Throughput Increase in Multi-Fiber Networks using Partial Lane-Change Capabilities

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Abstract: Effective application of lane change in multi-fiber (MF) networks is hindered by limitations in WSS-size in ROADMs. We show that introducing lane-change only at degree-2 nodes leads to significant throughput increase, for a commensurate additional equipment cost. © 2024 The Author(s)

OCIS codes: (060.4250) Networks; (060.4510) Optical communications

1. Introduction

Optical network operators are always looking for economically-sustainable architectural solutions to meet the 20-30% estimated yearly traffic growth. Installing multiple parallel single mode fibers is an unsophisticated, yet effective, approach to continuously increase network capacity. Multi-fiber (MF) networks can be deployed immediately and can be scaled indefinitely, while more advanced options such as multi-band [1], multi-mode or multi-core fibers [2] still require significant R&D efforts.

The main challenge to be faced for effective deployment of MF networks lays in the constraints imposed by the current Reconfigurable Add-Drop Multiplexers (ROADMs). MF network can be deployed in the form of *network with stacked fiber layers* (i.e., each fiber layer is isolated from the other layers, and signals are switched using independent parallel ROADMs within a single fiber layer) or in the form of *network with lane change* (in this case large ROADMs with full switching flexibility across multiple fibers allow to use spectrum more efficiently, but they require prohibitively large WSSs, complex internal node cabling and extra amplification [3, 4]).

To find an intermediate and effective trade-off between the stacked and layer/lane-change architectures one can observe that, in small-degree nodes (e.g., degree-2) even current WSS (e.g., 1x9) have a sufficient number of unused ports available to interconnect fibers at different layers. Such nodes can act as lane-change nodes, allowing a more efficient spectrum usage *using the same number and size of WSSs*. Therefore, in this study, we propose and investigate a MF network architecture where only nodes with degree-2 have lane-change capabilities.

In the next sections, we first describe the ROADM architecture in MF networks and the system model used in our study. Then we provide a numerical evaluation of the throughput increase enabled by lane-change capability in degree-2 nodes, as well as the increase in line cost, in two backbone topologies and various traffic scenarios.

2. ROADM Modelling for Multi-Fiber Deployments

In Fig. 1a we show a 3-node segment of a state-of-the-art MF network with 4 fibers in each link and 4 stacked ROADMs at each node. Optical signal (depicted in orange) can be switched to any arbitrary direction, but it always
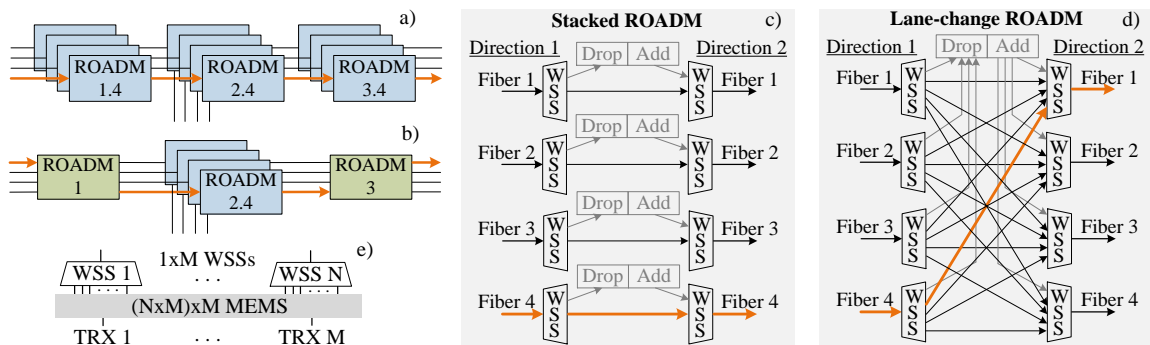

Fig. 1. a) State-of-the-art MF network with stacked ROADMs in all nodes b) MF network with lane-change ROADMs in degree-2 nodes c) Architecture of a stacked ROADM d) Architecture of a lane-change ROADM e) Architecture of an add (drop) block for a ROADM with N outputs (inputs)

remains in the same fiber layer. In Fig. 1b we show the proposed network architecture with lane-change ROADMs in degree-2 nodes that can switch the signal between different fiber layers.

