Sparse Spatial Lane Change Increases SDM Network Efficiency

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Abstract *We show that the sparse distribution of ports for core switching in optical SDM networks can significantly improve network performance. The results show that more than 70% of equipment capacity can be saved while obtaining performance equivalent to full core-switching.*

Introduction

This paper analysis the core-switching in the network which enables Spatial Lane Change (SLC) between a select set of fiber cores only, referred to as *Sparse-SLC*. We evaluate the impact of *Sparse-SLC* and compare it to *Full-SLC* as well as to *No-SLC* methods in terms of bandwidth blocking ratio and deployment cost. Numerical results show that even a small set of cores with *Sparse-SLC* can perform comparably well with respect to the *Full-SLC* method, while significantly reducing the need for new equipment. We also show that naive SLC distributions can worsen the network performance; thus, SLC must be applied with carefully chosen design criteria. To the best of our knowledge, this is the first study in the literature to explore the benefits of *Sparse-SLC*.

Reference architecture

Figures 1, 2, and 3 illustrate the core switching architectures considered in this paper. The wavelength selective switch (WSS) equipment (a component of the ROADM) performs core switching. A circuit (J, K, or L) can travel from one core s to a core d when the output WSS from core s has a port connected to the input WSS of core d.

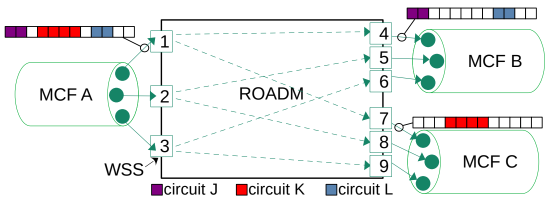

Fig. 1: Switching without spatial lane change (*No-SLC*).

In scenarios without SLC (Fig. 1), WSS connects only cores with the same index. Thus, in Fig. 1, the output WSS 1 is connected only to input WSS 4 and 7. ROADM architectures with full SLC present WSS port connections among all input and output cores in a node (Fig. 2), where any core can switch circuits to any other core in an output fiber. For example, the output WSS 1 connects to all its neighbor input WSS $(3, 4, \cdots, 9)$ of

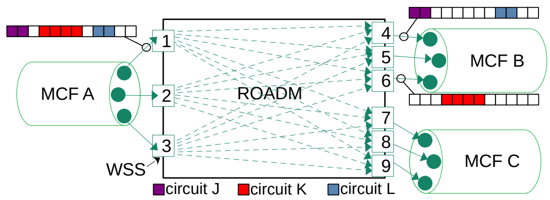

Fig. 2: Switching with full spatial lane change (*Full-SLC*).

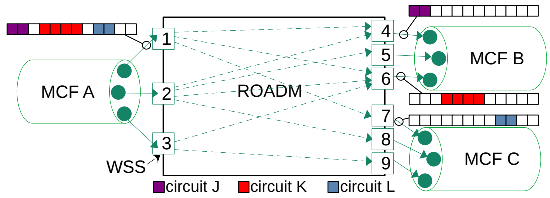

Fig. 3: Switching with *sparse* spatial lane change.

fibers B and C. The full SLC architecture requires the largest amount of WSS ports. Finally, Fig. 3 shows sparse allocation where each core has different levels of flexibility regarding its core index switching capabilities, which is our focus here. In the example of Fig. 3, the output WSS 1 is connected to input WSS 4 and 6 for MCF B, and input WSS 7 in MCF C.

Three main switching strategies have been associated with SDM: *Independent switching* (InS), *Joint switching* (JoS) and *Fractional Joint Switching* (FrJoS). The FrJs and JoS architectures require the creation of spatial super-channels, which demand the simultaneous allocation of multiple cores for a single circuit. Our paper, therefore, focuses on InS architecture only[1], since it does not utilize spatial super-channels and grants more flexibility for circuit allocation in different cores. The number of WSS can be calculated by $2 \times D_v \times S$, where D_v is the node degree and S is the number of cores. The port count per WSS is calculated by D_v for *No-SLC* nodes and by $S \times (D_v - 1) + 1$ for SLC-enabled nodes[2]. It should be noted that the WSS is the most expensive element in the ROADM design[3].

