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Coherent Optical Multiple-Input Multiple-Output communication

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Abstract: We propose and demonstrate the Coherent Optical Multiple-Input Multiple-Output (COMIMO) communication technique. In analogy to the spatial diversity in wireless communication, the concept exploits the modal diversity, inherent in a multi-mode fiber (MMF), to transmit independent data channels through a single fiber without the need for wavelength division multiplexing. Central to the MIMO concept is the requirement for sufficient modal diversity in the fiber. The coherent-optics implementation is the key as it ensures that the diversity requirement is met for practically any fiber length and at any data rate. A 2x2 proof-of-concept COMIMO system is experimentally demonstrated.

Keywords: Optical MIMO, Multimode Fiber, Coherent Communication System

Classification: Photonics devices, circuits, and systems

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1 Introduction

Wireless communication with multiple-input multiple-output (MIMO) has drawn tremendous research attention and experienced rapid commercial development. By increasing the number of transmitter/receiver antennas, MIMO systems are able to take advantage of a rich scattering channel to drastically increase the overall transmission capacity [1]. In other words, instead of trying to mitigate the multipath delay spread which is the traditional problem in wireless transmission, MIMO exploits it to boost the channel throughput. The benefit comes at the expense of greater complexity in signal processing and hardware implementation, but not at the cost of extra spectrum or higher signal power. From an information theoretic perspective, MMF has greater capacity than its single-mode counterpart, provided one can use the various modes as independent communication channels. The inherent high capacity of a multimode waveguide can be utilized, and hence modal dispersion can be avoided, if different data channels excite different modes of a multimode waveguide. To date, however, no practical means have been demonstrated for exciting individual modes and for detecting them separately at the receiver. A true MIMO approach where the modal dispersion is exploited, rather than avoided, is a more powerful solution. In this letter, we extend the true MIMO approach to enable multiple communication channels within a single MMF. The resulting increase in fiber capacity is attained through digital signal processing and does not rely on wavelength division multiplexing [2]. In our approach, coherent optical modulation and demodulation is used to satisfy the critical diversity requirement which would otherwise pose a fundamental challenge against optical implementation of MIMO.

2 Theory

It is convenient to introduce an NxM channel matrix $\mathbf{H}$ to characterize the MIMO system consisting of M transmitters and N receivers with each matrix element H_{ij} representing a complex weighting number indicating the coupling from jth Tx to ith Rx (with an amplitude attenuation and a phase delay). A critical requirement for MIMO to work is a rich-scattering channel with enough transmitter/receiver diversity (spatial diversity) that randomizes $\mathbf{H}$, causing each H_{ij} statistically uncorrelated to each other [1]. This type of rich-scattering environment arises naturally in wireless links due to spreading of radio waves and random reflection off objects, making wireless systems the most promising for MIMO operation.

The baseband input-output relationship for multi-mode data transmission in a MIMO system can be written as (ignoring fiber latency)

$$y_i(t) = \sum_{j=1}^{M} \sum_{k=1}^{Q} h_{ijk} e^{j\omega\tau_k} x_j(t) + n_i(t) = \sum_{j=1}^{M} H_{ij} x_j(t) + n_i(t), \qquad (1)$$

where h_{ijk} is the mode attenuation from jth transmitter to ith receiver via kth mode, Q is the number of modes in the MMF, and $n_i(t)$ is the additive

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white Gaussian noise. If we define the delay spread $\tau_d = \tau_Q - \tau_1$, the product of delay spread (τ_d) and carrier frequency (ω) and the number of modes (Q) will determine the spatial diversity of the channel. The baseband model of (1) can also be represented in the matrix form

$$\hat{y} = \mathbf{H}\hat{x} + \hat{n}, \tag{2}$$

where $\mathbf{H}$ is the channel matrix with complex element $H_{ij} = \sum_{k=1}^{Q} h_{ijk} e^{j\omega\tau_k}$. When Q is large and $\omega\tau_d > 2\pi$, the phase of H_{ij} can be considered a random variable uniformly distributed over $[0, 2\pi]$, and H_{ij} is modeled as a zero-mean complex random number which further implies that the magnitude, $|H_{ij}|$, is a Rayleigh distributed random variable. The narrowband model described above is then termed Rayleigh flat fading which is often considered the worst scenario in traditional single-input single-output (SISO) systems, but ironically is exploited in MIMO systems to increase the channel throughput [3].

