Demonstration of Multi-Hop Mode-Group Routing in a Field-Deployed Multi-Mode Fiber Network

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Abstract: Space-division multiplexing can enhance node flexibility in urban networks by exploiting routing of weakly coupled mode groups. We demonstrate multi-hop Tb/s group routing in different switching scenarios in the deployed 15-mode fiber-ring in L'Aquila, Italy. © 2023 The Authors.

1. Introduction

Mode division multiplexing (MDM) is a well-known technique to increase the capacity of single-core fibers. Combining MDM and wavelength division multiplexing (WDM) is essential to underpin reconfigurable optical networks and enable high capacity and flexible connections, particularly in the metropolitan areas. Classical MDM prevents mode routing at the intermediate network nodes because all the modes must traverse the network as a unit from the source to the destination for full multiple-input multiple-output (MIMO) processing [1]. For routing applications, multi-mode fibers (MFMs) allow addressing of different mode groups (MGs) separately [2,3] over short propagation distances, when inter-group crosstalk (IGXT) is low or even negligible. At the receiver the individual MGs are processed by a partial MIMO equalization, thereby considerably reducing the corresponding digital signal processing (DSP) complexity. In this regime, modes belonging to the same MG can be aggregated/dropped in an all-optical way and handled at the node level, improving the granularity in switching and enabling multi-hop routing in both spectrum and space dimensions.

In this paper, we demonstrate MG-based routing on the first field-deployed MMF cable, which was recently installed in the urban area of the city of L'Aquila, Italy [4]. The deployed MMF supports 5 MGs [5]. We show optical add/drop, full express, and routing operations of three MGs in different multi-hop node scenarios, carrying 50 Gbaud signals at different modulation formats in a 100 GHz-spacing WDM grid. In particular, the impact of the IGXT introduced by MMF propagation and by the mode multiplexer/demultiplexer (MUX/DEMUX) employed in each node on the performance in terms of transmission throughput is evaluated. The reported results demonstrate that MG-based routing is a viable approach to improve flexibility in urban-area networks through space switching at the node level.

2. MDM exploitation for network node multi-hop routing: setup and scenarios

The deployed fiber used in our field trial is a 15-mode fiber with a standard 125 μm cladding diameter supporting 5 groups [5], characterized in [6]. Fig. 1 shows the setup used to evaluate 4 node network. The nodes provide mode handling and add&drop modules, as described in [7]. The inset in light blue presents the MDM transmitter (Tx) block used to transmit six 50-Gbaud dual-polarization (DP) M-quadrature amplitude modulation (QAM) 100-GHz spaced WDM channels in each mode. The WDM channel under test (CUT), coming from a 100-kHz linewidth tunable external cavity laser (ECL), is 50-Gbaud modulated with either 4, 16 or 64 QAM with root-raised cosine shaping with a roll-off factor of 0.01, and then with 5 dummy 100-GHz spaced WDM channels. Using optical delays in multiples of 100 ns, 15 decorrelated signal replicas were generated and transmitted in the 15 spatial modes supported by the MMF. At the MDM receiver (Rx, in the yellow inset), after WDM channel selection by the bandpass filter (BPF), 4 coherent receivers (CoRxs) allowed the detection of up to 4 spatial modes simultaneously. After digitalization by a 16-channel 36-GHz bandwidth real-time digital storage oscilloscope (DSO), operating at 80 GSample/s, off-line DSP provides coherent QAM demodulation and partial MIMO equalization just for the modes within the same MG. In each node a pair of mode MUX/DEMUX based on 15 spatial modes multi-plane light conversion (MPLC) [8] was employed. The dashed blocks in Fig. 1 were not implemented in the experimental setup: in particular, the spatial switch (SW) operation in each node was performed manually. From preliminary characterization of the IGXT reported in [9] in case of 6.1-km MMF together with a pair of MPLC mode MUX/DEMUX, IGXT is not negligible, particularly between neighbor MGs, which is believed to mostly arise from the mode MUX/DEMUX. IGXT thus represented the main limitation for MG-based multi-hop routing, particularly considering that the IGXT introduced by the MMF propagation is small for metro links of a few kms.

