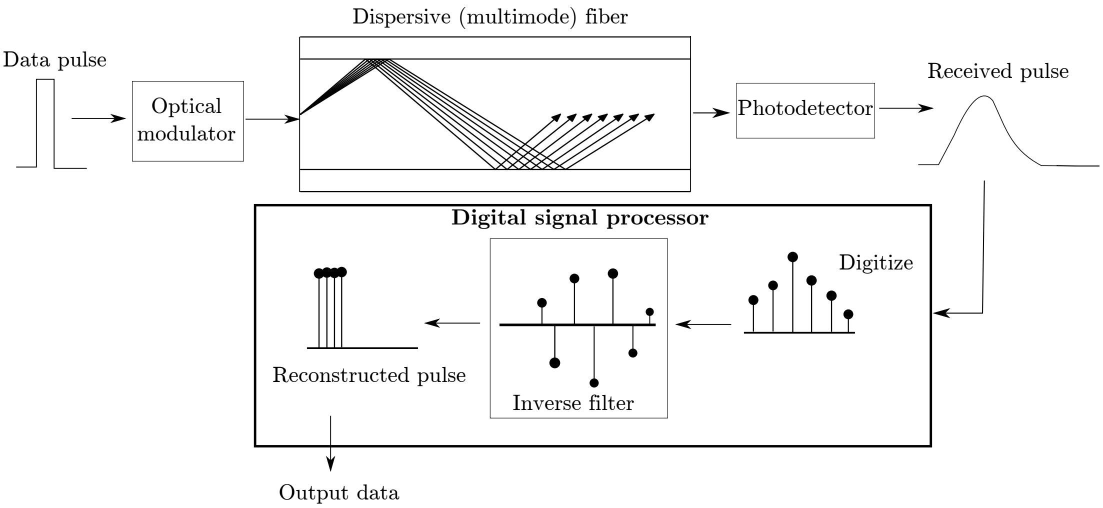


Fig. 1. A schematic of the implementation of digital signal processing for dispersion compensation in a multimode fiber link.

times are uncorrelated [35].

In particular, signal processing allows for techniques such as waveform shaping and advanced modulation schemes which allow for several benefits, including simpler algorithms for dispersion compensation and higher-level modulation for more spectrally efficient signaling [36]. It effectively abstracts the effects produced by various components of the communication system, and converts the problem of recovering the transmitted information into one of computation [37], [38]. With the ever increasing efficiency and reducing costs for computation, DSP implementations are becoming more powerful and cost effective, rendering them ideally suited to solve this class of problems. While the use of linear intensity modulation and direct detection for multiplexing on MMF links is unable to completely compensate for intermodal dispersion, we observe that signal processing based multiplexing is still effective in enhancing data rates at the bandwidths considered [35], both with and without feedback, while maintaining a low implementation complexity.

A. Spatial Effects of Multiple Modes

In this section, we use a channel model to account for the spatial effects caused by transmission through a multimode fiber. As in the earlier case, our model for signal processing is motivated by the channel model for the wireless MIMO case, which we adapt to the fiber channel. We also describe the key differences between these models and how they affects the system design.

1) Comparison of Wireless MIMO and Vector Intensity Modulation: The wireless MIMO channel consists of multiple transmitters and detectors connected to appropriately spaced antennas, which take advantage of the independence in channel properties to improve reliability and multiplexing. While the signal processing techniques applicable to the vector intensity modulation case are similar, there are some key differences which would prove essential in signal design. Figure 2 draws a qualitative comparison between the spatial diversity offered by the wireless channel and the modal diversity in the MMF channel.

The wireless channel model utilizes a heterodyne transceiver system, where the radio frequency (RF) carrier is used to modulate transmit signals, and the receiver locks to this carrier by means of a phase locked loop (PLL), and decodes the transmit information. A corresponding optical system would resemble the system demonstrated in [4], although a PLL was not used at the receiver in that experiment and its effect was simulated by providing the carrier laser signal directly to the receiver for implementation ease. The difficulty in realizing an efficient PLL at laser frequencies causes coherent communication over optical media to be particularly challenging. Practical systems which require carrier recovery at laser frequencies necessitate complex solutions involving tunable lasers with small linewidth drift to permit the use of PLL systems [39].

By contrast, in the vector intensity modulation case, the laser intensity is viewed to be modulated, thus simplifying the carrier recovery process to one of recovering the baseband used for intensity modulation. This utilizes the laser incoherently, thus restricting the modulation index of the data signal. However, it significantly simplifies the carrier recovery process, since only an high-speed baseband signal needs to be recovered from the directly detection received signal. This considerably reduces the complexity of implementing the link, which could potentially lead to much lower cost for implementation. In addition, this also obviates the need to have interferometers and other optical heterodyne components, which would complicate the design and implementation of a short-range optical fiber link. In terms of channel variation and linearity, it must be emphasized that the use of direct detection is inherently unable to coherently combine the impact of variation across individual modes of the fiber, since the impact of individual modes can result in destructive interference. Nevertheless, the experiments presented here emphasize that advanced multiplexing techniques that employ MIMO techniques and feedback result in data rate increases even with a low-cost implementation that does not require coherent detection. Moreover, we also demonstrate that techniques such as feedback based spatial multiplexing are not only applicable,

