Fundamentals and Challenges of Optical Multiple-Input Multiple-Output Multimode Fiber Links

Alireza Tarighat, Rick C. J. Hsu, Akhil Shah, Ali H. Sayed, and Bahram Jalali,
University of California at Los Angeles

ABSTRACT

In this article we discuss the application of MIMO processing to multimode fiber links. MIMO processing is shown to increase the information capacity of communication links linearly as the minimum number of transmitters/receivers increases. The fundamentals of optical MIMO fiber links are presented, and the promises and challenges of such systems are elaborated.

MOTIVATION

Multimode fiber (MMF) links are widely implemented in current high-speed local area networks (LANs) [1]. They can provide the necessary bandwidth for shorter-length applications at much lower expense than single-mode fiber (SMF) solutions, mainly due to the ease of optical alignment and packaging. In MMF, however, the signal on each of the fiber modes propagates down the fiber with its own distinct velocity and thus causes intersymbol interference (ISI). This so-called modal dispersion limits the maximum data speed for a fixed length of fiber. Thus, MMF links are considered to be dispersion limited rather than noise limited. However, a throughput enhancement in existing MMF links can support new applications such as fiber-based 10 Gb/s 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 different data channels could be established independently by exciting different modes of a multimode waveguide, higher throughput could be achieved, and hence modal dispersion could be avoided. To date, however, no practical means has been demonstrated for exciting individual modes and detecting them separately at the receiver. Although it seems that little can be done about the inherent modal dispersion associated with the multimode nature of fibers, researchers have achieved improvements in bandwidth-distance product of MMF using several techniques such as selective modal excitation and M-ary coding [1], electronic equalization [2], and subcarrier multiplexing (SCM) [3]. Wavelength-division multiplexing (WDM) based on MMF links is also a promising way to push the limit of overall transmission capacity [4]. However, the cost associated with multiwavelength systems is still too prohibitive to be extensively implemented. While each of these techniques has shown substantial increases in the bandwidth-distance product, they still do not exploit the MMF capacity to its full information theoretic potential.

Despite the limitations, from an information theoretic viewpoint, MMF has greater capacity than its single-mode counterpart, provided one can exploit the various modes as independent communication channels. A MIMO approach where modal dispersion is exploited, rather than avoided, is a promising solution. Note that for a long time the multipath nature of wireless channels was viewed as a limiting factor to be avoided. In recent years it has been realized that the multipath nature of a channel can actually enhance throughput if it is properly exploited. If each guiding mode is regarded as a scattering path, MMF behaves similar to a wireless channel with rich multipath scattering, as illustrated in Fig. 1. A similar approach could hold for the multimode nature of fiber links; it can be exploited for capacity improvement, rather than being avoided. Based on this analogy, the concept of multiple-input multiple-output (MIMO) transmission used in wireless communications can be applied to MMF channels. The feasibility of MIMO transmission over fiber has already been demonstrated in [6, 7] for a 2×2 system.

CHANNEL MODEL

A conceptual representation of an MMF channel is depicted in Fig. 1. Using a finite impulse response (FIR) model for the MMF channel, the input-output relationship for a single-input single-output (SISO) MMF system can be expressed as

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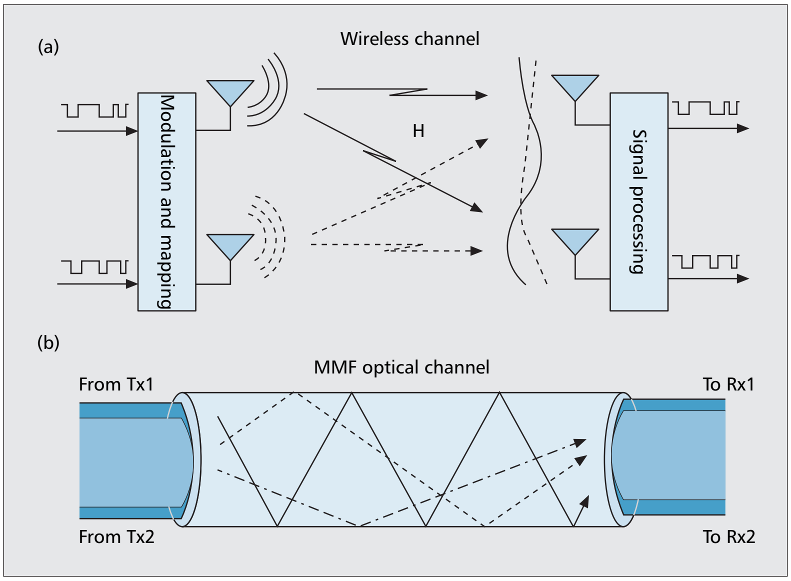

Figure 1. *a) Coupling diversity into and out-of MMF; b) ray tracing description of light beam scattering inside a multimode fiber.*

