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Zero-Cost Upgrade to Multi-Fiber Network with Partial-Lane-Change Capabilities

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Growing capacity requirements are leading to the deployment of multiple fibers in each optical network link. Even though deploying state-of-the-art multi-fiber network architectures with stacked and independent fiber layers simplifies network design and control, spectrum can be used more efficiently if the optical-network nodes allow to interconnect fiber layers, i.e., if the so called *lane change* is enabled. Unfortunately, lane change in high-degree optical nodes requires Wavelength Selective Switches (WSSs) with a high number of ports, which is prohibitively costly or even unfeasible with current WSS technology. Instead, lane change in low-degree optical nodes can be enabled at no extra cost, using WSS ports that are otherwise left empty. In this study, we describe our proposal for multi-fiber network with partial lane-change capabilities and perform a simulative study to identify the advantages of this architecture, as well discussing the emerging resource allocation challenges associated to it. We demonstrate that by enabling lane-change in degree-2 nodes we can increase network throughput by 3% and restore (5-8)% more traffic in case of single and double link failures at no additional equipment cost.

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1. INTRODUCTION

Optical network operators are always looking for economically-sustainable architectural solutions to meet the 20-30% estimated yearly traffic growth [1]. To accommodate traffic growth, C-band, which is traditionally used for optical data transmission, has been first extended from 4 to 6 THz (i.e., Super-C band), and then complemented by the neighboring L-band, doubling the available spectrum. However, multi-band architecture can provide only a fixed amount of extra capacity [2], limited by the amount of spectrum introduced by the new band. Moreover, each next band (e.g., S, E, O-band) can be introduced only after designing and producing market-ready equipment, such as transponders, optical amplifiers, Wavelength Selective Switches (WSSs), etc., and developing accurate Quality of Transmission estimation models [3].

Even more capacity can be obtained with Spatial Division Multiplexing (SDM) [4] by using multiple independent fibers or multiple fiber cores within a single fiber or multiple propagation modes within a multimode fiber. As single-mode fibers are already installed in bundles (known as SMF bundles), they can be lit up on demand, making it an unsophisticated, yet effective and common, approach to continuously increasing network capacity. Multi-fiber networks can be deployed immediately and can be scaled indefinitely, while more advanced options such as multi-mode or multi-core fibers still require significant R&D efforts [5].

One of the main challenges when deploying multi-fiber networks lays in the port-availability constraints imposed by the WSSs used at the input and output of the Reconfigurable Add-Drop Multiplexers (ROADMs). Multi-fiber networks can be deployed using *stacked ROADMs* or using *lane change ROADMs*. In a multi-fiber network architecture using stacked ROADMs, each ROADM in the stack can only switch signals within one fiber layer, so fiber layers are isolated from one another, and the number of WSS ports used for switching is independent from the number of fiber layers. Conversely, in the multi-fiber network architecture with lane-change ROADMs, large ROADMs with full switching flexibility can switch signals across all fiber layers, allowing a more efficient utilization of spectrum resources. However, this enhanced flexibility comes at a cost, as now the number of WSS ports used for switching grows proportionally to the number of fiber layers. Switching signals between a high number of fiber layers in nodes with high node degree requires WSSs with many ports, that can be prohibitively expensive or even unavailable on the market (the largest reported WSS sizes are 1x48 for commercial products [6] and 1x95 in research [7]).

To find an intermediate, effective and practical trade-off be-

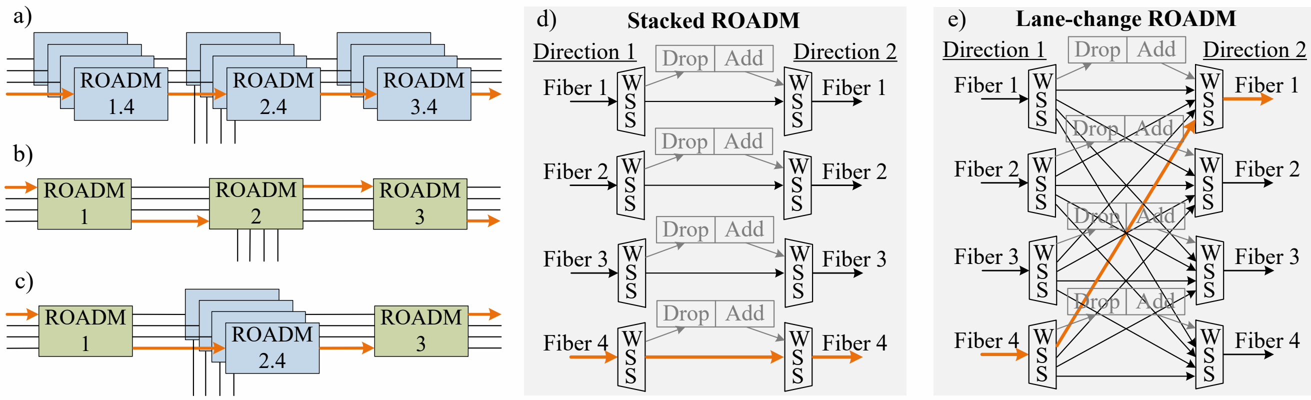

Fig. 1. a) State-of-the-art multi-fiber network with stacked ROADMs in all nodes; b) Multi-fiber network with lane-change ROADMs in all nodes; c) Multi-fiber network with lane-change ROADMs in degree-2 nodes (e.g., ROADM 1 and ROADM 3); d) Architecture of a stacked ROADM; e) Architecture of a lane-change ROADM. A possible signal path is depicted in orange.

