Resource Allocation in Optical Networks with Mode Group Division Multiplexing and Light Trail

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Abstract: We quantitatively evaluate resource efficiency enabled by mode-group-division multiplexing (MGDM) and light-trail (LT) in optical metro networks. Combining MGDM with LT reduces 95% of MIMO complexity of *Full-MIMO* with only 11% additional spectrum occupation.

1. Introduction

To cope with the continuous traffic growth in optical networks, few-mode transmission (FMT) is being explored to increase the capacity of optical channels by using mode division multiplexing (MDM), i.e., by transmitting multiple *spatial modes* over the same wavelength. For example, a common FMT configuration, also considered in this work, supports 15 spatial modes, which can be classified into 5 *mode groups* (MGs) [1]. One of the critical issues of FMT is that it requires full massive *multiple in multiple out* (MIMO) processing [1, 2], which burdens the system with high cost and low scalability especially with a large number of modes. Thus, *mode group division multiplexing* (MGDM) is now gaining attention as a new and more scalable implementation of a FMT-based space division multiplexing (SDM) optical networks [1, 3].

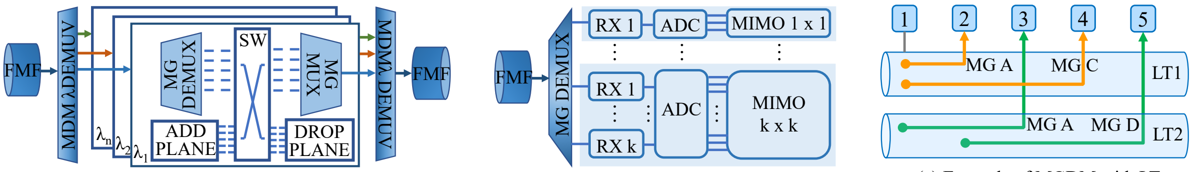
Benefits of MGDM are manyfold: *i*) MGDM requires only partial MIMO, as only the degenerate modes inside the same MG are processed together at the receiver; *ii*) MGDM not only provides higher bandwidths, but it also supports sub-wavelength communication capabilities [4], which are currently in high demand, e.g., for 5G/6G backhaul applications [4]; *iii*) thanks to its ability to multiplex several MGs, MGDM naturally fits for deployment within light trails (LTs) [4], by considering that different MGs could be added/dropped at different intermediate nodes along a single light trail (see Fig. 1(c) and next section for further details on LT).

Some preliminary investigation of the impact of MGDM on resource efficiency has been performed in Refs. [1, 5], but only comparing a limited subset of MGDM approaches in a dynamic scenario, and without considering LT. This study is the first to comprehensively investigate the spectrum occupation and MIMO complexity of all the main current FMT candidate technologies. Moreover, our study considers a more practical case of static traffic and investigates the resource efficiency deriving from the combination of MGDM with LT. To perform this quantitative evaluation, we develop a new heuristic algorithm extensible to all the compared FMT approaches, and we observed results on realistic metro network topologies after setting two different objectives (minimizing spectrum occupation and minimizing MIMO complexity).

2. MGDM with Light Trail

2.1. Classification of Single-Mode and Few-Mode Transmission Approaches

To investigate the impact of MGDM and LT on spectrum occupation and MIMO complexity, we consider six different transmission approaches. 1) *Single-mode* transmission (SMT). 2) *Full-MIMO* transmission: all the spatial modes in a wavelength must be switched all together. 3) *MGDM* transmission [1]: all the MGs are co-routed. 4) *MIMO-free MGDM (MF-MGDM)* transmission [5]: each MG only transmits one mode to reduce MIMO complexity of MGDM with a cost on channel capacity. However, this approach suffers from severe differential mode group delay (DMGD) [5], resulting in a shorter reach compared to *MGDM*. 5) *MGDM-LT* transmission: modes inside the same MG are co-routed and LT is allowed, which allows different MGs to be added/dropped at intermediate nodes according to the MDM node architecture in Fig. 1(a) [1]. 6) *MF-MGDM-LT* transmission: the *MF-MGDM* with LT. Table 1 reports the reach table for different approaches, which are obtained combining experimental evaluation and Gaussian Noise model as in [1, 5]. Some values in the table are not available, as these cases are not practical due to large inter-group crosstalk and DMGD. MGs are named as *A*, *B*, *C*, *D*, *E* as in Ref. [1].



(a) MGDM node architecture (b) Illustration of MIMO complexity of MGDM (c) Example of MGDM with LT

Fig. 1: MGDM node architecture, illustration of MIMO complexity, and an example of MGDM with LT.

2.2. *Comparison of MIMO Complexity and Spectrum Occupation*

MIMO complexity. The adoption of MGDM can significantly reduce the complexity of MIMO transponders, as in MGDM the modes in the same MG can be demultiplexed with reduced DSP complexity compared with *Full-MIMO*. As shown in Fig. 1 (b), a MG with k modes requires normalized MIMO complexity of k^2 [1]. The normalized MIMO complexity of the different MG combinations used in this study is reported in Table. 1.