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

where $x(t)$ is the transmitted signal modulated with an optical carrier frequency of ω_c, Q is the total number of guiding modes in MMF (an equivalent to multipaths in wireless channels), h_k is a complex number representing the gain on the kth guiding mode, and 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[1] 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

$$y_i(t) = \frac{1}{M} \sum_{j=1}^{M} \sum_{k=1}^{Q} h_{ijk} e^{j\omega_{c(t-\tau_{pk})}} x_j(t-\tau_{gk}) + v_i(t), \qquad (2)$$

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. The factor $1/M$ is added to keep the total transmit power the same as in the SISO case. 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., $x_j(t - \tau_{gk}) \approx x_j(t - \tau_g)$, 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 Eq. 2 can be written as

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

where $\mathbf{y}(n)$ contains the received samples by the N detectors at time nT_s and $\mathbf{x}(n)$ contains the transmitted samples by the M transmitters at time $nT_s - \tau_g$. Furthermore, the (i, j)th element of $\mathbf{H}$ represents the channel gain between the jth transmitter and the ith receiver.

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 and uniform distribution for their phase. Furthermore, if independent sets of modes are excited by different transmitters, and the receivers detect signals independently, the elements of $\mathbf{H}$ will be independent as well. It is known that these two conditions result in the maximum MIMO capacity [8, 9]. These conditions also guarantee a linear increase in MIMO capacity vs. the minimum number of transmit-receive antennas. In an optical MIMO fiber link, 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. Note that every detector receives a collection of modes out of the total Q modes in the fiber. Naturally, there can be some common modes received by both detectors, depending on the launching and detection profiles. This is similar to wireless channels where the signals received on multiple antennas can be correlated if the antennas are not spaced far enough.

Note that the multipath nature of the channel (due to scatterers in a wireless environment or guided modes in an MMF link) has two consequences. First, it results in a MIMO channel with less correlated elements. The degree of independence between the MIMO channel elements highly depends on the number of rays that arrive at the receiver at the same time but from different reflections. Therefore, the richer the scattering environment, the closer the channel to a complex Gaussian matrix with uncorrelated elements (known to maximize MIMO capacity). On the other hand, the rays that do not arrive within a symbol duration lead to ISI that might not benefit MIMO capacity (although it can still be exploited for improved multipath diversity). Techniques such as MIMO channel equalization or OFDM modulation are used to combat the ISI effects. In other words, while the rays that arrive within a symbol duration help enhance the channel matrix independence, the rays that arrive at different symbol periods lead to ISI in the system. While we exploit the many excited modes within a symbol duration for enhanced capacity (through MIMO transmission), the modes that arrive at different symbol periods can still be compensated through equalization techniques (Fig. 6).

A major difference between coherent and non-coherent optical modulation is in the value of f_c in Eq. 2. While f_c is on the order of hundreds of terahertz for coherent optical modulation, its value is on the order of multiple gigahertz for radio frequency (RF) subcarrier intensity modulation [2]. 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. However, for the case of noncoherent modulation, the term $f_c\Delta\tau_p$ may be close to zero for relatively short lengths of fiber, resulting in poor diversity conditions.

The key feature of optical MIMO is that it makes use of the modal dispersion in MMF,

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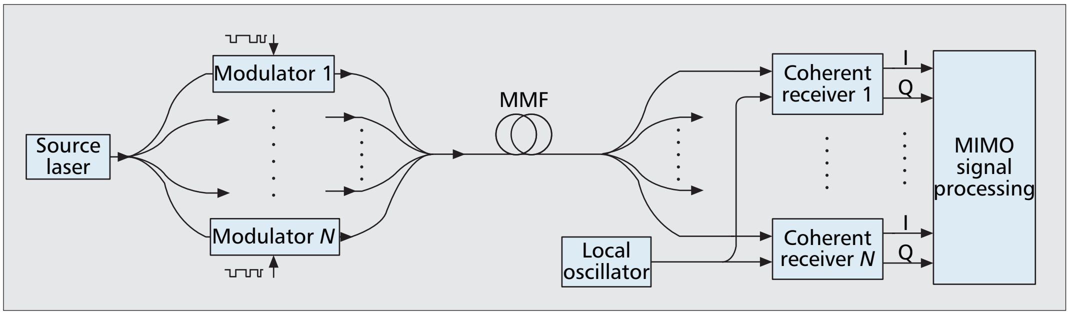
[1] *An important difference between the wireless channel and the MMF channel is in the value of the group delays. In wireless channels, the multipath delays are random values that can change from one realization to next. In contrast, the group delays in an MMF channel belong to a fixed set of values.*



■ **Figure 2.** *A coherent optical MIMO link.*

In general, there are trade offs between throughput, diversity, and receiver complexity and any capacity improvement through the MIMO approach will come at the cost of higher processing at the receiver.

rather than avoiding it. In [6] an RF subcarrier (~1 GHz) with phase shift keying (PSK) data format was used for transmitter modulation, followed by optical intensity detection and RF coherent demodulation at the receiver. The use of RF subcarriers required a long length of MMF to ensure enough modal diversity. Additionally, due to its incoherent nature, phase modulated transmissions such as optical quadrature amplitude modulation (QAM) constellations were not supported. A coherent optical MIMO MMF link was proposed and demonstrated in [3] (Fig. 2). 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), and QAM constellations can be supported.

