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Channel capacity and space-time block coding for coherent optical MIMO multi-mode fiber links

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ABSTRACT

The capacity enhancement for random coherent optical multiple-input multiple-output (MIMO) channels in multi-mode fiber (MMF) links is investigated theoretically. Additionally, the performance of space-time block coding (STBC) techniques for achieving high reliability optical MIMO transmission is numerically examined. A comparative study is performed by considering several schemes that employ multiple transmitters/receivers. Simulation results of these schemes, in terms of bit error rate (BER) as a function of optical signal to noise ratio (OSNR), are provided.

1. Introduction

The unabated growth of data network traffic requires a rapid, constant, and urgent enhancement of transmission capacity. Various technological efforts, such as multi-level signaling, polarization division multiplexing (PDM), and low loss or large-area optical fibers, are presently devoted to achieve high capacity by means of improving spectral efficiency for the installed single-mode fiber (SMF) base. However, experimentally achieved spectral efficiencies are approaching their fundamental limits for SMFs, which may result in a transmission capacity shortage in the near future [1]. In addition to physical dimensions of time, frequency, complex constellation, and polarization, spatial dimension can be the only left dimension to be explored for modulation and multiplexing [2]. Space-division multiplexing (SDM) may be performed using multi-mode fibers (MMFs), with increasing spatial information density at the cost of (linear or nonlinear) mode interactions [3]. These interactions have to be counteracted by multiple-input multiple-output (MIMO) signal processing, originally introduced for wireless systems, but also studied for optical fiber communications [4,5].

MMF links are widely implemented in buildings and used within current high speed local area networks (LANs) because of relaxed connector alignment tolerances and reduced transceiver component costs. The main drawback of MMF is the multi-mode nature of the fiber that gives rise to mode dispersion and dramatically limits its bandwidth. Hence, long distance optical communication systems have been exclusively based on SMFs. From an information theoretic perspective, MMF has greater capacity than its single-mode counterpart, provided one can exploit the various modes as independent communication channels to overcome the bandwidth limitation of MMF links introduced by mode dispersion [6,7]. If each guiding mode is regarded as a scattering path, MMF behaves similar to a wireless channel with rich multipath scattering. The linear increase in channel capacity of MIMO communications as a function of the number of transmitter/receiver (Tx/Rx) has positive consequences for the bandwidth-length (BL) product of optical fiber communications [8]. Based on the analogy between multipath fading in wireless channels and mode dispersion in MMF, the concept of MIMO used in wireless systems can be applied for transmission of multiple data channel simultaneously through a single fiber [9]. A key feature of optical MIMO systems is that it makes use of the mode dispersion in MMF, rather than avoids it. This application has the benefit that a boost of transmission capacity is not accompanied by an increase of fiber count and only one physical port has to be managed. It is possible to recover multiple data channels transmitted in parallel over a single MMF, at the expense of greater signal processing complexity, particularly at the Rx end. Yet with effective digital signal processing (DSP) algorithms and hardware implementations, this trade-off is capable of being managed and certainly worth the effort.

Even when an optical MIMO channel with high channel capacity is given, we still need to explore techniques for achieving high-speed data transmission and high reliable link between Tx/Rx pair [10]. As examining optical MIMO systems, two categories of multiple Tx/Rx techniques have to be considered, diversity and spatial multiplexing [11]: (1) the diversity techniques are related to the

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emission of a number of replicas of the same signal, each suffering independent fading, thereby improving the transmission reliability; (2) the techniques that are based on spatial multiplexing, which is the ability to simultaneously transmit different information over multiple sources, thereby achieving a higher transmission speed. In this paper, we investigate the optical MIMO system capacity for random channels. Also, by focusing on the diversity techniques, we present the potential application of space-time block coding (STBC) for the performance enhancement in optical MIMO MMF links through detailed numerical simulations.

2. Channel capacity enhancement of random optical MIMO channels

The new degrees of freedom for utilizing the MMF transmission capacity are stems from the analogy between transmission over multiple modes and mode coupling in MMF versus the multi-path and scattering phenomena occurring in wireless communication links [12]. Transmission over MMF in the wake of multimode propagation and mode coupling may be viewed in communication-theoretic terms as signaling over an optical MIMO system, and multiple optical sources and detectors are then introduced to take advantage of the spatial (modal) diversity. Therefore, it is convenient to introduce a $N_R \times N_T$ channel matrix (CM) **H** to characterize the optical MIMO with N_T transmitters and N_R receivers with each matrix element H_{ij} describing a complex weighting number indicating the channel gain between the jth Tx and the ith Rx (with an amplitude attenuation and a phase delay) [4]. The baseband input–output relationship for multi-mode data transmission in an optical MIMO MMF link can be written as (ignoring fiber latency):

