Going Coherent to Upgrade Data Centers MMF Links above 100G?

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(Invited paper)

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***Abstract*—Large Scale Data Centers are still using Multi-Mode Fibers (MMF) for short distance links up to 300 meters, and IEEE is currently working on standardizing a new generation of systems for 100Gbit/s/λ transmission using VCSEL+MMF transceivers on OM3 and OM4 fibers. These systems will still be based on IM-DD.**

In this paper, we experimentally and theoretically investigate on re-using already deployed OM3 and OM4 fibers using commercial coherent transceivers for bit rates up to 400G, showing that the only practical limitation of this solution is connector offsets. We experimentally show a 200G transmission tolerating offsets up to 6 μm, and 400G up to 3 μm offset.

***Index Terms*—Multi-mode fibers, MMF, coherent optical systems, data center interconnects.**

I. INTRODUCTION

In today's short-reach optical communication systems, the combination of vertical cavity surface emitting lasers- (VCSEL-) based transceiver and multimode fibers (MMF) is still the solution of choice thanks to reduced transceiver CAPEX cost and overall simplified installation. Anyway, in the never-ending increase in the required bit rates, the VCSEL+MMF intensity modulation direct detection (IMDD) systems are today showing their ultimate bottlenecks. Currently commercially available solutions using 25G-class devices can only provide up to 28 Gbps per lane over at most 100 m using OM3 and OM4 fibers. Recent standardization efforts by the IEEE P802.3cm Task Force have targeted 400 Gbps total bit rate transmitting 50 $Gbps/\lambda$ in different Short Wavelength Division Multiplexing (SWDM) configurations, over 100 m OM4 or 70 m OM3 fiber. Consequently, the next step in data centers interconnects (DCI) evolution will require transmission speed of 100 $Gbps/\lambda$ or more in the near future. Upgrading SWDM even further [1]–[3] or the use of higher order modulation formats [4] can help increase current short-reach IMDD-based systems capacity. In [5] we show that, using SWDM, data rates up to 200 $Gbps$ and 400 $Gbps$ per fiber can be achieved over up to 80 m of OM4 fiber using two wavelengths and feed-forward equalizer (FFE) and four wavelengths and maximum likelihood sequence estimation (MLSE)-based equalizer, respectively.

In DCI and Enterprise Networks, multimode fibers are largely deployed for distances up to 220 m or more, since this length is reachable for 10GBASE-LRM transceivers. Over this target distance (200-300 m), a capacity upgrade is even more difficult. The benefit, in terms of cost, of upgrading achievable bit rates without having to change the installed MMF fiber plant is thus an option to be investigated. Consequently, in [6], [7] we studied and demonstrated MMF-based short reach communication using commercial coherent transceivers (Coh-MMF). Coherent transceivers are coupled to a section of SMF fiber. The resulting optical path in an MMF-based coherent communication system has thus an SMF-MMF-SMF configuration, i.e. a solution in which standard SMF coherent transceivers are directly coupled to the MMF link. If perfect alignment between the different fiber sections is ensured, most of the optical power launched in the SMF at the transmitter side couples to the fundamental (LP_{01}) mode of the MMF and, at its output, to the receiver SMF. Thus, light propagation in an SMF-MMF-SMF transmission system is "quasi single-mode" [8], as we will better clarify later.

In installed DCI MMF links, fiber alignment can anyway be

The Authors would like to thank Jose Castro and his team at Panduit for the fruitful technical discussions and for extending and allowing us to use their MMF statistical database to 1550 nm (described in [5] but for 850nm).

This work was carried out under a research contract with Cisco Photonics. We also acknowledge the PhotoNext initiative at Politecnico di Torino (http://www.photonext.polito.it/) and its laboratory, where all experiments have been performed.

perturbed by the presence of patch panels and the related fiber connectors. The displacement introduced by the connectors inside the patch panels alters the geometrical properties at the fibers facet causing modes to mix randomly before coupling back into the output SMF at the receiver.

In this paper, we present an investigation of the Coh-MMF scheme focusing mainly on the analytical modeling of the signal propagation in an SMF-MMF-SMF configuration and on the statistical analysis of the effect of the connectors offset. We show that, in realistic datacenter conditions, up to 3 μm average values of lateral offset can be tolerated in practical conditions. We also experimentally characterize a Coh-MMF system based on 296 m OM3 fiber, by offset splicing two pieces of MMF with controlled lateral offset. Results show remarkable power budget margins enabled by the coherent solution and tolerance to connector offset up to 3 μm for 400G polarization multiplexed (PM) 16QAM modulation at BER=$2 \cdot 10^{-2}$ and up to 6 μm for 200G PM-QPSK at BER=10^{-2}.