Table 1: Reach table for different approaches

Approaches	Mode groups	Spatial modes	Total capacity (Gb/s)			Reach (km)			MIMO complexity
			4QAM	16QAM	64QAM	4QAM	16QAM	64QAM	
SMT/MGDM/MGDM-LT	A	1	104	208	312	7830	1686	426	1
MGDM/MGDM-LT	A+C	1+3	417	833	1250	426	84	12	10
	A+D	1+4	521	1042	1562	7578	1434	174	17
	A+E	1+5	625	1250	1875	7554	1416	156	26
	B+D	2+4	625	1250	NA	306	42	NA	20
	B+E	2+5	729	1458	NA	7248	640	NA	29
	C+E	3+5	833	1667	NA	228	12	NA	34
	A+C+E	1+3+5	937	1875	NA	186	6	NA	35
Full-MIMO	A+B+C+D+E	1+2+3+4+5	1562	3125	4687	7830	1686	426	225
MF-MGDM/MF-MGDM-LT	A	1	100	200	NA	21	21	NA	1
	A+E	1+1	200	400	NA	21	21	NA	2
	A+C+E	1+1+1	NA	600	NA	NA	3	NA	3

Spectrum Occupation. To reduce spectrum occupation of MGDM, in this study we evaluate also the effect of using LT. An LT is a generalization of a lightpath, that allows traffic requests to be optically added/dropped at intermediate nodes. As shown in Fig. 1(c), four requests are served with two LTs, occupying two wavelengths rather than four wavelengths (one wavelength for each request) thanks to joint utilization of FMT and LT. Note that LT operation is achieved in traditional works by using Time Division Multiplexing [4], while in our study we achieve the same result by using MGDM. LT and MGDM naturally fit together as MGs with different reaches can be used to map different requests over the same LT, and these requests can join/leave the LT at intermediate nodes.

3. Routing, Modulation Format, Wavelength, and Mode Group Assignment with Light Trails

The resource allocation problem for MGDM with LT can be stated as follows: **Given** a network topology, a set of traffic requests, and a reach table for different combinations of MGs and modulation formats, **decide** the routing, modulation format, wavelength, and mode group assignment for each traffic request, **constrained** to reaches and data capacity of the combination of MGs, the maximum number of wavelengths, the data rate of traffic requests, with the **objective** to minimize either the MIMO complexity or the overall spectrum occupation.

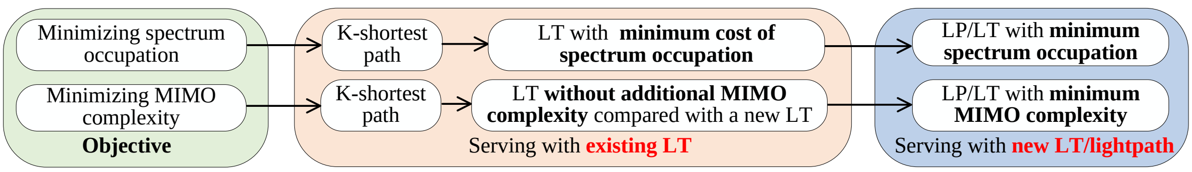


Fig. 2: Illustration of heuristic algorithm for minimizing spectrum occupation or normalized MIMO complexity.

We designed a scalable heuristic algorithm extensible for all the compared approaches as shown in Fig. 2. Details are omitted due to space limitations. When minimizing one objective (e.g., spectrum occupation), the heuristic algorithm is capable of minimizing the other objective (e.g., MIMO complexity) as second objective. For both optimization objectives, if serving requests with LT is allowed, the heuristic algorithm first tries to serve requests with the shortest path that traverses the existing LT as shown in the middle of Fig. 2. Specifically, we devised an auxiliary-graph-based approach, which incorporates the capability of using LT by adding auxiliary links among nodes inside the same LT. If a request can not be served with an existing LT, the algorithm serves the request with a new LT/lightpath. More specifically, when minimizing spectrum occupation, the algorithm selects the modulation format and MGs with the largest data rate to serve the request, which minimizes the number of wavelengths used. When minimizing MIMO complexity, the algorithm selects the modulation format and MGs with minimum MIMO complexity for all the wavelengths needed to serve the request.

4. Case Studies and Results

We compared the 6 FMT approaches in Table 1 on a large metro network topology [6] with 52 nodes (8 metro cores, MC, nodes and 44 metro aggregation, MA, nodes) and 72 links, each supporting 100 50-GHz dense-WDM channels. We considered two different network scenarios, namely, a short-link-length scenario where link lengths are uniformly distributed in [1,3] km (the cases for minimizing spectrum occupation and MIMO complexity are named as *S-Spectr* and *S-MIMO*, respectively), and a long-link-length scenario where link lengths are uniformly distributed in [100, 300] km (the cases for minimizing spectrum occupation and MIMO complexity are named as *L-Spectr* and *L-MIMO*, respectively). We consider bidirectional traffic requests between each MA node and the nearest MC node, as well as requests among 50% of MC node pairs. The requests between MC and MA nodes are randomly distributed within 100 Gb/s and 300 Gb/s with 50 Gb/s step and requests among MC nodes are randomly distributed within 1200 Gb/s and 1600 Gb/s with 100 Gb/s step. Results are averaged from 8 traffic matrices.