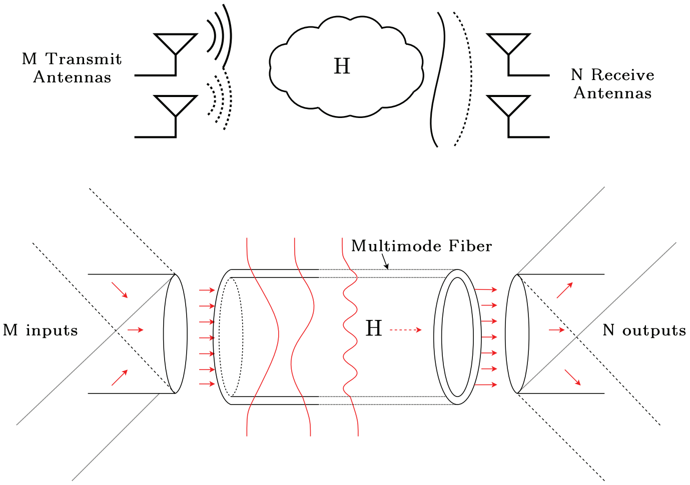


Fig. 2. A comparison of multi-device signaling for wireless and multimode fibers. **H** corresponds to the transfer function that describes transmission through the channel.

but also effective in enhancing the performance of incoherent MIMO-MMF links.

2) Vector Intensity Modulation Channel Model: To arrive at a model for this system, we assume a system with M transmit components (modulators) which can modulate independent signals which can be coupled into the fiber, and N detectors at the receiver. We characterize the system using a matrix transfer function. In order to not depend on modulating different modes independently, we account for the fact that the modes excited by each transmitter may be a superposition of various modes. In addition, due to intermodal coupling, the energy in different modes fluctuate among each other for a sufficiently long distance of propagation. In a linear superposition regime, this process can be accounted for in estimating the matrix impulse response of the system. The validity of this model has been observed experimentally in existing literature in this domain [5], [40]. While this channel modeling approach is limited by the fact that linear intensity modulation and direct detection do not permit extensive modulation of individual fiber modes, the simple approach we take allows for evaluation of the performance of signal processing and multiplexing techniques to enhance data rates while retaining low deployment complexity.

We now present a brief description of the model for a discrete-time vector intensity based channel used to place our system in context. The general input-output relationship as

$$\mathbf{y}[n] = \mathbf{H}[n] * \mathbf{x}[n] + \mathbf{w}[n] \tag{1}$$

where $\mathbf{y}[n]$ is the $N \times 1$ receive intensity vector, $\mathbf{x}[n]$ is the $M \times 1$ transmit intensity vector, $\mathbf{w}[n]$ is the $N \times 1$ noise vector and $\mathbf{H}[n]$ is the $N \times M$ channel matrix, and $*$ refers to the convolution operation. Such an equation resembles the input/output relationship that is seen in conventional wireless MIMO channels. However, since this is an intensity modulation channel, it is not obvious how this channel can be used for complex modulation. Thus, we provide a brief description of how such an intensity modulation channel admits complex modulation. We describe this initially for a 1×1 channel, extend it to allow orthogonal frequency division multiplexing, and finally extend it to the MIMO case.

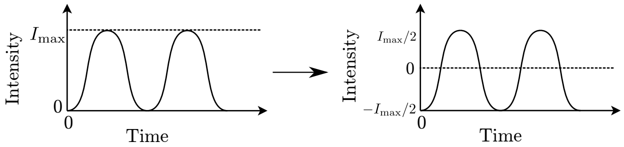


Fig. 3. A transformation to allow non-negative values with intensity modulation. Such a transformation permits all transmitted and received signals to be real signals, rather than purely non-negative signals.

The first assumption is a transformation of the non-negativity constraint. The use of intensity modulation and direct detection causes data to be modulated by varying the power of the optical signal, thus making the transmitted and received quantities are non-negative. To allow for a more conventional view of modulation, as is considered in the rf case, we view the non-negativity as a bias, and recalibrate our axes to allow positive and negative values for modulation. Figure 3 describes an example of this situation, where a signal that varies between intensity values 0 and $I_{\max}$ is viewed, with an offset of $I_{\max}/2$, to be a signal that varies between $\pm I_{\max}/2$.

Following this transformation, we can now transmit real baseband signals, much like modulated signals in the rf case, on each transmitter. We can, thus, transform into an OFDM channel by taking an inverse Discrete Fourier Transform (IDFT) on both sides of Equation 1, with a cyclic prefix chosen based on the dispersion introduced by then channel. Thus, the effective channel under an OFDM that uses N_{FFT} subcarriers can be viewed as:

$$\mathbf{Y}[k] = \mathbf{H}[k]\mathbf{X}[k] + \mathbf{W}[k], \quad k = 1, 2, \ldots, N_{\text{FFT}}, \tag{2}$$

where k denotes the subcarrier index.