To the best of our knowledge, no papers so far explored the SLC with sparse allocation through the network and its related implementation cost in the context of the number of core-switching ports required, which is our goal here. It should be noted however that the Routing, Modulation, Spectrum, and Core Allocation (RMSCA) problem is well-known in the SDM-EON literature. A solution to this problem has to find the proper route, modulation format, core set, and slot range to establish an optical circuit in the network[3],[4]. The first constraint to solve is the slot contiguity constraint, in which the slots for the same circuit should be adjacent in the spectrum. The second constraint is the slot continuity constraint, which demands the utilization of the same slot index in all links along the selected route. The third is the core continuity constraint[5], which demands the continuation of the same core index for a circuit along all fiber links traversed. The Spatial Lane Change (SLC) paradigm, on the other hand, does not require the core index continuity constraint.

Algorithms for sparse-SLC circuit setup

We now present the heuristics for *Sparse-SLC*, which we use to evaluate the network efficiency defined in terms of the insertion cost of WSS ports (i.e., installation or purchase cost) given a budget. In this approach, we enable the WSS ports only between predefined core pairs. The core pairs represent the WSS connection between two cores. As example, in Fig. 3, the core 1 of MCF A pairs with cores 4, 6 in MCF B, and core 7 on MCF C. The distribution of ports is a similar problem to regenerator distribution[6][7] when equipment is inserted in the network planning phase to improve performance in the operational phase. Each heuristic creates its core pair priority list, used in the performance analysis to distribute the available budget.

Most Used (MU) and *Most Simultaneously Used* (MSU) heuristics distribute the SLC ports to the most used core pairs. For both solutions, an a priori simulation is required to evaluate the traffic profile and provide a priority list for each heuristic. The difference between MU and MSU is in the rule to build a priority list. For MSU, the prioritized core pairs are the most used by WSS connections in the entire test simulation. In turn, the MSU prioritizes the cores with the highest peak of simultaneous utilization (highest number of active circuits). The priority lists are used for the subsequent WSS port distribution. Pseudo-code 1 describes the WSS port distribution.

We also consider two other solutions in addition to MU and MSU. One heuristics, referred to *Nodal Degree First* (NDF) creates the core pair output list and inserts all input-output core pairs from the highest degree node to the lowest degree node. Another one, called *Random* heuristic is implemented for comparison. It populates the core pair output list by inserting randomly picked output-input core pairs in a node. Moreover, the network scenarios with *Full-SLC* and *No-SLC* are used as benchmarks.

All four heuristics used create priority lists of cores, which are then used in WSS port distribution method according to Agorithm 1.

Algorithm 1 SetPorts(CorePairList, Budget)

for $pairAB \in CorePairList$ **do**
  $coreA \leftarrow get\_output\_core(pairAB)$
  $coreB \leftarrow get\_input\_core(pairAB)$
  $cost \leftarrow cost\_port\_insertion(coreA, coreB)$
  if $Budget \geq cost$ **then**
    $insert\_outputPort(coreA)$
    $insert\_inputPort(coreB)$
    $Budget \leftarrow Budget - cost$

In performance evaluation, Algorithm 1 is executed first. The WSS port assignment follows the heuristics and their corresponding output list $CorePairList$. The insertion cost of WSS ports (i.e., installation or purchase cost) is computed for each core pair $pairAB$ in the list. The two ports (output and input) are added in their respective WSS if the insertion cost is lower than the available budget. The insertion cost is subtracted from the available budget after the WSS port insertion. This process repeats until the budget is exhausted or the list ends. After the execution of Alg. 1, the network nodes have a sparse allocation of WSS ports relative to the value of $Budget$ provided as input. The impact on the network performance of the different heuristics and budgets will be analyzed in the next section.

Performance Analysis

The numerical evaluation is performed with an open-source ONS simulator[8]. All links are MCF, with 7 cores and 320 slots in each core, on USA topology (24 nodes and 43 bidirectional links) and NSFNet topology (14 nodes and 21 bidirectional links). Each measurement is the average of 10 replications created with the independent replication method. Each replication consists of the generation of 10^6 circuit requests. The connection requests follow a Poisson process with a mean holding time of 600 seconds. The demanded capacities are 10, 40, 100, 160, and 400 Gbps, with uniform distribution. The guard band between adjacent circuits is 1 slot. The K-shortest path algorithm is used for routing (K = 3), and the first-fit policy is applied for core and slot selection. The adaptive modulation technique is applied, with available modulation formats BPSK, QPSK, 8QAM, 16QAM, 32QAM, and 64QAM, and maximum distances thresholds of 8000, 4000, 2000, 1000, 500, and 250 kilometers, respectively. To obtain blocking results closer to 1%, the network load was set to 2400 and 3900 Erlangs for the USA and NSFNet topologies, respectively. In addition to the performance evaluation simulation, MSU and MU require an additional simulation previously to create their respective priority list, with the same mentioned parameters, and in a *full-SLC* scenario. Finally, regarding relative equipment cost, we adopt the cost models from[1],[9]. The WSS types can be defined in terms of port count (1×5, 1×9, 1×20, 1×40, 1×80, 1×160 and 1×320) and its cost (respectively $\$0.63$, $\$1$, $\$1.58$, $\$2.5$, $\$3.95$, $\$6.25$, $\$9.87$).