The remainder of this manuscript is organized as follows: in Section II we present the main results of the statistical analysis of VCSEL-based SWDM system, to give an overview of the maximum possible capacity achievable today with this technology and to give an ultimate benchmark which we can compare with Coh-MMF. Then, in Section III, we introduce the analytical model for the statistical study of a Coh-MMF system affected by connectors misalignment and show the main results of an extensive Monte Carlo analysis. In Section IV we present the experimental measurement campaign on the Coh-MMF system using a commercial coherent transceiver. Lastly, in Section V we discuss the results and draw some conclusions.

II. Statistical analysis of SWDM 100G sytems

In this analysis, we use 8 VCSELs and a large dataset of OM3 and OM4 fibers generated by differential mode delay (DMD) modeling and measurements. First, a set of ∼500 experimental fibers were measured in terms of DMD profiles as the initial dataset population. Elaborating this experimental dataset, new fibers were numerically added by random variation of the measured DMD profiles to produce desired effective modal bandwidth (EMB) probability distributions for OM3 and OM4 MMFs. Once the dataset was generated, the VCSEL-to-fiber coupling was simulated using coupling matrices (CM) that represent VCSEL launch conditions [9]. The resulting frequency response of all the possible combinations (i.e. 251392: 8 VCSELs, 7856 MMFs and 4 SWDM λs (850, 880, 910, and 940 nm)) was evaluated following the approach presented in [9]. All cases are then evaluated for a discrete set of MMF lengths L from 0 to 400 m. We then used the computed transfer function to simulate PAM-4 100 $Gbps/\lambda$ transmission based on realistic transceiver and different types of receiver adaptive equalizers. We considered i) a Feed Forward Equalizer (FFE); ii) a combination of FFE + Decision Feed-back Equalizer (DFE) (termed just as "DFE" for simplicity); iii) a Maximum- Likelihood Sequence Estimation (MLSE) equalizer. Our metric is the maximum achievable reach using two different forward error correction (FEC) schemes: a soft KP4 FEC with bit error rate (BER) target (BERT) of $2 \cdot 10^{-4}$ (raw bit rate R_b = 106.25 $Gbps$) and a stronger enhanced-FEC (E-FEC) with BERT=$4 \cdot 10^{-3}$ (raw R_b = 110.35 $Gbps$). The details of the simulation setup can be found in [5]. Here we report only the main results. Fig. 1 shows, for the two R_b and all equalizers, the maximum reach that can be achieved by 99% of both the OM3- and OM4-based links ($L^{99\%}_{max}$). In each case the performance of the overall SWDM system is limited by the performance at 940 nm due to the so called "right-tilt effect" of the MMFs [9], which increases with the wavelength and prevents chromatic dispersion from counteracting the effect of modal dispersion. Using OM4 fibers 80 m transmission distance can be achieved with MLSE and E-FEC. Regarding OM3, $L^{99\%}_{max}$=50 m can be achieved with both FECs and DFE or MLSE. This figure is a good indication of the maximum achievable capacity and distance when using VCSEL+MMF systems with current optoelectronic technology, and can be summarized by observing that 100Gbit/s/λ truly seems to be an ultimate limit for this technology if the MMF target distance is above 50 meters.

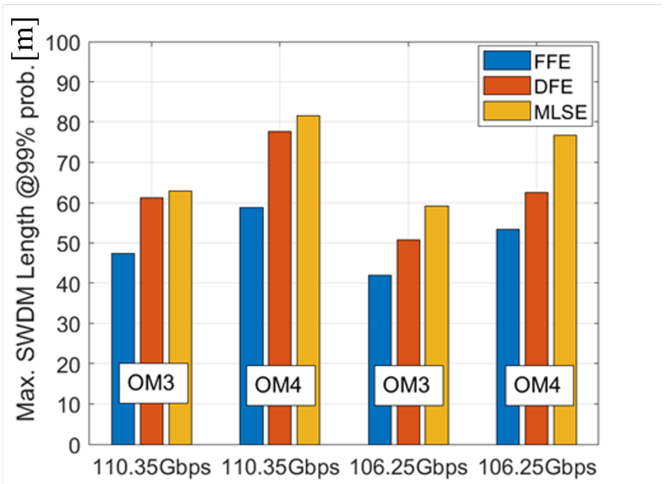

Fig. 1. Comparison of the achievable SWDM reach for 99% of the 100G links for E-FEC and KP4-FEC thresholds, and for the three equalizers.