DIFFERENT TRANSMISSION SCHEMES

In a coherent optical MIMO system, different transmission schemes can be used to exploit the MIMO nature of the channel. In general, there are trade-offs between throughput, diversity, and receiver complexity, and any capacity improvement through the MIMO approach will come at the cost of higher processing at the receiver. Although the power consumption in optical fiber links is not as limited as in wireless systems, still the higher data rates in fiber links (~ 10 Gb/s compared to ~ 100 Mb/s) require careful consideration of receiver complexity for feasible very large-scale integration (VLSI) implementation.

Consider a single-tap (flat-fading) MIMO channel of dimension $M \times N$ with an input-output relation, again given by Eq. 3. Depending on the availability of channel state information (CSI) at the transmitter, either space-time coding, beamforming, or spatial waterfilling can be used by the transmitter.

CHANNEL STATE INFORMATION AVAILABLE AT THE TRANSMITTER

It is known that the channel capacity for a fixed channel matrix realization **H** is given by

$$C(\mathbf{H}) = B.\log_2 \left| \mathbf{I} + \frac{1}{s_v^2} \mathbf{H}\mathbf{R}_\mathbf{x}\mathbf{H}^* \right| (bits/s), \qquad (4)$$

where $\mathbf{R}_\mathbf{x}$ is the covariance matrix of the transmitted data $x(n)$, B is the bandwidth of the channel in Hertz, and σ_v^2 is the variance of the noise elements in $\mathbf{v}(n)$. Moreover, the notation $|:|$ denotes the determinant of its matrix argument. The capacity in Eq. 4 is achieved when $\mathbf{x}(n)$ has elements with Gaussian distribution. The total transmit power is given by $\mathrm{Tr}(\mathbf{R}_\mathbf{x})$ and is usually constrained to be less than some value P. Among all possible choices for $\mathbf{R}_\mathbf{x}$, there is one that maximizes the capacity formula in Eq. 4 and is calculated according to a *waterfilling* scheme [9]. The waterfilling solution basically maximizes the channel capacity for every channel realization, since the channel is assumed to be known at the transmitter.

CHANNEL STATE INFORMATION NOT AVAILABLE AT THE TRANSMITTER

In this case, the ergodic channel capacity is defined by

$$C(\mathbf{H}) = B.\mathbf{E}_\mathbf{H}\left(\log_2 \left| \mathbf{I} + \frac{1}{\sigma_v^2} \mathbf{H}\mathbf{R}_\mathbf{x}\mathbf{H}^* \right| \right), \qquad (5)$$

where $\mathbf{E}_\mathbf{H}$ denotes expectation over channel realizations. The covariance matrix $\mathbf{R}_\mathbf{x}$ can also be chosen to maximize this capacity. Assuming Gaussian independent and identically distributed elements for **H** and subject to the power constraint $\mathrm{Tr}(\mathbf{R}_\mathbf{x}) \le P$, it can be shown that the ergodic capacity is maximized when $\mathbf{R}_\mathbf{x} = \{P/N\}\mathbf{I}$. Space-time block codes (STBCs) can be used to approach this capacity. Orthogonal STBCs (OSTBCs) result in simple maximum likelihood receivers due to an inherent orthogonality structure. Figure 3b shows the effect of using OSTBCs on the achievable capacity in a 2 × 2 system. While using orthogonal codes greatly simplifies the receiver structure, it can also reduce the achievable capacity.

CHARACTERIZATION OF A COMIMO CHANNEL

The statistical temporal and spatial properties of the elements of the channel matrix **H** influence the resulting link capacity. While both these statistics have been studied and modeled for wireless MIMO channels, they are not well characterized for optical MIMO fiber links. With respect to the temporal characterization, the issue is whether the MIMO optical channel can be considered constant over a relatively long period of time. This would determine the feasibility (or overhead) of feeding the CSI back to the transmitter. The rate of the channel varia-