Figure 4 present the bandwidth blocking rate results for the proposed heuristic adaptations under different budget scenarios for the USA topology. In this topology, the required investment to turn a standard (*No-SLC*) architecture into a *Full-SLC* one is of $\$1739.08$ units and the performance gain is of 30%.

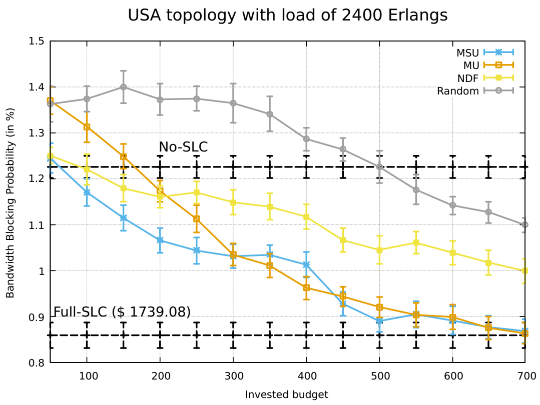

Fig. 4: Heuristics performance in USA topology.

From the results presented in Fig. 4, it is noted that some heuristics yield a better distribution of core-switching ports, by its close proximity with the *Full-SLC* results. We note that some heuristics perform better under specific budget availability. For example, the *MU* performs poorly in scenarios of up to $\$300$ units of budget but maintains one of the best performances for higher budgets. However, with only a $\$500$ budget, the MSU distribution reaches the same performance as of the *Full-SLC* scenario. Thus, it is possible to obtain a network performance equivalent to a *Full-SLC* network with the application of only 28.75% of the budget required for it.

Moreover, *MU* and *Random* heuristics have inferior performance when compared to the standard SDM-EON network (*No-SLC*) for a budget under $\$200$ and $\$500$, respectively. Thus, the insertion of core-switching ports without criterion selection can worsen the network performance due to resource fragmentation.

The same evaluation on NSFNet topology is presented in Figure 5. In this topology, the required investment to turn a *No-SLC* architecture into a *Full-SLC* one is $\$629.16$ units, and the performance gain is 79%.

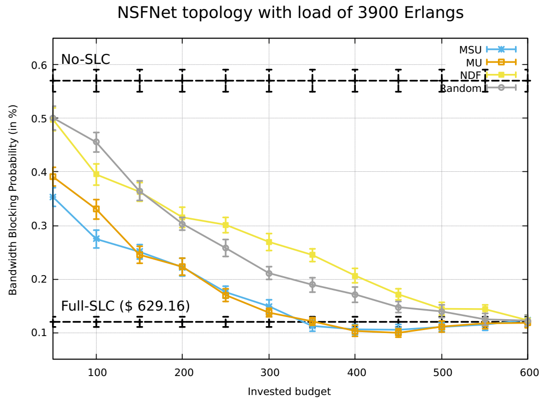

Fig. 5: Heuristics performance in NSFNet topology.

The NSFNet has less variety of solutions for distributing core-switching ports because it is a less connected topology. Thus, all the heuristics have comparable performance in terms of bandwidth blocking. Since the lowest budget test ($\$50$ units), the $Random$ solution performs better than the scenario without SLC. The best solution now is either MU or MSU algorithm (with a preference for MSU in low-budget cases). For both, a *Full-SLC* performance is reached with only $\$300$ of budget, 47.68% of the total.

Conclusions and future work

We showed that sparse spatial lane change (SLC) allocation can obtain the comparable level of performance gain as the full one. Future work will develop an analytical model for optimal Sparse-SLC allocation with equipment budget constraints.

Acknowledgements

The authors acknowledge the financial support by the Federal Ministry of Education and Research of Germany in the programme of “Souverän. Digital. Vernetzt.” Joint project 6G-RIC, project identification number: 16KISK031.

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