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

where $y_i(t)$ is the signal received by the ith Rx, h_{ijk} is the mode attenuation form the jth Tx to the ith Rx via the kth mode, $v_i(t)$ is the additive white Gaussian noise (AWGN), τ_{pk} and τ_{gk} are the phase and group delay associated with the guiding mode, respectively. Assuming that Eq. (1) is written in order of ascending delay, the group delay spread is defined as $\Delta\tau_g = \tau_{gQ} - \tau_{g1}$ and the phase delay is defined as $\Delta\tau_p = \tau_{pQ} - \tau_{p1.}$ The spatial diversity of the channel is determined by the product of group delay spread ($\Delta\tau_g$), carrier frequency (ω_c), and the number of modes (Q). When $\Delta\tau_g$ 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 baseband equivalent of Eq. (1) (sampled at rate $1/T_s$) can be written in the matrix form as:

$$y(n) = \mathbf{H}\mathbf{x}(n) + \mathbf{v}(n) \tag{2}$$

where **H** is the CM with complex element $H_{ij} = \sum_{k=1}^{q} h_{ijk} e^{-j\omega_c \tau_{pk}}$, $\mathbf{y}(n)$ contains the received samples by the N_R detectors at time nT_s while $\mathbf{x}(n)$ contains the transmitted samples by the N_T Transmitters at time $nT_s - \tau_g$.

For the utilization of optical MIMO MMF links, selective mode launching at the Tx end for shaping the distribution of transmitted modes, are adopted to spatially multiplex data with multiple Tx/Rxs. The requirement of complete invertibility of **H** is fulfilled by identity matrices **K** for input/output coupling [13]. Thus, it is important that low loss coupling elements can be achieved between Tx/Rx and the MMF, and the corresponding devices are ideal mode splitters connecting each Tx/Rx to one dedicated mode of the MMF [14]. Furthermore, the propagation through the fiber, including mode coupling and mode dispersion is described by the **H** for modal fields. An advantage of using optical MIMO techniques is that selective orthogonal coupling to or from individual modes are no longer required, i.e., the subsets of modes launched by different optical sources need not be disjoint nor do the subsets of modes collected in each of the multiple detectors [15]. The essential requirement is that not all laser sources excite precisely the same modal power distribution, and likewise, not all detectors receive the same combination of modes, which conditions are readily met in practice. The crosstalk, resulting from the coupling or mixing of modes due to perturbations and scattering in MMF transmission, can be redressed by means of post-detection signal processing at the Rx and possibly at the Tx as well [15]. Here, we are considering the transmission regime of the weak mode coupling. Coherent optical transmission is used for significantly eliminating the fiber length requirement and allowing for transmission of any quadrate amplitude modulation (QAM) constellation due to its coherent nature [5]. On the other hand, by using coherent detection, the baseband data are already upconverted to the optical carrier frequency (hundreds of terahertz), entirely satisfying the diversity requirement [8]. For optical MIMO transmission using coherent optical detection, the photocurrent is proportional to the square of the field envelop, which rendering coherent optical system formally equivalent to wireless MIMO system [5].

To reap the benefits of optical MIMO, such as linear capacity growth with the number of Tx/Rx elements, a critical requirement is a rich scattering channel with enough Tx/Rx diversity that randomizes **H**, causing each H_{ij} statistically uncorrelated to each other [16]. That is, one must ensure that the matrix elements of **H** are sufficiently uncorrelated and, in the best case, are independent and identically distributed (i.i.d.) complex Gaussian random variables (i.e., Rayleigh flat fading) [17]. Two important requirements are needed for assuring the i.i.d. condition [8]: 1) a large product of phase delay spread and carrier frequency $\omega_c \Delta\tau_{pd} \gg 2\pi$, so the phase of each element of **H** can be considered a uniformly distributed random variable over [0,2π]; and 2) a large number of modes/paths, so that each Tx and Rx can launch into and sample from sufficiently different modes/paths. Coherent optical MIMO eases the restriction on minimum phase delay spread by using a very large carrier frequency, namely the optical carrier frequency.

Note that the multipath nature of the channel in a coherent optical MMF link has two consequences: firstly, it results in a MIMO channel to a complex Gaussian matrix with less correlated elements; secondly, the rays that do not arrive within a symbol duration lead to inter-symbol interference (ISI) that might not benefit MIMO capacity (although it can still be exploited for improved multipath diversity) [6]. As 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 such as orthogonal frequency division multiplexing (OFDM) modulation or MIMO channel equalization [18].

Since the channel in fiber varies at a relative slower rate compared to the data transmission rate, sending the estimated channel state information (CSI) back to the transmitter is feasible [6]. Therefore, we evaluate the channel capacity for the following two different scenarios:

(1) For CSI available at the transmitter (informed transmitter), the channel capacity per hertz for a fixed CM realization **H** is given by:

$$C(\mathbf{H}) = \log_2 \det \left(\mathbf{I} + \frac{1}{\sigma_v^2} \mathbf{H}\mathbf{R_x}\mathbf{H}^* \right) \tag{3}$$

where $\mathbf{R_x}$ is the covariance matrix of the transmitted data, σ_v^2 is the variance of the noise in $\mathbf{v}(n)$. Among all possible choices for $\mathbf{R_x}$ with constant Tr($\mathbf{R_x}$), the water filling scheme maximized the capacity.