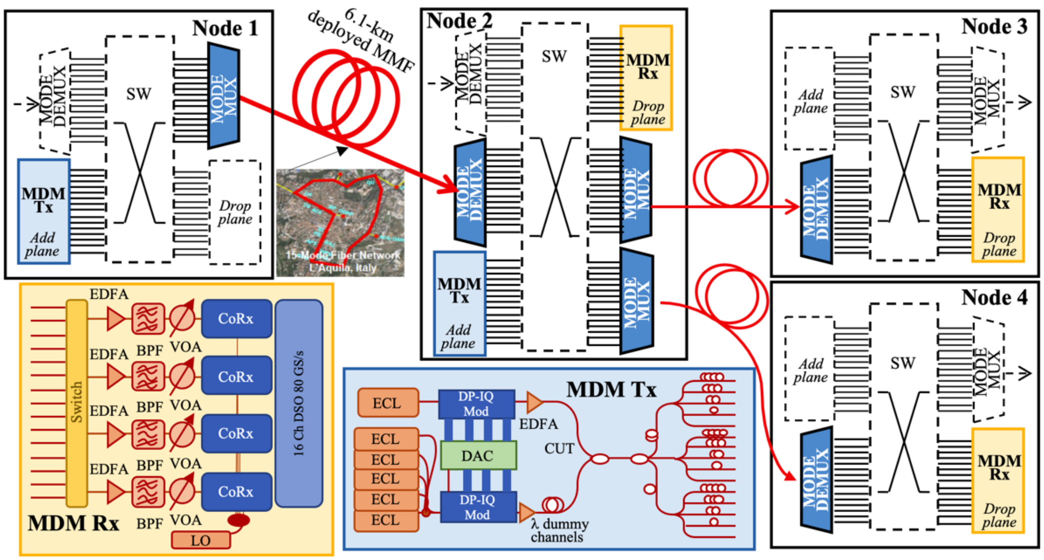


Fig. 1. Experimental setup for MG-based multi-hop routing. In the insets the MDM Tx and MDM Rx.

For our experiment, we select a possible combination of excited MGs, corresponding to group A (including LP01 spatial mode), group B (with the degenerate modes LP11a and LP11b), and group D (LP12a, LP12b, LP31a, and LP31b). Group B is impaired by IGXT both from A and D: this leads to the highest cumulative IGXT, while mode group D is mainly affected by the contribution from group B, while the presence of A is negligible. Fig. 2 reports the routing scenarios tested in our experimentation in the presence of the excited three MGs. In particular, node 2 enables also the selection of the proper output direction, with nodal degree 3. Scenario α implements full express operation, scenario ε full drop of the three MGs, scenario δ partial add/drop for the group A, and scenario β and γ routing in different directions. The link connecting node 1 and 2 consists of 6.1 km of deployed MMF with co-propagation of all the three MGs, in order to take in account also the impact of the IGXT introduced by propagation over typical metro-haul distance. The connection between node 2 and 3 and node 2 and 4 is short (less than 100 m) in order to take into account just the impact of the mode MUX/DEMUX operating in each node.

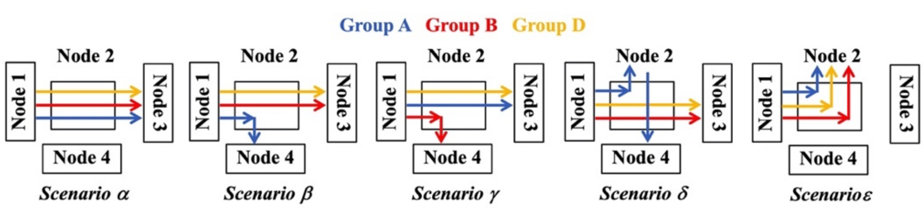
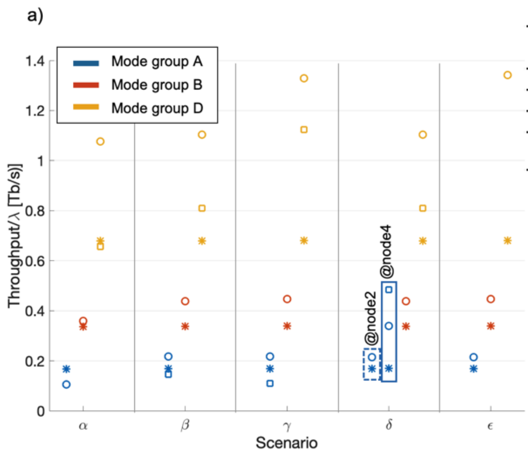


Fig. 2. Multi-hop routing scenarios experimented in the testbed considering 4 nodes.