tween the stacked and layer/lane-change architectures one can observe that WSSs commonly deployed in small-degree nodes (e.g., 1x9 WSSs in degree-2 nodes) already have a sufficient number of unused ports available to interconnect fibers at different layers. Such nodes can act as lane-change nodes, and, as additional fibers are lit up during network evolution, lead to a more efficient spectrum usage *with the same number and size of WSSs*. Therefore, in this study, we propose and investigate a multi-fiber network architecture where only nodes with degree-2 have lane-change capabilities.

Extra routing options that are made available by the lane-change architecture become valuable especially when network spectrum is filled, and no continuous spectrum channel can be found along any single fiber layer. Moreover, extra routing options can help postponing the deployment of new fiber layers and increasing the amount of traffic that can be restored in case of failures.

To summarize, fibers are typically deployed in large bundles and dark fiber is plentiful. To provision additional capacity we can (i) add fibers to the existing networks and use larger-scale WSSes, but WSS scale has reached a plateau (a 1x95 WSS prototype was published in 2015, with no progress since then [7]), or (ii) deploy new, independent networks and increase operational complexity. Instead, we propose to add (light) fibers to an existing network, such that WSS size and the number of networks to operate are both kept constant, while the capacity of the upgraded network increases.

A. Related Work

Two possible directions to increasing network capacity, i.e., spectral and spatial, has been extensively studied in literature.

Both directions have their pros and cons [8]. Scaling the network along the spectral dimension allows to reuse the existing fiber infrastructure and can provide large (but finite) amounts of extra capacity, estimated in [2]. However, introducing each new spectrum band requires to design and produce suitable optical transponders, optical amplifiers, Wavelength Selective Switches, etc., and develop Quality of Transmission estimation models [3]. Moreover, wide-band optical transmission systems require sophisticated strategies for launch power and amplifier gain control [9], to address the stimulated Raman scattering (SRS) effect. Despite these challenges, multiband architecture is currently being widely deployed (in the C+L configuration) and its application is being investigated even for metro networks [10].

Authors in [11] analyze the scalability limits of optical communication systems and conclude that spatially parallel transmission is the only long-term sustainable way to keep increasing the capacity of optical networks. Spatial Division Multiplexing (SDM) can be achieved with parallel fiber cables, multi-core fibers (MCFs) and few-mode fibers. A thorough overview of the research on the multicore and multimode and the issues preventing their operational use can be found in [5]. Many works investigate possible directions of ROADM architecture evolution in the SDM networks. Authors in [12] discuss switching technologies and cross-connect architectures for flexible spatial and spectral switching, while [13] proposes different architectures for fully spatial-switching cross-connects. Authors in [14] describe ROADM architectures for switching at both fiber, band and frequency scales, and [15] investigates the benefits of spatial flexibility of the add-drop sections in SDM networks. Works [16], [17] investigate the effect of different switching granularities on network capacity.

Few works focus on enabling switching optical signals between multiple layers in multi-fiber networks given the limitations of the existing wavelength switching technology. For example, in [18] authors propose to reduce the size of WSSs in a lane-change ROADM by partially sacrificing the directionless feature of a ROADM. In the preliminary version of our paper [19], we proposed to enable lane-change capabilities in degree-2 nodes at no extra cost, using WSS ports that are otherwise left empty, and reported the potential gains in throughput. We now extend that study by improving the system model and extending the set of considered network scenarios[1].

B. Paper contribution and organization

This paper proposes multi-fiber network architecture with partial lane-change capabilities in degree-2 nodes.

[1]Note that, in this work, we significantly evolved the assumptions of our simulations with respect to Ref. [19], and this led to the change in results with respect to the preliminary version of the paper (*nb*: the new assumptions, in our opinion, are more reflective of operation in real network deployments). Firstly, we now avoid blocking due to the lack of transponders, so that our simulations reach the point in network evolution when there is a lack of spectrum. To achieve that we i) consider a higher number of transponders per add-drop block (i.e., 20 rather than 9) and ii) consider as many add-drop blocks available as there are free WSS ports in the ROADM rather than postponing their deployment. Secondly, we now consider k-link-paths during routing rather than k-fiber-paths (see Section 3B for definitions) to fairly evaluate the gain from the extra routing options (i.e., extra fiber-paths) that are made available by the lane-change architecture while using the same link-paths as in the scenario without lane-change.

We compare the throughput and the ability to restore traffic in two main network architectures, namely (A) No lane change and (B) Partial lane change in degree-2 nodes. We also quantify the upper-bound gains in the architecture with lane change in all nodes and investigate how much lane change can postpone the deployment of new fiber layers. To quantify the gains we consider two realistic core-network topologies with 70 and 132 nodes and demonstrate that we can increase network throughput by 3% and restore (5-8)% more traffic in case of single and double link failures.

