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MMF-based Data Center Interconnect using Commercial Coherent Transceivers

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***Abstract*—In this manuscript we present an experimental analysis of a multi-mode fiber (MMF) link based on coherent detection. We propose the use of a commercial coherent transceiver to increase the transmission speed of a short-reach optical communication system over 300 m OM3 fiber. The performance of the system is studied in terms of bit rate as a function of the power budget margin (PBM) defined as the extra attenuation that can be introduced on the optical path. We investigate polarization multiplexed (PM) QPSK and 16-QAM modulation formats achieving up to 400 $Gbps$ net bit rate transmission. Moreover, we analyze the impact of the lateral offset introduced by the connectors between MMF segments, showing decreasing PBM for increasing lateral offset. Nevertheless, PBM in excess of 28 dB for PM-QPSK modulation at 100G and 200G, 23 dB for 200G PM-16QAM modulation and 16 dB for 400G PM-16QAM, shows that commercial coherent transceivers can be used on MMF links up to much higher bit rates than those achieved by current VCSEL+direct detection based systems, provided that connections along the MMF have connectors connectors with offsets in the 3 μm to 6 μm range.**

***Index Terms*—Data center interconnects, coherent detection, short-reach optical communications**

I. Introduction

Currently, vertical cavity surface-emitting lasers (VCSELs) coupled with MMF links and intensity modulation (IM) and direct detection (DD) are still used in data center interconnects (DCIs) for transmission distances up to a few hundred meters. VCSEL+MMF-based communication has been defined at 28 $Gbps$ per lane over 70 m and 100 m by the Ethernet 100GBASE-SR4 and Fiber Channel (FC) 32G-FC standards, using on-off keying (OOK) modulation. Moreover, the 400GBASE-SR8 and 400GBASE-SR4.2 standards define 50 $Gbps/\lambda$ with PAM-4 modulation. However, multimodal dispersion strongly affects MMF-based transmission systems [1], making communication at speed above 50 $Gbps$ very challenging. An upgrade of DCIs beyond this limit will be needed in the mid-term to cope with the increasing intra-data center traffic demand. Coherent detection coupled with advanced modulation formats would be an interesting option, provided that the cost associated with coherent transceivers can be drastically reduced. Previous works have shown the advantages in terms of sensitivity and overall power budget that coherent detection can provide in the traditional SMF-based short-reach communications scenario [2]. But coherent transceivers are intrinsically SMF-coupled, whereas data centers are often still equipped with sections of legacy MMF of the OM2 or OM3 type, for an annual worldwide revenue of more than 5 billions USD per year.

Therefore, in order to avoid the replacement cost of already installed MMF fiber deployments in Data Centers or in Enterprese networks, coherent detection would have to coexist with MMF fibers. We already showed through simulations and experiments in one of our previous paper [3] that as long as good central alignment is ensured at the SMF-MMF and/or MMF-MMF connector interface, a "quasi single-mode" propagation can be established along the optical path [4], [5], yielding remarkably good transmission performance and very high optical power budget margin (PBM). On the other hand, when a lateral offset is introduced by a non-perfect connection between two fiber sections, the fundamental LP_{01} mode traveling inside the SMF at the transmitter side couples to higher order modes inside the MMF, causing modal dispersion and mode interference to degrade the system performance. In this paper, extending the work presented in [6]–[8], we experimentally investigate the impact of connectors lateral offset in a coherent over MMF (coh-MMF) system using a commercial coherent transceiver. Results are presented in terms of BER as a function of the optical power budget margin, comparing the back-to-back with SMF only to the configuration with variable offset, with net bit rates ranging from 100 $Gbps$ using polarization multiplexed- (PM-) QPSK to 400 $Gbps$ based on PM-16QAM modulation. The remainder of this manuscript is organized as follows: in Section II we present the experimental setup and we show the results for a variable single offset. In Section III we use an MMF fiber shaker that implements TIA-455-203 specifications for MMF fiber testing and we show the impact of fiber mechanical stress on the sustem performance. In Section IV results obtained with more than one offset are introduced and in Section V we draw some final conclusions.