3. Experimental demonstration

Fig. 3a reports the throughput achievable for each group per single wavelength (for the three M-QAM modulations) in the considered routing scenarios (Fig. 2). After signal reconstruction based on partial 2Nx2N MIMO equalization, based on a data-aided algorithm processing the N modes within the same MG, we calculate the generalized mutual information (GMI) and obtained the net-throughput after decoding with a binary soft-decision FEC code and a receiver, applying bit-wise decoding and optimal variable-rate codes [10]. In particular, in scenario ε, corresponding to the full drop of all the three MGs, the group A and B coming from node 1 are limited by the mutual IGXT (they are neighbor groups), affecting above all the higher-order QAM formats. Their performance in terms of achievable rate per group is further limited in scenario α in the case of three groups full express, owing to additional mode MUX/DEMUX pair required for the second hop. In scenario δ the group A added at node 2 and routed to node 4 is not limited by IGXT. Moreover, the group A coming from node 1 and dropped at node 2 (1 hop) has similar performance to the scenario β, where group A performs 2 hops but without IGXT added in the second mode MUX/DEMUX. In scenario γ, group D throughput is good as the IGXT introduced by the presence of A through the second mode MUX/DEMUX is negligible. Its performance decreases in scenario β and δ, when group D is affected by the presence of group B at the second mode MUX/DEMUX. In Fig. 3b) Table we report the maximum decoded throughput measured per each MG in the experimented routing scenarios, considering all the 6 WDM 100-GHz spaced channels, achieving Tb/s routing capabilities. Only occasionally does the maximum capacity correspond to 64QAM modulation, since the highest number of symbols makes this format less robust to the IGXT impairment: to counteract the impact of IGXT, a lower rate error correcting code is needed to correctly recover the signal, at the expense of reducing the net transported capacity and hindering the advantages due to the higher spectral efficiency.



b)

Routing scenario	WDM maximum decoded throughput per MG [Tb/s]		
	Group A	Group B	Group D
α	@node3: 1	@node3: 2.16	@node3: 6.46
β	@node4: 1.3	@node3: 2.63	@node3: 6.62
γ	@node3: 1.3	@node4: 2.7	@node3: 7.98
δ	@node2: 1.28 @node4: 2.91	@node3: 2.64	@node3: 6.62
ε	@node2: 1.28	@node2: 2.68	@node2: 8.05

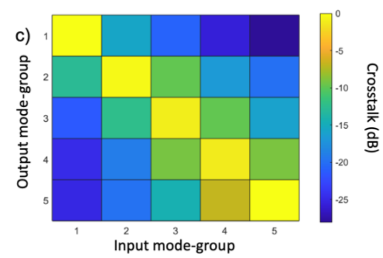


Fig. 3. a) Decoded measured throughput per MG and per wavelength. Star: QPSK modulation; Circle: 16QAM; Square: 64QAM. b) Table with the maximum decoded measured throughput per MG for all the 6 WDM channels. c) IXGT characterization vs MG.

4. Conclusions

We experimentally demonstrated the use of space switching based on the routing of groups of degenerate spatial modes in urban networks, improving network flexibility at the node level. The feasibility of MG-based routing has been tested in the first field deployed 5-group MMF ring network, in the city of l'Aquila, Italy. The results show how IGXT affects the performance in terms of maximum allowed throughput. IGXT impairment seems to primarily arise within the mode MUX/DEMUX rather than the short MMF transmission spans in the urban scenario and forces the choice of suitable combinations of modes to achieve the routing of Tb/s rates.

5. Acknowledgement

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