Now, in the rf case, an rf carrier is used to modulate the signal before transmission. The same technique can be used here by introducing an rf oscillator that is used to modulate the signal, and a heterodyne reception in rf can be implemented following direct detection at the receiver. However, in our implementation, we do not employ rf modulators and radio heterodyne receivers. Instead, we restrict ourselves to baseband transmission and reception. That, however, means that the baseband signal cannot be complex, and needs to be real. For the OFDM case, this constraint can be met by enforcing the following condition on the subcarriers used:

$$X[N_{\text{FFT}} - k] = X[k]^*, \quad , k = 1, 2, \ldots, N_{\text{FFT}}/2, \qquad (3)$$

where a^* denotes the complex conjugate of a. Thus, the use of complex modulation with baseband OFDM in direct detection systems causes a loss of spectral efficiency by a factor of two, owing to the constraint in Equation 3. In addition, the transformation introduced to avoid the non-negativity constraint, as described in Figure 3, also prevents the use of the dc subcarrier ($X[0]$) for transmission of data. Nevertheless, the use OFDM on intensity modulation/direct detection links has been shown to be effective in enhancing data rates over optical fiber links [28], [31], [41]–[43]. Thus, we chose to implement an OFDM based system to evaluate the performance of MIMO techniques, with and without feedback, in our system. To restrict the signal to within the swing permitted by the intensity of operation, we restricted the modulation index to prevent excessive clipping. Such an approach to limiting clipping, although clipped OFDM has also been shown to be effective in optical systems [44], [45].

With this model, we can develop signal processing techniques to learn the transfer functions which occur due to the transmission medium, and generate dynamic digital compensation to achieve the same in a system that does not employ channel state feedback, where the transmitter has no prior knowledge of the transfer function. The focus of this paper is to develop a closed loop approach to digital dispersion compensation, where some information about the channel transfer function is made available by the receiver to the transmitter in order to perform preprocessing to improve transmission.

III. BEAMFORMING AND SPATIAL MULTIPLEXING IN VECTOR INTENSITY MODULATION LINKS

In this section, we describe the implementation of a feedback based compensation system for vector intensity modulation links. The focus is on estimating the channel properties, adapting the transmitter and receiver dynamically to changes in operating conditions and predistorting the transmit signal to minimize distortion after propagation through the medium. While the concepts discussed are generic, the focus is on orthogonal frequency division multiplexing (OFDM) and discrete multitone (DMT) systems.

Open-loop diversity and multiplexing schemes consist of algorithms which allow the receiver to compensate for the effects caused by the channel without any channel state information being present at the transmitter, while utilizing diversity benefits provided by the channel. This is particularly useful, since it allows operation of the system without a reverse data link between the receiver and transmitter, and thus significantly simplifies the implementation of MIMO-like systems. We skip details on these methods since their evaluation under similar conditions has been covered in prior work [40].

Modulation techniques that use channel state feedback are useful, in that they operate by sharing knowledge on the current channel state with the transmitter. This is an attractive solution when a reverse link is available between the receiver and transmitter. This offers the advantage that the transmitter can predistort the data, which results in improved performance using more appropriate coding suitable to the current channel state. For instance, the available power can be distributed appropriately in the modulators to obtain the best performance benefits offered by the optical link. In addition, performing some of the compensation computations in advance at the transmitter significantly simplifies the algorithms to be used at the receiver. This distribution of computation load could prove useful in designing signal processing algorithms whose speeds need to scale to the high speeds offered by optical fiber links.

In many communication systems, particularly those in which the channel causes distortion of the transmitted signal, an open loop approach to transmission and reception, where no exchange of channel state information occurs between the transmitter and receiver, requires that the receiver learn the channel details accurately. An alternate approach, wherein the receiver conveys some information about the state of the channel to the receiver, significantly improves the performance of the system in several cases [46]. Even in the case of channels which vary with time, as is the case with wireless communication, feedback of channel state at regular intervals within which the channel is assumed to be stationary proves to be useful for transmitter preprocessing [46]. The temporal duration over which the link is considered stationary is termed the *"coherence time"*.

In this section, we discuss issues of feedback of channel state, and describe the closed-loop transmit diversity scheme, viz. beamforming, as well as a feedback based multiplexing scheme called spatial multiplexing.

A. Transmission of feedback information

The most significant issue with feedback of channel coefficients is that of accurately passing the channel state to the transmitter. In general, this is achieved by obtaining an accurate channel estimate, and then feeding it back with much protection in the form of redundancy, since inaccurate channel estimates undermine the utility of this method. While perfect channel knowledge at the transmitter would completely do away with the requirement of additional equalization at the receiver, the complexity in this method rests on providing a sufficiently accurate channel estimate to the transmitter.

Tradeoffs exist on the exact extent of how feedback quality affects data rates, both in terms of the rate at which feedback is provided as well as the quantization details of the feedback [47]. In the optical communication context, the link coherence time is sufficiently large for feedback of channel state to be useful [48], and, since the amount of feedback to be transmitted is a small fraction of the data rate, the extent of overheads incurred are bound to be negligible at the data rates of interest.

In this paper, we restrict ourselves to a simple quantization technique, owing to implementation limitations. We utilize a

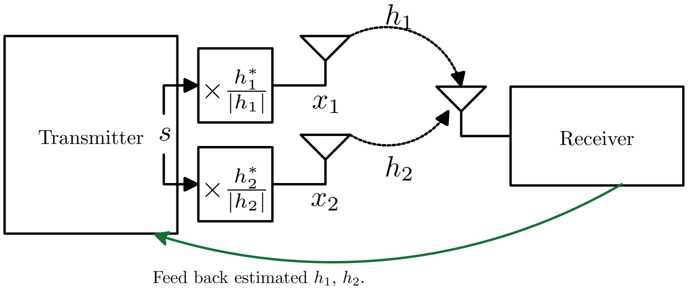


Fig. 4. Maximum ratio transmission.

conventional linear MMSE estimator to find channel coefficients using pilot-based estimation, and feed back the channel estimates directly to the transmitter for preprocessing. As the implementation is OFDM based, we utilize an OFDM symbol all of whose subcarriers represent pilot symbols, calculate the channel coefficients based on this symbol, and feed back these channel coefficients for use in preprocessing. This is done periodically to adapt to changes in the channel parameters. In addition, we also employ a final equalization step to compensate for errors incurred due to noisy channel estimates.