We would like to emphasize that the present paper was intentionally focused on our latest experimental results. After the preliminary one-page abstract was accepted for this ICOP2022 conference, another paper of ours on the same topics [3] was also accepted for publications. For the interested reader, in [3] we also present a detailed theoretical/simulative model to statistically study our system in the presence of multiple connectors with random offsets, and we were thus able to derive the scalability of this type of systems in a more general framework than the one that is experimentally tested in the present paper.

II. Impact of a single connector offset

Our experimental setup is depicted in Fig. 1. It includes an SMF patchcord at the transmitter output connected to a 2 m MMF patchcord. An intentional lateral offset is introduced by fusion splicing the two halves of the MMF patchcord with a controlled lateral misalignment, to emulate non-perfect connections on the optical path. Then, a MPX-SR3 MMF fiber shaker is used to introduce up to 10 Hz standardized mechanical vibration to the fiber, as required by TIA-455-203 procedures (originally introduced for 10GBase-LRM testing). A 300 m OM3 fiber spool is used to emulate intra-data center transmission and is connected to a SMF section at the input of the coherent receiver. Before the receiver a variable optical attenuator (VOA) is used to vary the received optical power and thus emulate a variable power budget. All the connectors in the system are lab-grade mating sleeves to ensure that no additional misalignment is introduced in addition to the spliced offset.

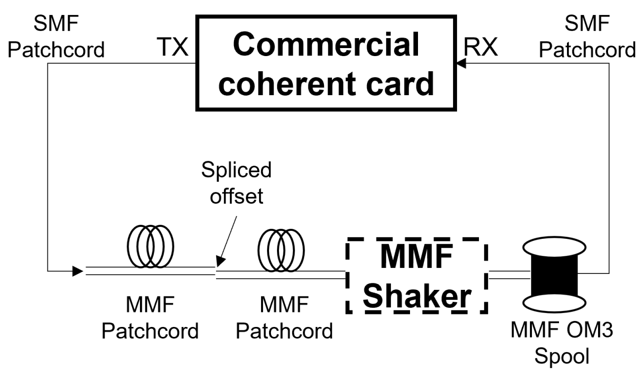

Fig. 1. Experimental Setup.

We investigated the following configurations:

1) "back-to-back" with SMF only as the reference benchmark;
2) "OM3 only" with only the 300 m fiber spool without offset;
3) "3 μm offset-OM3" with a 3 μm lateral offset induced on the MMF patchcord before the OM3 fiber spool;
4) "6 μm offset-OM3" with a 6 μm lateral offset induced on the MMF patchcord before the OM3 fiber spool.

Fig. 2 highlights the performance of the four configurations showing the BER as a function of the power budget margin defined as the extra attenuation introduced via the VOA. The PM-QPSK results in Fig. 2a show that the PBM penalty is very small when we compare transmission along the OM3 fiber without connector offset with the back-to-back. It increases with the lateral offset up to 2.2 dB at 10^{-2} bit error rate in the worst case of the configuration with 6 μm offset. In any case, very high margins can be achieved if we consider a 10^{-2} BER threshold. 30 dB is the minimum observed at 200G with 6 μm offset. For 100G, we get always more than 34.5 dB. Without any offset this system gives about 36.5 and 31.6 dB PBM respectively for 100G and 200G.

With PM-16QAM modulation (2b) the situation is slightly more critical, especially at 400G. The penalty can be observed even without any offset. It is about 2.2 and 3 dB and increases to 3.3 and 4 dB respectively for 200G and 400G in the worst case of 6 μm offset. In terms of margins, we can still observe reasonably good performance with a minimum of 19.4 dB at 10^{-2} BER for the worst case of 400G transmission with 6 μm lateral offset. Interestingly, this PBM can be increased by about 3 dB by using a more powerful FEC with $2 \cdot 10^{-2}$ BER threshold. At 200G, on the other hand, we have 26.3 dB PBM in the worst case.