Figures 1c-d illustrate the difference in the architecture of the stacked and the lane-change ROADMs. We always use route-and-select architecture with WSSs at the input and output node-ports. In a degree-2 stacked ROADM only a single port of the WSS is used for switching at a single fiber layer, while in a degree-2 lane-change ROADM 4 ports are needed to switch across the 4 different fibers. In this work we consider current 1x9 WSSs at the input and output ROADM ports, meaning that 8 (respectively, 5) remaining ports can be used to connect add-drop blocks in the stacked (respectively, lane-change) ROADM. Thus, each isolated ROADM in the stack can use up to 8 add-drop blocks (i.e., 24 across 4 fiber layers), while lane-change ROADM provides full routing flexibility, but is limited to 5 add-drop blocks overall.

3. System Model

To evaluate the impact of the lane-change nodes on spectrum usage we perform a network-level simulations with incremental traffic. We start with a single fiber layer in the network and a single add-drop block in each ROADM.

When provisioning a traffic request, we first verify the availability of the transponders in the source and destination nodes. We then perform Routing and Spectrum Allocation using k-Shortest Path First-Fit heuristic. Among the paths with the same length, we first verify spectrum availability along the paths that use lower fiber layers. If at a certain point during network evolution there are no transponders available to provision a traffic request that originates/terminates in the node, and WSSs have unused ports, we install an additional add-drop block. If at a certain point during network evolution there is not enough spectrum to provision the traffic request along any of the k shortest paths, or there are no WSS-ports left to install another add-drop block, we add another fiber layer in all the links of the network.

We consider a WSS at each input and output port of the ROADM. Add-drop blocks are colorless, directionless and contentionless as in [5]. In a ROADM with N inputs (outputs) a drop (add) block is built of N 1xM WSSs and one (NxM)xM MEMS-switch that connects M transponders to any of the WSSs (see Fig. 1e). We estimate the cost of the line-system (i.e., WSSs, MEMS-switches and EDFAs) with prices [6] listed in Fig. 2d.

We use closed-form Gaussian Noise model [10] to estimate non-linear interference. We always consider fully occupied spectrum and, thus, worst-case amount of interference. Erbium-Doped Fiber Amplifiers (EDFAs) compensate for propagation loss and have Noise Figure of 5 dB. Power optimization is done according to Locally-Optimized Globally-Optimized (LOGO) strategy [10].

4. Case Studies and Results

We consider two main case studies, illustrated in Fig. 1a and b: deploying stacked ROADMs in all nodes and deploying lane-change ROADMs in degree-2 nodes and stacked-ROADMs in the other nodes. We deploy at most 4 fiber layers to ensure a sufficient number of add-drop blocks.

We perform our numerical evaluations on two realistic topologies, a 50-node German (GE50) [7] and a 70-node Japanese (JP70) [8] networks shown in Fig. 2a and b, and their parameters summarized in Fig. 2c. Note that 20 (44)% of nodes in GE50 (JP70) are degree-2 (shown in green), and thus, can be used to perform lane-change.

Random service demands are incrementally added until reaching a certain percentage B of blocked traffic requests (due to lack of either spectrum or transponders). Traffic matrix is mesh between the core nodes (major cities, shown in red), while service nodes exchange traffic only with the two closest core nodes, as in [9]. Data rate requests are randomly distributed within 400 Gb/s and 1600 Gb/s with a 400 Gb/s step. Results are averaged over 100 different random traffic instances. We consider 6 THz C-band and 190 Gbaud transponders with a maximum

Topology	GE50	JP70
Service/core nodes	42/8	59/11
Degree-2 nodes	10	31
Avg/max link length, km	100/219	79/237

c)

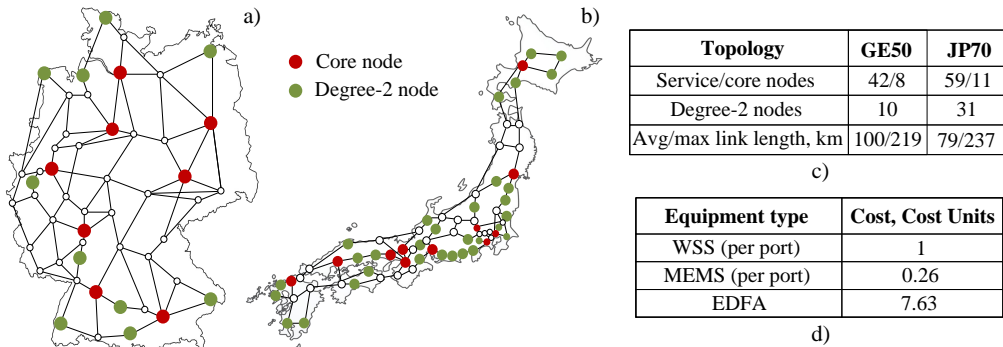| Equipment type	Cost, Cost Units
WSS (per port)	1
MEMS (per port)	0.26
EDFA	7.63

d)

