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Experimental Demonstration of Real-Time 400G Coherent Transmission over 300m OM3 MMF

G. Rizzelli[1], F. Forghieri[2], R. Gaudino[1]

[1] *Politecnico di Torino, PhotoNext Center, Corso Duca degli Abruzzi 24, Torino, Italy*
[2] *Cisco Photonics Italy S.r.l., 20871 Vimercate, Italy*
giuseppe.rizzelli@polito.it

Abstract: We experimentally demonstrate real-time coherent transmission up to 400Gbps over 300m OM3 multimode fibers, showing resilience to connector offsets up to 3-6 μm and fiber mechanical shaking using rigorous TIA-455-203 procedures. © 2022 The Author(s)

1. Introduction

Multimode fibers (MMF) are largely deployed in intra-data center (IDC) for links of up to 300 m, since they enable using VCSEL-based transceivers at 850 nm, which have significantly lower costs than all other short reach transceiver options. However, VCSEL+MMF transmission, even using newer OM4 and OM5 category fibers, has well-known maximum capacity limits due to multimodal dispersion, that make today transmission at more than 50 Gbit/s/λ and more than 100 m an extremely challenging task.

In this paper, extending the work presented in [1, 2, 5], we experimentally investigate on the transmission of coherently detected PM-QPSK or PM-16QAM signals over MMF (CoH-MMF) under practical IDC conditions, showing excellent performances up to 300 m of OM3 MMF fiber, made possible by central-launching and by the well-known properties of graded-index MMF, in which the LP01 fundamental mode does not couple significantly with the higher order modes unless the MMF is strongly mechanically perturbed [4]. The novelty of this paper compared to the existing literature, and in particular to our previous work [5], is in that (i) we use a commercial coherent transceiver to allow long-term real-time Bit Error Rate (BER) monitoring, (ii) we address the impact of lateral offsets in MMF connectors along the link and (iii) we rigorously tested resilience to MMF fiber shaking using TIA-455-203 FOTP–203 procedures.

Our results can be of practical interest for IDC situations having a large installed MMF infrastructure, which could be upgraded to much higher bit rates by changing the transceivers without substituting the fibers. Obviously, the cost saving due to MMF re-use is traded-off by the significantly higher cost of coherent transceivers (that is anyway constantly decreasing, as shown for instance in the 400G-ZR scenario), but this techno-economic discussion is outside the scope of our paper. As a key result, we show reliable operation under continuous fiber shaking of 200G PM-QPSK up to 6 μm lateral offset in MMF connectors, and 400G PM-16QAM up to 3 μm.

2. Theoretical Background

Several previous papers, such as [4], have shown that in graded-index MMF, the LP01 fundamental mode does not couple significantly with the higher order modes (unless the MMF is strongly mechanically perturbed), and also that a standard single-mode fiber (SMF) that is centrally connected to a MMF fiber couples most of its power to the MMF LP01 mode [3]. As a consequence, an optical link obtained by cascading three SMF-MMF-SMF fibers, if all three fibers are centrally aligned in the connectors, appears to a first approximation as a "quasi single-mode system" and, moreover, has a low attenuation. In fact, we showed in [5] that using standard connectors, an SMF-MMF-SMF link used around 1550 *nm* has an extra attenuation (above the intrinsic length-dependent attenuation of each fiber spool) below 2 *dB*, and thus potentially enable the direct use of SMF transceivers centrally coupled to an MMF link. Even more importantly, this quasi-single mode propagation leads to a much lower impact of modal dispersion, since most of the power remains in the fundamental LP01 mode [3]. Anyway, the quasi-single mode and low-loss operation of an SMF-MMF-SMF link can degrade due to (i) lateral offsets in connectors along the link, that do not ensure central launching conditions and (ii) mechanical stress applied to the MMF segment. Both issues are clearly fundamental for IDC environments, where MMF connectors have their intrinsic mechanical tolerances (typical offset is below 3 μ m) and the MMF can obviously be moved or continuously perturbed, for instance when it passes close to fan coolers. Clearly, for increasing connector offsets and mechanical stress, the SMF-MMF-SMF system progressively departs from the quasi-single mode operation, thus introducing increasing loss and higher modal dispersion impact.

In this paper, we experimentally address these two issues, by introducing in the MMF link MMF-to-MMF transitions with a controlled offset, and by applying the same mechanical stress procedure introduced for testing IEEE 10GBase-LRM systems, which requires inserting a specific instruments called "MMF fiber shaker" to introduce up to 10 Hz standardized mechanical vibration to the fiber, according to TIA-455-203 procedures. Due to the resulting time constants (the MMF shaker continuously generates vibration with periodicity in the [0.1-1] second range), a typical off-line processing BER measurement approach would give unreliable results (since it acquires only very short time-windows) and this is why it was fundamental in our work to use a commercial coherent card to enable long-term pre-FEC measurements.