The rest of the paper is organized as follows. Section 2 introduces the architecture of the stacked and lane-change ROADMs in multi-fiber networks. Section 3 introduces the problem of multi-fiber network design and describes the Routing, Fiber Assignment and Spectrum Allocation heuristic algorithm used to solve it. Section 4 provides numerical results, reporting the increase in throughput and amount of traffic that can be restored enabled by lane-change capability in degree-2 nodes. Section 5 draws the conclusion of our study.

2. PARTIAL-LANE-CHANGE OPTICAL NETWORK ARCHITECTURE

In Fig. 1a we show the schema of a 3-node segment of a state-of-the-art multi-fiber network with 4 fibers in each link and 4 stacked ROADMs in each node. For the sake of readability, "fibers" in Fig. 1 are bidirectional, i.e., each plain black line corresponds to a fiber pair, where the two fibers supporting traffic in opposite directions. An optical signal (depicted in orange) can be switched to any arbitrary direction, but it always remains in the same fiber layer. In this scenario, the number of WSS ports used for switching optical signals between multiple directions is independent from the number of fiber layers and is equal to:

$$N_p = d - 1 \tag{1}$$

where d is the node degree (i.e., number of directions).

Stacked architecture can be easily and indefinitely scaled, as a fiber layer can be added by simply deploying a new ROADM into each stack. However, isolation of fiber layers does not allow to use spectrum resources efficiently.

In Fig. 1b we show the network architecture with lane-change ROADMs in all nodes. It allows to use network spectrum more efficiently, but the number of WSS ports required for switching optical signals between multiple directions and fibers in lane-change nodes increases with the number f of fiber layers and is equal to:

$$N_p = (d - 1) \times f \tag{2}$$

In Table 1, using Eq. 2, we summarize how the number of WSS ports required for switching in lane-change nodes scales with the number of directions and fiber layers.

In Fig. 1c we show the proposed network architecture with lane-change ROADMs in degree-2 nodes that can switch the signal between 4 fiber layers, while the number of WSS ports used for switching optical signals between multiple directions and fibers in lane-change nodes remains relatively low due to the low node degree.

Figures 1d-e illustrate the difference in the internal architecture of a degree-2 stacked ROADM vs. a degree-2 lane-change ROADM. In this paper, we consider a route-and-select ROADM architecture with WSSs at the input and output node-ports. In the 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

Table 1. WSS port requirements in lane-change nodes for different values of node directions and fiber layers

Degrees (d)	Fibers (f)	№ WSS ports used for switching	№ WSS ports left for add-drop		
			1x9	1x20	1x40
2	1	1	8	19	39
5	1	4	5	16	36
2	5	5	4	15	35
5	5	20	-	-	20
2	10	10	-	10	30
5	10	40	-	-	-

ROADM, 4 ports are needed to switch across the 4 different fibers. In this work we consider 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., 32 across 4 fiber layers), while lane-change ROADM provides full routing flexibility, but is limited to 5 add-drop blocks per layer (i.e., 20 overall). Note that with 1x9 WSSs it is practical to allow lane-change only in degree-2 nodes, as already in degree-3 nodes, 8 WSS ports would be needed to switch between 4 fiber layers in each direction, leaving only a single port for add-drop. We assume that add-drop blocks are colorless, directionless and contentionless as in [20].

It could appear more appropriate to consider add-drop blocks shared across fiber layers (i.e., any-lane add-drop [15]) in the large ROADM and per-layer add-drop blocks in the independent ROADMs of the stack. However, this may introduce a deficit of transponders in lane-change nodes (following the example above, 5 add-drop blocks will be shared across 4 layers), and network under-utilization, while we are interested in investigating the benefits of lane-change in a fully filled network. The interplay between the flexibility of anylane add-drop and the lower availability of transponders is an interesting topic for future research.

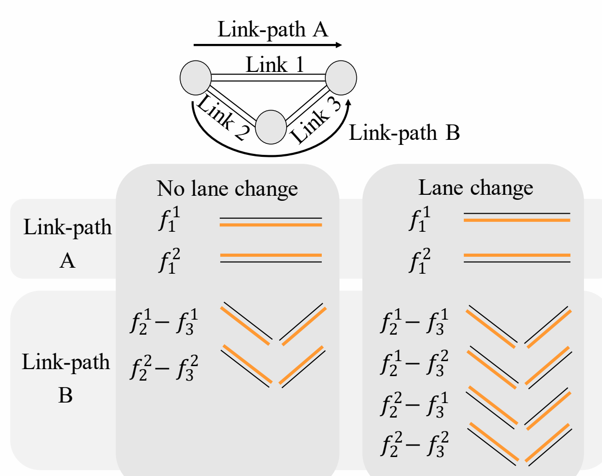

Fig. 2. Example of link and fiber paths in case of k Shortest Link Path routing heuristic with k = 2 for a service to be established between the two upper nodes

Algorithm 1. Routing, fiber and spectrum allocation algorithm

Input: (s, d): source-destination pair, R: traffic request in Gbit/s, F: number of fiber layers in the network, K: number of link-paths between (s, d), $LinkPathList_i, i = 1...K$: list of link-paths between (s, d), $FiberPathList^i_j, i = 1...K, j = 1...M$: list of fiber-paths for each link-path between (s, d)

