Device Design and Signal Processing for Multiple-Input Multiple-Output Multimode Fiber Links

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ABSTRACT

Multimode fibers (MMFs) are limited in data rate capabilities owing to modal dispersion. However, their large core diameter simplifies alignment and packaging, and makes them attractive for short and medium length links. Recent research has shown that the use of signal processing and techniques such as multiple-input multiple-output (MIMO) can greatly improve the data rate capabilities of multimode fibers. In this paper, we review recent experimental work using MIMO and signal processing for multimode fibers, and the improvements in data rates achievable with these techniques. We then present models to design as well as simulate the performance benefits obtainable with arrays of lasers and detectors in conjunction with MIMO, using channel capacity as the metric to optimize. We also discuss some aspects related to complexity of the algorithms needed for signal processing and discuss techniques for low complexity implementation.

Keywords: fiber optics, signal processing, communication, multimode fiber, MIMO

1. INTRODUCTION

Optical fiber communication has enabled communication at extremely high speeds over long distances, and has allowed for supporting high bandwidth links. The primary impairment which limits data rates over optical fiber links is dispersion induced pulse spreading, which limits switching speeds over such links. Multimode fibers, which permit the propagation of a large number of modes with differing phase velocities, are severely limited by modal dispersion, which is the primary motivation for the use of single mode fibers (SMFs). However, packaging and alignment requirements are more stringent in SMF interconnects, owing to the requirement of sub-micron alignment, while the large core diameter of MMFs does not impose this requirement. Recent research has revealed that MMF links with signal processing has allowed for increasing data rates through multimode fibers. Moreover, it has been established that the use of multiple lasers and detectors can aid in effectively utilizing the multiple modes of the fiber as independent paths, and much like multi-antenna wireless links, the reliability and capacity of the link can be enhanced significantly. In this paper, we discuss theoretical and experimental considerations in implementing such links, as well as their advantages and limitations.

This paper is divided into the following sections: In Section 2, we discuss some research results related to the use of multiple devices, multiple-input multiple-output (MIMO) and signal processing techniques in MMFs, and the potential advantages and benefits of such techniques. In Section 3, we describe an experimental evaluation of some these MIMO and signal processing techniques. In Section 4, we discuss the use of using arrays of devices in MIMO-MMF links. Section 5 provides some concluding remarks.

2. MIMO AND DSP FOR MULTIMODE FIBERS

MIMO and signal processing techniques have been revolutionized wireless communication over the past couple of decades, owing to the phenomenal improvements in data rates and reliability they provide. MIMO techniques aim to utilize statistically independent channel characteristics by means of multiple transmit and receive devices, and, in conjunction with efficient signal design and processing, are able to make use of the inherent "diversity" present within the system for greatly improved performance.

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Several communication strategies over multimode fibers have mostly been within dispersion limits or by means of dispersion avoidance strategies[1]. In order to scale up the data rates in multimode fibers, it is essential to utilize the complete information in data pulses which spread due to dispersion. The fundamental limits imposed by dispersion can be overcome by several strategies, such as using adaptive optics[2] and electronic techniques[3]. In our work, we make use of digital signal processing with advanced modulation, precoding and estimation and equalization techniques to overcome dispersion induced limitations.

Recent research in optical fiber communications has shown that signal processing is indeed a viable option over MMF links. The possibility of utilizing ideas from MIMO for multimode fibers was initially demonstrated experimentally by Stuart[4], using a 50 Mb/s PSK transmission setup with analog equalization. The signal processing employed in this work[4] was simple and the data rates achieved somewhat modest, although it was successful in demonstrating the utility of MIMO communication over multimode fiber media. The use of spatial signal design by means of a spatial light modulator with a feedback link from the receiver to the transmitter has been shown to be a means of realizing similar benefits[5]. More recently, a coherent demodulation MIMO implementation for MMF links has been demonstrated[6,7] as a means of utilizing MIMO over optical fibers. While coherent communication is very effective in useful in reducing the stringent requirements on receiver sensitivity, thereby allowing high data rates, its deployment places a stringent requirement on accurate recovery the carrier signal in frequency and phase. Achieving such carrier recovery for practical systems is complex, expensive and a non-trivial problem for optical systems. Finally, adaptive optics based approaches to dispersion compensation and avoidance have been suggested for altering the transmit spatial characteristics of the signal based on feedback received from the receiver[8]. In addition, a related technique called mode group division multiplexing has also proved to be useful in improving data rates in shorter MMF links with multiple lasers and detectors, while being operated within the dispersion imposed limits[1].

