Effect of the MMF Curvature in the System Capacity of an Optical MIMO Channel Using MGDM Technique

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Abstract

Due to its enormous bandwidth, MultiMode Fiber (MMF) seems the only medium able to offer a broadband multiservice system using Mode Group Diversity Multiplexing (MGDM) technique. As an Optical Multiple Input Multiple Output (O-MIMO) method, MGDM exploits efficiently the fiber bandwidth by spatial launching and reception, so that the capacity is increased. However, the propagation of modes in the MMF is subjected to several spreading effects which disturb and degrade the transmission performance of the optical fiber. In addition, the choice of optimal injection and reception conditions are not enough to improve the transmission, but the mechanical effects acting on the channel play an important role in the use of this technique. In this paper, we study the impact of the fiber curvature as the single factor which affects an O-MIMO channel using MGDM technique. Simulation results showing the decrease of the system capacity are also presented to support the efficiency of this study.

Keywords: Channel Capacity, Fiber Curvature, O-MIMO, MGDM, MMF.

1. Introduction

The utility of an MGDM system in terms of capacity expansion gives a major interest in most applications of optical communication. Being an O-MIMO technique, MGDM aims at creating independent communication channels over an MMF, using subsets of propagating modes. It provides larger robustness and capacity for data communication. It was introduced recently to improve the ability of MMF to integrate different services on a network [1]. MGDM has been proposed for the transparent transmission of several signals over short reach MMF links, such as in future in-house networks [2]. The principle of MGDM is shown in Fig. 1. At the transmitting side, Ns sources are used to launch a different group of modes each. At the output facet of the MMF, each of M photo-detectors responds to a different combination of the optical power carried by the Ns mode groups. The set of modes excited depends on launch conditions at the input facet of the fiber. Although the MGDM technique is used to increase the capacity of MMFs, the conversion of a Single Input Single Output (SISO) system to a multi-user one encounters many difficulties such as mechanical effects, modal dispersion and system cost. Therefore, to improve the functioning of this technique, it is important to consider the restrictive effects which affect the transmission. In this work, we study the effects of the curvature of the fiber on the MGDM system. We compare the performance of the channel in terms of system capacity with and without curvature.

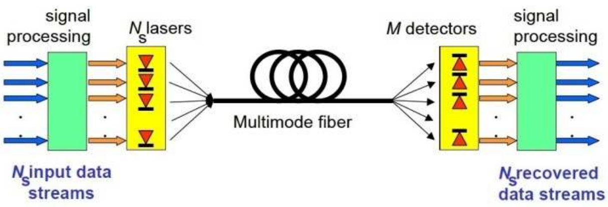

Fig. 1 Mode Group Diversity Multiplexing principle.

The paper is organized as follows. In Section 2, the classical MGDM technique description is given. Moreover, the impact of the fiber curvature on the system performance is presented. In Section 3, simulation results, showing the system capacity decreasing in the presence of the curvature, are given.

2. Effect of the fiber curvature in an MGDM link

Multiplexing is widely used in telecommunication systems. It allows several users to access the same transmission medium. MGDM is a modal multiplexing technique that creates parallel communication channels over an MMF. It has been proposed as a way to integrate various services over an MMF network. For an $M \times N_s$ MGDM system, the M received signals are related to the N_s transmitted ones via an $M \times N_s$ transmission matrix H, whose elements h_{ij} are the impulse responses of the *i*th output to the *j*th input. The relationship between the M electrical signals received (y_i) and the N_s emitted electrical signals (s_i) is written in the following matrix form:

$$y = H.s + n \qquad (1)$$

where y, s, n are, respectively, the received signal vector, the emitted signal vector, and the additive noise from the receivers. Having the hypothesis that H is known at the receiver, the capacity of the system is expressed as follows [3]:

$$C = B.\log_2\left[\det\left(I_M + \frac{\rho}{Ns}.H \times H^*\right)\right] \quad \text{bits/s/Hz} \qquad (2)$$

where B is the channel bandwidth, I_M is the unity M×M matrix and ρ is the Signal to Noise Ratio (SNR). The values of h_{ij} are given by [4]:

