Capacity of Multi-Core Fiber with Maximum-Ratio Combining Optical Receiver

Amira M. Hussein[§], Ziad A. El-Sahn[§], and Hossam M. H. Shalaby[§¶]
[§]Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt
[¶]Egypt-Japan University of Science and Technology (E-JUST), Alexandria 21934, Egypt
Email: amira.hussein13@gmail.com, ziad.elsahn@ieee.org, shalaby@ieee.org

***Abstract*—Balance between spatial capacity and diversity in a multi-core fiber system adopting maximal-ratio combining receiver is studied. Compared to standard single-mode fiber, the bit-error rate is improved when partially sharing multi-core fiber cores among users.**

***Index Terms*—Crosstalk, diversity, multi-core fiber, space-division multiplexing.**

I. Introduction

Space division multiplexing (SDM) technologies over multi-core fibers (MCFs) have been intensively investigated to overcome the transmission capacity limit of approximately 100 Tb/s/fiber for the conventional optical communication system over a single-mode fiber (SMF) [1]. One of the significant properties in MCF transmission is the inter-core crosstalk (XT) caused by the mode coupling between adjacent neighbor cores due to the impact of fiber bending and twisting which distorts the signal waveform and limit the transmission performance over long distances [2]. However, the SDM technique over MCF cannot overcome the issue of power limit per fiber and the nonlinearity phenomenon. As well known the fiber nonlinearity is limiting factor of the Q-value in the SMF.

Optical diversity transmission across MCF with maximal-ratio combination (MRC) is a simple approach to mitigate fiber nonlinearity and also enables the power limit to be increased [3]. The system Q-factor is enhanced by 2 and 4 dB using 2 and 4 diversity cores of MCF, respectively. Consequently larger transmission distance and higher signal-to-noise ratio (SNR) could be achieved. It has been expected that the improvement in the Q-factor could be increased with the increase of the number of diversity cores in MCF. However, the effect of the inter-core XT has not been considered in [3], In [4] MRC diversity though weekly-coupled MCF has been explained by considering a more realistic system that includes inter-core XT. The MCF has been modeled and simulated for 2, 4, and 8 diversity cores. The Q-factor has been enhanced by 2.5 and 5 dB for the 2 and 4 cores diversity in case of zero XT, while for 8 cores an additional 1 dB is achieved (compared to 4-cores). That is, the Q-factor cannot be increased linearly with the diversity cores. Thus, for better spatial utilization efficiency, balance between spatial diversity and spatial capacity should be considered.

In this paper we discuss how we can balance between the spatial diversity and capacity, without the need of complex MIMO-DSP system. We divide the MCF cores among multiple users instead of only one user and hence enhance the system capacity performance. Our simulations focus mainly on 5 and 7-cores fiber. In the 5-cores fiber, 1, 2, 3, and 5 users are considered, while in the 7-cores fiber, 1, 3, 4, and 7 users are considered. In addition, we explore the effect of the inter-core XT in case of 3 users in a 7-cores fiber

II. Proposed MCF Based System using MRC Receiver Diversity

The setup of the proposed MCF based system adopting MRC receiver diversity for multiple users is illustrated in Fig. 1(a). The figure shows the case of 2 users sharing a 5-cores fiber. For each user the modulated optical total power to be transmitted P_{Tx}, is split into M branches. Each component, $P_M = P_{\text{Tx}}/M$ is launched into a different core of the same MCF. At the receiver side, all signals for each user are coherently detected from different cores and passed to a DSP block, where phase estimation and compensation are carried out to ensure adding signals up coherently at the MRC combiner. Next, the M divided signals are combined after weighting with a weight that is inversely proportional to the branch noise power to maximize the signal-to-noise ratio (SNR).

