Partial MIMO-based Mode Division Multiplexing Transmission over the First Field-Deployed 15-Mode Fiber in Metro Scenario

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Abstract: We assess mode division multiplexing transmission based on partial MIMO equalization over 6.1 km of the first deployed 15-mode fiber in L'Aquila, Italy. We demonstrate more than 13-Tb/s throughput with reduced receiver DSP resources. © 2023 The Authors.

1. Introduction

The exploitation of multi-mode fibers (MMFs) supporting a large number of spatial modes in fibers with standard 125-μm cladding diameter is a possible solution to cope with rapidly increasing data traffic in optical transmission systems and networks. Mode-division multiplexing (MDM) in MMFs can multiply the throughput by a factor approaching the number of spatial modes, mainly limited by modal crosstalk, when high order multiple-input multiple output (MIMO) systems are used to fully undo inter-modal crosstalk [1]. However, its use may be prohibitive in short-reach, and cost-limited applications, which may favor transmission over fibers with uncoupled spatial channels, e.g. multicore fibers [2]. As an alternative, considering that the inter-group crosstalk (IGXT) remains limited or even negligible among different mode groups (MGs) for sufficiently short distances [3], an intermediate solution [4] is based on transmission of signals only within specific MGs that are distant enough to neglect or tolerate the IGXT. In these cases, the receiver MIMO can be reduced to handle each transmitted MG separately, which yields a substantial reduction of the required resources.

In this work, we demonstrate partial-MIMO based MDM transmission in a cabled 15-mode, 6.1 km MMF, recently deployed in an underground tunnel in the city of L'Aquila, Italy. The deployed MMF supports 5 MGs [5] and has been fully characterized in [6]. Combined with a multi-plane light conversion (MPLC) [7] based mode multiplexer and demultiplexer, the system had sufficient mode selectivity to support multiple combinations of MGs in MDM transmission with partial MIMO with reduced complexity. We evaluate the achievable throughput as a function of the required partial-MIMO receiver resources considering multiple combinations of MGs as well as multiple modulation formats. In particular, the performance for 50-Gbaud 4, 16 and 64- quadrature amplitude modulated (QAM) signals is measured, assuming six 75-GHz-spaced wavelength division multiplexed (WDM) channels. It is shown that partial-MIMO MDM can be used to reduce the required MIMO resources as a function of the necessary throughput, which allows optimizing the complexity of the required receiver DSP.

2. Experimental demonstration

The experimental setup used to assess the MDM transmission performance in the field-deployed 15-mode fiber cable is shown in Fig. 1 (details on the cable structure in [6]). The light from a tunable external cavity laser (ECL) with linewidth of less than 100 kHz was modulated in a dual-polarization (DP) IQ-modulator, driven by a 4-channel digital to- analog converter (DAC). The DAC was operated at 100 GSample/s and produced a 50 GBaud QAM signal with a cardinality of 4, 16 or 64 and with a root-raised cosine shaping with a roll-off factor of 0.01. Five dummy WDM channels were coupled with the channel under test (CUT) with a spacing of 75 GHz (see Fig.1 inset spectrum); all the 5 signals were modulated with another DP-IQ modulator driven by the negative DAC output ports. A split-and-delay method was used to produce 15 optically decorrelated copies of the signal with delays of multiples of 100 ns, hence uncorrelated within the length of accumulated differential mode delay in the 15-mode MMF. These signals fed the MPLC mode multiplexer (Mode MUX) [7] to be coupled into the deployed graded-index MMF. The 15 spatial modes were transmitted in the following 5 MGs: group *A* includes the LP01 mode; group *B* LP11a and LP11b; group *C* LP02, LP21a and LP21b; group *D* LP12a, LP12b, LP31a, LP31b; group *E* LP03, LP22a, LP22b, LP41a, LP41b. However, with partial MIMO-based MDM only some of the MGs will transport information signals whereas the remaining will not be illuminated.