$$h_{ij} = \frac{I_j(R_i, L)}{I_j(R, L)} \qquad (3)$$

where I_j is the light flux intensity emitted by the *j*th transmitter, R_i is the area of the *i*th receiver, R is the total area of the core fiber, and L is the fiber length. The light flux intensity is given by:

$$I(R,L) = \frac{1}{2}\sum_{\mu,\nu}\left|a_{\mu,\nu}(L)\right|^2 \int_S \Psi^2{}_{\mu,\nu}\, dS$$

$$+ \sum_{\mu\neq\mu'}\sum_{\nu\neq\nu'}\left[a_{\mu,\nu}(L).a_{\mu',\nu'}(L) \times \int_S \Psi_{\mu,\nu}\Psi_{\mu',\nu'}\, dS\right]$$

$$.\cos\left(\left(\beta_{\mu,\nu} - \beta_{\mu',\nu'}\right)L\right) \qquad (4)$$

where $a_{\mu,\nu}$ and $\psi_{\mu,\nu}$ are respectively the modal amplitude and the modal function of the (μ,ν) mode, and $\beta_{\mu,\nu}$ is the propagation constant. The parameters μ and ν are called respectively the radial and azimuthal mode numbers. The determination of the intensity for each channel allows us to determine the coefficients of the matrix H which defines the MGDM channel. The incident field at the input side of the fiber along the axis Oz is considered as a Gaussian beam given by the following equation [5]:

$$E(x,y) = \frac{\sqrt{2}}{\sqrt{\pi w}}.\exp\begin{pmatrix} -(x-F)^2 - (y^2/w^2) \\ -i.(2.n_0.\pi.\theta.y/\lambda) \end{pmatrix} \qquad (5)$$

where n_0 is the refractive index coefficient of the fiber, λ is the wavelength used and F, w and θ are three parameters determining the condition of excitation of the MMF. These parameters, shown in Figure 2, are the offset F, the spot size w and the angular offset θ. The field E is the superposition of the fields caused by the sources s_i.

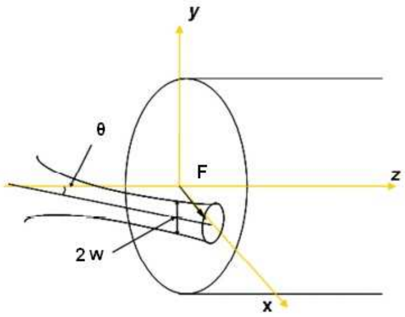

Fig. 2 Excitation geometry of the MMF fiber by a Gaussian beam.

During installation, the MMF can undergo several mechanical effects which cause loss of power and mixtures of modes in the fiber [6]. Since the optical path is not necessarily a straight line, the optical fiber is sensitive to the curvature. In order to determine the new modal power distribution at the end of the curved fiber associated with each MGDM channel, we will decompose the MMF to N successive sections having the same length l. Figure 3 shows the geometry of this curvature with a radius R_c and a fixed angular aperture α.

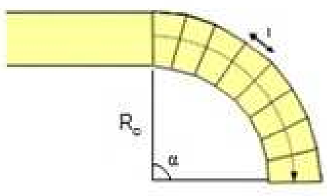

Fig. 3 Fiber curvature.

Each section excites a new group of mode at the input of the next section. At the end of the last section, we can determine the sum of the total group mode curvature. We assume that each section is inclined by an angle θ to the next section. Figure 4 shows the geometry of two successive sections.

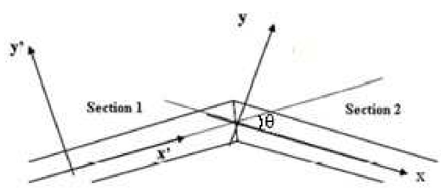

Fig. 4 Geometry of the two successive sections of a curved fiber.