B. Beamforming

Beamforming is a simple scheme by which the transmitter performs a premultiplication on the transmitted symbols in order to align them along the same direction in the complex plane, so as to get the maximum received SNR. In other words, beamforming corresponds to precoding to obtain an equivalent of the maximum ratio combining by using pure transmitter preprocessing.

The aim of precoding in a multiple-input single-output system is to learn the transformation (i.e. distortion) effected by each channel, and use this information to preprocess signals, so that they arrive at the receiver in a co-phased manner to provide the maximum effective signal-to-noise ratio (SNR). In our implementation, we used a variant of the maximum ratio transmission method [49], as is shown in Figure 4, to obtain the best effective SNR. It must be noted that this differs from the conventional approach to beamforming as is used in wireless communications, where the power constraint is over the sum power of the transmit antennas. In the case of optical modulators, since the modulating signals do not need to satisfy a sum total power constraint, the modulating signal sent to each modulator is precoded by altering the phase without affecting the amplitude.

For a simple mathematical justification, consider a 2 × 1 complex-baseband equivalent model representation of a MISO system, with transmitted symbols x_1 and x_2, received symbol y_1, flat-fading complex channel responses h_1 and h_2 respectively and complex additive noise n. The "flat-fading" (i.e., single-tap channel) assumption can be justified since we use OFDM as modulation, which reduces the frequency span of each symbol (subcarrier) to a very small value. Suppressing the OFDM subcarrier number j, the input-output relation is given by

$$y = h_1 x_1 + h_2 x_2 + w, \tag{4}$$

where x_1 is the complex symbol transmitted by the first modulator, x_2 over the second modulator, h_1 and h_2 are the channel transformations from the first and modulators to the receiver respectively, y is the received signal and w is the additive white Gaussian noise. These signals are complex values, as described in Equation 2. If the transmitted data symbols s is precoded, as in Figure 4, by multiplying it with $h_1^*/|h_1|$ to obtain x_1 and $h_2^*/|h_2|$ to obtain x_2 respectively, then the effective input output relation is given by

$$y = (|h_1| + |h_2|)s + w \tag{5}$$

which provides a higher effective SNR than the case of transmission with no preprocessing and predistortion, the factor of improvement being $(|h_1| + |h_2|)^2/|h_1 + h_2|^2$.

In the vector intensity modulation case, the key advantage afforded by the use of beamforming is that the phase of the symbol transmitted on each arm can be aligned to maximize the effective data rate, when channel knowledge is available at the transmitter. Dynamically altering the preprocessing on each transmit arm in such a situation is facilitated with regular feedback and updates on the channel state.

1) Spatial Multiplexing: Spatial multiplexing is a closed-loop multi-stream communication scheme, which allows transmission of $\min(M, N)$ streams across the vector intensity modulation channel, as shown in Figure 5. The method of operation of spatial multiplexing is that the transmitter precodes the transmitted information to align them along the singular vectors of the channel, and the receiver post-processes the received signal to separate the streams. This is facilitated by possessing the channel state information at both the transmitter and receiver. We demonstrate the method using an example for the $M \times N$ case.

We use the input-output relationship given by Equation 1 for the vector channel (adapting it for the narrow band case), and using the singular-value decomposition (SVD), we can expand $\mathbf{H}$ as $\mathbf{H} = \mathbf{U\Sigma V}^*$, where $\mathbf{U}$ is a $N \times N$ unitary matrix, $\mathbf{V}$ is a $M \times M$ unitary matrix, $\mathbf{\Sigma}$ is a $N \times M$ diagonal matrix and * represents the Hermitian transpose of a matrix. $\mathbf{\Sigma}$ is a diagonal matrix which has r non-zero diagonal elements, where r is the rank of $\mathbf{H}$. These non-zero (non-negative) entries (singular-values) are represented as $\sigma_i, i = 1, 2, \ldots r$. Since the singular-value decomposition is unique, possessing the channel information is sufficient to determine $\mathbf{U}$, $\mathbf{V}$ and $\mathbf{\Sigma}$ uniquely. Thus, representing $\mathbf{U}^*\mathbf{y}$ as $\mathbf{y_0}$, $\mathbf{V}^*\mathbf{x}$ as $\mathbf{x_0}$, and $\mathbf{U}^*\mathbf{w}$ as $\mathbf{w}'$, the transmitted streams can be represented in a parallelized form, as

$$\mathbf{y_0}(i) = \sigma_i \mathbf{x_0}(i) + \mathbf{w}'(i), \quad i = 1, 2, \ldots r \tag{6}$$

where $\mathbf{w}'$ is the transformed noise, which has the same statistics as $\mathbf{w}$ owing to $\mathbf{U}$ is a unitary matrix.

Thus, in effect, the channel is parallelized into r parallel channels, with the i-th channel having an effective SNR of σ_i^2/N_0. Thus, r independent data streams can be transmitted. Based on the SNR of each parallel channel, the constellation chosen for each stream is optimized based on the effective SNR of the channel.