Our experimental evaluation utilizes signal processing using off-the-shelf components, requiring no device/fiber design changes. We use a combination of orthogonal frequency division multiplexing (OFDM) with intensity modulation and direct detection to evaluate a non-coherent optical MIMO system. Our experimental results indicate that we obtain performance that is at least an order of magnitude (10× or more) higher than the bandwidth-length product rating of the fiber. We also evaluate the benefits of feedback to enable preprocessing and improve performance of the link.

Following the experimental evidence, we evaluate further possibilities with the use of arrays of lasers and detectors using a simulation model, and, with the Shannon capacity of the link as metric, characterize the achievable data rates with various configurations of devices. Our results indicate that the use of device arrays enables significant increases in data rates while also making the system robust to alignment offsets.

3. AN EXPERIMENTAL EVALUATION

In order to experimentally evaluate the benefits of MIMO over MMF links, we utilized the experimental setup shown in Figure 1[9]. The optical link consisted of a conventional distributed feedback (DFB) diode laser 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 coupled in 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. At the receiver splitter was used, with each output arm connected to a photodetector. A storage oscilloscope was utilized to store the received signal, and signal processing and detection was performed offline. The transmit and receive systems were appropriately altered 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).

The modulation employed for signal design was orthogonal frequency division multiplexing (OFDM), where a FFT-based preprocessing allows for efficient compensation for dispersion effects at the receiver while also combining copies of data obtained at different receivers. OFDM with a cyclic-prefix and error control coding is a robust and widely used technique which, in conjunction with signal processing, significantly simplifies the task of combining multiple delayed versions of signals obtained in wireless systems due to the multipath propagation effect[10], and has been shown to be useful in optical systems as well[7]. In addition, these modulation and coding

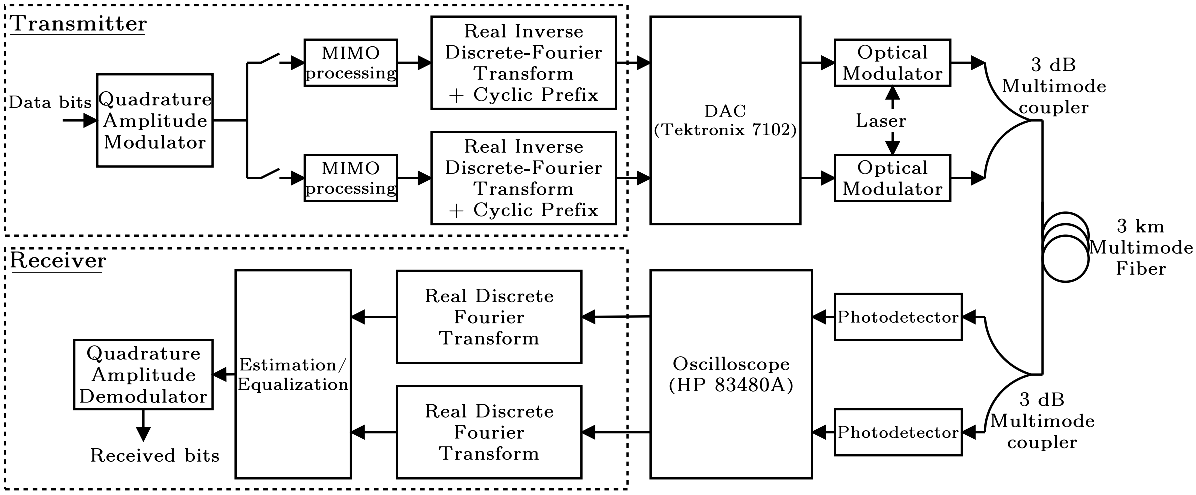


Figure 1. Schematic of the 2 × 2 MIMO experimental setup: Used for 1 × 2, 2 × 1 and 2 × 2 V-BLAST signaling

techniques extend themselves in a very simple way for the MIMO case. In our system we use a "pilot-based" estimation and equalization approach to learn the channel state at the receiver, where the impulse response of the channel is learned periodically by means of training symbols, and this training is used to correct for the changes effected by the fiber channel.

When referring to MIMO systems, it is conventional to represent them in terms of the number of transmit and receive devices in the system. For instance, an $N_L \times N_D$ system is one which contains N_L transmitters and N_D detectors.

