Capacity Enhancement in Coherent Optical MIMO (COMIMO) Multimode Fiber Links

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***Abstract*— In this paper, we study a coherent optical MIMO (COMIMO) multi-mode fiber link proposed for enhancing the fiber information capacity. We examine the statistical characterization of the equivalent MIMO channel and the improvement in the fiber capacity due to MIMO transmission. It is shown that the equivalent channel behaves similarly to a complex Gaussian MIMO channel, suggesting that the available results on wireless MIMO communication systems can be applied to optical fiber links for capacity enhancement.**

***Index Terms*— Optical MIMO, coherent optical communication, channel capacity, channel statistics.**

I. Introduction

MULTIMODE fiber (MMF) links provide the necessary bandwidth for shorter length applications at much lower expense than single-mode fiber (SMF) solutions [1], [2], mainly due to the ease of optical alignment, packaging, and cost. In MMF, however, the signal on each of the fiber modes propagates down the fiber with its own distinct velocity and thus, causes inter-symbol interference (ISI). This so-called modal dispersion limits the maximum data speed for a fixed length of fiber. Therefore, a throughput enhancement in existing MMF links can introduce new applications such as fiber-based 10Gbps local area networking (LAN), ultra high throughput fiber interconnects for data storage centers, and multimode planar waveguides with application in optical printed circuit boards for backplane interconnects.

If each guiding mode is regarded as a scattering path, MMF behaves similar to a wireless channel (see Fig. 1). Based on this analogy, the concept of multiple-input-multiple-output (MIMO) transmission used in wireless communications can be applied to MMF channels. The key feature of optical MIMO is that it makes use of the modal dispersion in MMF, rather than avoids it. In [3], RF subcarrier ($\sim$1 GHz) with PSK data format was used for transmitter modulation, followed by optical intensity detection and RF coherent demodulation at the receiver. The use of RF sub-carriers requires a long length of MMF to ensure enough modal diversity. Additionally, due to its incoherent nature, phase modulated transmissions such as optical QAM constellations are not supported. To address both these issues, a coherent optical MIMO MMF link was proposed and demonstrated in [4]. Once coherent optical transmission is used, the requirement on the fiber length is significantly reduced (roughly, by the ratio of the RF subcarrier frequency to the optical carrier frequency). This eliminates the length requirement and allows for transmission of any QAM constellation due to its coherent nature. Furthermore, the issue of inter-symbol-interference (ISI) in the context of MIMO transmission due to the multi-mode nature of fiber is studied and addressed in [5].

However, the promised linear increase in MIMO capacity versus the number of transmit-receive antennas is achieved only when the channel elements have identical and independent complex Gaussian distributions. The required transmitter/receiver diversity for MIMO operation is realized by each transmitter launching light into MMF with a different modal power distribution, and furthermore, each receiver gets power from all the transmitters via a different distribution of modes. The temporal and spatial statistics of the optical MIMO channel as well as achievable MIMO channel capacity have not been studied in any of the previous works [3], [4], [5]. This paper investigates the statistics of the equivalent MIMO channel in a practical set-up. Such statistics are crucial in quantifying the achievable capacity.

The capacity enhancement is made possible through MIMO signal processing at the receiver. This processing is performed in the digital domain through a VLSI implementation. There are two advantageous factors in support of using digital processing in optical systems. In contrast to portable wireless systems, power consumption due to increased complexity is not an immediate concern for optical systems. Furthermore, the increase in cost due to MIMO signal processing is tolerable in comparison to the high cost associated with the optical components used in the system. Moreover, VLSI implementations of signal processing algorithms benefit from Moore's law and technology scale down and represent a cost-effective approach to improve the optical system's performance.