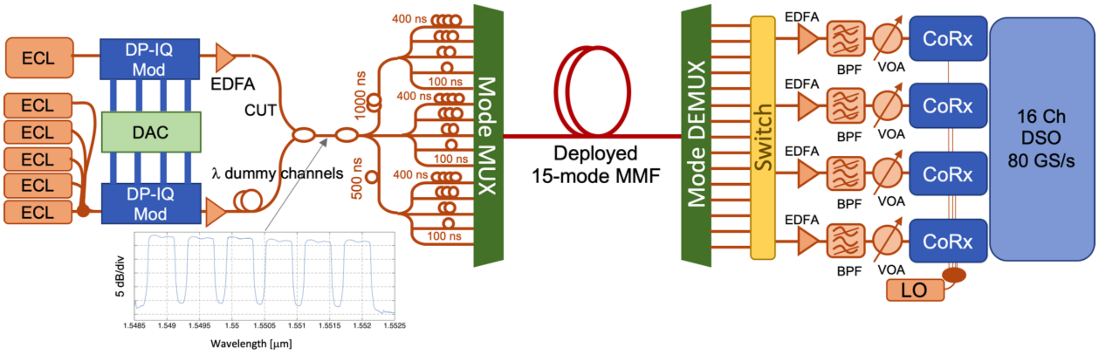

Fig.1 Experimental setup, deployed MMF cable of 6.1 km. Inset: example of spectrum of the 50 Gbaud WDM signal for group A

After propagation the signals were demultiplexed by a similar MPLC mode-demultiplexer (Mode DEMUX) and the signals belonging to a given MG were selected for detection. After amplification in erbium-doped fiber amplifiers (EDFAs) and CUT selection through an optical bandpass filter (BPF), they were sent to up to 4 coherent receivers (CoRxs) using a local oscillator (LO) laser, with a nominal linewidth of less than 100 kHz. The electrical signals from the CoRxs were digitized in a 16-channel real-time digital storage oscilloscope (DSO) with an electrical bandwidth of 36 GHz, operating at 80 GSample/s. Off-line digital signal processing (DSP) provided coherent QAM demodulation and 2Nx2N MIMO equalization with up to 132 taps, where N is the number of modes of the MG under measurement. The equalizer used a data-aided algorithm, which switched to the decision-directed mode after convergence. Carrier recovery was embedded in the equalizer loop. The DSP estimated the generalized mutual information (GMI) [8], giving the maximum achievable data-rate using a binary soft-decision FEC code, while the bit error rate (BER) was estimated through error counting. The measurements were repeated tuning the CUT wavelength over the spectrum occupied by the WDM grid (Fig.1inset).

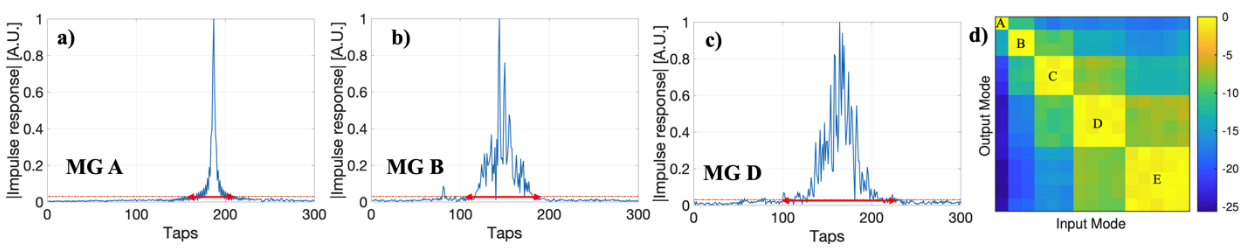

Fig. 2. a)-c) MIMO impulse response length for MG *A, B, D* measured in the combination *ABD*, 3% threshold (red line).
c) Measured crosstalk matrix at 1556.6 nm wavelength after 6.1km MMF, the 5 possible MGs are clearly visible on the diagonal.

For the assessment of the performance of the MDM transmission in the deployed 15-mode MMF cable, we selected 9 MG combinations considering that we were able to detect simultaneously up to 4 modes, i.e. the complexity corresponding to MG *D*. Moreover, considering the measured crosstalk (Fig.2 d), we excluded the combinations with excessive IGXT introduced by MMF propagation and mode MUX/DEMUX, since it would drastically impair the performance and the reach of the specific MG combination. The 9 combinations were *A*; *B*; *C*; *D*; *AB*; *AC*; *AD*; *BD*; and *ABD*. The evaluation of their transmission performance allowed estimation of the system throughput, based on the GMI [8], as a function of the necessary DSP resources. Although the latter may depend strongly on the system implementation, we used a simple metric based on the total number of equalizer MIMO taps needed at the receiver to correctly recover the signals. This is given by the number of equalizers and the MIMO tap number; we estimated the effective duration of the MIMO impulse response by using a threshold of 3% on its absolute value (Fig. 2a-c) then we calculated the equivalent MIMO taps adding a 10% margin to obtain the necessary DSP resources. Fig. 3a) shows the throughput per wavelength channel per MG combination for 50 Gbaud QPSK (asterisks), 16QAM (circles) and 64QAM (squares) signals, with the colors representing different MG combinations. As expected, the transported throughput increases with the number of utilized MGs at the expense of a higher MIMO complexity; a linear increase can be noticed for the different modulation formats in function of the employed resources, as evidenced by the dotted/dashed lines shown in Fig. 3a). On the other hand, exploiting a partial MIMO strategy contains the required equalizer MIMO taps with respect to the full MIMO solution, at the expense of IGXT impairments on the transmission.