III. Statistical analysis of Coh-MMF sytems

Short reach optical communication systems based on polarization multiplexed high order modulation and coherent detection can provide remarkably higher speeds and longer reach than their IMDD-based counterparts. In this section, we thus study coherent transceivers "direct" use over MMF links. In particular, we study how they are affected by connectors misalignment on the optical path, which we anticipate is the only limitation of the Coh-MMF idea (apart obviously from transceiver cost, an issue that is anyway outside the scope of this paper).

To analyse Coh-MMF performance on a statistical basis, we have developed an analytical numerical model that describes the setup shown in Fig. 2, where up to 4 connectors are equally spaced along the MMF section of the optical path, resulting in up to 5 MMF segments. Each of these connectors can have a random lateral offset with a Rayleigh distribution with different means ranging from 1 μm to 3 μm (as specified by several IEEE documents released for the 10GBASE-LRM standard). At interface of each connector, all the modes of one MMF couple to the other modes of the following MMF in random ways and depending on the connector lateral offset. We compute the per mode coupling coefficients following the approach presented in [10], obtaining a coupling matrix. We assume perfect alignment at the SMF-MMF and MMF-SMF interface, respectively at the transmitter and receiver side.

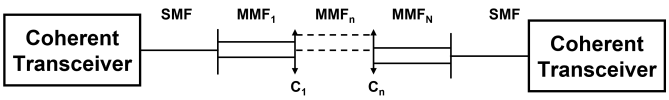

Fig. 2. Setup of the Coh-MMF transmission system with SMF-MMF-SMF configuration. MMF: Multimode Fiber; SMF: Single Mode Fiber; C: Connector.

The proposed model simulates propagation of all the modes, starting from the fundamental LP_{01} mode of the SMF at the transmitter, through a complex system of matrices, including the generation of per mode random unitary matrices to take into account the effect of fiber birefringence on each mode. It can be shown that the input-to-output relation of the Coh-MMF system is:

$$\begin{bmatrix} E^x(f) \\ E^y(f) \end{bmatrix}_{OUT} = \boldsymbol{H}_{TOT}(f) \cdot \begin{bmatrix} E^x(f) \\ E^y(f) \end{bmatrix}_{IN} \quad (1)$$

where $\boldsymbol{H}_{TOT}(f)$ is the overall [2x2] matrix frequency response of the SMF-MMF-SMF systems, which is a frequency dependent transfer function due to the modal delays.

In our analysis, for a given number of connectors and for a given mean of the offset Rayleigh distribution, we generate 9000 transfer functions $\boldsymbol{H}_{TOT}(f)$, each for a different Coh-MMF system configuration, including random fibers taken from a dataset such as the one used in Section II and random realizations of the unitary birefringence matrix. Then we use these $\boldsymbol{H}_{TOT}(f)$ to compute the SNR for each polarization at the output of an ideal equalizer with an infinite number of taps, modifying the model presented in [11] to account for both polarizations. Since $\boldsymbol{H}_{TOT}(f)$ is not unitary, depending on the specific realization of the Jones matrices, the two polarizations have (randomly) different performance. Thus, we compare the minimum of the two SNRs (one for each polarization) against the SNR that we would get in a back-to-back (BtB) configuration without MMF in the system, and use as a metric the system SNR penalty ΔSNR in dB (due to the SMF-MMF-SMF propagation effect). This penalty is the result of two different contributions: a net optical power loss due to the connectors lateral displacement (the ratio between the total transmitted power to the total received power), and the SNR reduction due to frequency dependence of the system transfer function. Fig. 3 shows the inverse cumulative distribution function (ICDF) of the difference between the ΔSNR and the net loss in a 220 m OM3-based link, for number of connectors from 0 to 4 and for two Rayleigh offset distribution mean values equal to 1 μm and 3 μm. The selected modulation format is 25 $GBaud$ PM-16QAM with squared root raised cosine shaping with 0.2 roll-off. The ΔSNR is calculated as the difference between the SNR required by the Coh-MMF system to have a $BER = 10^{-2}$ and the SNR required in BtB at the same target BER. The equalizer-induced penalty