The bit-error rate vs. SNR observed experimentally is shown in Figure 2, where it can be seen that the use of multiple lasers and detectors does improve the bit-error rate. The incremental improvement in the 2×2 case is probably due to correlated paths, which is likely an effect of suboptimal launch conditions. With optimized offset launch, improved performance can be expected.

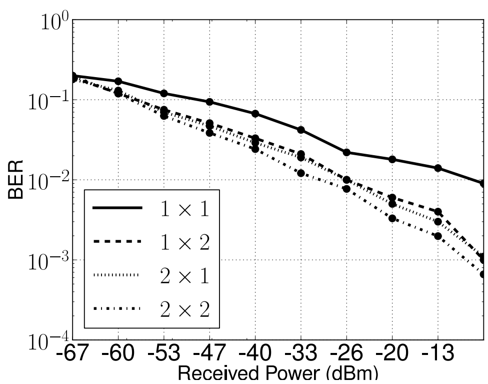


Figure 2. Measured BER vs. SNR for MIMO configurations

In terms of data rates, with appropriate error control coding, the 12 Gb/s could be achieved over the 3 km MMF-MIMO link. This is a 15× improvement over the conventional 1 Gb/s-km. 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[11].

In addition to these, it was also found that the use of feedback to make available channel state at the transmitter enables improved signaling to get a further performance advantage through better preprocessing of the transmit signal.

Motivated by these observations, we consider the case of a much larger number of lasers and detectors specifically to leverage the advantages of MIMO and DSP in MMF links, which leads us to a modeling based approach to design and simulate the performance more advanced MIMO-MMF links.

4. DEVICE ARRAYS FOR MMF-MIMO LINKS

In this section, we consider models to evaluate the potential of MIMO-MMF links with a large number of transmit and receive devices. While it has been established that the use of multiple lasers and detectors in conjunction with signal processing greatly improves the bandwidth-length product of the MMF link, further increases in performance can be expected with a larger number of transmitters and receivers, suggesting the use of compact laser and detector arrays as a scalable alternative to additional discrete components. With the recent advances in nanoscale lasers and detectors[12], such device arrays could prove useful in MIMO systems. With this in mind, we consider two approaches to device arrays in MIMO-MMF links: we first consider the design of an optimal array of lasers and detectors for a fixed fiber link, and then discuss a situation with a fixed array of lasers and detectors with efficient signal processing algorithms to achieve performance improvements with limited complexity.

4.1 MMF Propagation Model

We develop a model for signal propagation through an MMF by adapting the tools developed by Shemirani et al[13] to arrive at MIMO and signal processing metrics which can be optimized. This framework is well suited to analyze propagation through multimode fibers since it uses an electric field propagation based approach that results in a matrix based description for the input-output characteristics of a multimode fiber. It treats modal coupling in a perturbation framework where the perturbing effect is due to bending and twisting of the fiber. Using this model, experimentally observed phenomena have been with predicted with reasonable accuracy[13]. Other models which could potentially be considered for this purpose include the diffusion power flow approach that treats modal coupling as a continuous power diffusion equation along the length of the fiber[14]. This diffusion model assumes that coupling occurs between nearest neighbor modes and accounts for a power loss mechanism with a mode-dependent parameter that is found experimentally[15]. While this approach[14] is suitable for modeling modal coupling, it does not take into account the polarization of the electric field and changes to its polarization by fiber non-idealities.

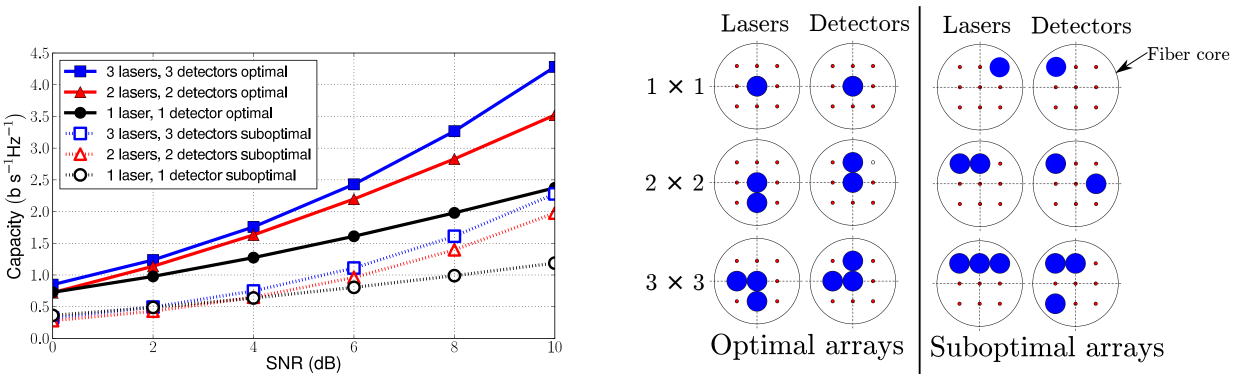
We do not present complete details of this model, but we briefly discuss the development of the input output characteristics obtained from the model, consisting of a laser array, a detector array and a multimode fiber:

- The propagating wave at any point is represented in the basis of the modes of the fiber, as a complex vector, with each vector representing the magnitude and phase of the individual mode.
- The input signal from the lasers is obtained by projecting the fields of the input lasers onto the basis of propagating modes of the fiber by means of the overlap integral.
- The fiber is modeled as a concatenation of many small sections, and each section involves a linear stochastic interaction between neighboring modes of the propagating wave. The interaction of each section is described as a matrix multiplication, the result of which is the modal content vector after propagation, and the combination of all of these modes for the entire fiber describes the transformation effected by the complete fiber.
- The output signal at the detectors is obtained by projecting the output mode vector onto the electric field of each photodetector.

The details of the model can be found in in another paper[16]. Combining the above, we obtain a linear input-output relation describing the transformation from the transmit-end to the receive-end. The metric we use for evaluating the performance of this system is the Shannon channel capacity. While the Shannon capacity provides a theoretical bound on the maximum possible performance obtained from the system, it is a good metric to optimize for, since conventional system implementations are designed to perform as close to the channel capacity as possible, and the achieved data rates and channel capacity display similar trends with increased numbers of transmit and receive devices. With this model, we consider the efficient design and use of laser and detector arrays.

4.2 Design of Laser/Detector Arrays

We initially consider the problem of designing a laser and detector array that is optimal for an MMF link. We constrain the number of lasers and detectors, generate an ensemble of propagation matrices as described in Section 4.1, and evaluate the channel capacity with various laser/detector configurations to obtain the configuration that optimizes the capacity. To restrict the search space for the optimal configurations, we choose a grid of possible locations for the lasers and detectors, and optimize over the possible configurations of devices.



(a) (b)

Figure 3. (a) Calculated capacity vs. SNR for 1×1, 2×2, and 3×3 MIMO systems for the best device configurations. (b) The optimal device configurations in each case. Note that severe penalties (40-50%) are incurred with the use suboptimal configurations.

To determine the effect of device geometries on the data rate, we conducted simulations using the MMF propagation model discussed above. A statistical analysis of 700 system matrices was performed where, each matrix represented a 1 km fiber that was split into 10,000 sections of 10 cm each. The fiber diameter was taken to be 50 μm, core index of refraction was 1.444 and numerical aperture was 0.19. The lasers and photodetectors were 5 μm in diameter and operated in the fundamental mode with a wavelength of 1.55 μm. The devices were restricted to a 3×3 grid of possible placement points on the input and output facets of the fiber for simulation of feasible device configurations.

We denote the MIMO system in each case as $N_L \times N_D$, where N_L number refers to the number of lasers, and N_D the number of detectors. We compared the calculated capacities of a 1×1, 2×2 and 3×3 links. In each case, the total transmit power was assumed to be the same (e.g., for a 3 laser system, each laser would utilize one-third of the total transmit power). Figure 3(a) shows that the capacity increases with an increasing number of devices used for the same transmit power. For a particular number of lasers and detectors, our simulation revealed that device geometries can have a significant impact on data rate. We performed a combinatorial search to find the optimal geometry for each case. The optimal device configurations obtained from the grid search are found on Figure 3(b), and it can be observed that they outperform the suboptimal configurations by a factor of up to 2. Our current research focus is on the use of a finer grid with more devices would allow further improvements owing to a more accurate grid configuration.

4.3 Efficient Utilization of Laser/Detector Arrays

While large arrays of lasers and detectors would allow significant increases in performance of MMF links , such an approach would warrant a prohibitively large amount of signal processing power to enable simultaneous transmission and detection of signals. In this section, we outline a MIMO-MMF link employing laser and detector arrays and we develop a dynamic detector selection method that significantly reduces detection complexity by efficiently selecting a small subset of all the available detectors. We perform simulations of the same, and these indicate that 90% of maximum link capacity can be obtained using only a small fraction all detectors, while requiring only $\sim$2% of the computation required if information from all detector elements is utilized for decoding.

