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Core Selection for Capacity on Demand in Multi-Core Fiber Transmission System

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Abstract: We propose and validate a core selection method on coupled-based MCF transmission system. This method allows to answer the question of capacity on demand of future application, without sacrificing the performance.

Keywords: Optical fiber communication, MIMO, Spatial multiplexing, Selection, Multi-core fiber

I. INTRODUCTION

The optical fiber communication systems have seen many evolutions during the last decade. All degrees of freedom in a single-mode fiber have been exploited: wavelength, amplitude, phase, and polarization. Nowadays, the currently deployed optical fiber reaches Shannon limit while the demand for network bandwidth increases exponentially. To overcome the capacity demands in the future, the last degree of freedom (Space) should be used. Space division multiplexing (SDM) is the most promising solution to increase optical fiber transmission throughput. The SDM is approached through multi-mode fibers (MMFs), which utilize more than one linearly polarized (*LP*) mode in a single core; or multi-core fibers (MCFs) where each core can carry a single-mode or more in the same cladding [1]. Due to the crosstalk between the cores and the imperfection in the built-in component of the transmission system (Fan-{In/Out}, amplifiers), the received energy at each core varies, which induces a non-unitary effect known as core dependent loss (CDL).

Several MCF layouts have been proposed in the last years [1][2]. In the uncoupled fiber, the main challenge is to reduce the coupling level to the minimum. This approach leads to better transmission performance on the cost of multiplexing a few cores, such as {3, 4}-core MCF. The main focus in this category is the fiber fabrication while preventing linear coupling induced between the cores. In a coupled fiber, the number of cores can be increased to reach, for example, {7, 12}-core MCF and allow the cores to exchange energy. In coupled MCF, there is a need of advanced MIMO digital signal processing (MIMO-DSP) techniques, which increase the receiver complexity. Another possibility to reduce coupling in this case, is to use heterogenous cores instead of homogeneous cores. In this work, we propose a new core selection method to answer the question of the capacity on demand of future maximization. We show that selecting 3 out of 7 cores in a 7-core coupled MCF performs the same or better as a 3-core MCF while keeping the flexibility to grow the capacity on demand.

II. MCF CHANNEL MODEL

We consider a long-haul MCF transmission system with a linear regime of propagation. We focus on the core crosstalk, which is estimated based on the coupled-power theory (CPT) [3] and the misalignment losses which arise due to the imperfection of the optical fiber at the splices, the connectors, and the Fan-{In/Out} devices [4]. These two effects induce an imbalance in the energy per core (CDL). All non-linearities related to Kerr effects are not considered to focus on the impact of the CDL on the transmission system performance. Also, the dispersion effects are not considered since they can be mitigated by using either Time domain equalization (TDE) or frequency domain equalization (FDE), and it does not reduce the system capacity. Considering MCF transmission with C cores, the resulting MIMO received signal can be described as [5]:

$$\mathbf{Y}_{C \times 1} = \mathbf{H}_{C \times C} \mathbf{X}_{C \times 1} + \mathbf{N}_{C \times 1} = \sqrt{L} \prod_{k=1}^K \mathbf{T}_k (\mathbf{H}_{XT})_k \mathbf{M}_k + \mathbf{N}_{C \times 1} \quad (1)$$

\mathbf{X} and \mathbf{Y} are respectively the emitted and the received vectors. \mathbf{N} is an Additive White Gaussian Noise with zero mean and variance \mathbf{N}_0 . MCF channel matrix (\mathbf{H}) is a concatenation of K fiber sections. Each span is equivalent to the multiplication of the crosstalk channel matrix $(\mathbf{H}_{XT})_k$ and the misalignment channel matrix (\mathbf{M}_k) that includes a random Gaussian misalignment loss with *zero* mean and standard deviation $\sigma_{x,y} = \% r_c$, where r_c is the core radius. \mathbf{T}_k is a diagonal matrix with random phase entries $\exp(j\varphi_c)$ where $\varphi_c \in [0, 2\pi]$ represents the phase fluctuation between the different cores. L is a normalization factor used to compensate for the link loss.

In this work, we evaluate the MCF system performance for four MCF designs, as shown in Fig. 1. The {3 and 7}-core homogeneous MCF structure (Homo-MCF) with one type of core as shown in Fig. 1(a) and (b). The {3 and 7}-core heterogeneous MCF structure (Hetero-MCF) with three types of cores (Black, Blue, and Red) as shown in Fig. 1(c) and (d). The illustration of the MCF design is shown in Table. 1, the core pitch (Λ) equal $40 \mu\text{m}$ and $24 \mu\text{m}$ for Homo-MCF and Hetero-MCF, respectively. The cladding diameter (CD) is equal to $125 \mu\text{m}$. n_0 is the refractive indices, and Δ is the relative refractive index difference between the core and 1st cladding.