II. Channel Model

A conceptual representation of MMF channel is depicted in Fig. 1. Using an FIR model for the MMF channel, the input-output relationship for a SISO MMF system can be written as

$$y(t) = \sum_{k=1}^{Q} h_k e^{j\omega_c(t-\tau_{pk})} x(t-\tau_{gk}) + v(t) \qquad (1)$$

where $x(t)$ is the baseband transmitted data modulated with a carrier frequency of ω_c, Q is the total number of guiding

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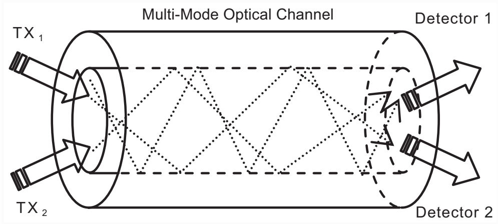

Fig. 1. Propagation inside a MMF and the coupling into and out-of fiber.

modes in MMF (an equivalent to multipaths in wireless channels), h_k is a complex number representing the gain on the kth guiding mode, τ_{pk}, and τ_{gk} are the phase and group delay associated with the guiding mode, respectively. Assuming that the above sum is written in order of ascending delay, the phase delay spread is defined as $\Delta\tau_p = \tau_{pQ} - \tau_{p1}$ and the group delay spread as $\Delta\tau_g = \tau_{gQ} - \tau_{g1}$.

Now consider a MIMO system over MMF with M transmitters and N receivers, the input-output relation can be written as

$$y_i(t) = \sum_{j=1}^{M}\sum_{k=1}^{Q} h_{ijk} e^{j\omega_c(t-\tau_{pk})} x_j(t-\tau_{gk}) + v_i(t) \tag{2}$$

where $y_i(t)$ is the signal received by the ith receiver and h_{ijk} is the channel gain from the jth transmitter to the ith receiver through the kth mode. When the group delay spread ($\Delta\tau_g$) is small compared to the symbol period, all paths arrive at approximately the same time compared to the symbol period, i.e., $x(t-\tau_{gk}) \approx x(t-\tau_g)$, for $k = \{1,\ldots,Q\}$. This is the case when the fiber is shorter than a certain length. Then a sampled (at rate $1/T_s$) baseband equivalent of (2) can be written as

$$\mathbf{y}(n) = \mathbf{H}\mathbf{x}(n) + \mathbf{v}(n) \tag{3}$$

where

$$\mathbf{y}(n) = \begin{bmatrix} y_1(nT_s) \\ \vdots \\ y_N(nT_s) \end{bmatrix}, \quad \mathbf{x}(n) = \begin{bmatrix} x_1(nT_s) \\ \vdots \\ x_M(nT_s) \end{bmatrix} \tag{4}$$

and the ith and jth element of $\mathbf{H}$ is given by

$$\mathbf{H}_{ij} = \sum_{k=1}^{Q} h_{ijk} e^{-j\omega_c\tau_{pk}} \tag{5}$$

When the number of modes Q is large, the elements of $\mathbf{H}$ will have a complex Gaussian distribution, with Rayleigh distribution for their amplitude–see Sec. III. Furthermore, if independent sets of modes are excited by different transmitters and the receivers detect signals independently, then the elements of $\mathbf{H}$ will be independent as well. It is known that these two conditions result in the maximum MIMO capacity given a constant transmit power [7].

A major difference between the coherent and non-coherent optical modulation is in the value of f_c in (2). While f_c is in the order of hundreds of Tera-hertz in the case of coherent optical implementation [5], however, this value is in the order of multiple Giga-hertz in an RF subcarrier intensity modulation [3]. A large value of f_c guarantees that the phase term $f_c\Delta\tau_p \gg 1$ spans the entire range of $[0, 2\pi)$ even for small values of $\Delta\tau_p$ (corresponding to short fiber lengths), ensuring the term $\mathbf{H}_{ij}$ is a random complex Gaussian variable.

III. COMIMO Channel Statistics

The spatial and temporal statistics of the channel matrix determine the MIMO channel capacity. The linear increase in MIMO capacity versus the number of transmit-receive antennas holds only if the elements of $\mathbf{H}$ are identically and independently distributed complex Gaussian variables [6].