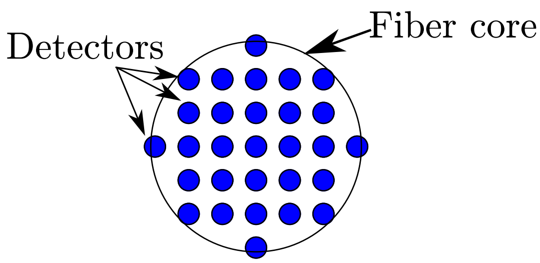


Figure 4. Detector array pattern used for the simulations, overlayed upon a 50 μm fiber core. Photodetectors are 5 μm in diameter, separated by a pitch of 8 μm.

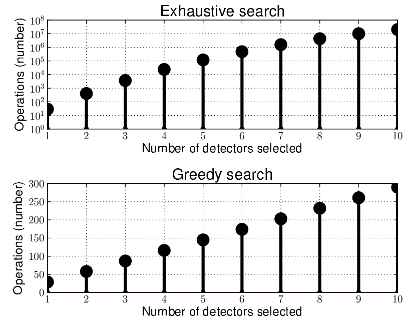
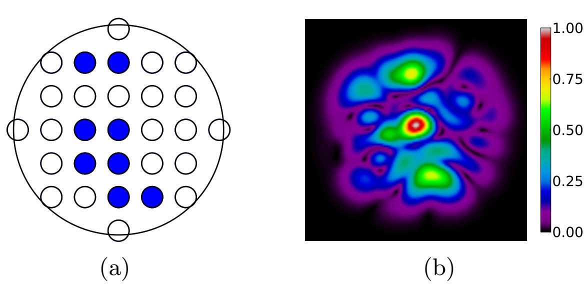


Figure 5. Comparison of the number of arithmetic operations for exhaustive (log scale) vs. greedy search (linear scale).

We begin with the fact that the capacity of an optical MIMO-MMF link satisfies the condition of *submodularity* with increasing number of active detectors[17]. Therefore, by choosing detectors one-by-one in such a way that every additional detector provides the maximum improvement in capacity, called the *greedy* selection algorithm, the achieved data rate can be at most constant factor away from the maximum capacity. Figure 5 compares the number of operations required for the exhaustive and greedy searches. In order to evaluate the performance of the greedy selection algorithm, we performed a simulation of a 1 km fiber link using a matrix model of the MMF[13], 29 lasers and detectors in the configuration shown in Figure 4, and compare optimal and greedy selection of detectors. Figure 6 shows a specific detector subset selection obtained by the greedy algorithm. Averaging over 700 channel realizations, we obtain Figure 7 and we make three observations:

1. Selecting 8 detectors for each channel realizations obtains 90% of the capacity obtainable by using all 29 detectors.
2. The addition of detectors to the "active detector" subset provides diminishing returns.
3. The greedy detector selection achieves within 98% of the capacity that can be realized using the optimal subset of detectors obtained by an exhaustive search. For each channel realization, greedy selection of the best 8 detectors out of 29 requires about 250 comparisons, while processing every megabit of data requires about 2.1% of the computation cost with all 29 detectors. This saves about 98% in total computational cost over using all detectors.



(a) (b)

Figure 6. (a) The optimal subset of detectors (shaded blue) obtained by the algorithm for (b) a particular output modal pattern.

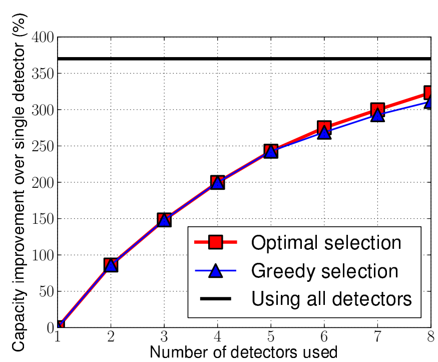


Figure 7. Capacity improvement with selected detectors: optimal (exhaustive) selection vs. greedy selection

5. CONCLUSION

In this paper, we evaluate the benefits of using MIMO and signal processing to improve the bandwidth-length product of multimode fibers, making them more suitable for modern data rate requirements while having the benefits of low cost and complexity deployment. We further develop models of fiber propagation to design and simulate the performance of arrays of lasers and detectors which maximize the channel capacity of the fiber link, and observe that large improvements in data rates can be obtained with such arrays. However, implementing advanced algorithms for large arrays also leads to a significant increase in the complexity of signal processing algorithms, and we propose low complexity algorithms to circumvent this limitation while still obtaining ∼90% of the optimal performance of the link.

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