While spatial multiplexing is the optimal strategy to transmit multiple data streams, an imperfect channel estimate would

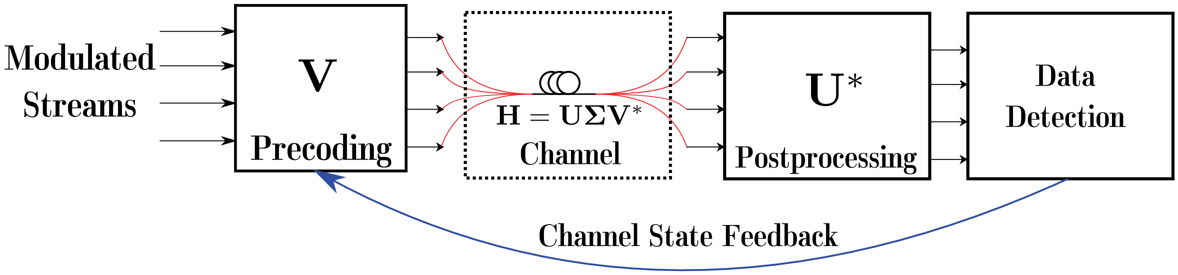


Fig. 5. A conceptual understanding of spatial multiplexing.

result in suboptimal performance. However, an additional channel estimation and equalization step at the receiver is sufficient to recover the data with sufficient integrity. In practice, though, the accuracy of the channel estimates proves important in achieving significant benefits from spatial multiplexing.

IV. EXPERIMENTAL RESULTS

We verify the concepts and ideas detailed in previous sections experimentally in a multimode fiber setup, using various configurations and modulation schemes in order to optimize performance. The experiment is performed with conventional off-the-shelf components to demonstrate the efficacy of the methods discussed in this context.

We initially describe the experimental setup, and follow this up with the generic modulation and coding details. Finally, we present the results of our data transmission experiments, and discuss the implications of our observations.

A. Vector Intensity Modulation Experimental Setup

The system schematic is shown in Figure 6. We employed an optical link consisting of a pigtailed 1517 nm distributed feedback (DFB) laser connected to two JDSU Lithium Niobate Mach-Zehnder modulators. Although we have conducted these experiments with DFB lasers, MIMO techniques can be applied effectively over MMFs using VCSELs, indicating that the approach is broadly applicable [50]. Mach-Zehnder modulators at C-band were used for measuring data rates achievable in these links since this provide a convenient benchmark to evaluate the utility of the techniques discussed in this paper, as in references [4], [5], [24], [51]. The maximum output power of the laser was 13 dBm, and subsequent to splitting and the modulator, the maximum output power from each modulator was about 8 dBm in the cases where the laser signal was split by a coupler (2×1 and 2×2), and about 11.5 dBm from a single modulator for the cases where a single-transmitter was used (1×2 and 1×1), since the power launched from the laser was varied over the same range in all cases to provide a fair comparison. External modulation is utilized due to convenience in building the setup; the techniques discussed would be equally applicable for direct modulation. Transmission through optical couplers induces variations in the signals that are split. The variations are likely due to inherently different splitting ratios and mode-dependent losses and transformations that are introduced with the use of these couplers. Our observation is that signal processing techniques can be used significantly mitigate data rate losses due to these effects. The impact of coherent modal interference can be minimized by using mode scramblers, or by using two different laser sources for the two transmit arms [52]. 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 the 3 dB coupler and launched into the 3 km section 62.5 $\mu\mathrm{m}$ diameter graded-index multimode optical fiber, whose bandwidth-length product is rated to be 1 GHz-km [53]. The couplers used were conventional MMF directional couplers, as in the case of [4]. The receiver subsystem consists of a 1×2 splitter, with each output arm connected to a photodetector, and had insertion losses of less than 1 dB. An oscilloscope is used to store the received signals, and signal processing and detection is performed offline. The feedback link is implemented by using a personal computer to adapt the waveform generated based on periodically measured channel properties. The transmit and receive systems are appropriately adapted to support different MIMO-like transmit-receive configurations (1×1, 1×2, 2×1 and 2×2; where, in each pair, the former number indicates the number of active modulators, the latter the number of active photodetectors which were connected to the system). For the 1×1 case, the splitters at the transmit and receive sides were removed. In the 2×1 case and the 1×2 cases, the splitters were removed from the receive and transmit sides respectively. The data rate was measured by varying the laser power at the transmitter. The bit-error rates are reported in each case versus the total power received at the two detectors (for the 1×2 and 2×2 cases) or single detector (for the 2×1 and 1×1 cases). A standard personal computer was used for signal processing. Some parts of the signal processing, such as the feedback transmission, were performed real time, but the data decoding was performed offline.

The diversity benefits are obtained due to excitation of a multitude of modes by the different modulators, and the sensing of different modes by the photodetectors. This diversity advantage is obtained by the natural asymmetry present in the couplers, as has also been observed in [4], [21]. A more sophisticated implementation could be used to tune and optimize the diversity which could be obtained using specifically designed couplers, but we restrict ourselves to the simplest scenario using off-the shelf components for implementation ease.