Modes (μ,ν) propagate in section 1 with a modal output amplitude $a_{\mu,\nu}(l)$. At the input of section 2, the modal amplitude $a_{\mu',\nu'}(0)$ of the excited modes calculated by the overlap integral is given by:

$$a_{\mu',\nu'}(0) = \iint (\overrightarrow{E_1} \times \overrightarrow{H_2^*}).U_z.dA \qquad (6)$$

where $\overrightarrow{E_1}$ and $\overrightarrow{H_2^*}$ are the electric and the magnetic fields in sections 1 and 2 respectively. The modal amplitude $a_{\mu',\nu'}(0)$ is related to $a_{\mu,\nu}(l)$ by the following equation:

$$a_{\mu',\nu'}(0) = \sum_{\mu,\nu} a_{\mu,\nu}(l).\iint \left(\vec{E}_{(\mu,\nu)_1} \times \vec{E}_{(\mu',\nu')_2}\right).U_z.dA = \sum_{\mu,\nu} a_{\mu,\nu}(l).C_{\mu,\nu}^{\mu',\nu'} \qquad (7)$$

where $C_{\mu,\nu}^{\mu',\nu'}$ is the coupling coefficient. Equation 7 must be repeated N times to determine the input modal amplitude of the last section of the curved fiber. The modal amplitude is calculated for each offset at the input of the cross section of the fiber. The determination of the coupling coefficient and the modal amplitude is carried by numerical calculation using Matlab. For a parabolic fiber, the mode coupling between two sections of the curved part will be held only between modes which have the same polarization and the same orientation. The coupling coefficients of modes E_x and E_y, are equal respectively. This is why only E_x modes are taken into account in the calculation. The coupling coefficient is then determined by [7]:

$$C_{\mu,\nu}^{\mu',\nu'} = \begin{cases} \frac{w_0}{2}.\exp(\eta^2).\pi.2^{\mu+\nu}.\ \mu!.\nu!.\eta^{\nu-\nu'} \\ .L_{\nu}^{\nu-\nu'}.(-2.\eta^2) & if\ \nu \le \nu' \\ \frac{w_0}{2}.\exp(\eta^2).\pi.2^{\mu+\nu'}.\ \mu!.\nu'!.\eta^{\nu'-\nu} \\ .L_{\nu'}^{\nu'-\nu}.(-2.\eta^2) & if\ \nu \ge \nu' \\ 0 & if\ \mu \ne \mu' \end{cases} \qquad (8)$$

where $\eta = \frac{-i.k.\theta.w_0}{2\sqrt{2}}$ and L is the Gauss-Laguerre function. The parameter k is the wave number and ω_0 is the angular frequency. The analytical determination of the coupling coefficient followed by the determination of the modal amplitude of the curve at the output of the section allows as to determine the modal shift at the output of the bent portion of the fiber associated with each MGDM channel.

3. Simulation Results

The calculation of the modal amplitude depends on the curve modal section number (N). The higher the number is, the more we approach to the practical case of the uniform curvature. Figure 5 shows the change in the power distribution by the mode group number (m) for different section number N for the case of a uniform curvature R_c = 100 mm and α = 60° for the case of an MMF (62.5/125µm).

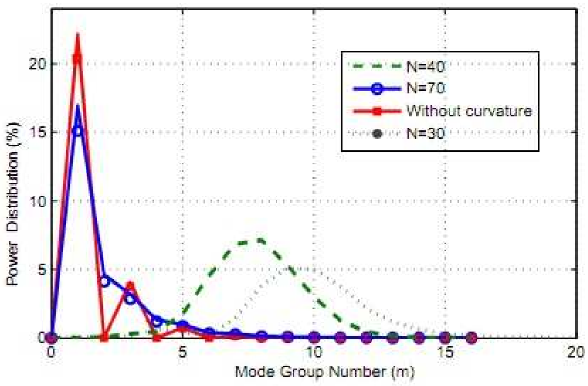

Fig. 5 Modal power distribution at the output of the curved fiber.