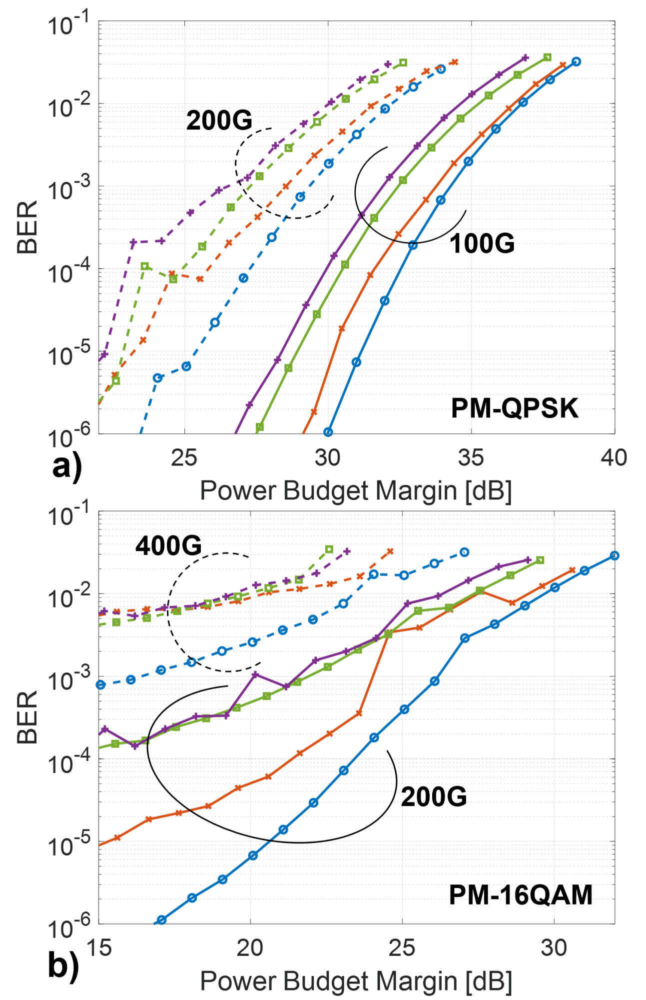

Fig. 2. Measured BER vs power budget margin for a) PM-QPSK and b) PM-16QAM modulation in different conditions: back-to-back (blue, circles), 'OM3 only' (red, crosses), '3 μm offset-OM3' (green, squares) and '6 μm offset-OM3' (purple, plus signs) configurations.

III. Robustness to mechanical stress

As a stress test, we checked on the stability of the system following a procedure similar to that applied to 10GBase-LRM transceivers, using the fiber shaker which, as previously discussed, was defined in TIA-455-203 standards. We also manually changed the position of the fiber. The MMF patchcord was rolled 4 times on a 10 cm circular bobbin, so as to intentionally enhance the impact of the mechanical movements. This has two effects: it affects mode mixing due to a change in the spatial distribution of the modes and moreover it leads to a variable optical loss due to the offset, indicated by the numbers next to each curve in Fig. 3. We tested: 200G PM-QPSK modulation with 6 μm offset (Fig. 3a), observing good tolerance to modal noise at 10^{-2}. In the 400G PM-16QAM case (Fig. 3b) the effect of modal noise is already present when the offset is 3 μm, and increases significantly when the offset is 6 μm. Nevertheless, in good modal noise condition, we still observe over 19 dB power budget margin.

IV. Impact of multiple offsets

The results shown in Sections II and III prove that the coh-MMF system is rather stable and provides very good performance when a single connector lateral offset up to 3 μm is introduced. In this section we report on the effect of multiple connectors offset.