In all experiments, the transmit power is the same, since only one laser is used. In other words, if two modulators are

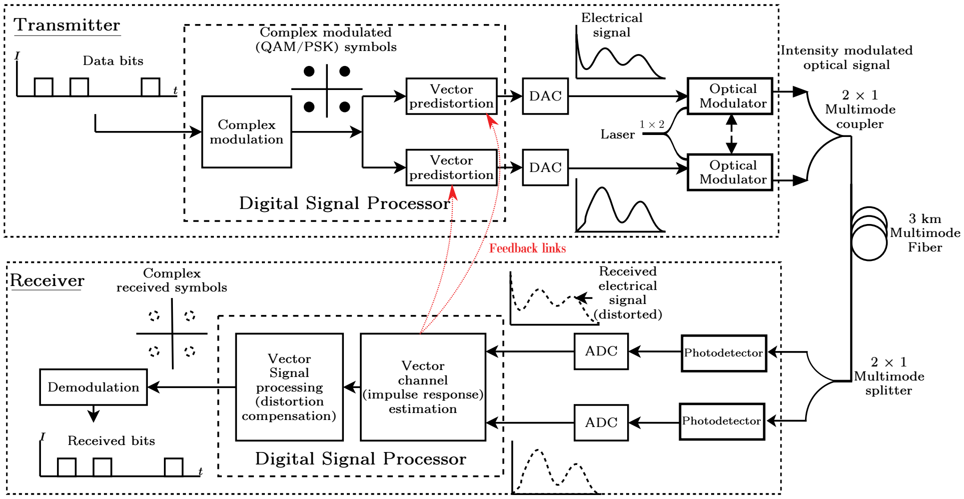


Fig. 6. Schematic of the system used for the experiments.

active, each receives the laser signal split into two components with the same power in each.

B. Modulation and Coding

The concepts described in the previous chapter are sufficiently general and thus applicable to any modulation and coding methods. For the experiments described in this paper, we chose to use coded OFDM, due to its simple and efficient implementation using the Fast Fourier Transform.

Coded OFDM along with quadrature amplitude modulation is used as the modulation technique, with signal processing for dispersion compensation and coherent combination of the symbols obtained from different receivers. OFDM in optical communication with intensity modulation and direct detection has been considered in the past both for coherent approaches [54] and incoherent approaches [55]. Owing to the non-negativity constraint imposed by direct detection of the intensity, we do not use the dc subcarrier to transmit data, and offset the signal to modulate the non-negative intensity of the laser. To estimate the channel, we use a pilot based estimation approach wherein some subcarriers are reserved solely for the purpose of channel estimation. Such simple channel estimation and equalization methods are necessary to scale up algorithm speeds to the high data rates used in optical communication. A summary of the parameters used for the data transmission experiments is presented in Table I. Signal processing is performed offline to recover the transmitted data. To obtain data rates, the best combination of forward error correction (Reed-Solomon codes of appropriate rates) and modulation to yield the highest data rates is utilized. Thus, the data rates reported from the experiments are actual data rates which account for overheads so as to obtain a bit-error rate of 10^{-9} or lower.

C. Feedback and Precoding

In this section, we describe experiments to evaluate the performance of feeding back channel state information to the transmitter, so that precoding can be performed to predistort the transmitted waveform for dispersion and diversity benefits. Channel state information is obtained at the receiver using a pilot OFDM symbol consisting of known values, and the receiver's estimate of the channel is provided to the transmitter for preprocessing further transmitted OFDM symbols. For simplicity of implementation, we feed back the channel estimates directly to the transmitter without sophisticated quantization. Despite this simplification, the results are indicative of what is possible with the use of feedback based precoding. A practical system could potentially perform better when using more sophisticated limited feedback techniques, where much less information feedback is required to achieve a similar performance [46].

TABLE I
OFDM SYSTEM PARAMETERS

Sampling rate	10 GS/s
FFT Size	128
Cyclic Prefix	5
Occupied subcarriers	58
Constellation	QAM-2, 4, 8, 16, 32, 64
Laser wavelength	1517 nm

1) Beamforming: With the above described setup, a QAM-16 constellation was used to transmit a data stream for various input powers, and this was compared to the performance with a single transmitter. Operating the laser at rated power, we employed a QAM-16 constellation and observed a bit-error rate (BER) of 4.5×10^{-7}. By using a Reed-Solomon code for error correction, we incurred an overhead of 5% and achieved an effective data rate of 8.83 Gb/s. The constellations of received symbols are shown in Figure 9. We observe from Figure 9(b) that precoding alone was insufficient to perform complete equalization. As has been discussed in Section III-A, this can be attributed to the quality of the channel estimate fed back to the transmitter, since the estimate could be noisy. However, a simplified estimation and equalization step at the receiver allowed us to recover the data symbols reliably. We emphasize that the utility of the feedback based precoding is in simplifying the estimation and equalization algorithms used at the receiver, as well as in reducing the amount of estimation overhead, which is much larger in pilot based methods for

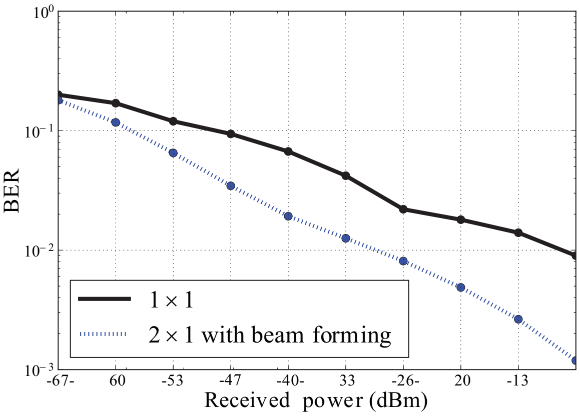


Fig. 7. A comparison of the BER vs. received power for the 1×1 system and the 2×1 beamforming system.

acquiring an accurate channel estimate.