To quantify the achievable capacity we use an industry-standard tool (RSoft's LinkSIM) for modeling multi-mode fiber links. In this set up, two independent streams of BPSK data are coherently modulated by two different lasers and transmitted through a multi-mode fiber. At the receiver, two receivers are used to collect the received data, which in general are complex valued. The transmitted and received streams of data are then used as training data to estimate the equivalent MIMO channel in a least-squares fashion. This channel is then used to evaluate the channel capacity. This experiment is repeated over many channel realizations to obtain the statistics of the channel. The results from the simulator are highly accurate since they include the details of mode launching from the laser into the fiber and the propagation behavior of each mode within the fiber. The simulator also takes into account the details of power coupling from the fiber output to photo detectors. The measurement is repeated for different laser launching conditions at the transmitter to provide different random realizations of the channel. The set-up environment is as follows: laser wavelength of 1550nm, multi-mode fiber with core diameter of size 62.5μm (corresponding to a total of $Q = 76$ possible modes), fiber length of 300m, and transmitted block length of $P = 128$.

A. Channel Statistics

An important characteristic of MIMO channels is the probability distribution function (PDF) of the channel elements. The channel model investigated in many MIMO system analysis use i.i.d elements with complex Gaussian distribution. Fig. 2 shows the histogram (or PDF) of the amplitude of the elements in $\mathbf{H}$ compared to an ideal complex Gaussian variable[1]. This plot confirms the assumption in Sec. II that with a large number of modes (Q) and for typical values of f_c in coherent optical link (in the orders of hundreds of Tera-Hertz), the elements of $\mathbf{H}$ will have a complex Gaussian distribution.

B. Average Capacity

Using the channel estimates from the previous section, the channel capacity is evaluated for every channel realization and the result average capacity versus SNR is shown in Fig. 3. Since the channel in fiber varies at a relatively slower rate compared to the data transmission rate, sending the estimated channel state information (CSI) back to the transmitter is feasible. Therefore, we evaluate the channel capacity for the following two different scenarios:

[1]We have calculated the maximum likelihood estimate of the parameter of the Rayleigh distribution given the measurement data.

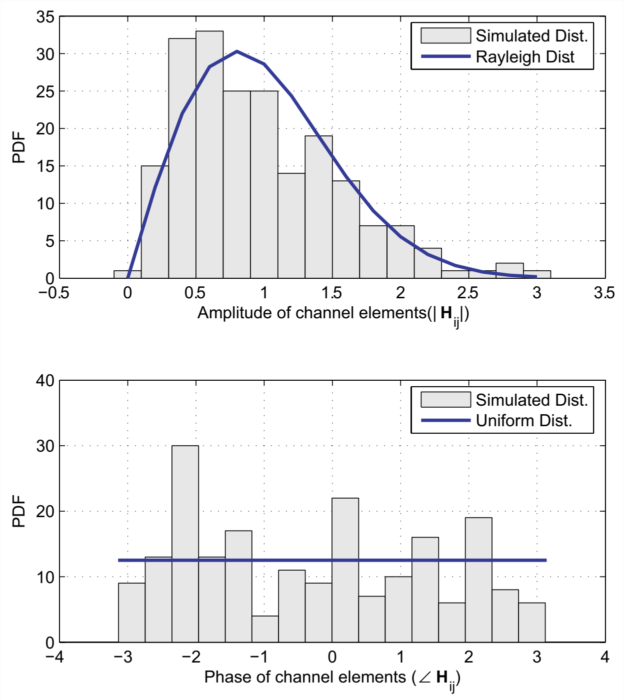

Fig. 2. Probability distribution function (PDF) of the amplitude and phase of MMF channel elements compared to a complex Gaussian distribution.