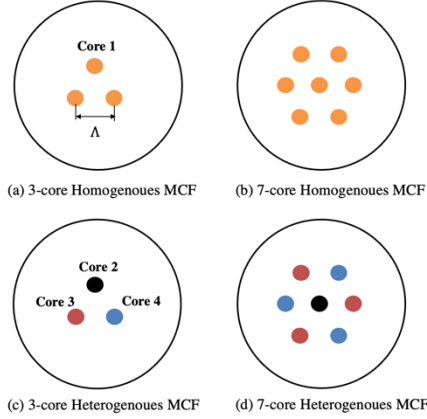


Fig. 1: Considered MCF layouts

Table 1: Cores Parameters

Core	Core 1	Core 2	Core 3	Core 4
r_c [μm]	4.5	4.68	4.76	4.68
n_0	1.45	1.45	1.45	1.45
Δ [%]	0.335	0.305	0.338	0.388

III. CORE SELECTION

We consider MCF transmission system as shown in the previous section with core selection technique. In this system, we excite C_T out of C cores ($C_T < C$) to be multiplexed at the transmitter side. Then, we detect C_R out of C cores ($C_R < C$) at the receiver side, as shown in Fig. 2. The MIMO system with core selection can be rewritten as:

$$\mathbf{Y}_{C_R \times 1} = \mathbf{H}_{C_R \times C_T} \mathbf{X}_{C_T \times 1} + \mathbf{N}_{C_R \times 1} \quad (2)$$

where $\mathbf{H}_{C_R \times C_T}$ is a subspace of $\mathbf{H}_{C \times C}$. The first selection method was previously proposed in wireless communication; it was proven that the antenna selection provides a rate gain with lower hardware cost [6]. Also, the authors show in [7] that the mode selection in MMF can allow deploying large-core MMF and having the same performance as smaller-core MMF. In this paper, we apply the same concept in MCF systems. The selection criterion is to choose the cores with the highest average received energy after propagating in the MCF channel impaired by CDL. However, the selected cores strongly depend on the MCF fiber design, unlike MMF, where the modes with the highest energy are known and fixed. For simplicity, we illustrate the benefit of core selection on the MCF designs shown in Fig. 1. To determine the selection criterion, we excite all the cores at the transmitter with unit energy $E_s = 1$. At the receiver side, we compute the singular value decomposition (SVD) of \mathbf{H} to define the cores with the highest energy.

We consider 300 fiber sections ($K = 300$) with $\sigma_{x,y} = 7\% r_c$ and 100km fiber length. We simulate 10^5 realizations of the 7-core HOMO-MCF and Hetero-MCF as shown in Fig. 3(a) and 3(b), respectively. In Fig. 3, we plot the probability distribution function of the singular values at the receiver side. We notice that for the 7-core HOMO-MCF, the cores have the same energy. In this case, we base our selection decision on the cores with the lowest surrounding cores neighbors. In addition, we observe that for 7-core Hetero-MCF, the cores with higher received energies are core 3, core 4, and core 2, respectively.

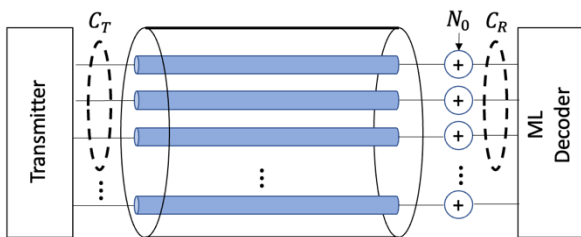


Fig. 2: Core selection scheme

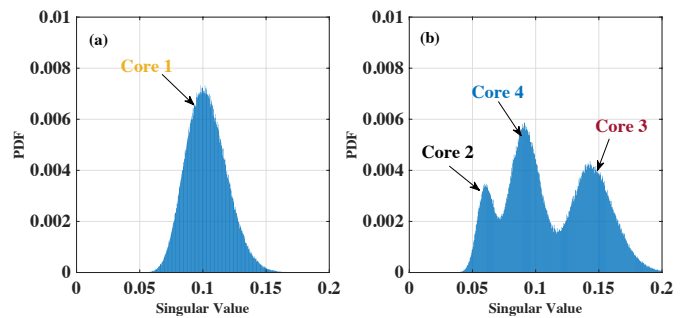


Fig. 3: PDF of the singular value for each core: (a) 3-core HOMO-MCF and (b) 3-core Hetero-MCF

IV. SIMULATION RESULTS

To validate the benefits of the core selection, we test the performance of the $\{3, 7\}$ -core Homo-MCF and Hetero-MCF. We plot the bit-error-rate (BER) versus the signal-to-noise ratio (SNR = E_s/N_0). We apply 16-QAM modulation at the transmission side, and we develop the fiber parameters mentioned in the previous section. At the receiver side, we detect the signals using an optimal maximum-likelihood (ML) MIMO decoder.