If each propagation mode in MMF is regarded as a scattering path in fiber, MMF behaves very similarly to a rich-scattering wireless channel, as shown in Fig. 1. H. R. Stuart [4] noticed this analogy and demonstrated the feasibility of MIMO over MMF in a 2×2 experiment ($N = M = 2$), using the term "Dispersive Multiplexing". Spectral space-time coding over MMF links has also been investigated in [5, 6]. MIMO signal processing requires detection of both intensity and phase information, in contrast to pure intensity detection used in conventional fiber optic links. In [4], RF subcarrier (~1 GHz) modulation with PSK data format was used in the transmitter, followed by recovery of In-phase (I) and Quadrature (Q) RF components

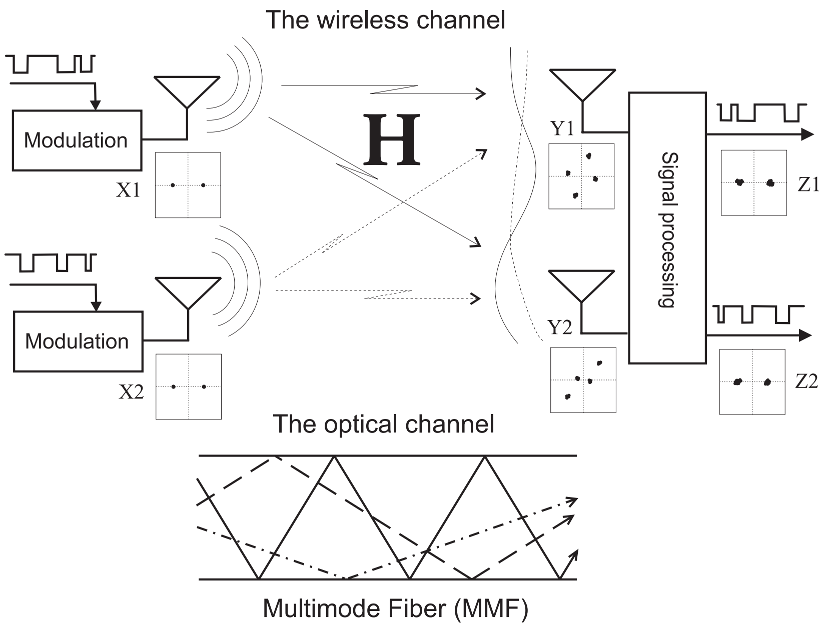

Fig. 1. (a) A 2x2 MIMO communication system. X1, X2, Y1, Y2, Z1, and Z2 represent symbol constellations at different stages. (b) Multimode fiber can also be regarded as a channel with multipath diversity.

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through synchronous RF demodulation in the receiver. The data rate was 1 Mbit/s for each channel. Recalling the diversity requirement ($\omega\tau_d > 2\pi$), the use of RF subcarriers requires a much longer delay spread (longer link length) to ensure enough spatial diversity as opposed to optical carriers, since $\omega_{opt} \gg \omega_{rf}$. For example, when a 1-GHz RF subcarrier is used in a 62.5-μm fiber system operating at 850 nm, independent Rayleigh statistics are realized for fiber longer than ~1 km. In contrast, if an optical carrier is used in a coherent system, sufficient diversity exists even in a 1-mm link. Similarly, for a given length of fiber, the diversity requirement imposes a low frequency limit. For example, using 300 m of 62.5-μm MMF, the diversity requirement is only satisfied for frequencies greater than ~3 GHz. This necessitates upconversion of baseband digital data. On the other hand, using coherent optical communication, the baseband data is already upconverted to the optical carrier frequency (100's of THz), entirely satisfying the diversity requirement.

3 Experiments

As a proof a concept, we have built a 2×2 coherent optical MIMO system operating at 100 Mbit/s, as shown in Fig. 2. A 1545-nm laser output is split into two arms which are BPSK modulated by two independent data streams respectively, using standard $LiNbO_3$ modulators. A MMF directional coupler is used to combine two input arms into a single 62.5-μm MMF before another coupler is used to separate and direct two different outputs to two detectors. Each input is coupled to the MMF with a slightly different modal power distribution. Furthermore, the sequence of MMF launching, connection, combining, and splitting creates a natural tendency for each detector to receive power from both transmitters via a different distribution of modes.

For coherent demodulation, the necessary local laser oscillator signal is derived from the original narrow-linewidth laser source to ensure phase and frequency locking. The transmitted signal, S, and local oscillator, L, are directed into the commercial Lithium Niobate Quadrature optical hybrid which gives two pairs of outputs (1) $S + L$, (2) $S - L$, and (3) $S + jL$,

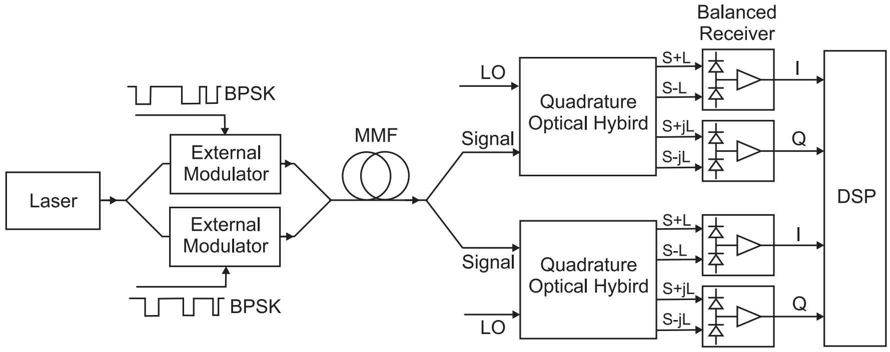

Fig. 2. Block diagram of a 2x2 COMIMO system showing two independently modulated optical carriers and two receivers.