1) **Informed Transmitter** (CSI available at the transmitter): The channel capacity per hertz for a fixed channel matrix realization $\mathbf{H}$ is given by

$$C(\mathbf{H}) = \log_2 \left| \mathbf{I} + \frac{1}{\sigma_v^2} \mathbf{H}\mathbf{R_x}\mathbf{H}^* \right| \tag{6}$$

where $\mathbf{R_x}$ is the covariance matrix of the transmitted data and σ_v^2 is the variance of the noise in $\mathbf{v}$. Among all possible choices for $\mathbf{R_x}$ with constant $\mathrm{Tr}(\mathbf{R_x})$, the waterfilling scheme maximizes the capacity [7].

2) **Uninformed Transmitter** (CSI not available at the transmitter): The ergodic channel capacity per hertz is given by

$$C(\mathbf{H}) = \mathsf{E}_\mathbf{H} \left(\log_2 \left| \mathbf{I} + \frac{1}{\sigma_v^2} \mathbf{H}\mathbf{R_x}\mathbf{H}^* \right| \right) \tag{7}$$

Assuming i.i.d. complex Gaussian elements for $\mathbf{H}$ and subject to a total transmitted power constraint, it can be shown that the ergodic capacity is maximized when $\mathbf{R_x}$ is a multiple of identity.

The capacity of a 2×2 MMF system is plotted for both informed and uninformed scenarios in Fig. 3. For comparison purposes, the capacity of an equivalent 2×2 system with i.i.d. complex Gaussian elements is also shown in Fig. 3. As expected, there is a degradation in capacity in the case of simulated MIMO MMF compared to the ideal i.i.d. complex Gaussian case. This is mainly due to the fact that there is some correlation between the channel elements in $\mathbf{H}$ in practice. Such correlation is a result of the fact that some common guiding modes are excited by both transmitters. Note that no attempts were made to optimize the launching conditions in order to minimize the dependency between the channel taps. This is in line with the observations in wireless systems

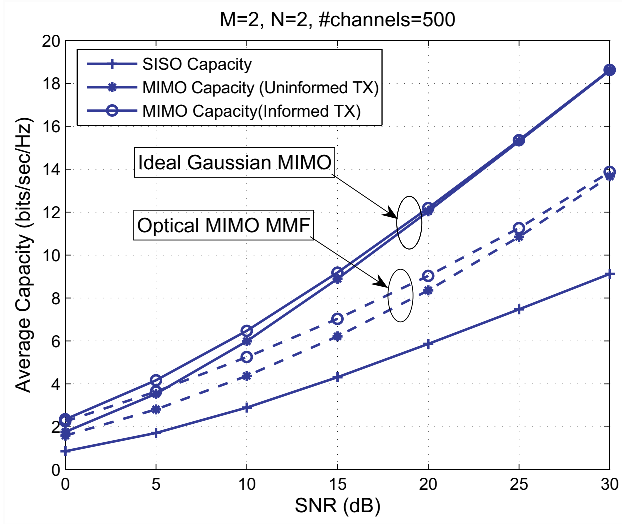

Fig. 3. Average capacity versus SNR comparing a SISO channel with a 2×2 MIMO channel compared for two scenarios: an ideal complex Gaussian channel and the simulated MIMO MMF channel.

where the capacity is degraded due to correlation between antennas. An interesting observation is that the capacity of the correlated optical channel approaches that of the uncorrelated channel as the SNR decreases. This effect is consistent with the results reported in the literature on correlated wireless channels. Similar capacity results were achieved for different fiber diameters, or equivalently, fiber modes.

The following conclusions can be made according to the results in this section. The elements of the equivalent baseband COMIMO MMF channel behave sufficiently close to a complex Gaussian distribution. This paves the way to apply the existing rich body of wireless MIMO communications in the literature to optical systems.

IV. Conclusion

We examined the statistical characteristics of the MIMO channel and capacity for the proposed coherent optical MIMO multi-mode fiber links. It was shown that the equivalent channel behaves similar to a complex Gaussian channel and the achievable improvement in channel capacity was evaluated and compared to the ideal case.

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