3. Experimental Results

The block diagram of our experimental setup is shown in Fig. 1a). A coherent transceiver inside a commercial line card is used to transmit up to 200 *Gbps* net bitrates using PM-QPSK, and up to 400 *Gbps* using PM-16QAM. The complete setup includes an SMF patchcord at the transmitter output connected to an MMF patchcord through a lab-grade mating sleeve, to ensure central launch conditions, an MPX-SR3 MMF fiber shaker (implementing TIA-455-203 specifications for MMF fiber testing) and a 300 *m* MMF fiber spool connected to the SMF patchcord at the receiver input through another mating sleeve. The MMF patchcord is composed of two MMF pigtails fusion spliced together with a lateral offset to emulate non-perfect connections, such as introduced by IDC patch panels. The four MMF elements in Fig. 1a) have actually been swapped to analyze in the following different configurations: i) 'back-to-back': no MMF in the optical path; ii) 'OM3 only': the SMF patchcords are connected to the OM3 fiber spool with zero offset and without using the shaker; iii) 'offset-OM3': a 3 or 6 μm lateral offset is induced on the MMF patchcord before the OM3 fiber spool; iv) 'offset-shaker-OM3': the MMF shaker is inserted in between the offset MMF patchcord and the OM3 spool; v) 'offset-OM3-offset': a 3 μm lateral offset is inserted before and after the OM3 fiber. Finally, a variable optical attenuator is inserted before the coherent receiver for RX sensitivity measurements.

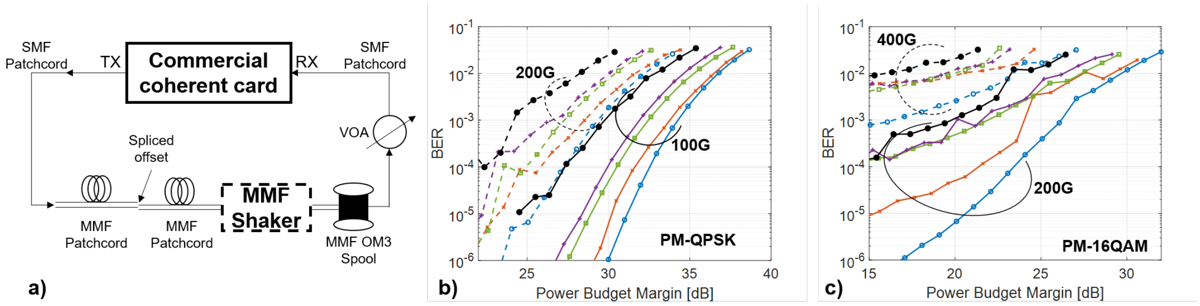

Fig. 1. a) Experimental setup. b), c) measured BER vs power budget margin for b) PM-QPSK and c) PM-16QAM modulation in different conditions: back-to-back (blue, circles), in 'OM3 only' (red, crosses), '3 μm offset-OM3' (green, squares), '6 μm offset-OM3' (purple, plus signs) and '3 μm offset-OM3-3 μm offset' (black, dots) configurations.

Fig. 1b) shows the measured BER as a function of the power budget margin (PBM) for 100G and 200G PM-QPSK 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 here as the extra attenuation we introduced in the optical path via the VOA, which can thus be interpreted as the available system power margin. For both bitrates, the PBM penalty due to transmission over 300 *m* OM3 fiber with respect to back-to-back conditions is negligible when central launch is ensured, and increases as the lateral offset increases due to higher-order modes excitation. As previously mentioned, this penalty is caused by moving away from the "quasi single mode" propagation condition, with the consequent increase in the average power loss in the SMF-MMF-SMF system and in the impact of modal dispersion. Nevertheless, very high margins can be obtained at a 10^{-2} BER threshold. For instance, at 200G more than 30 *dB* extra loss can be tolerated in a system with 6 μm offset, and more than 28 *dB* in a system with two separate 3 μm offset connectors.

The same type of results are shown in Fig. 1c) for 200G and 400G PM-16QAM modulation. The effect of connector offset on the performance becomes more evident, especially for large offsets and high bitrate. For instance, the PBM penalty of the '3 μm offset-OM3-3 μm offset' configuration is 4.5 *dB* at BER=10^{-2} with respect to the 'OM3 only' at 400G. However, achievable PBM is in the order of 20 *dB* for single connector offsets up to 6 μm at BER=10^{-2} or even for two 3 μm separate offsets assuming a slightly stronger FEC is used with BER threshold at $2 \cdot 10^{-2}$.