Output: $SolutionPathList$: list of selected fiber-paths, $SolutionSlotList$: list of starting spectrum slots along the corresponding fiber-paths

```
1:  SolutionPathList ← [ ]
2:  SolutionSlotList ← [ ]
3:  for i = 1 ... K do
4:      for j = 1 ... M do
5:          Slot ← FirstFitSpectrumAllocation(FiberPathList^i_j)
6:          if Slot ≠ −1 then
7:              SNR ← QotModel(FiberPathList^i_j, Slot)
8:              C ← BitrateAssignment(R, SNR)
9:              R ← R − C
10:             SolutionPathList.Add(FiberPathList^i_j)
11:             SolutionSlotList.Add(Slot)
12:             if R == 0 then
13:                 Traffic request is provisioned
14:                 return SolutionPathList, SolutionSlotList
15:             else if j < M then
16:                 j ← j + 1
17:                 GoTo line 5
18:             else if j == M AND i < K then
19:                 i ← i + 1
20:                 GoTo line 4
21:             else if j == M AND i == K AND F < 4 then
22:                 Install a fiber layer
23:                 F ← F + 1
24:                 Recompute FiberPathList
25:                 i ← 0, j ← 0
26:                 GoTo line 3
27:             else
28:                 Traffic request is blocked
29:                 return [ ], [ ]
```

3. PROBLEM STATEMENT AND METHODOLOGY

To evaluate the impact of the lane-change capabilities in degree-2 nodes on network throughput and traffic restorability, we develop a multi-fiber network design algorithm to perform network-level simulations. We focus on a scenario with incremental traffic, that is deemed to be representative of the real-world traffic.

A. Problem Statement

The problem of multi-fiber network design is stated as follows: **Given** i) a physical network topology consisting of optical nodes and fiber-bundles with multiple fibers and ii) a set of traffic requests, **decide** i) routing, ii) fiber assignment, iii) spectrum allocation for each traffic request and iv) when to lit up new fibers with the **objective** of maximizing network throughput and postponing the use of new fiber layers, **constrained by** i) spectrum availability ii) SNR requirements for the considered modulation formats, iii) WSS port availability.

B. Definitions and Notation

We distinguish between a *link path* (a sequence of network links represented by fiber bundles in network deployment) and a *fiber path* (a sequence of specific fibers in the fiber bundles of the link path). In other words, given a link path in the network with l fiber layers, we can choose between l fiber paths if there is no lane change and between l^{n+1} fiber paths if n ROADMs along the link path (apart from the source and destination nodes) have lane-change capabilities.

Fiber f^j_i in the fiber path has two indexes: index i refers to the corresponding fiber bundle and index j refers to the corresponding fiber layer (i.e., fibers with fiber-layer index 0 are available since Beginning of Life, while fibers with fiber-layer index l are lit up the last).

We show an example of two link paths A and B and the corresponding fiber paths in Fig. 2, where $l = 2$. Without lane change there are 2 fiber paths for each of the link paths A and B, and by enabling lane change in the intermediate node we can obtain $l^2 = 4$ fiber paths for link path B.

C. Routing, Fiber and Spectrum Allocation Algorithm

We provision traffic requests according to the Routing, Fiber and Spectrum Allocation (RFSA) algorithm with the pseudocode reported in Algorithm 1. We perform routing using k-Shortest Link-Path heuristic. Among the possible fiber paths corresponding to the link path, we first verify spectrum availability along the fiber paths that use fibers with lower fiber layer indexes, postponing the use of new fiber layers. To achieve that, we sort fiber paths starting with the ones with the lowest sum of fiber-layer indexes (i.e., we use a First-Fit fiber assignment). We then perform spectrum allocation in the First Fit manner, while guaranteeing frequency contiguity and continuity constraints (i.e., we do not consider wavelength conversion). We refer to the RFSA algorithm we use as kSP-FF-FF (k Shortest-Path First-Fit First-Fit). We remark here that many other algorithms would be possible, using different RFSA policies, but in this paper we focus on comparing the two architectures by fixing a number of link-path, and exploring all the possible fiber paths within those link paths under the standard first-fit approaches to quantify the increased flexibility of the lane-change architectures vs. the no-lane-change one.

Regarding the decision on when to start using new fibers in the network, we start with a single fiber layer in the network, then, whenever a new traffic request needs to be provisioned and there is not enough spectrum to accommodate it along any of the k shortest link paths in the first fiber layer, we add the second fiber layer, i.e., we assume that a new fiber is lit on in all the links of the network. The same procedure is repeated for the other fiber layers after then second one, up to the maximum number of 4 fiber layers.