In order to verify the presence of a diversity benefit, we measured the bit-error rate obtained when the optical system is operated in the 2×1 configuration with feedback and beamforming and compared it to the performance of the 1×1 case, and the data is shown in Figure 7. We observe that the slope for the 2×1 system is better than that for the 1×1 system, due to the effective use of the modal properties of the multimode fiber.

Finally, we repeated the transmission experiment with a QAM-64 constellation, and observed an uncoded BER of 4.3×10^{-6} for a transmission rate of 13.98 Gb/s. With an overhead of 9% for a Reed-Solomon error correcting code, the effective data rate observed was 12.60 Gb/s at a BER of 10^{-9}. The operating bandwidth-length product was 15 GHz-km. In order to visualize the utility of the processing technique, the average SNR of each subcarrier is shown in Figure 8 for both the 1×1 case as well as beamforming case. This was obtained by averaging the signal properties over 100 OFDM symbols which were during which channel conditions did not change appreciably. We can infer that the signal processing, indeed, is able to utilize the diversity present in the system. Moreover, the benefits are more pronounced at the higher subcarriers, owing to their presence at higher frequency bands, where the modal dispersion is higher.

2) Spatial Multiplexing: We conducted a spatial multiplexing experiment as described in Section III-A. In this case, the channel information is utilized by both the transmitter and receiver to perform precoding and post-compensation using the singular-value decomposition. Two parallel data streams are transmitted over the 2×2 channel using the SVD technique described in [3]. The amount of overhead required for the feedback is about 100 bits for every 10 Mb of data for the beamforming case, and 200 bits for the spatial multiplexing case, which is less than 0.001%.

The BER vs. received power for each of the two spatial multiplexing streams is shown in Figure 10. The power represented on the x-axis of the figure is the net mean power launched into the multimode fiber. The fact that the 1×1 curve and the first (higher SNR) spatial stream follow a similar trend indicates that we can expect a performance and data rates from the first stream that is similar to a conventional 1×1 link. However, since the second stream offers a higher BER, it is likely to support a lower data rate than the first stream.

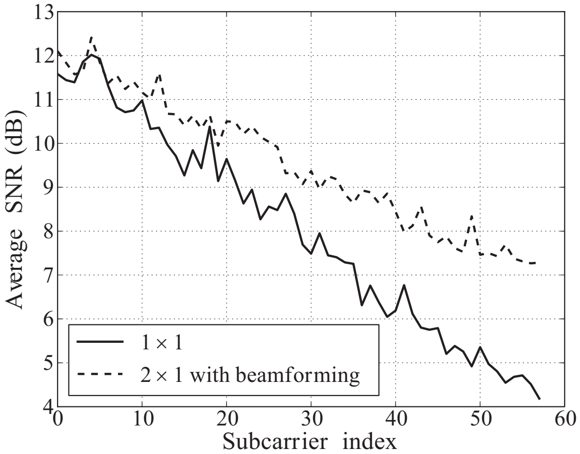


Fig. 8. A comparison of average SNR of the 1×1 and beamforming (2×1) are compared for each subcarrier.

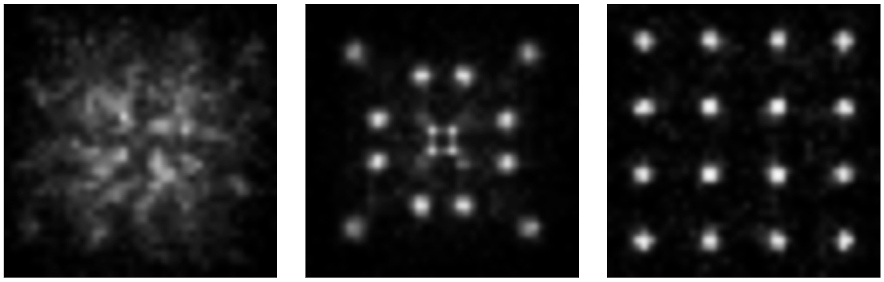
TABLE II
RESULTS FOR SCHEMES WITH CHANNEL STATE FEEDBACK

MIMO scheme	**Data Rate (Gb/s) @ BER** 10^{-9}
1×1	8.11
2×1 (Beamforming)	12.60
2×2 (Spatial multiplexing)	12.2

We observed that the two streams which could be sent at a BER of 10^{-9} were 8.1 Gb/s and 4.1 Gb/s respectively. While this is an improvement over the V-BLAST data rates obtained in [40] under a similar experimental setup, it is not an improvement over beamforming. This can be attributed to multiple causes. First, the modal diversity present in the system is likely insufficient to produce a significant improvement in the 2×2 case, owing to correlation of the paths (this possibility has been alluded to in [35], [56]). This effect is compounded by the fact that the channel estimate passed back from the receiver to the transmitter is not sufficiently accurate to achieve the best possible transmission rate owing to implementation constraints. With a more sophisticated channel estimation and feedback mechanism, this performance is likely to improve. The effective data rates are summarized in Table II.