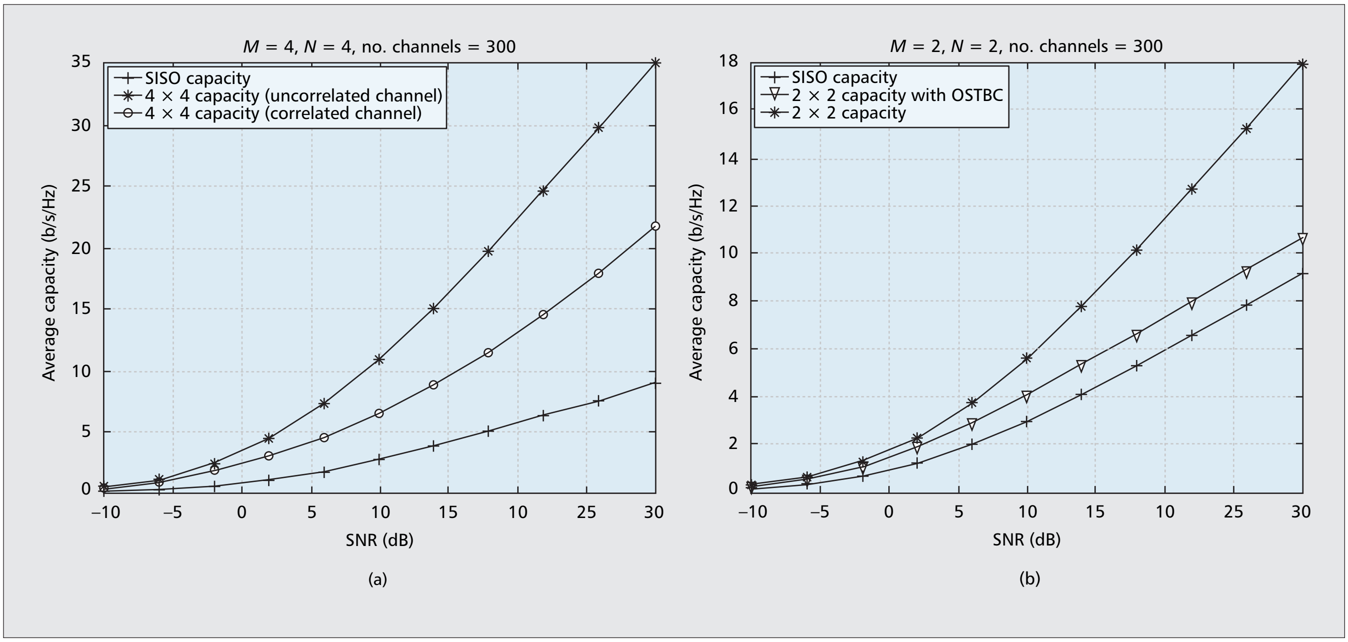


Figure 3. *Capacity vs. SNR compared for SISO and MIMO systems for a complex Gaussian channel: a) the effect of channel correlation on the channel capacity; b) the effect of limiting the transmission scheme to orthogonal designs on the capacity.*

tion will also determine whether we can achieve diversity gain in the case of STBC transmission by forming long blocks of data. It will also determine whether we should consider the instantaneous capacity in Eq. 4 or the ergodic capacity in Eq. 5.

With respect to the spatial characterization, Fig. 3a depicts the effect of channel spatial correlation on capacity. As shown in this figure, the capacity in the case of correlated 4 × 4 channels is significantly reduced compared to uncorrelated 4 × 4 channels (reduced from 35 b/s/Hz to 22 b/s/Hz at signal-to-noise ratio [SNR] = 30 dB). This figure emphasizes the importance of the diversity condition (uncorrelated channel taps) for maximum capacity improvement.

To quantify the achievable capacity we use an industry-standard simulation tool (RSoft's LinkSIM) for modeling MMF links. In this setup two independent streams of binary PSK (BPSK) data are coherently modulated by two different lasers and transmitted through an MMF. Two receivers are used to collect the received data. The transmitted and received streams of data are then used offline to estimate the MIMO channel, which is subsequently 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 parameters used by the MMF simulator to generate the data samples are as follows: laser wavelength of 1550 nm, MMF with core diameter of size 62.5 μm (corresponding to a total of $Q = 76$ possible modes), fiber length of 300 m, and transmitted block length of 128.

CHANNEL STATISTICS

Figure 4 shows the histogram of the amplitude of the elements in **H** compared to an ideal complex Gaussian variable. This plot confirms the assumption that with a large number of modes (Q) and for typical values of f_c in a coherent optical link (on the order of terahertz), the elements of **H** will have a complex Gaussian distribution. Specifically, the amplitude of the elements of H will be Rayleigh distributed and their phases will be uniformly distributed. While we showed earlier that the equivalent channel has a complex Gaussian distribution (for large values of Q), the degree to which the real channel has such statistics depends on many parameters. The channel statistics will depend on system parameters such as fiber diameter, fiber length, laser frequency, symbol duration, number of excited modes, and the impairments in the fiber and connectors. While a complex Gaussian distribution is the most widely studied case in the MIMO literature that leads to the maximum MIMO capacity, still significant improvement in capacity is achievable even if the channel does not exactly follow a complex Gaussian distribution. The importance of the Rayleigh distribution can be considered in two areas:

- It is known that with normalized channel power (and uninformed transmitter), the complex Gaussian distribution results in the maximum capacity for an ($M \times N$) configuration. Although the optical MIMO configuration would see capacity enhancement with distributions other than Rayleigh, optical MMF can potentially enjoy the maximum possible capacity enhancement.
- There is a comprehensive literature on system performance analysis, space-time codes, and transmission schemes all designed and optimized for MIMO systems with complex Gaussian distribution (within the wireless communications community).