D. Restoration

We also consider restoration against link failures. We assume that the failure of a link leads to the failure of all the fibers in the bundle in both directions. Hence, we restore the traffic requests carried by the lightpaths that were routed on any fiber in the failed bundle. We start with the traffic requests with the highest disrupted bitrate and restore them according to the RFSA algorithm described above. We assume that only the transponders already deployed to carry traffic requests before the failure(s) occurrence can be reused for the restored lightpath (i.e., no transponders are preinstalled to facilitate restoration and no additional transponders are installed during restoration. Therefore, in case restoration paths are longer than the primary ones, and lower modulation formats are configured, traffic will

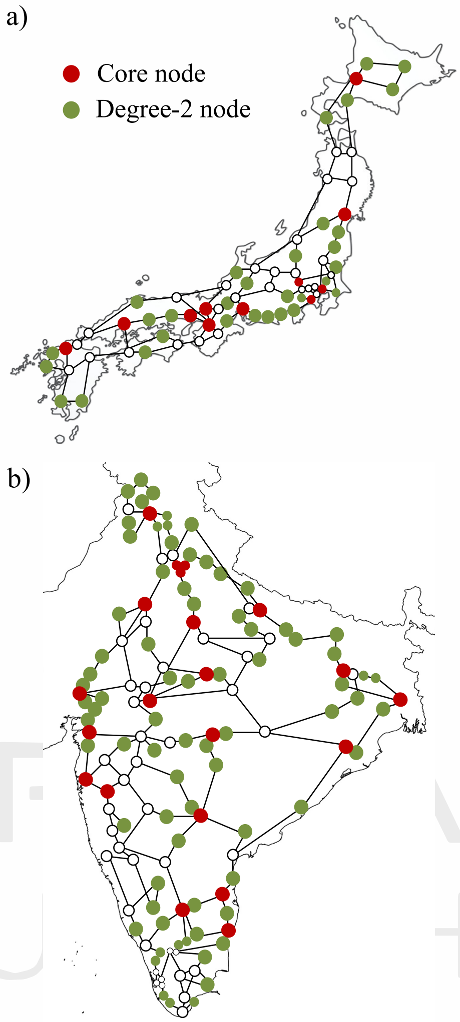

Fig. 3. a) 70-node Japanese topology (JP70), b) 132-node Indian topology (IND132)

Table 2. Topology parameters

Topology	JP70	IND132
No. of service/core nodes	59/11	112/20
No. of degree-2 nodes	31	84
Avg/max link length, km	79/237	95/417

be only partially restored.

4. CASE STUDIES AND NUMERICAL RESULTS

We now discuss numerical results that demonstrate the impact of the lane-change nodes on network throughput and on the ability to restore traffic in multi-fiber networks. We compare the three multi-fiber network architectures illustrated in Fig. 1a, b and c, i.e.: (i) deploying stacked ROADMs in all nodes (we refer to this scenario as NLC, No Lane Change), (ii) deploying lane-change ROADMs in degree-2 nodes and stacked-ROADMs in the other nodes (we refer to this scenario as PLC, Partial Lane Change), (iii) deploying lane-change ROADMs in all nodes (we refer to this scenario as FLC, Full Lane Change). Note that FLC is tested in a limited set of scenarios, due to the very high computational requirements.

We carry out our numerical evaluation using two realistic topologies, i.e., a 70-node Japanese (JP70) network [21] and a 132-node Indian network [22] (where link lengths have been scaled by a factor 0.7 to avoid the need for regenerators — a study out of the scope of this work), shown in Fig. 3a and b, respectively, and with topology information summarized in Table 2. Networks contain core nodes (major cities, shown in red in Fig. 3) and service nodes (all the other nodes). Note that 44 (respectively, 64)% of nodes in JP70 (resp., IND132) are degree-2 (shown in green in Fig. 3), and thus can be used to perform lane-change.

Random service requests are incrementally added until reaching a certain percentage B of traffic requests blocked due to lack of spectrum. We report results for B equal to 1, 2.5 and 5%. We allocate network resources for one traffic request at a time, according to the kSP-FF-FF algorithm described in Section 3 and report the results with k = 1, 5 and 10.

As for the traffic matrix, we consider a mixture of mesh global traffic between the core nodes, and local traffic between service nodes and two of their closest core nodes, as in [23]. We report the results with 25, 50 and 75% of service-core (SC) traffic. Data rate requests are randomly distributed within 400 Gb/s and 1600 Gb/s with a 400 Gb/s step. Results are averaged over 25 different random traffic instances.

We consider 6 THz C-band and 200 GHz channels without guard-bands for optical signals generated by 190 Gbaud transponders with Probabilistic Constellation Shaping and a maximum capacity of 1600 Gb/s. SNR thresholds are taken from [24] and an additional 1 dB system margin is applied. We consider 1x9 WSSs at the input and output ports of ROADMs, that are sufficient for the considered topologies and arbitrarily large WSSs at the input and output ports of ROADMs in the case of FLC. We deploy at most 4 fiber layers to leave enough WSS ports for add-drop blocks. In order to avoid blocking due to the lack of transponders, we assume that each add/drop block can transmit 20 and receive 20 optical signals.

We use the closed-form Gaussian Noise model [25] to estimate non-linear interference. We always consider *ASE loading* scenarios, i.e., fully occupied spectrum even in case there are free wavelengths in the fiber links and, thus, worst-case amount of interference is account. Erbium-Doped Fiber Amplifiers (EDFAs) compensate for propagation loss and have Noise Figure of 5 dB. To maximize lightpaths SNR, power optimization is done according to Locally-Optimized Globally-Optimized (LOGO) strategy [25].