In order to test the system robustness to mechanical vibration and stresses, we used a procedure similar to the one used for IEEE 10GBase-LRM transceivers, investigating the effects introduced by the MMF fiber shaker. Moreover, we also manually changed the position of the MMF patchcord. Following a conservative approach, the MMF patchcord was rolled 4 times on a 10 *cm* circular bobbin, so the impact of the mechanical movements was intentionally enhanced. It is worth mentioning that moving the MMF patchcord increases mode mixing by changing the spatial distribution of the modes inside the fiber, thus increasing the power in the higher order modes, and consequently also increasing the net optical loss introduced by the offsets in the SMF-MMF-SMF system. We studied this effect in detailed numerical simulations (not shown here for space limitations), obtaining that propagation has a random characteristic due multi-path interference between the fundamental mode and all the higher order modes. The information on the resulting net optical loss is included in Fig. 2 next to each curve. Fig. 2a) shows three measurements of the '6 μm offset-shaker-OM3' configuration with 200G PM-QPSK modulation, each performed after moving the MMF patchcord in a different position. We actually performed many more repeated measurements, and here we just show three cases corresponding to the worst and best cases, and a typical intermediate one. PM-QPSK modulation exhibit good tolerance to modal noise even for a very large 6 μm offset with only about 1 dB PBM variation at BER=10^{-2}, due mainly to the net loss variation. Fig 2b) highlights that 400G PM-16QAM modulation in the '3 μm offset-shaker-OM3' configuration is also quite robust to the fiber position variation, although the shaker somewhat affects the system performance at such high bitrate, inducing oscillations on a BER that is already very close to 10^{-2} in the considered PBM range. On the other hand, at BER=$2 \cdot 10^{-2}$ the three curves are essentially superimposed, showing PBM better than 20 dB even when the MMF shaker is used. Lastly, Fig. 2c) shows the '6 μm offset-shaker-OM3' configuration with 400G PM-16QAM modulation. This is the configuration where our stress-test is most critical. In "good" modal noise conditions (black curve) the system is capable of providing PBM in excess of 19.5 dB and 21.5 dB at BER=10^{-2} and BER=$2 \cdot 10^{-2}$, respectively. However, this solution is strongly dependent on the mode distribution and, in some worst-case conditions, does not provide sufficiently good performance below FEC threshold.

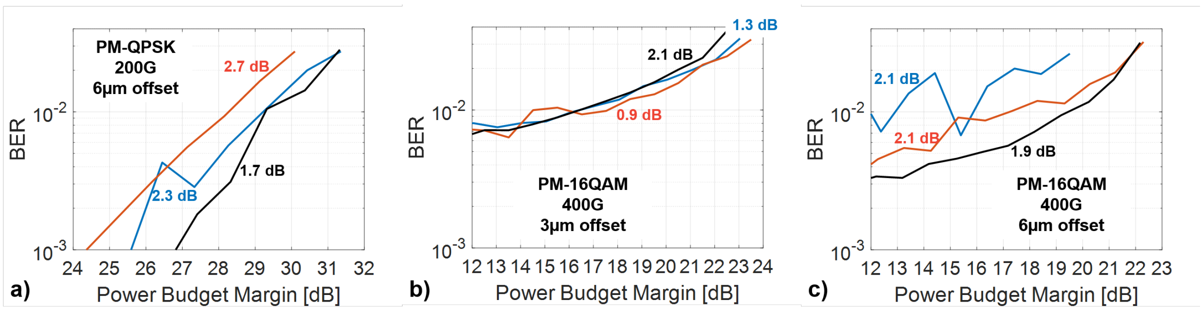

Fig. 2. Repeated measurement on BER vs. power budget margin for different positions of the MMF patchcord for a) '6 μm offset-shaker-OM3' configuration with 200G PM-QPSK modulation, b) '3 μm offset-shaker-OM3' configuration with 400G PM-16QAM modulation and c) '6 μm offset-shaker-OM3' configuration with 400G PM-16QAM modulation. The number next to each curve is the net optical loss introduced by the offset patchcord at each position.

4. Discussion and Conclusions

We demonstrated that commercial coherent transceivers can be used also on MMF fiber links up to much higher bit rates than those achieved by current VCSEL+direct detection based systems, provided that connections along the MMF have good quality (i.e. connectors with offsets in the 3μm to 6μm range). The ample system margin in dB that we showed in the last graphs, even under strong mechanical stresses, confirms the practical feasibility of the proposed systems. In particular, we show that 200G PM-QPSK can tolerate one 6μm offset or two 3μm offsets with ample margin at BER=10^{-2}, while 400G PM-16QAM can tolerate one 3μm offset at BER=$2 \cdot 10^{-2}$.

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