The impact of IGXT on the throughput performance appears on group configurations *AB* and *ABD*, where the quality of 64QAM modulated signals was severely degraded due to the strong crosstalk between groups *A* and *B*. If we consider a 7-mode transmission, as in case of *ABD* combination, the full 30x30 MIMO complexity would have been around one order of magnitude higher [6] than the partial 14x14 MIMO MDM of this work. Fig. 3b) shows the combined 6-wavelength net-throughput estimated from GMI, but after decoding with a binary soft-decision FEC code and a receiver applying bit-wise decoding and optimal variable-rate codes [8]. As can be seen, more than 13 Tb/s can be transmitted using 50 Gbaud 64QAM modulation both with *AD* and *BD* MG configurations. With respect to Fig.3a), *BD* 64QAM decoded throughput is lower than the *AD* one, since due to the IGXT experienced by the *BD* pair higher than *AD* a lower rate FEC is necessary, reducing the advantage of having a larger number of transmitted modes. For the same reason the 3-tuple *ABD* is impaired by IGXT between groups *A* and *B*, strongly limiting the performance of 16QAM modulation; anyway, in the latter scenario all the 3 MGs could be used in case of MG routing [4]. The performed demonstration in case of 6 WDM channels would lead to data-rate of > 80 Tb/s with approximately 8000 taps per WDM channel if maintained over the full C-band.

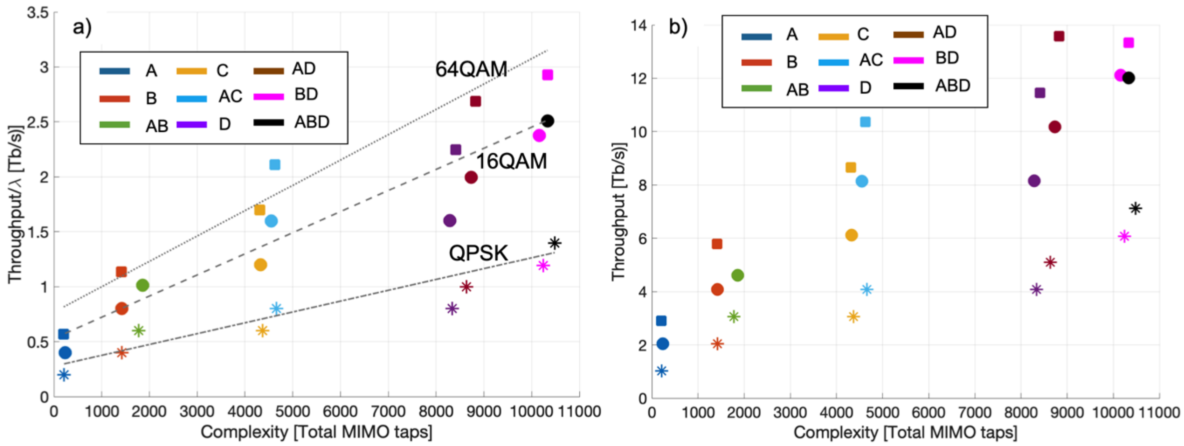

Fig. 3. Experimental results of partial-MIMO MDM transmission per MG combination vs. resources in terms of total MIMO taps: a) throughput per wavelength channel estimated from GMI b) decoded throughput for 6 WDM 50 Gbaud QPSK (asterisks), 16QAM (circles) and 64QAM (squares).

3. Conclusions

We measured the partial-MIMO based MDM performance for several MG combinations in the first field deployed 15-mode MMF cable in the city of L'Aquila, Italy. In the case of WDM transmission we evaluated the maximum throughput achievable for the MG combinations affected by the IGXT introduced by MMF propagation, over distances typical of urban applications and by the mode MUX/DEMUX. A partial MIMO processing handles the polarization diversity and the mode degeneracy for the modes belonging to the same MG, hence the receiver configuration can be significantly simplified and the number of resources in terms of taps for MIMO signal processing is reduced with respect to the classical full MIMO approach.

5. Acknowledgement

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