To quantify the impact of the lane-change nodes on network throughput we sum the bitrate of all provisioned traffic requests and compute the gain in throughput (e.g., in scenario PLC) as follows:

$$Gain_{PLC} = \frac{Throughput_{PLC} - Throughput_{NLC}}{Throughput_{NLC}} \times 100\% \quad \textbf{(3)}$$

To quantify the ability to restore traffic in case of link failures, we calculate restoration coefficient by averaging the ratio between the amount of restored traffic (in Gbit/s) and the amount of disrupted traffic (in Gbit/s) across the set of fault scenarios F that includes all single link-failures (the number of scenarios is equal to the number of links L) and double link-failures (the number of scenarios is equal to $L \times (L-1)/2$):

$$R = \frac{1}{|F|} \sum_{F} \frac{T_{Restored}}{T_{Disrupted}} \times 100\% \quad \textbf{(4)}$$

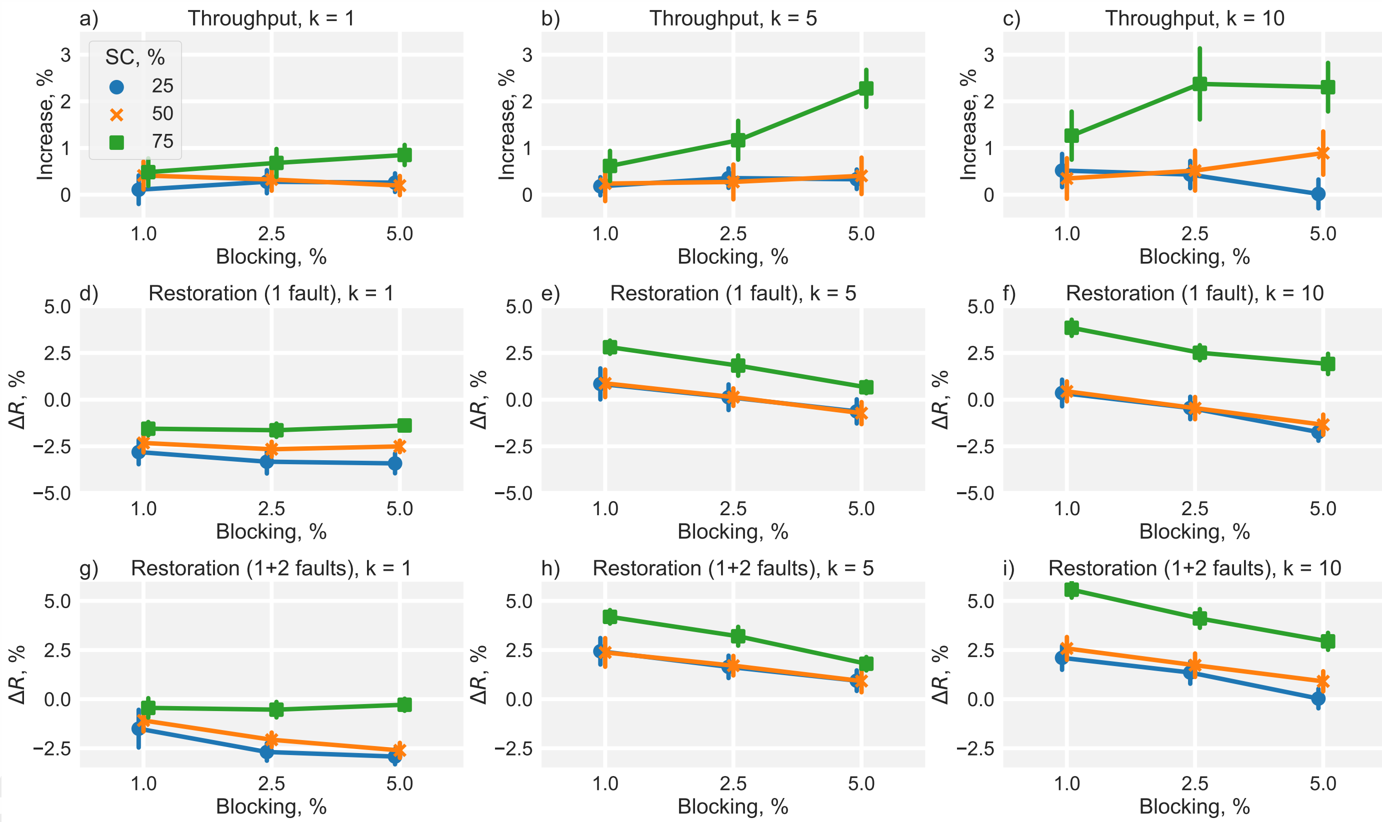

Fig. 4. Gains from Partial Lane Change in JP70 network: a), b), c) Increase in network throughput with = 1, 5, 10; d), e), f) Increase in restoration ratio for single faults with k = 1, 5, 10; g), h), i) Increase in restoration ratio for single and double faults with k = 1, 5, 10