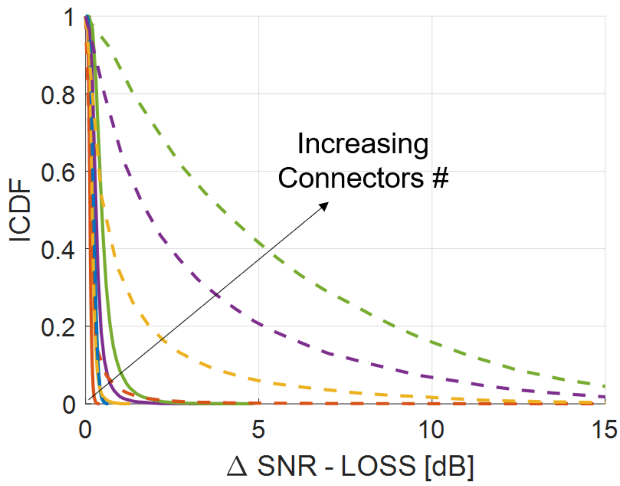

Fig. 3. ICDF of the $\Delta SNR - Loss$ parameter in a 25 $GBaud$ 220 m OM3-based Coh-MMF system for number of connectors from 0 to 4 and for offset Rayleigh distribution mean of 1 μm (solid) and 3 μm (dashed).

increases with the number of connectors. For a low Rayleigh mean value of 1 μm, the $\Delta SNR - Loss$ is below 2 dB even when four connectors are present on the MMF path. When a high, but still possible, 3 μm mean value is considered, the tails of the ICDFs can reach much higher SNR penalty.

Table I shows the overall system penalty on the ΔSNR parameter for variable numbers of connectors and Rayleigh mean in the 25 $GBaud$ 220 m OM3-based system. For 99% of the cases, the Coh-MMF SNR penalty is always below 4.5 dB when the offset distribution mean is 1 μm, regardless of the number of MMF connectors. However, it grows to 26 dB in the worst simulated case of 4 connectors with a 3 μm Rayleigh mean.

TABLE I
ΔSNR IN dB FOR 99% OF THE 9000 CASES.

Connectors	Mean = 1 μm	Mean = 2 μm	Mean = 3 μm
0	1.5	1.5	1.5
1	2.1	8.5	10.5
2	2.8	11	19.4
3	3.6	13.4	23.6
4	4.3	15.2	26

IV. Experimental analysis of Coh-MMF sytems

For a fairer validation of the analytical results presented in Section III, we have performed an experimental characterization of a Coh-MMF communication system equipped with a commercial coherent card capable of transmission up to 400 $Gbps$ net rate. The experimental setup is shown in Fig. 4. At the transceiver output an SMF patchcord connects to an MMF pigtail via a mating sleeve to ensure perfect alignment. The MMF pigtail is fusion spliced to a second MMF pigtail with a controlled misplacement to introduce a lateral offset. An MPX-SR3 MMF fiber shaker is used to implement TIA-455-203 specifications for MMF fiber testing and a 296 m OM3 fiber spool represent the MMF DCI link. An SMF variable optical attenuator (VOA), used to vary the received optical power, is connected on either side to the fiber spool and to the receiver SMF patchcord through mating sleeves to avoid additional offset. Several different configurations have been tested:

1) 'back-to-back': without MMF on the optical path
2) 'OM3 only': only the 296 m fiber spool is present
3) 'offset-OM3': a 3 or 6 μm lateral offset is induced on the MMF patchcord before the OM3 fiber spool;
4) 'offset-shaker-OM3': the MMF shaker is inserted in between the offset MMF patchcord and the OM3 spool;
5) 'offset-OM3-offset': a 3 μm lateral offset is inserted before and after the OM3 fiber.

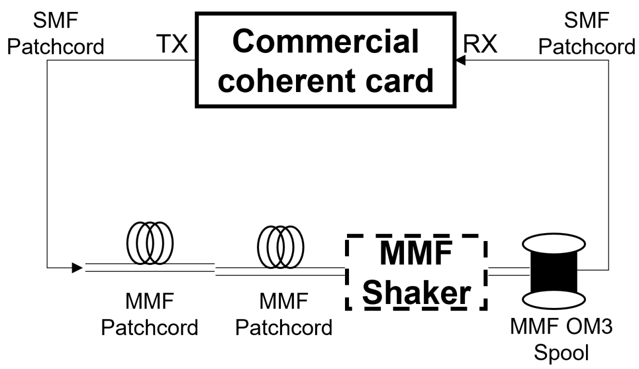

Fig. 4. Experimental setup of the Coh-MMF system.

Fig. 5 shows the measurements results in terms of power budget margin (PBM) for 100G and 200G PM-QPSK modulation and 200G and 400G PM-16QAM modulation in 'back-to-back', 'OM3 only', '3 μm offset-OM3', '6 μm offset-OM3' and '3 μm offset-OM3-3 μm offset' configurations. The PBM is defined as the extra attenuation introduced through the VOA on the optical path. For PM-QPSK modulation (Fig. 5a) at both bit rates propagation along 296 m OM3 gives negligible penalty with respect to the back-to-back experiment, as central launch is ensured by perfect fiber alignment. As the offset is increased, propagation is no longer in 'quasi single-mode' condition and the PBM decreases steadily by about 4 dB in the worst 'offset-OM3-offset' case. Nevertheless, remarkable power margins above 28 dB can be observed at BER=10^{-2} in all cases.