The effect of the inter-core XT is considered in the simulation by modeling the MCF using conventional coupled mode equations [5]. The XT introduces discrete changes in power levels caused by coupling between cores:

$$\frac{dA_m}{dz} = -j \sum_{n \neq m} \kappa_{mn} A_n(z) e^{j\Delta\beta_{mn} z}, \qquad (1)$$

where A_n represents the amplitude of the electric field, κ_{mn} is the mode-coupling coefficient from core n to core m, and $\Delta\beta_{mn}$ is the difference in the propagation constant between two cores. Notice that the value of κ_{mn} varies between adjacent and non-adjacent cores. In addition, $\Delta\beta_{mn}$ includes two terms one of them is constant due to intrinsic propagation constant difference and the other is random due to random perturbations. Consequently, we model the MCF using cascaded SMF segments, where each segment is characterized by a random variation in the propagation constant that captures the effect of bending and twisting. Then the effect of accumulated XT through each segment is added by solving the coupled mode equations analytically within each segment. Also, the differential group delay (DGD) between cores can be modeled

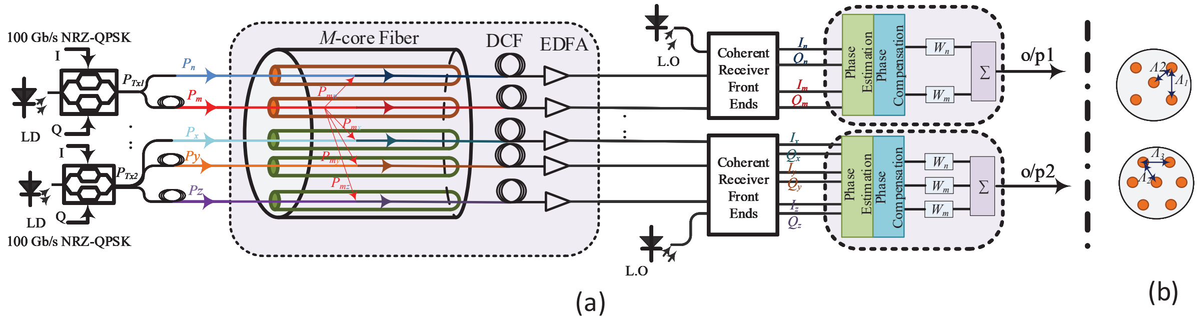


Fig. 1: (a) MCF system with MRC receiver diversity. (b) MCF for 5 and 7 cores. (DCF: dispersion compensating fiber, EDFA: erbium-doped fiber amplifier, κ: coupling coefficient, LD: laser diode, L.O: local oscillator, NRZ-QPSK: non-return-to-zero quadrature phase-shift keying). Fiber Parameters: fiber attenuation = 0.2 dB/km, chromatic dispersion = 17 ps/nm/km, DGD: 0 ps, nonlinear refractive index = 3.1×10^{-20} m^2/w and effective area = 72 $\mu\mathrm{m}^2$. EDFA noise figure = 5 dB.)

by introducing a delay between signals at the end of each segment.

III. System Performance and Simulation Results

The performance of the proposed system shown in Fig. 1(a) is evaluated via MATLAB/OptiSystem co-simulation. A 100 Gb/s NRZ-QPSK signal for each user is generated and equally divided among identical cores of a homogenous 1040 km MCF link composed of 13 spans. Each span consists of 80 segments of MCF that is fully compensated by a DCF and conventional EDFA per core. Each MCF span is modeled by 8 segments of SMF.

The BER performance improvement is shown in Fig. 2 for the case of 5 and 7 cores MCF (cf. Fig. 1(b)) with no XT (zero XT is considered) compared to a reference SMF case, which mimics the system without MRC diversity. From the results

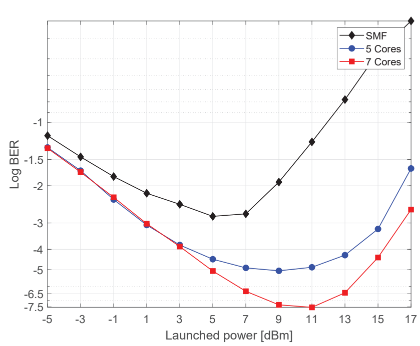


Fig. 2: BER versus launched power P_{Tx} for 5 and 7 cores in MCF.

in this figure, the system performance is enhanced when using the MRC when compared to SMF. This is because the total launched power P_{Tx} is divided among the cores. This yields a reduction of the peak power at each core which in turn reduces the fiber nonlinear effects.