In Fig. 4, we compare the performance of the 3-core Homo-MCF to 7-core Homo-MCF with an exciting of 3 cores ($C_T = 3$). For a fair comparison, the two transmission systems have equal spectral efficiency $SE = 12$ bits/channel use, and average received energy normalized to the 3-core MCF system. We observe that the 3×3 channel in 7-core Homo-MCF has the same performance as the 3×3 channel in 3-core Homo-MCF. To enhance the transmission performance, we can increase the number of detected cores to be equal to 4 cores ($C_R = 4$) by detecting the center core. In this case, we notice the 4×3 channel has an SNR gain of 1dB at BER = 10^{-3} compared to the 3×3 channel in the 3-core Homo-MCF. For further enhancement, we detect all the cores ($C_R = 7$) to obtain an SNR gain of 3dB compared to the 3×3 channel.

In Fig.5, we compare the performance of the 3-core Hetero-MCF to 7-core Hetero-MCF with an exciting of 3 cores ($C_T = 3$) considering the same SE and average received normalized energy with respect to the 3-core MCF. Since the cores have different energy levels, unlike Homo-MCF, we notice that the 3×3 channel in 7-core Hetero-MCF has an SNR gain of 1dB at BER = 10^{-3} compared to 3-core Hetero-MCF. When we detect the center core ($C_R = 4$), the SNR gain reaches 2.2dB compared to the 3-core Hetero-MCF. In addition, we observe an SNR gain of 3dB compared to the 3-core Hetero-MCF by detecting all the cores.

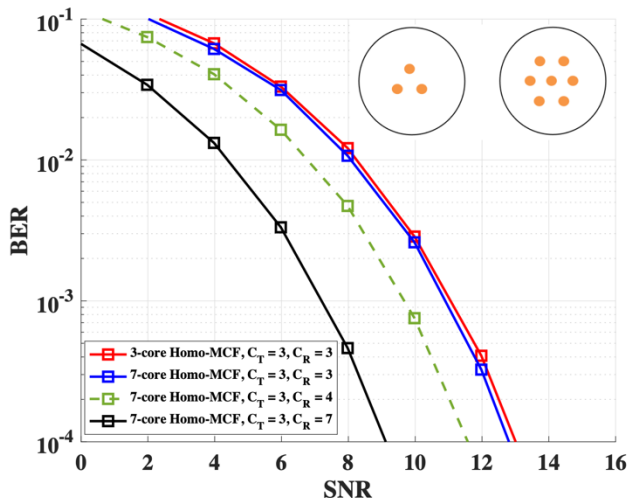


Fig. 4: Performance of 3-core Homo-MCF and 7-core -MCF with core selection, C_T is the transmitter core selection and C_R is the receiver core detection

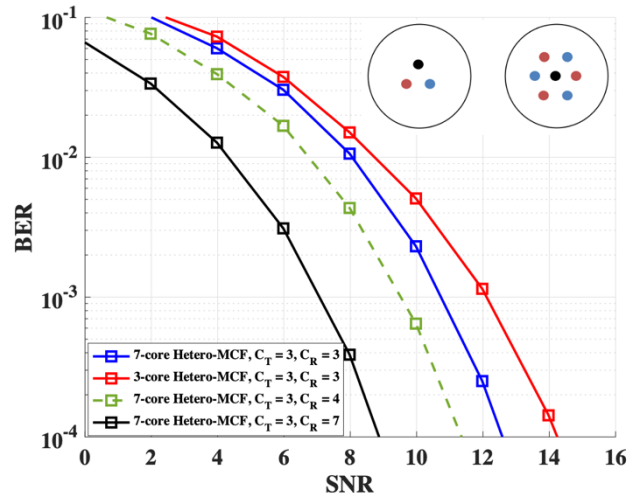


Fig. 5: Performance of 3-core Hetero-MCF and 7-core Hetero-MCF with core selection, C_T : the transmitter core selection. C_R : the receiver core detection

V. CONCLUSION

In this paper, we proposed and validated a core selection method in 7-core MCF. However, the selection techniques can be applied for any MCF configuration. At the receiver side, the sub-optimal MIMO decoding can be used such as Zero-Forcing decoder at the cost of transmission performance degradation compared to ML decoder. We have shown the potential of core selection to enhance the transmission performance of a large number of cores compared to a few numbers of cores. In addition, the performance of the system can be further enhanced by increasing the number of detected cores at the receiver side. Thus, core selection can play a key role in the future of MCF deployments since the infrastructure can support a large number of cores while using a low-complex MIMO scheme based on the capacity demands of the users. The capacity of the system can be increased with the multiplexing of more cores without changing the infrastructure.

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