Mode-group division multiplexing for provisioning in SDM networks

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Abstract *We introduce the concept of mode-group division multiplexing (MGDM) in SDM-network provisioning. Modes belonging to different groups follow different paths in the network with simplified MIMO detection for the modes within the same group. Simulations show high throughput increase while limiting the complexity of the nodes.*

Introduction

Space Division Multiplexing (SDM) over few-mode fibers (FMFs) has been demonstrated as an attractive solution to increase the whole transported capacity in optical networks. Even if significant inter-modal crosstalk is accumulated during FMF propagation with respect to the employment of multi-core fibers (MCFs), the use of full digital MIMO allows to demultiplex all the received spatial modes[1]. This very complex DSP implementation reduces the limitations due to in-band inter-modal crosstalk, but all the spatial modes must cover the same physical path to be processed together at the receiver after coherent detection. An advantage in optical networks would be the exploitation of mode-division multiplexing (MDM) also for mode routing, enabling all-optical switching/aggregation both in spectrum and space[2-5].

In this paper, we analyze for the first time the capabilities of mode-group division multiplexing (MGDM) for dynamic provisioning in SDM networks: spatial superchannels (per wavelength) are constituted by spatial degenerate modes belonging to the same mode group. By exploiting all-optical passive mode multiplexers/demultiplexers (MUXs/DEMUXs), MGDM allows to combine/separate the mode groups in each node, enabling mode group routing for each independent group. Inside each mode group, after travelling along the same network path, the degenerate modes are then separated after coherent detection, with reduced DSP complexity with respect to a full-MIMO solution. The crosstalk among the mode groups is considered on the MGDM propagation, as limitation of the transmission reach.

Dynamic network simulations will show how the flexibility introduced by MGDM permits to increase traffic throughput (with respect to single-mode and full-MIMO approaches) and reduce the complexity of MIMO receivers (with respect to a full-MIMO).

MGDM-based network architecture and transceiver and node model

For our analysis we have considered state-of-the-art components and devices commercially available on the market to implement the network exploiting MGDM. A FMF is considered, supporting 9-LP modes (15 spatial modes)[6], to be deployed in L'Aquila city (Italy) network ring in the frame of the project FIRST. We assume that the 15 modes are organized in 5 groups: 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. To multiplex and demultiplex the modes at the transmitter and at the receiver, respectively, MUX/DEMUX based on Multi-Plane Light Conversion[7] (MPLC) handling 15 spatial modes has been taken in account. Inside each mode group, after travelling along the same network path and after the DEMUX, the polarization-division multiplexed (PDM) degenerate modes are then separated thanks to coherent detection, with reduced DSP complexity with respect to the full-MIMO approach. A pair of the same mode MUX/DEMUX is employed in each node to perform all-optical passive switching/aggregation enabling mode group routing. Starting from the specifications of the considered FMF and MUX/DEMUX, the OSNR penalty of each mode group combination has been calculated with a suitable simulation tool based on the so-called Gaussian Noise model[8], considering the crosstalk induced during the FMF propagation and the crosstalk due to the coupling efficiency introduced by the MPLC MUXs/DEMUXs. We considered an amplified multi-span link with one EDFA for each span. The network (with spans of 25 km and 12 nodes) assumed in our simulations corresponds to a ring topology covering *suburban* areas as considered in[9] for 5G applications. The losses due to the crossing of a node are completely compensated by a further EDFA: hence, the node model includes the introduction of ASE such as in case of span propagation. Also nonlinear penalties due to dense wavelength-division multiplexed (WDM) propagation with 37.5-GHz spacing are considered in our simulations. The results in terms of maximum transmission reach (ensured by the target OSNR required for $4{\cdot}10^{-3}$ BER) as a function of the modulation format (PDM-QPSK and PDM-16QAM) at 28-Gbaud and of the different mode group combinations (per wavelength), have been processed for a network-level perspective, in order to analyze the benefits introduced by MGDM in a network. The results will be shown in the next section.