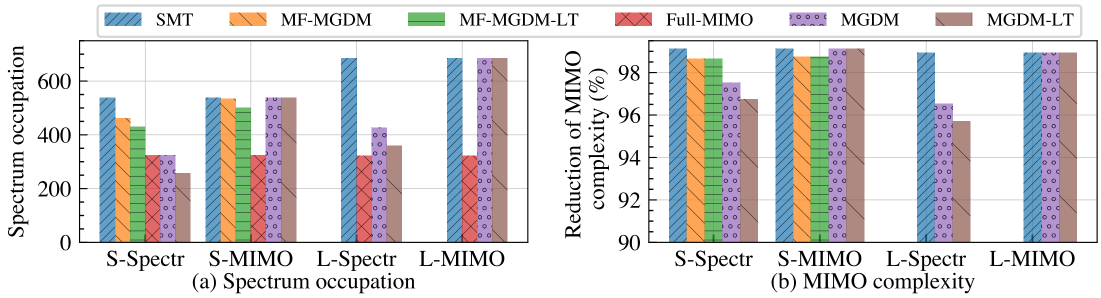


Fig. 3: Evaluation of spectrum occupation and MIMO complexity reduction compared with *Full-MIMO*.

We first discuss the results obtained in the short-link-length scenario when minimizing spectrum occupation (*S-Spectr)*). As shown in Fig. 3(a), *MF-MGDM*, *Full-MIMO*, and *MGDM* reduce spectrum occupation of about 14%, 40%, and 40% with respect to *SMT*. Note that *MGDM* achieves the same reduction of *Full-MIMO* because metro area do not require very large data rate and reaches, and hence do not need the whole capacity and reach of *Full-MIMO*). When introducing LT, *MF-MGDM-LT* and *MGDM-LT* can further reduce spectrum occupation by another 7% and 21% with respect to *MF-MGDM* and *MGDM*, which are obtained paying off only less than 1% smaller reduction of MIMO complexity compared with *MF-MGDM* and *MGDM* as shown in Fig. 3 (b). Moreover, all the approaches achieve more than 96% of reduction of MIMO complexity with respect to *Full-MIMO*.

When minimizing MIMO complexity in short-link-length scenario (*S-MIMO*), as expected, both the spectrum occupation and MIMO complexity of *MGDM* and *MGDM-LT* are exactly the same as *SMT*. In fact, to minimize the MIMO complexity, *MGDM* and *MGDM-LT* serve requests using only MG *A*, which has the same capacity and MIMO complexity as the mode used for *SMT*. Besides, for *MF-MGDM* and *MF-MGDM-LT*, the spectrum occupation decreases by $\approx$ 1% and 7%, respectively, compared with the *SMT*. This is because all the MGs for *MF-MGDM* and *MF-MGDM-LT* have the same MIMO complexity, and one request can be served with several MGs in the same wavelength.In addition, the improvement on spectrum occupation of *MF-MGDM* and *MF-MGDM-LT* is obtained with less than 1% less reduction of MIMO complexity with respect to *SMT* since *SMT* can use a higher modulation format (64QAM) and a request can be served with fewer MGs, and hence smaller MIMO complexity.

We now evaluate long-link-length scenario (note that *MF-MGDM* and *MF-MGDM-LT* are not shown due to limited reach). When minimizing spectrum occupation (*L-Spectr*), spectrum-occupation savings of *MGDM-LT* over *MGDM* reduce from 21% to 16% compared to the savings in *S-Spectr* scenario. This happens as for larger reaches, one LT is less likely to accommodate more than one connection. Regarding MIMO complexity as already seen in *S-MIMO*, *MGDM-LT* and *MGDM* lead to the same reduction of MIMO complexity, while spectrum occupation with respect to *Full-MIMO* increases from 32% to 112% due to reduction of channel capacity in *L-MIMO*.

5. Conclusion

We investigated resource allocation in optical networks with MGDM and LT, comparing six approaches, i.e., adopting single-mode or few-mode transmission, and utilizing different MDM approaches w/o LT. Results show that when minimizing spectrum occupation, *MGDM-LT* reduces 95% of MIMO complexity with only 11% of additional spectrum occupation with respect to *Full-MIMO*. When minimizing MIMO complexity, *MF-MGDM-LT* reduces 7% of the spectrum occupation of *MF-MGDM*, paying off only 1% additional MIMO complexity.

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