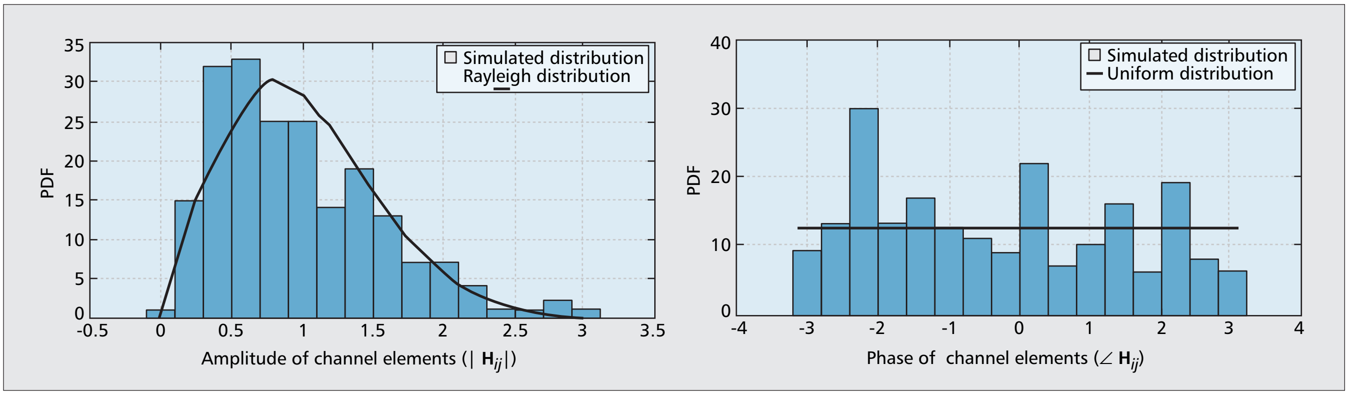


Figure 4. *Probability distribution function (PDF) of the amplitude and phase of simulated MMF channel elements compared to those of an ideal complex Gaussian distribution.*

Although many such results can be used for distributions other than Rayleigh as well, the complex Gaussian nature of MIMO MMF would ensure that such existing results (space-time codes, transmission schemes, and performance analysis) are optimal and accurate when applied to optical MIMO MMF systems. Furthermore, note that the Gaussian model is a theoretical model based on idealistic assumptions. Although it is based on reasonable assumptions, it still requires careful validation in a more realistic environment, as depicted in this section. As is the case with wireless systems, channel characterization is a fundamental step in designing communication systems. Conducting experiments on the statistics of the MMF channel is an important step toward establishing the promise of MIMO technology for MMF systems in practice.

AVERAGE CAPACITY

Using the channel estimates, the channel capacity is evaluated for every channel realization, and the resulting average capacity vs. SNR is shown in Fig. 5. Since the channel in fiber varies at a relatively slower pace compared to the data transmission rate, sending the estimated channel state information (CSI) back to the transmitter is feasible. Therefore, the channel capacity for the following two different scenarios is depicted. The capacity of a 2 × 2 MMF system is plotted for both informed and uninformed scenarios in Fig. 5, using the channel measurements from the simulator. For comparison purposes, the capacity of an equivalent 2 × 2 system with i.i.d. complex Gaussian elements is also shown in Fig. 5. 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 **H** in practice. Such correlation is a result of the fact that some common guiding modes are excited by both transmitters, and no attempts were made to optimize the launching conditions in order to minimize the dependency between the channel elements. This behavior is in line with the observation in wireless systems where the capacity of a channel is degraded due to correlation between antennas or due to poor antenna spacing. The fact that the elements of COMIMO channel behave sufficiently close to a complex Gaussian distribution enables us to apply the existing rich literature on wireless MIMO communications to optical systems.

COHERENT DEMODULATION AND PHASE NOISE

There are clearly some challenges in adapting MIMO processing in coherent optical links. For instance, implementation imperfections play a critical role in optical links such as the phase noise associated with the transmitter and receiver lasers. In a coherent receiver, a local oscillator (LO) is required to down-convert the received signal. Let us denote the transmitted baseband signal by $s(t)$ and the equivalent complex carrier signal by $e^{j\omega_c t}$. Then the transmitted signal is $s(t)e^{j\omega_c t}$. At the receiver side, this signal is down-converted with the LO, which has the form $e^{-j[\omega_c t + \phi_n(t)]}$ where $\phi_n(t)$ describes random phase fluctuations. Due to the phase noise, rather than recovering the original signal $s(t)$ after down-conversion, a distorted version is obtained, namely $y(t) = s(t)e^{j\phi_n(t)}$.