Table 1 Supported reach, bit rate and complexity per mode group combination

Mode groups	**S**	**C**	**R [Gb/s]**	**L [km]**
		PDM-QPSK		
a	1	1	100	>250
a + c	4	10	100+300	250
a + d	5	17	100+400	>250
a + c + e	9	35	100+300+500	75
a+b+c+d+e FULL MIMO	15	225	1500	>250
		PDM-16QAM		
a	1	1	200	>250
a + c	4	10	200+600	50
a + d	5	17	200+800	100
a+b+c+d+e FULL MIMO	15	225	3000	200

Provisioning in MGDM-based SDM networks

MGDM enables transponders supporting multiple optical flows, similarly to a sliceable transponder[10]. Table 1 reports the supported bit rate values (R) and the maximum reach (L), as described in the previous section, depending on the modulation format and mode group division, where S is the number of exploited spatial modes and C a parameter indicating the DSP complexity of the receiver (expressed as the number of equalizers[11] employed in the DSP, normalized to the case of 2x2 MIMO for standard single-mode detection). As an example, with PDM-QPSK, the *a*+*c*+*e* groups support three independent optical flows with rates of 100, 300, and 500 Gb/s, respectively, with L=75 km; in this case, the DSP complexity factor C is 35. Each of the three optical flows can serve an optical connection and can be routed independently to the other two along the network. A full-MIMO receiver presents C=225.

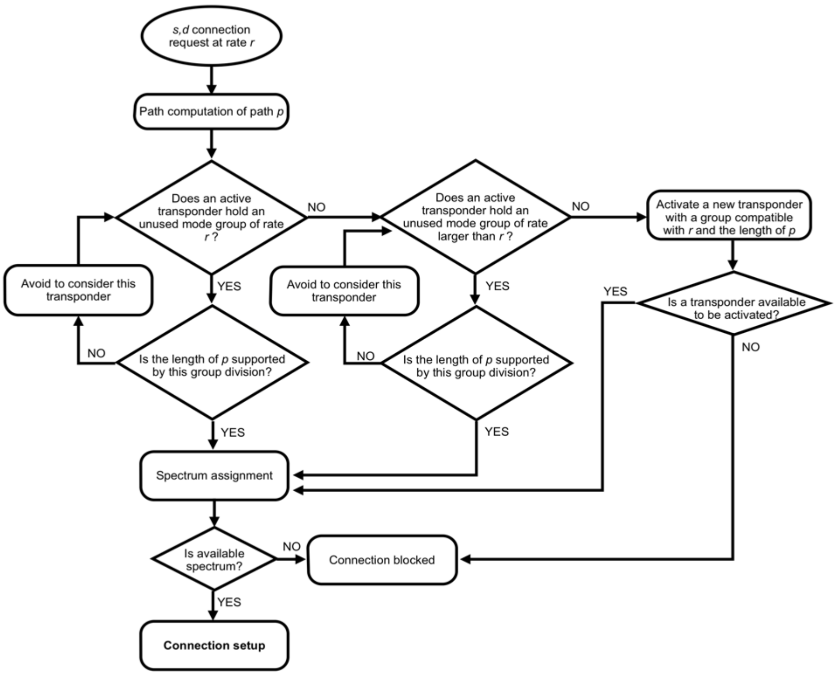

Fig. 1 Flow chart of the MGDM-based setup

The flow chart of the proposed MGDM-based provisioning is presented in Fig. 1. Assuming a connection request of rate r between a source-destination pair s-d, a path p is first computed (e.g., shortest path). Then, a transponder is selected. Preference is given to the already active transponders since each new activation increases costs (or complexity) associated to the transponders. Among the already active transponders, preference is given to the ones with available groups of modes supporting exactly the requested rate, with the aim of avoiding an under usage of optical flows' capacity. Thus, an active transponder is first searched at both s and d, with an available group of modes supporting a rate equal to r and the length of p. If these conditions are not met, an active transponder is searched at both s and d, with an available group of modes supporting a rate larger than r and supporting the length of p. If also these conditions are not met, a new transponder is activated with a group division compatible with the requested rate r and the length of p. After transponder selection, spectrum assignment is performed (e.g., first fit strategy) considering in our study signals switched in 37.5 GHz. Then, the connection is set up. A connection request is blocked when no transponder can be selected or when no available spectrum (satisfying the continuity constraint) is present along p.