Fig. 4 shows the achievable power budget when two lateral offsets are introduced on the MMF path through splicing, compared to the back-to-back and the "OM3 only" configuration. A large PBM penalty with respect to the back-to-back can be observed for both modulation formats: using PM-16QAM the PBM penalty at 10^{-2} BER is 5.3 dB and 6.4 dB at 200G and 400G, respectively; with PM-QPSK the penalty is abot 4 dB for both 100G and 200G transmission. Moreover, for both modulations, we compared the configuration where the two 3 μm spliced offsets are placed before the OM3 fiber spool (green curves in Fig. 4) and the configuration with one 3 μm offset at either side of the OM3 spool (purple curves in Fig. 4). No significant difference can be observed, thus the location of the offset does not have any effect on the system.

Lastly, we analyzed the effect of mechanical stress in the most critical case of 400G transmission based on PM-16QAM modulation, when three 3 μm offsets and the MMF shaker are placed before the OM3 spool. Fig. 5 shows five repeated measurements with a huge variation of the performance. In some conditions the system can provide remarkably good PBM close to 20 dB at 10^{-2} but, in some other conditions, the modal dispersion is so strong that below threshold BER cannot be measured. Interestingly, the system works in all the investigated conditions provided that the BER threshold is increased to $2 \cdot 10^{-2}$.

V. Conclusions

We have experimentally analyzed coherent detection and advanced modulation applied to a short-reach intra-data center MMF link using a commercial coherent transceiver. We have shown that if the connections between MMF fibers are good