The variance of the phase noise is approximately given by

$$\sigma_\phi^2 = \frac{\Delta\nu_T + \Delta\nu_{LO}}{f_{BW}},$$

where $\Delta\nu_T$ is the laser linewidth at the transmitter, $\Delta\nu_{LO}$ is the laser linewidth at the receiver, and f_{BW} is the locking bandwidth of the PLL. The impact of the phase noise on uncoded BER (i.e., with no error correction coding) for a 2 × 2 system was investigated with Monte Carlo simulations, using 1000 realizations of randomly generated channel matrices for various values of laser linewidth. For each channel realization, 100 randomly generated BPSK symbols were sent from each transmitter. The objective was to ensure that the required coherent MIMO detection at the receiver is feasible with typical laser linewidths. Considering a 10MHz optical PLL loop-bandwidth, the uncoded BER was observed to be not affected by the phase noise for laser linewidths less than 10KHz. In other words, the link's performance was dominated by the additive Gaussian noise rather than the phase noise.

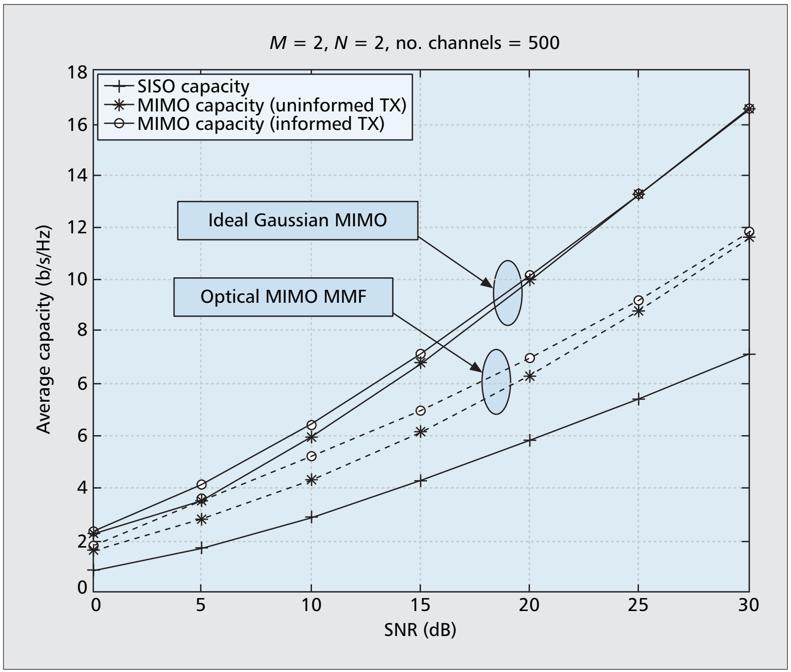


Figure 5. *Average capacity vs. SNR comparing a SISO channel with a 2 × 2 MIMO channel compared for two scenarios: an ideal complex Gaussian channel and the simulated MIMO MMF channel.*

MIMO ADAPTIVE EQUALIZATION

Earlier, it was assumed that the group delay spread ($\Delta\tau_g$) is small compared to the symbol period and all paths arrive at approximately the same time compared to the symbol period. For relatively longer MMF lengths (for instance, a few kilometers of 62.51µm MMF), however, the channel model has to be modified such that the modes that have a group delay within a data symbol period are grouped together. Different techniques exist in the literature to address the ISI in MIMO communications, including

- Orthogonal frequency division multiplexing (OFDM) to avoid the need for equalization
- MIMO channel estimation using training symbols, where the estimated channel matrices are subsequently used to recover the transmitted information bits according to maximum-likelihood (ML), least-squares (LS), or minimum-mean-square-error (MMSE) estimation schemes
- MIMO equalization to compensate for the ISI, where the training symbols are used to directly estimate the equalization coefficients [8]

These techniques have been extensively studied in the literature in the context of wireless and wireline communications. We illustrate the effectiveness of applying the existing MIMO signal processing techniques for ISI cancellation in the context of COMIMO systems. In other words, the ISI caused by modal dispersion in MMF can be effectively compensated for the MIMO case as well.

EXPERIMENTAL SET-UP

We have built a proof-of-concept 2 × 2 coherent optical MIMO system as shown in Fig. 6. A 1545nm laser output is split into two parallel arms, which are BPSK modulated using standard LiNbO3 modulators. A MMF directional coupler is used to combine two input arms into 2.8km of 62.51µm 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 different modal power distribution. 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 guiding modes. The local laser oscillator for coherent demodulation is derived from the original narrow linewidth laser source. This simplifies the experiment and is sufficient for conceptual demonstration of COMIMO by ensuring accurate phase and frequency locking.[2] The transmitted signal is directed into the commercial Lithium Niobate Quadrature optical hybrid, which gives both the inphase and quadrature-phase branches. The received signals are collected by two balanced detectors. This provides the full signal space information of the baseband signal (i.e., both I and Q components). The collected data are digitized and processed offline for symbol recovery by applying MIMO equalization algorithms [10]. It is seen in Fig. 6 that the ISI caused by modal dispersion in MMF links can be effectively compensated in the digital domain.