We can notice that the MRC achieves minimum BER at higher values of optical launched power when compared to the SMF. The BER decreases with the increase of the diversity order. The minimum achievable BERs for the 5 and 7 cores fiber occur at 9 and 11 dBm of the optical launched power, respectively. While for the SMF the minimum BER is at 5 dBm of the launched power. That is, the optical launched power is increased by 4 and 6 dBm and minimum BER is decreased by about -20.2 and -40.7 dB for 5 and 7 cores fibers, respectively.

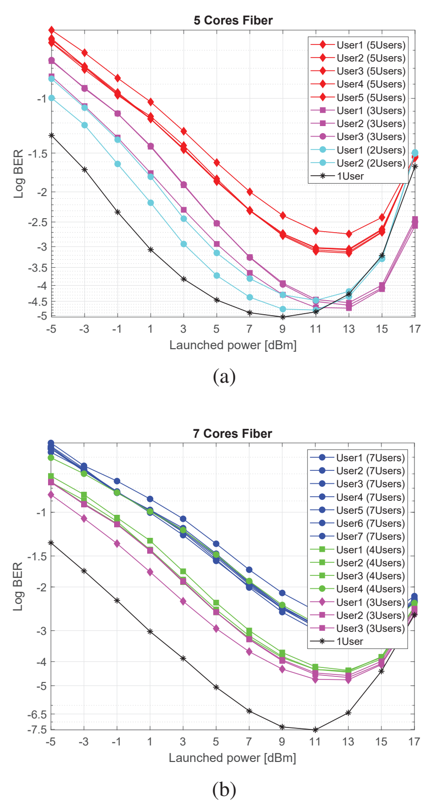


Fig. 3: (a) BER versus launched power P_{Tx} for 1, 2, 3, and 5 users in 5 cores in MCF. (b) BER versus launched power P_{Tx} for 1, 3, 4, and 7 users in 7 cores in MCF.

In Figs. 3(a) and (b), the balance between spatial diversity and spatial multiplexing is considered by varying the number of users sharing same MCF considering zero XT for 5 and 7 cores fiber. From Fig. 3(a), the BER performance for the 5 cores fiber cases are shown. Red, magenta, cyan, and black lines are for 5, 3, 2, and 1 user sharing the 5 cores fiber, respectively. For the 5 users, the MCF cores are divided equally among users. For the 3 users, users 1 and 2, each of them shares 2 cores of the MCF, whereas the 3rd user shares only 1 core. For the 2 users, user 1 utilizes 3 cores of the MCF and the 2nd user shares 2 cores. However, for the case of only 1 user, the 5 cores are totally dedicated by only one user. Fig. 3(b) shows the BER performance of the 7 cores fiber of multiple users sharing the same MCF. Blue, green, magenta, and black lines are for 7, 4, 3, and 1 user sharing the 7 cores fiber, respectively. For the 7 users, the MCF cores are divided equally between users. For the 4 users, users 1, 2, and 3, each of them share 2 cores of the MCF, whereas the 4th user shares only 1 core. For the 3 users, user 1 utilizes 3 cores of the MCF while the 2nd and 3rd users, each of them shares 2 cores. However for the case of only 1 user, the 7 cores are totally dedicated for him. From the results in these figures, one can conclude that one can avail balance between capacity and diversity by sharing the cores of MCF between multiple users instead of just one user.