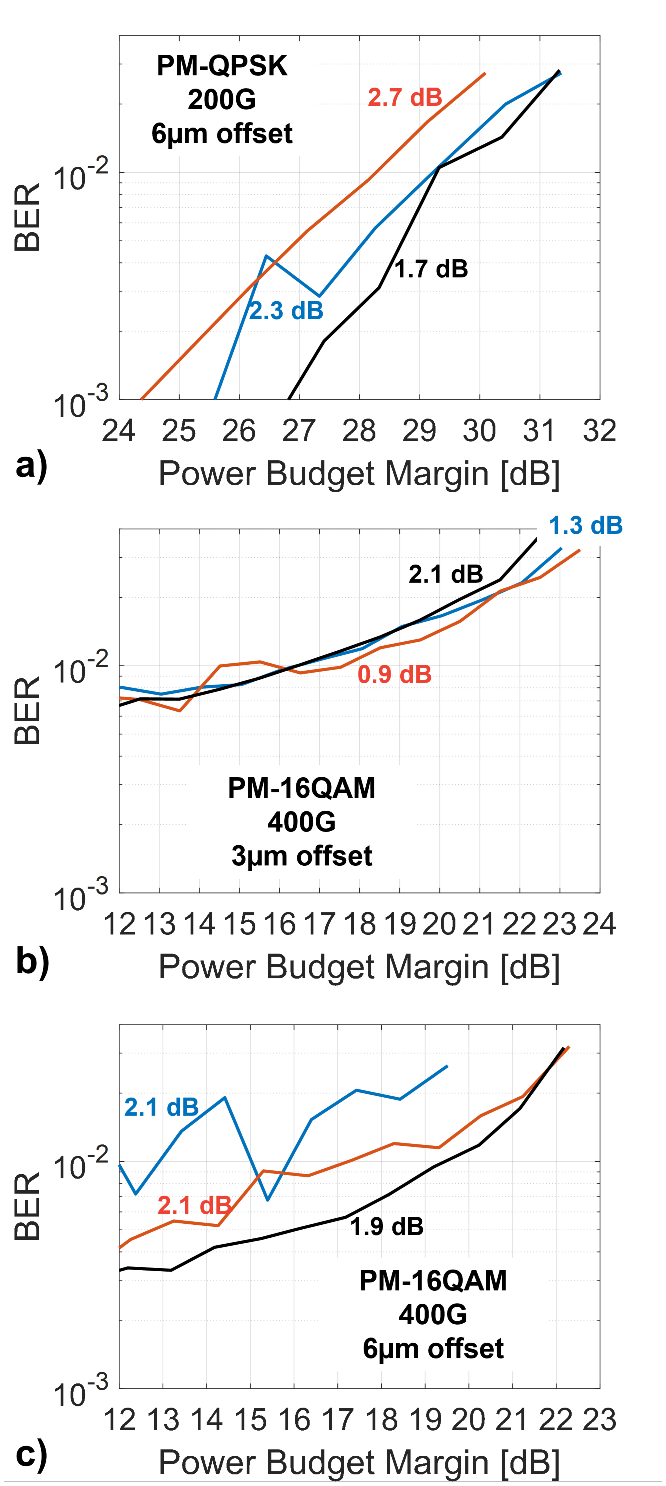

Fig. 3. Repeated measurements on BER vs. power budget margin for different positions of the MMF patchcord for a) '6 μm offset-shaker-OM3' configuration with 200G PM-QPSK modulation, b) '3 μm offset-shaker-OM3' configuration with 400G PM-16QAM modulation and c) '6 μm offset-shaker-OM3' configuration with 400G PM-16QAM modulation. The number next to each curve is the net optical loss introduced by the offset patchcord at each position.

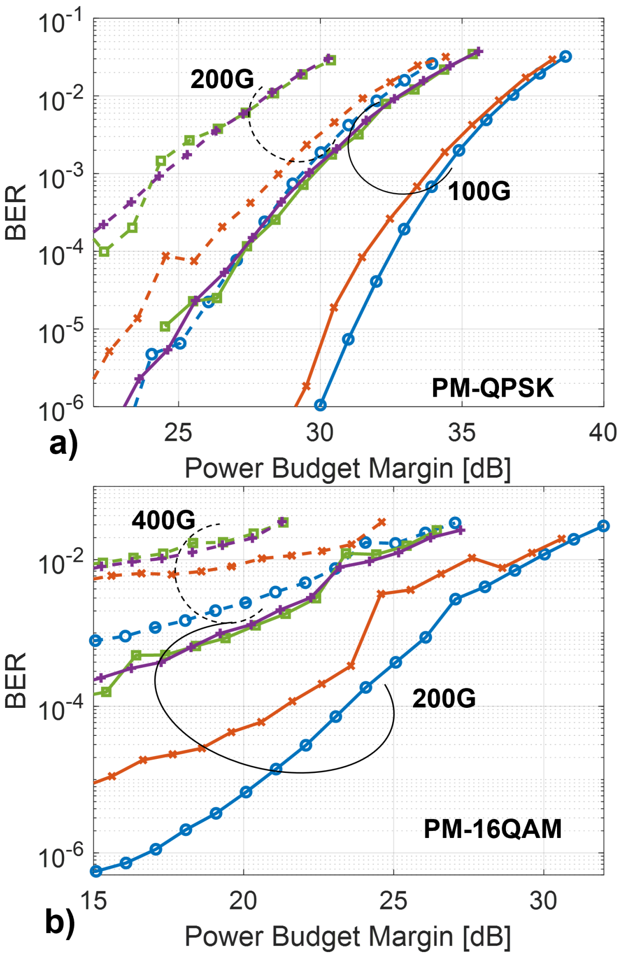

Fig. 4. Measured BER vs power budget margin for a) PM-QPSK and b) PM-16QAM modulation in different conditions: back-to-back (blue, circles), 'OM3 only' (red, crosses), '3 μm offset-3 μm offset-OM3' (green, squares) and '3 μm offset-OM3-3 μm offset' (purple, plus signs) configurations.

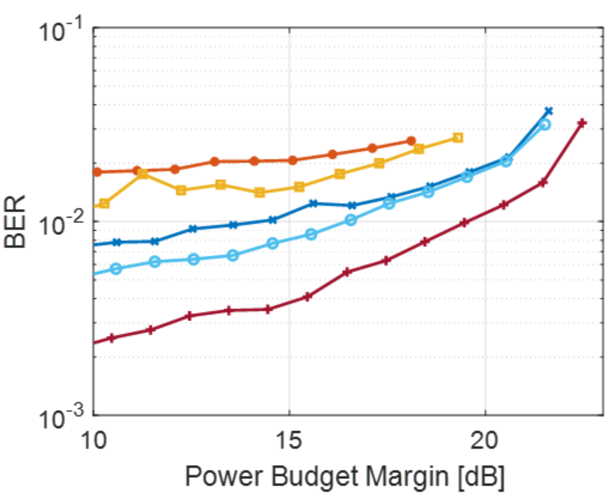

Fig. 5. Repeated measurements on BER vs. power budget margin for different positions of the MMF patchcord for the '3 μm offset-shaker-3 μm offset-3 μm offset-OM3' configuration with 400G PM-16QAM modulation.