Fig. 2. a) 50-node German topology (GE50), b) 70-node Japanese topology (JP70), c) Topology parameters, d) Equipment costs
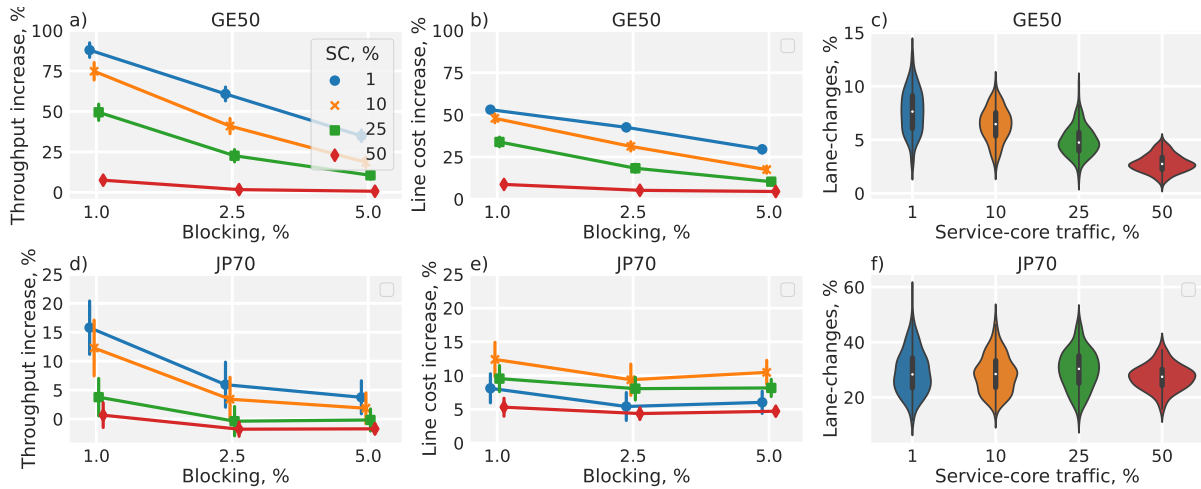
Fig. 3. Increase in a) throughput, b) cost in GE50, c) % of lightpaths that use lane-change in GE50; Increase in d) throughput, e) cost in JP70, f) % of lightpaths that use lane-change in JP70 for different % of blocking and % of service-core (SC) traffic

capacity of 1600 Gb/s with SNR thresholds taken from [11] and an additional 1 dB system margin. We consider 1x9 WSSs in add-drop blocks, so that each block can transmit 9 and receive 9 optical signals.

In Figure 3 we report, with 95% confidence interval, increase in throughput and in line cost (from the add-drop blocks that facilitate the extra traffic) that comes from deploying lane-change ROADMs in degree-2 nodes for 1, 10, 25 and 50% of service-core (SC) traffic and B equal to 1, 2.5 and 5%. We also report which % of lightpaths deployed at 1% blocking performs lane-change. We start with an analysis of GE50 network. We observe that increase in throughput reaches 80% at 1% blocking and 1% of SC traffic (for an increase in line cost of only 55%) and decreases for higher % of SC traffic and blocking. With 50% of SC traffic throughput is almost the same as in the scenario without lane change. Line cost increase follows the same trend, but it is worth noting that the increase in line cost is only a minor contribution to the overall network cost, that should include transponder cost that is neglected in our analysis as it is mostly load dependent and not significantly affected by our analysis. Regarding number of lane changes, at most 15% of lightpaths perform lane-change with 1% of SC traffic, while the number decreases to at most 5% with 50% of SC traffic.

We then focus on the results for the JP70 network. Increase in throughput in JP70 is lower than in GE50 despite the fact that more nodes have lane-change capabilities. GE50 is very meshed, and blocking mostly happens due to the lack of available transponders, while there is still available spectrum in all 4 fiber layers. As gains from statistical multiplexing are the highest with more available fibers, lane-change provides a bigger advantage, even if it is only available in 20% of the nodes. JP70 is more stretched with potential bottlenecks in the middle, and blocking happens only due to the lack of spectrum. Despite a higher % of lightpaths performing lane-changes (30% in JP70 vs. 5-10% in GE50), statistical multiplexing cannot be fully used across 4 fiber layers, and increase in throughput is lower.

5. Conclusion

For the considered traffic scenarios, introducing lane-change capabilities in the degree-2 node provides significant increase in throughput, for a commensurate increment of line cost due to extra add-drop blocks. We observed though that the advantage of lane-change is highly dependent on the topology and the distribution of service and core node, hence such dependencies will be subject of future investigation.

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