The effect of the inter-core XT is considered in Fig. 4 for the case of 3 users sharing 7 cores fiber. The solid lines with

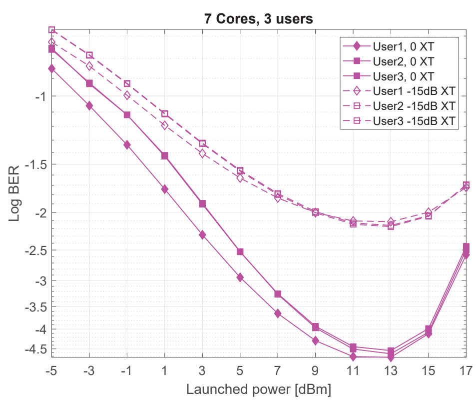
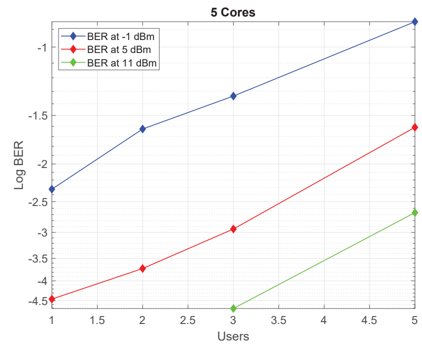


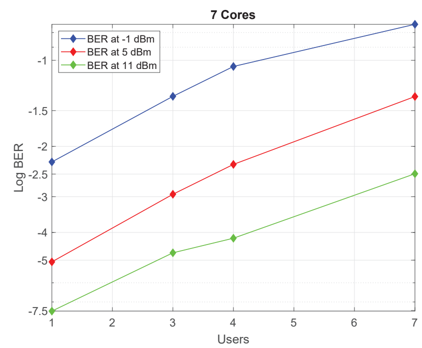
Fig. 4: BER versus launched power P_{Tx} for 3 users in 7 cores in MCF at 0 and -15 dB crosstalk level.

solid markers are for the case with 0 XT, while the dotted lines with open markers are for the case of -15 dB inter-core XT. It is obvious that the minimum values of BER of the 3 users in case of the effect of the XT are approximately near to the value of SMF. That is, even with inter-core XT in MCF, the diversity system with multiple numbers of users still enhances BER of MCF compared to that of SMF.

In Fig. 5(a) and (b), the BERs versus number of users at different optical launched power values in linear and nonlinear regimes are shown for the 5 and 7 cores fiber MCF, respectively. We can deduce that the MCF can be consumed by more than 1 user and the BER will be better than that of the case of SMF. In case of 5 cores fiber, 2 and 3 users can share same fiber with moderate values of BER. In addition, for the 7 cores



(a)



(b)

Fig. 5: (a) BER versus the number of users for 5 cores in MCF. (b) BER versus the number of users for 7 cores in MCF.

fiber, 3 and 4 users can share the MCF at the same time.

IV. Conclusion

A balance between spatial diversity and spatial capacity is proposed for a MCF-based system adopting MRC. The cores in a MCF are partially shared among multiple users so that performance improvement is achieved compared to that of SMF. The performance of MCF-based system adopting MRC diversity shows improvement in system BER compared to that of SMF even when considering the effect of inter-core crosstalk.

References

[1] T. Sakamoto, K. Saitoh, S. Saitoh, K. Shibahara, M. Wada, Y. Abe, A. Urushibara, K. Takenaga, T. Mizuno, T. Matsui, K. Aikawa, Y. Miyamoto, and K. Nakajima, "Six-mode seven-core fiber for repeated dense space-division multiplexing transmission," *Journal of Lightwave Technology*, 2018.

[2] M. J. Hossain and S. P. Majumder, "Performance limitations due to crosstalk in an optical transmission link over multi-core fiber," in *ICTP*, 2016.

[3] M. Koga, A. Mizutori, and T. Iida, "Optical diversity transmission and maximum-ratio combined receiver in multi-core fiber to mitigate fiber non-linear phenomenon," *IEICE Communications Express*, 2013.

[4] M. A. F. Banawan, A. M. Hussein, Z. A. El-Sahn, and H. M. H. Shalaby, "Performance of space-division multiplexed systems adopting multi-core fibers and receiver diversity," in *Asia Communications and Photonics Conference (ACP)*, 2015.

[5] T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber," *Opt. Express*, 2011.