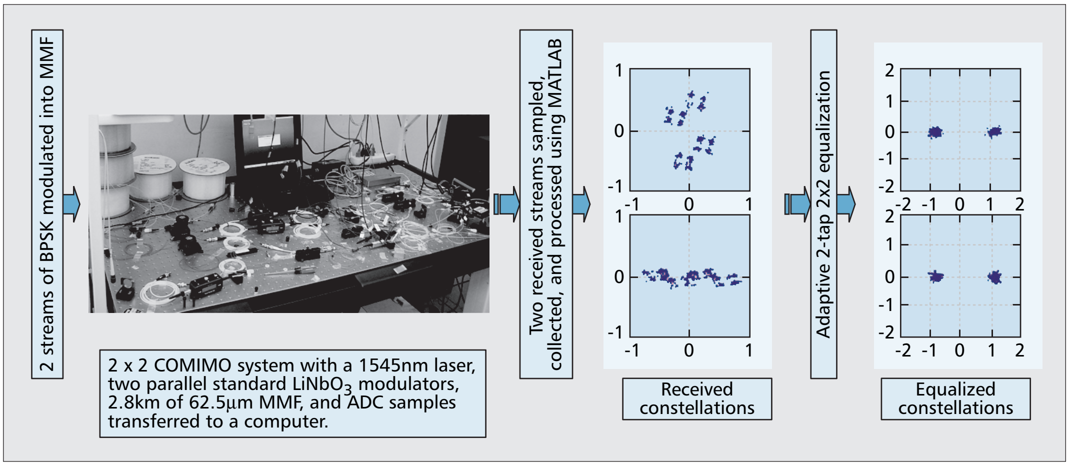


Figure 6. *The experimental laboratory setup, the received constellations for an MMF channel with ISI, and the recovered constellations after adaptive MIMO equalization.*

REAL-TIME IMPLEMENTATION AND COMPLEXITY

The complexity of the receiver algorithm is also a crucial issue to be considered, especially in light of the data rates targeted in fiber optic links (~ 10Gb/s). This means that the received data samples should be processed in the digital domain at clock rates of the order of Gb/s. Still, using efficient receiver algorithms as well as VLSI techniques, a real time implementation of optical MIMO systems is feasible. In the current experimental set-up, the MIMO signal processing is performed offline on a computer using MATLAB codes. The data received by the detectors are first collected and then processed. This processing includes MIMO channel estimation and data recovery. For more practical scenarios, the required signal processing can be implemented on dedicated hardware (e.g., a field programmable gate array [FPGA] board or VLSI chip) for real-time processing of the received data. Another possibility is an analog domain implementation of the core MIMO receiver algorithms. In this case the data decoding portion of the receiver is implemented in the analog domain, while the channel estimation portion of the receiver is performed on a digital chip (application-specific integrated circuit [ASIC] or FPGA). Analog implementation of the computationally heavy portion of the receiver is advantageous since implementing those functionalities in the analog domain could be more efficient in terms of power. This will be a natural extension of electronic domain equalization in SISO MMF links to electronic domain MIMO processing in COMIMO systems.

CONCLUDING REMARKS

It is shown that MIMO communications has great potential in enhancing the capacity of fiber links. Furthermore, it applies the concept of digital signal processing techniques in the context of optical communications. While electronic domain equalization has been the only dominant application for signal processing in optoelectronics, MIMO communications presents a new opportunity for applying signal processing techniques in optoelectronics on a greater scale and scope.

While electronic domain equalization has been the only dominant application for signal processing in optoelectronics, MIMO communications presents a new opportunity for applying signal processing techniques in optoelectronics in a greater scale and scope.

REFERENCES

[1] IEEE Std. 802.3ae, “10 Gigabit Ethernet, 2002.

[2] L. Raddatz *et al.*, “”An Experimental and Theoretical Study of the Offset Launch Technique for the Enhancement of the Bandwidth of Multimode Fiber Links,” *IEEE J. Lightwave Tech.*, vol. 16, no. 3, Mar. 1998, pp. 324–31.

[3] X. Zhao and F. S. Choa, “Demonstration of 10-Gb/s Transmissions over a 1.5-km-Long Multimode Fiber Using Equalization Techniques,” *IEEE Photon. Tech. Lett.*, vol. 14, 2002, pp. 1187–89.

[4] T. K. Woodward *et al.*, “1.6Gb/s BPSK Transmission at 850 nm over 1 km of 62.5-1m-core Multimode Fiber Using a Single 2.5-GHz Subcarrier,” *IEEE Photon. Tech. Lett.*, vol. 11, 1999, pp. 382–84.