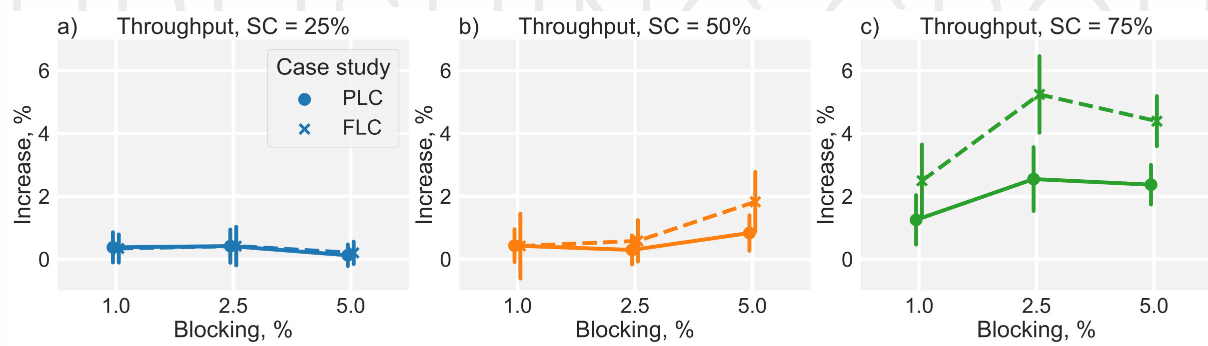

Fig. 5. a), b), c) Increase in network throughput with k = 10 for 25, 50 and 75% of service-to-core traffic in JP70 network with Partial Lane-Change in degree-2 nodes and Full Lane-Change in all network nodes

We compute the gain in restoration coefficient (e.g., in scenario PLC) as follows:

$$\Delta R = R_{PLC} - R_{NLC} \quad \textbf{(5)}$$

A. Gains from lane-change in a 70-node network

We first perform our evaluations for a 70-node Japanese topology. In Fig. 4 we report the increase in network throughput and restoration coefficient (with 95% confidence interval) due to zero-cost lane change in degree-2 nodes. In the first row we report the increase in throughput, in the second row - the increase in restoration coefficient for single-link failures, and in the third row - the increase in restoration coefficient for single- and double-link failures. The three columns correspond to $k = 1, 5$ and 10 in kSP-FF-FF algorithm, respectively, meaning that more link-paths are available with higher k.

Results show that the increase in network throughput and restoration coefficient are the highest for k = 10 and with 75% of service-core traffic. Network throughput increases by at most 3%, while restoration coefficient increases by at most 4% for single-failures and 6% for single- and double-failures.

The gains are the highest with k = 10, as longer link paths include more degree-2 nodes and offer a larger number of extra fiber-paths that are not available without lane-change. The gains in both network throughput and restoration coefficient increase with the percentage of service-to-core traffic, meaning that local traffic benefits more from the presence of lane-change nodes.

We can also see how the gains from lane-change capabilities in degree-2 nodes increase with network blocking, as extra routing options enabled by lane-change become more useful in a fully filled network. For the same reason we obtain a higher gain in the scenarios with both single- and double-link failures vs.

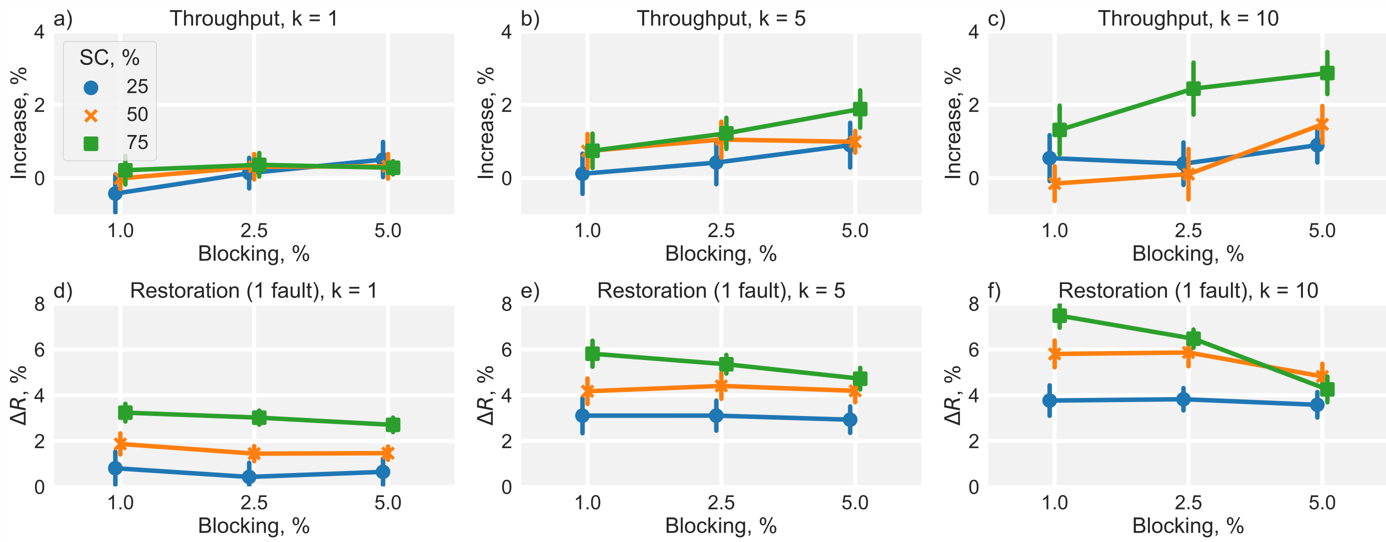

Fig. 6. Gains from Partial Lane Change in IND132 network: a), b), c) Increase in network throughput for k = 1, 5, 10; d), e), f) Increase in restoration ratio for single faults for k = 1, 5, 10

the scenarios with only single-failures, when more traffic must be rerouted in an already filled network.