enough, commercial coherent receivers can be used to achieve much higher bit rates than those provided by current direct detection-based solutions. Using PM-QPSK modulation up to 6 μm single offset or two 3 μm offsets can be tolerated. PM-16QAM modulation at 400G is more critical, but still able to tolerate a single 3 μm offset, considering a $2 \cdot 10^{-2}$ bit error rate threshold.

We have thus shown that, when "good" connectors are used along the MMF link, the coherent-over-MMF systems works with unexpectedly good performances even under mechanical stresses, thanks to a "quasi-single mode" type of propagation, that is discussed in detail from a theoretical/simulative vewepoint in our companion paper [3].

In this paper, we focused on physical layer performance, while we did not perform any type of techno-economics evaluation, since it was outside the scope and the available space. As discussed at length in the conclusion of [2], the actual future penetration of coherent transceivers in very short reach applications (as the one needed for optical interconnect inside data centers) will strongly depend on the reduction of the related CAPEX costs which are expected to decrease in the near future, but with a trend that is not yet totally clear.

Acknowledgment

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References

[1] J. M. Castro, R. Pimpinella, B. Kose, P. Huang, A. Novick and B. Lane, "Modal-Chromatic Dispersion Interaction Effects for 850 nm VCSEL Channels at 100 Gb/s per Wavelength," *IEEE/OSA Journal of Lightwave Technology*, vol. 39, no. 7, pp. 2067-2076, 1 April1, 2021.

[2] G. Rizzelli, A. Nespola, S. Straullu, F. Forghieri and R. Gaudino, "Scaling Laws for Unamplified Coherent Transmission in Next-Generation Short-Reach and Access Networks," *IEEE/OSA J. Lightwave Technol.*, vol. 39, no. 18, pp. 5805-5814, 2021.

[3] G. Rizzelli Martella, P. Torres-Ferrera, F. Forghieri, A. Nespola, A. Carena and R. Gaudino, "Coherent Communication over Multi Mode Fibers for Intra-Datacenter Ultra-High Speed Links," *Journal of Lightwave Technology*, doi: 10.1109/JLT.2022.3174422.

[4] D. Donlagic and B. Culshaw, "Propagation of the fundamental mode in curved graded index multimode fiber and its application in sensor systems," *Journal of Lightwave Technology*, vol. 18, no. 3, 2000.

[5] A. Amphawan, F. Payne, D. O'Brien and N. Shah, "Derivation of an Analytical Expression for the Power Coupling Coefficient for Offset Launch Into Multimode Fiber," *Journal of Lightwave Technology*, vol. 28, no. 6, pp. 861-869, 2010.

[6] G. Rizzelli, F. Forghieri and R. Gaudino, "Experimental Demonstration of Real-Time 400G Coherent Transmission Over 300m OM3 MMF," *Optical Fiber Communication Conference (OFC)*, Paper W1G.2, 2022.

[7] Z. Wu, J. Li, J. Zhu, Y. Yang, Y. Xin, Y. Zhang, J. Yu, Z. Li, Z. Chen, and Y. He, "Experimental Demonstration of MMF Fundamental-mode MMF Transmission Enabled by Mode Conversion," *Asia Communications and Photonics Conference*, paper M1B.3, 2017.

[8] Y. Ma, Y. Tang and W. Shieh, "107 Gb/s transmission over multimode fiber with coherent optical OFDM using center launching technique," *35th European Conference on Optical Communication*, 2009.