Connectors offset has a stronger impact on PM-16QAM modulation, especially at a very high 400 $Gbps$ bit rate. At 200G about 23.5 dB PBM can be achieved in the worst 'offset-OM3-offset' case, whereas at 400G the PBM in the same case is only 16 dB. However, about 4 extra dB could be gained by using a softer FEC with $2 \cdot 10^{-2}$ BERthreshold

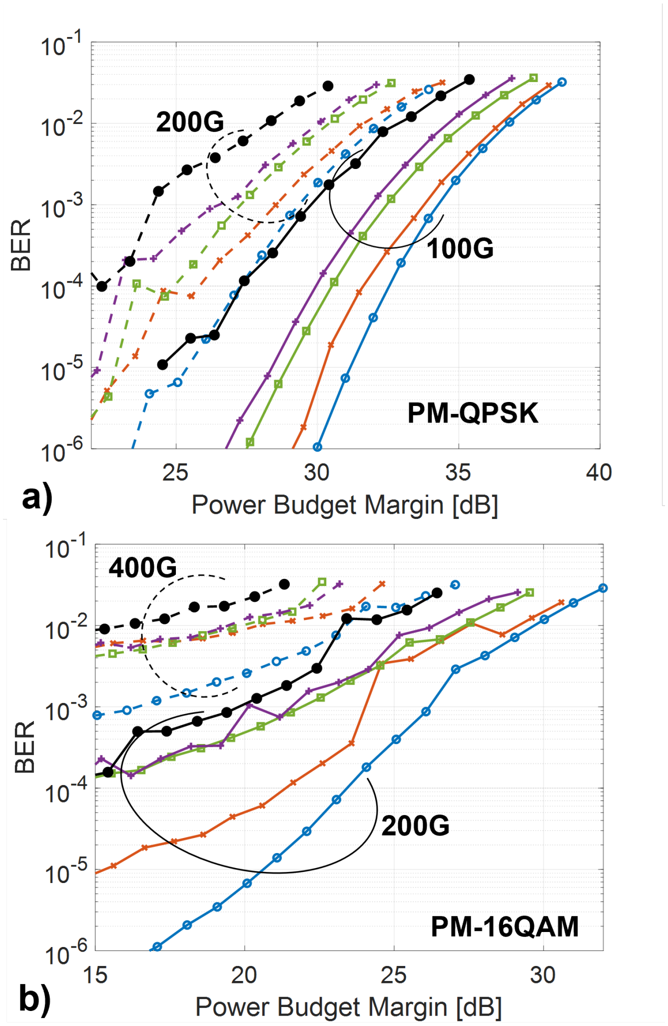

Fig. 5. Measured BERvs power budget margin for a) PM-QPSK and b) PM-16QAM modulation in different conditions: back-to-back (blue, circles), in 'OM3 only' (red, crosses), '3 μm offset-OM3' (green, squares), '6 μm offset-OM3' (purple, plus signs) and '3 μm offset-OM3-3 μm offset' (black, dots) configurations.

V. Conclusion

We have presented the numerical and experimental analysis of two different short-reach communication solutions. We have shown, through a statistical analysis on 251392 cases that a 100 $Gbps/\lambda$ SWDM system can work in 99% of the cases on OM4 fibers with a maximum of reach of 80 m using MLSE and a strong E-FEC, or on OM3 fibers over 50 m using both DFE or MLSE and KP4 FEC or E-FEC. We have also statistically analyzed a Coh-MMF system based on 25 $GBaud$ PM-16QAM modulation showing its tolerance to connectors offset at BER=10^{-2}. Our findings show that, the system is affected by an SNR penalty that increases with the number of connectors and their lateral misalignment. In the worst case scenario of 4 connectors with a Rayleigh distribution mean of 3 μm, the penalty is about 26 dB. Lastly, experimental results on a Coh-MMF system equipped with a commercial coherent card show power budget margins 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. Interestingly, the PBM in this last case can be increased by 4 dB by using a softer FEC with $2 \cdot 10^{-2}$ BERthreshold. When compared to the simulation results, this 20 dB PBM would be enough to allow up to 2 connectors with 3 μm Rayleigh mean or more than 4 connectors with 1 μm or 2 μm Rayleigh mean.

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