We now investigate how much extra throughput can be achieved from enabling lane-change capabilities in all network nodes. In Fig. 5 we report the increase in network throughput and restoration coefficient in scenarios with Partial and Full Lane-Change capabilities for k = 10. Results show that (1-3)% of additional throughput can be obtained by transforming all network nodes into lane-change nodes, which suggest thata most of the gains achievable with lane change in a scenario of incremental traffic can already be achieved using lane change only in degree-2 nodes.

Note that degree-3 nodes equipped with 1x9 WSSs can also be upgraded to lane-change architecture at zero cost, hence we have performed an additional analysis to investigate the potential gain from the use of lane-change in both degree-2 and degree-3 nodes. With a single WSS port remaining for the add-drop block in a degree-3 lane-change node, traffic requests get blocked due to the lack of transponders early in the evolution of the network, before the extra routing options provided by lane-change become useful, so there is no gain in throughput. If we perform a non-zero-cost upgrade and substitute 1x9 WSSs with 1x20 WSSs at the input/output node ports of the degree-3 nodes (leaving 12 ports for add-drop sections), we observe an increase in throughput and restoration coefficient by 1-2% with respect to the scenario with lane-change limited to degree-2 nodes.

B. Gains from lane-change in a 132-node network

We now repeat our evaluations for a 132-node Indian topology. In Figure 6 we report the increase in network throughput and restoration coefficient (with 95% confidence interval) due to lane-change in degree-2 nodes. In the first row we report the increase in throughput and in the second row - the increase in restoration coefficient for single-link failures. The three columns correspond to k = 1, 5 and 10 in k-Shortest Link Path routing algorithm.

Again, it is confirmed that the highest increase in network throughput and restoration coefficient is achieved for k = 10 and with 75% of service-core traffic. Network throughput increases by at most 3%, while restoration coefficient increases by at most 8% for single-failures. The gains are the highest with k = 10 and higher network blocking, which are the conditions that make extra routing options enabled by lane-change more useful.

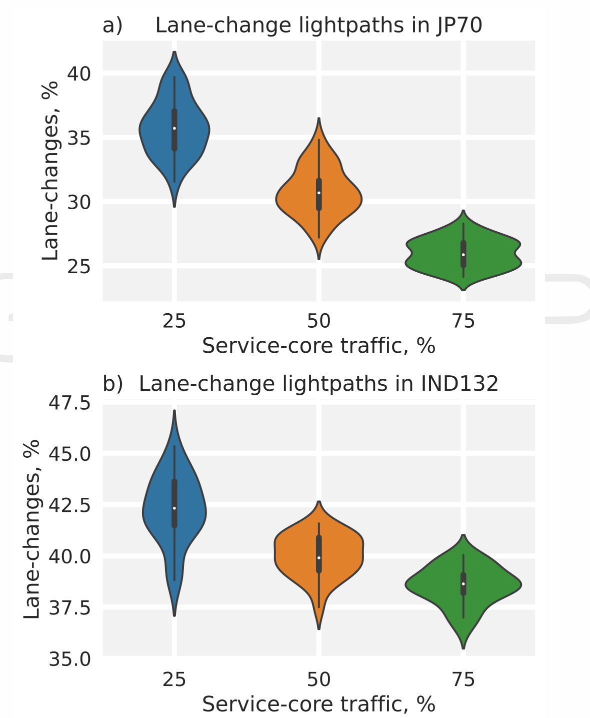

Fig. 7. % of lightpaths that use lane-change in a) JP70 and b) IND132

We do not report the results for single- and double-link failures due to high computational requirements. We were able to obtain the results for k = 1, and they follow the same trend as in the JP70 network: restoration coefficient increases by a few % if we consider double failures.

C. Statistics of lane-change utilization

In Fig. 7 we report the percentage of lightpaths in JP70 and IND132 with k = 10 that performs lane-change at 5% blocking. We can see that lane-change is used the most in scenarios with 25% of service-core traffic, namely, 35% of lightpaths perform lane-change in JP70 and 42.5% - in IND132. These scenarios include many lightpaths between far-away core nodes that pass through a lot of lane-change nodes and thus have a higher probability of performing lane-change. However, in Fig. 4 and 6 we have seen that lane-change provides the highest gain in scenarios with higher percentage of service-core traffic, despite the fact that lane-change is used by fewer lightpaths. These results are highly dependent on the RFSA algorithm used, and a more thorough analysis of the impact of the RFSA algorithm is left as future work.

5. CONCLUSION

In this work, we have investigated the possible increase in throughput and ability to restore traffic from the introduction of lane-change capabilities in degree-2 nodes of multi-fiber networks. We have demonstrated that for the considered network and traffic scenarios, partial lane-change capabilities provide up to 3% increase in throughput and up to 8% increase in restoration abilities. Proposed approach allows to use spectrum resources in optical networks more efficiently, while using the same number and size of WSSs and only requiring extra cabling (in other words, our proposed solution does not require any additional capital expenditure to enable lane-change).

As future work, we aim at improving the Routing, Spectrum Allocation and Fiber Upgrade algorithm to balance the gain from extra fiber-paths enabled by lane change with the higher amount of spectrum occupied by the longer paths that have available spectrum in the fully filled network.

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