[5] L. A. Buckman *et al.*, “Demonstration of a Small Form Factor WWDM Transceiver Module for 10-Gb/s Local Area Networks,” *IEEE Photon. Tech. Lett.*, vol. 14, 2002, pp. 702–04.

[6] H. R. Stuart, “Dispersive Multiplexing in Multimode Optical Fiber,” *Science*, vol. 289, July 2000.

[7] A. R. Shah *et al.*, “Coherent Optical MIMO (COMIMO),” *J. Lightwave Tech.*, vol. 23, no. 8, Aug. 2005, pp. 2410–19.

[8] I. E. Telatar, “Capacity of Multi-Antenna Gaussian Channels,” *Euro. Trans. Telecommun.*, vol. 10, no. 6, Nov./Dec. 1999, pp. 585–95.

[9] E. G. Larsson and P. Stoica, *Space-Time Block Coding for Wireless Communications*, Cambridge Univ. Press, 2003.

[10] A. H. Sayed, *Fundamentals of Adaptive Filtering*, Wiley, 2003.

BIOGRAPHIES

ALIREZA TARIGHAT [S’00, M’05] (tarighat@ee.ucla.edu) received a B.Sc. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1998. He received M.Sc. and Ph.D. degrees in electrical engineering from the University of California, Los Angeles (UCLA) in 2001 and 2005, respectively. From 2001 to 2002 he was with Innovics Wireless, Los Angeles, working on systems and ASIC development of advanced antenna diversity and rake processing for 3G WCDMA mobile terminals. Since 2005 he has been with WiLinx, Los Angeles, working on systems and silicon development of UWB wireless networks. His research interests are in communications theory and signal processing, including MIMO OFDM systems, multi-user MIMO wireless networks, algorithms for impairments compensation, and experimental and practical communication systems. He was the recipient of the Gold Medal of the National Physics Olympiad, Iran, 1993, and the Honorable Mention Diploma of the 25th International Physics Olympiad, Beijing, China, 1994. He received the 2006 Outstanding Ph.D. Award in electrical engineering from UCLA.

RICK C. J. HSU (cjhsu@ee.ucla.edu) received a B.S. degree in physics and an M.S. degree in electrical engineering from National Taiwan University, Taipei, in 1999 and 2001, respectively. Since 2003 he has been pursuing a Ph.D. degree with the Department of Electrical Engineering at UCLA. His current research interests are in fiber optic communication systems and microwave photonics.

AKHIL R. SHAH (akhil@ee.ucla.edu) received his B.S. in physics and electrical engineering from the University of California, Irvine in 2000, and his M.S. in electrical engineering from UCLA in 2003. Since 2000 he has worked in industry, characterizing and designing RFICs, and modeling novel photonic devices. Currently he is pursuing a Ph.D. with the Department of Physics at UCLA. His current research interests are quantum communication and mathematical physics.

ALI H. SAYED [F’01] (sayed@ee.ucla.edu) is a professor and chairman of electrical engineering at UCLS. He has over 270 journal and conference publications, and is the author of the textbook *Fundamentals of Adaptive Filtering* (Wiley, 2003) and co-author of the research monograph *Indefinite Quadratic Estimation and Control* (SIAM, 1999) and the graduate-level textbook *Linear Estimation* (Prentice Hall, 2000). He is the recipient of the 1996 IEEE Donald G. Fink Award, a 2002 Best Paper Award from the IEEE Signal Processing Society, the 2003 Kuwait Prize in Basic Science, the 2005 Frederick E. Terman Award, the 2005 Young Author Best Paper Award from the IEEE Signal Processing Society, and two Best Student Paper awards at international meetings. He has served as Editor-in-Chief of *IEEE Transactions on Signal Processing* 2003–2005) and is now serving as Editor-in-Chief of *EURASIP Journal on Applied Signal Processing*. He is serving as General Chair of ICASSP 2008 and sits on the Board of Governors of the IEEE Signal Processing Society.

BAHRAM JALALI [F] (jalali@ee.ucla.edu) is a professor of electrical engineering, and director of the Optoelectronic Circuits and System Laboratory at UCLA. His current research interests are in silicon photonics and ultrafast photonic signal processing. He has published over 200 scientific papers and holds six U.S. patents. He is a Fellow of Optical Society of America (OSA) and Chair of the Los Angeles Chapter of the IEEE Lasers and Electro Optics Society (LEOS). In 2005 he was chosen by *Scientific American* as one of 50 Leaders Shaping the Future of Technology. While on leave from UCLA from 1999 to 2001, he founded Cognet Microsystems, a Los Angeles-based fiber optic component company. He served as the company’s CEO, president, and chairman from the company’s inception through its acquisition by Intel Corporation in April 2001. He has received the BridgeGate 20 Award for his contribution to the southern California economy.

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[2] *A more practical approach would be to use an optical PLL.*