V. DISCUSSION

In this section, we analyze some of the observations and compare them to theoretical predictions. In particular, we comment on the diversity order observed. It was shown in [40] that the the measured diversity order for the experimental cases is about 1.5, which is less than the ideal diversity order 2. Similarly, the experimentally evaluated performance of the multiplexing methods discussed in [40] is found to be less than that which could be expected in a conventional MIMO system with appropriately similar parameters. This can be attributed to the fact that the system, as is, does not fully leverage all available independent paths, and there is a significant correlation among the modes utilized during transmission [35], [56]. Nevertheless, the performance benefits was obtained without explicit optimization of launch conditions, which indicates the



(a) Unequalized: No precoding (b) Unequalized: precoded (c) After equalizer

Fig. 9. Constellation diagrams at various stages at the receiver.

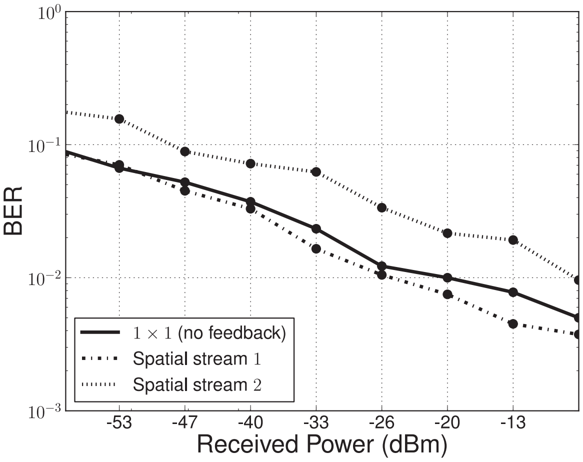


Fig. 10. BER vs. received power for the two spatial multiplexing streams compared with standard 1×1.

simplicity in realizing such systems. The presence of modal diversity can be attributed to the modal dynamics of the MMF which cause variations in fiber characteristics that can be exploited by signal processing techniques such as those discussed in this paper. A detailed theoretical consideration of the mode characteristics can be found in [33], [57]. In addition, we remark that the diversity achieved in this scheme is comparable, or even an improvement, over the diversity achieved in wireless systems, primarily owing to the presence of correlated signals on wireless transceiver antennas.

This experiment was conducted using off the shelf equipment, including conventional MMF couplers, similar to the experiment described in [4], and this is sufficient to exploit the the multiplexing capabilities of the multimode fiber. In order to fully utilize the spatial diversity offered by the system, several methods such as offset launch and multisegmented detectors [23] can be considered to increase diversity. This, along with dispersion compensation by means of channel estimation and equalization could close the gap between the observed performance and theoretical best performance. Implementing a more efficient system using these approaches is a topic for future research.

The feedback mechanisms we use in this paper represents simplistic assumptions on the reverse channel. However, based on the actual coherence time of the optical link, an improved feedback quantization method can be developed, which is tailored appropriately to the requirements of the link in question. By using the best quantization scheme for the optical link in question, the maximum benefit from feedback can be obtained for a given constraint in the rate available from the feedback channel.

The direct detection based approach results in a significant simplification of system implementation in terms of transceiver complexity. The significant advantage of this approach is that it obviates the need to have a laser at the receiver that is matched in frequency and phase to the transmit laser to aid carrier recovery, while also not needing inteferometers and matched detectors, thus making it much more suitable for inexpensive links. Coherent detection is also susceptible to phase noise of the laser, since the phase of the laser carries the modulated data [56]. Since phase shift modulation encodes the phase onto the phase of the laser signal, sudden variations in the laser phase owing to phase noise would cause erroneous detection at the receiver, both in case of PSK modulation [58] as well as advanced modulation such as OFDM [59]. However, in the case of intensity modulation, the signal is carried on an rf carrier or baseband signal modulated onto the laser intensity. Due to the fact that the phase of signals with in the rf range can be maintained with sufficient fidelity at the frequencies of interest to us in this work (10 GHz), intensity modulated communication does not suffer from the phase noise limitation. However, the use of direct detection limits the ability to multiplex effectively through several modes and mode groups of the fiber. Characterizing the limits of multiplexing through multimode fibers using linear techniques and an intensity modulation/direct detection approach is currently under investigation.

Finally, it remains to be seen as to how the performance would scale in practice with more than two devices at the transmitter and receiver from a MIMO and signal processing perspective. Specifically, the modeling and design of optical components with large numbers of lasers/modulators and detectors, and improving signal processing techniques to scale the performance in vector modulation systems is a topic for future research.

VI. CONCLUSION

In this paper, we describe a framework for building a vector intensity modulation system based on multimode fibers. Such a system resembles MIMO as developed for wireless and some optical systems, with a key difference being the use of incoherent intensity modulation in this paper compared to coherent techniques used in conventional MIMO systems.

Modal dispersion is traditionally seen as the bane of fiber optic communication, and considerable efforts are devoted in nulling, canceling and avoiding it through fiber design and other optical means. We illustrate that signal processing techniques can naturally be used to compensate for modal dispersion and, more importantly, that modal dispersion is not a necessarily an impairment for fiber optic communication. The presence of multiple modes results in multiple coupled but distinct paths from source to destination, which can be leveraged using vector signal processing techniques to get significant performance improvements in optical systems. In addition, we use feedback and preprocessing effectively to combat the distortion introduced by the system, and thus allow for flexible implementation of signal processing algorithms. Our experiments revealed that the efficient use of multiple modulators and detectors and signal processing with feedback in MMF links enable data rates in excess of 12 Gb/s over a multimode fiber; exceeding the bandwidth-length product by a factor of 15. Further experiments would involve refining the feedback methods and studying the effect of optimizing coupling conditions via offset coupling and detection of the signals to improve diversity gains in the MMF link.

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