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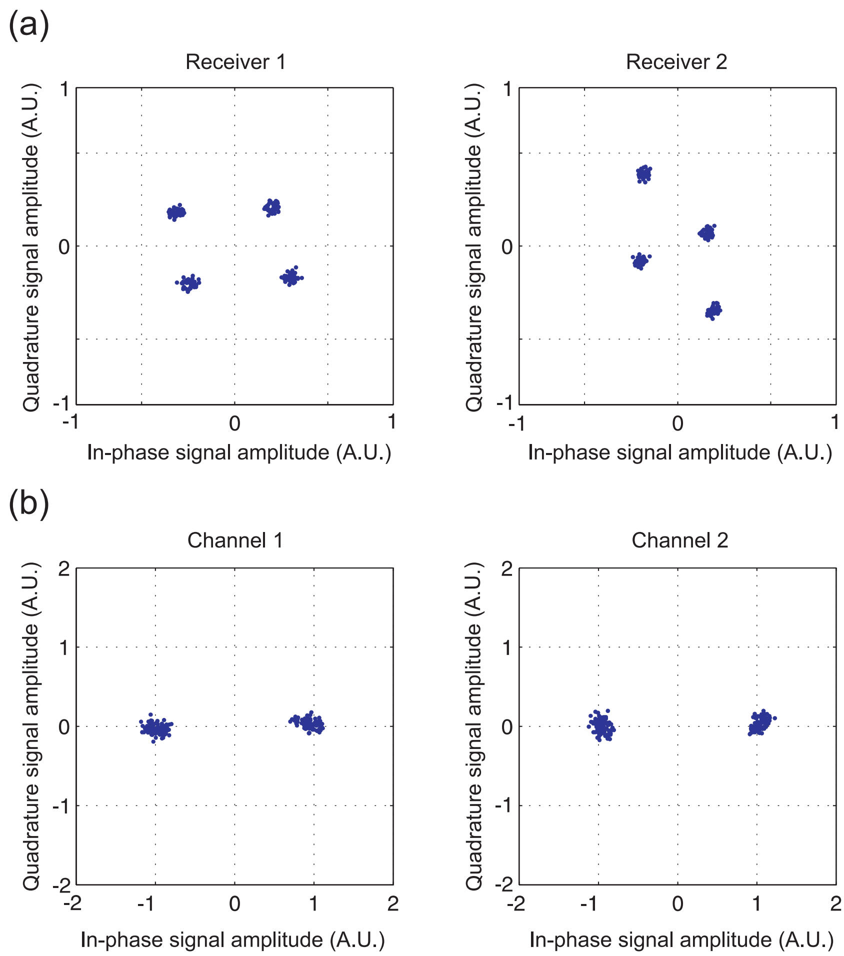

Fig. 3. (a) Meassured constellation diagrams for the two receivers before MIMO signal processing. (b) Measured constellation diagrams after MIMO signal processing, showing error-free recovery of the transmitted data streams.

(4) $S - jL$. (1), (2) and (3), (4) are collected by two balanced detectors. This provides the full signal space information of the baseband signal, i.e. both I and Q components. These are digitized and applied to the signal processing algorithm for MIMO symbol recovery. The system runs at a bit rate of 100 Mbit/s per channel, and all signal processing is done off-line in the computer program. MIMO signal processing consists of two steps: (i) estimating the channel matrix $\mathbf{H}$ using a sequence of training symbols and, (ii) using the channel estimate to recover the transmitted symbols. In this work, we have used the *V-BLAST* MIMO algorithm described in [7].

Figure 3 (a) shows the complete signal space constellations for two receivers in a 2x2 COMIMO system where 100 m of 62.5-μm MMF is used. The four clusters of points in the constellation diagram, corresponding to transmitted symbol pairs $\{1, 1\}$, $\{1, -1\}$, $\{-1, 1\}$, $\{-1, -1\}$, manifest the modal-coupling diversity at the input end of fiber. If sufficient diversity does not exist, the symbol pairs $\{-1, 1\}$ and $\{-1, -1\}$ will overlap in the constellation and will not be distinguishable. The fact that they are distinguishable

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in Fig. 3 (a) is the indication that sufficient transmitter diversity is achieved. Furthermore, modal-coupling diversity present at the output end of the fiber causes the constellations for the two receivers to be different. This clearly demonstrates the required transmitter/receiver diversity in the system for MIMO operation. After applying the MIMO signal processing algorithm, the transmitted data streams are recovered, as shown in Fig. 3 (b). Specifically, the 256-bit transmitted data streams in both channels are correctly recovered. For the present experiment, we have determined that five training symbols are sufficient to obtain an accurate channel estimate and to recover error-free data. The Condition Number of the estimated channel matrix is 1.8 in this example. Such a well-conditioned channel matrix validates the existence of sufficient diversity and the accuracy of symbol recovery.

4 Summary

In this work, we have proposed and demonstrated the concept of Coherent Optical MIMO Communication System. This implementation can tolerate small delay spreads and ensure the necessary modal diversity, independent of fiber length and data rate. In addition, unlike the previously proposed optical MIMO technique, our approach does not require RF subcarrier modulation.

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