Simulation results

Dynamic network simulations are carried out on a custom-built C++ simulator to compare a MGDM-based network with a single-mode-based and a full-MIMO-based network (*a* and *a+b+c+d+e* FULL MIMO, respectively, in Table 1). A ring topology of 12 nodes and 25-km links is assumed, as previously stated. Traffic follows a Poisson process with mean inter-arrival time $1/\lambda$. Connection holding time is exponentially distributed with average $1/\mu$=500s. Traffic load, expressed as λ/μ, is varied through λ. The requested bit rate is randomly selected among the following values: 100, 200, 300, 400, 500, 600, 800, 1500, 3000 Gb/s, reflecting the rate values in Table 1. In the single-mode-based network, a connection request may use more transponders with complexity 1 (e.g., a connection request of 600 Gb/s uses 3 transponders with PDM-16QAM of complexity 1 and occupies a portion of spectrum equal to 3×37.5 GHz). In the full-MIMO-based network, each bit rate is supported by a single (a+b+c+d+e)-full-MIMO transponder. Nodes are equipped with 30 transponders. The approaches are compared in terms of: overall blocking probability; blocking probability contributions; average transponder complexity per node.

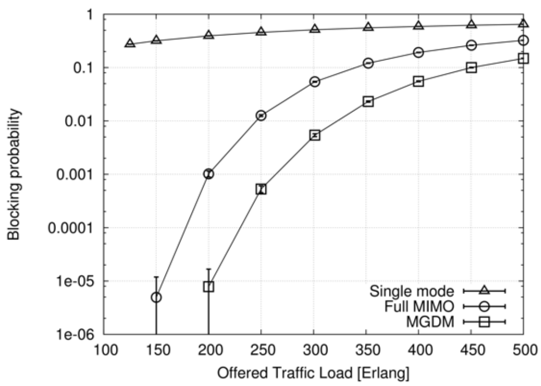

Fig. 2 Blocking probability vs. traffic load

Fig. 2 shows the overall blocking probability versus traffic load. The single-mode approach experiences the highest blocking probability because each connection request uses both more transponders and spectrum, thus transponder and spectrum resources are quickly consumed. The full-MIMO approach obtains a lower blocking probability because each connection is served with a single transponder and a single portion of spectrum of 37.5 GHz. The lowest blocking probability is obtained by the proposed MGDM approach, which offers more flexibility: each transponder can serve more connections, each one occupying 37.5 GHz. Thus, MGDM uses a less number of transponders than full MIMO. This statement is also supported by Fig. 3, which shows the blocking probability contributions (i.e. blocking due to the lack of transponders and of spectrum satisfying the continuity constraint). Single mode experiences high blocking both due to transponders and spectrum. With MGDM and full-MIMO, blocking is mainly dominated by transponders (that are more efficiently used by MGDM). Spectrum blocking of MGDM is larger than the one of full MIMO because with the former more connections are accommodated in the network, thus consuming more spectrum.

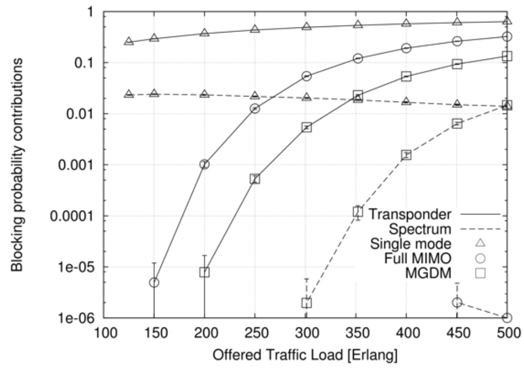

Fig. 3 Blocking probability contributions

Finally, Fig. 4 shows the average complexity per node versus traffic load. MGDM behavior is between the two benchmarks: i.e., the most complex full-MIMO and the least complex single-mode approach.

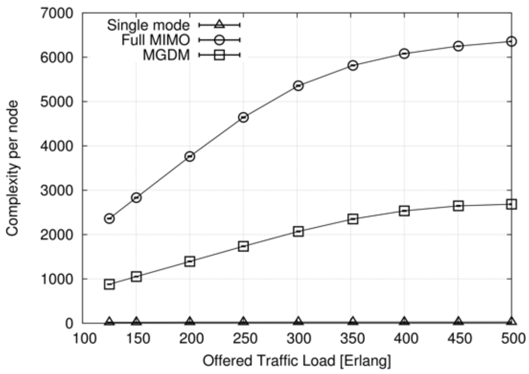

Fig. 4 Complexity per node vs. traffic load

Conclusions

We investigated MGDM for connection provisioning in SDM networks. MGDM may enable the development of transponders supporting multiple independent spatial superchannels, thus providing high flexibility. Network simulations have shown that MGDM strongly reduces the complexity of the required transponder with respect to a full-MIMO approach, while increasing network throughput (e.g., at a blocking probability of 10^{-2}, MGDM achieves 30% of traffic increase).

Acknowledgements

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