We deduce that for N = 30, there is an inter-modal coupling at the output of the curved portion. For N = 40, this inter-modal coupling decreases to almost a nil coupling for N = 70. In order to determine the optimal section number, we must determine the change of the channel orthogonality factor by the number of sections N. The parameter which measures the orthogonality among the various optical channels at the reception is the optical interference factor (σ_i). This parameter is given by:

$$\sigma_i = 10.log_{10}\left(\frac{\sum_{i\ne j} h_{i,j}}{h_{i,i}}\right) \qquad (9)$$

This coefficient measures the orthogonality between the receivers and allows us to determine the best receiver. It is used also to study the interference of a receiver relative to the others. In order to show the impact of this parameter on an MGDM system, the case of a (3×3) MGDM link is studied. For this system, three separate channels are created in an MMF by the injection of the light in three different offsets. The central transmitter launches only lower-order modes, the two other transmitters launches higher-order modes which are mainly traveling in the outer region of the MMF core. At the reception, every subgroup modes has a specific area of optical energy distribution at the output facet of the fiber. The segment areas are chosen so as to minimize, on average, the optical cross-talk at the detector segments. Figure 6 shows the change of $|\sigma_3|$ (the interference factor of the extremely channel of the (3×3) MGDM system) by the section number N for various R_c for α = 60 ° and for the case of an MMF (62.5/125µm). The choice of N depends on the R_c value. For Rc = 1000*a = 62,5mm the ideal section number is N = 60 as shown in Figure 6. For R_c = 200mm, the optimal section numbers are N=60 and N = 70 respectively. For N=70 the coupling between modes is negligible. In the case of a non-uniform curvature, we decompose the curved part into M_c series of uniform curved sections (each including N = 70 elements).

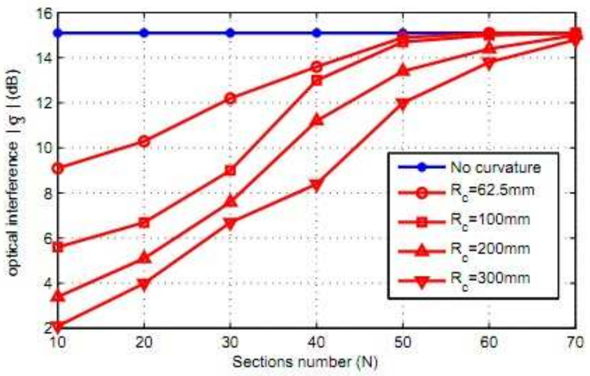

Fig. 6 Change by N of the interference factor of the extremely channel.

The transfer matrix determination of the MGDM channel with curvature is similar to that without curvature but with a change in the modal amplitude determining at the output of the curvature. The choice of the section number for a uniformly curved fiber depends on the stability in the values of the matrix H. Thus, M_c must be taken so that the angle α between the sections is low (<5 °). Ending with the choice of this number and in order to analyze the effect of the curvature on an MGDM system, we will compare its capacity with and without curvature. Figure 7 shows this comparison for a (3×3) MGDM link for the case of a GI-MMF fiber (62.5/125µm). Three systems are analyzed. The first one for an MGDM link without curvature, the second for the same link but with a curvature by taking R_c=100 mm and α = 60° and the third for a SISO link.

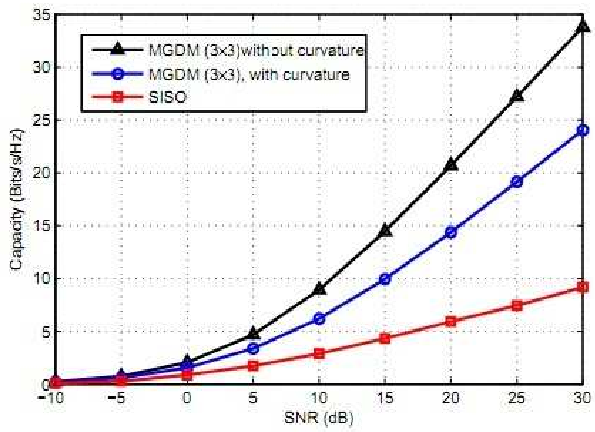

Fig. 7 Effect of the curvature on the system capacity of a (3×3) MGDM link.

For SNR = 30dB, the capacity is reduced significantly by the curvature. For this curve, the system capacity is not far from the SISO system.

4. Conclusions

In this paper, we studied the effect of the curvature which disturbs the propagation and degrades the transmission performance of the optical fiber. Thus, in order to reconcile our study to the reality, this mechanical effect acting on the MMF is modeled analytically. A full theoretical study supported by simulation results is presented. The decrease of the system capacity of an O-MIMO link using MGDM technique in the presence of the curvature effect has been demonstrated.

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