

Evaluation of the Impact of Different SDM Switching Strategies in a Network Planning Scenario

Behnam Shariati^{(1),(2)}, Pouria Sayyad Khodashenas⁽¹⁾, José Manuel Rivas-Moscato⁽¹⁾, Shalva Ben-Ezra⁽³⁾,
Dimitrios Klonidis⁽¹⁾, Felipe Jiménez⁽⁴⁾, Luis Velasco⁽²⁾, Ioannis Tomkos⁽¹⁾

(1) Athens Information Technology (AIT), 44 Kifisias Ave., GR-15125 Marousi, Attica, Greece

(2) Universitat Politècnica de Catalunya (UPC), C/ Jordi Girona 1-3, ES-08034 Barcelona, Spain

(3) Finisar Israel, Holon 58858, Israel

(4) Telefónica Investigación y Desarrollo, Ronda de la Comunicación, 28050 Madrid, Spain

b.shariati@ait.gr

Abstract: We compare SDM joint and independent switching strategies in a planning scenario involving a European backbone network. Joint switching can achieve cost savings of 40-50% with a performance similar to that of independent switching.

OCIS codes: (060.1155) All-optical networks; (060.4250) Network

1. Introduction

Network traffic volume has been exponentially increasing at annual rates varying from 30% to 60% in the past years due in part to bandwidth-hungry applications such as cloud computing, HQ online video streaming or social networking [1]. Space-division multiplexing (SDM) has been proposed as a promising solution to address the requirement for higher capacities owing to its scaling potential, with foreseen network capacities reaching far beyond the Petabit per second (Pbps) mark [1-2], and the expected cost per bit reduction due to the sharing of network elements among different spatial dimensions.

However, the selection of a cost-effective technology for each element of an SDM network (e.g. transmission media, transceivers, amplifiers, or switches) may result in the introduction of additional physical-layer constraints as a consequence. While there are several studies investigating SDM transceiver technologies [2], limited research has been carried out regarding SDM switching technologies. Switching in WDM networks is realized on a spectral-slice-by-spectral-slice basis, whereas in SDM a number of switching paradigms can be exploited [3]: (a) *independent switching* (Ind-Sw): all spectral slices and spatial modes/cores can be independently directed to any output port; (b) *joint switching* (J-Sw): all spatial modes/cores are treated as a single entity, while spectral slices can be freely switched by the WSS; and (c) *fractional joint switching* (FrJ-Sw): a kind of hybrid approach in which a number of subgroups of G spatial modes/cores, as well as all spectral slices, can be independently switched to all output ports.

Ind-Sw brings a high level of flexibility for routing, space, modulation-level and spectrum assignment (RSMsA) since it allows the allocation of demands over different cores/modes and spectral slices with variable widths. In contrast, J-Sw constrains the RSMsA to one spatial super-channel (Sp-Ch) connection (spread over a number of modes/cores) per spectral slice, and therefore the unused modes/cores over a certain spectral width cannot be allocated to other demands. Note that different transmission media will impose different requirements and will affect the applicability of the different switching schemes: i.e. J-Sw is necessary for coupled multi-core fibers (MCF) or few-mode fibers (FMF) on account of inter-core crosstalk and mode coupling [4], but any switching option is suitable with uncoupled MCFs or bundles of single mode fibers (SMFs). While the choice of switching technology can restrict the flexibility RSMsA algorithms (given that the coarse granularity of J- and FrJ-Sw penalizes the network spectral occupancy), it can also boost the economic feasibility of SDM solutions. For instance, J-Sw and FrJ-Sw allow the use of joint digital signal processing (DSP) at different degrees, which can lead to cost and power consumption savings of integrated receivers in SDM networks [5].

In this paper, the performance of the different switching paradigms has been investigated in a network planning scenario for Telefónica Spain national network assuming bundles of SMFs across all links as a near-term SDM solution. We show that the performance of J-Sw and FrJ-Sw converge to that of Ind-Sw as the traffic increases. In fact, when the total offered load to the network justifies the introduction of SDM, the performance of J-Sw and FrJ-Sw becomes similar to Ind-Sw, while the cost of the SDM switching infrastructure for J-Sw and FrJ-Sw is much lower.

2. SDM switching technologies

Recent investigations on WSSs suitable for SDM have demonstrated the suitability of existing WSS technologies in combination with 2D SMF arrays to handle J-Sw and FrJ-Sw [3,6]. Under these switching paradigms, SDM WSSs are configured to operate as $S \times (M \times N)$ WSSs, capable of directing M input ports, each carrying S spatial modes/cores, toward N output ports [6]. This has the implication that for large S , WSSs with very high port count (HPC) are required. For instance, assuming a route-and-select (R&S) ROADMs architecture with nodal degree D , two WSSs with port count of at least $S \times (1 \times D)$ per degree would be required for J-Sw;

$2 \cdot \lceil S/G \rceil$ WSSs with port count $G \times (1 \times D)$ per degree would be required for FrJ-Sw, and finally S WSSs with port count $1 \times D$ per degree would be required for Ind-Sw. Therefore, if we assume bundles of 12 SMFs, $G = 3$, and $D = 5$, the following WSSs would be required: 2 WSSs with $12 \times (1 \times 5)$ –i.e. 72– input/output ports per degree for J-Sw, 8 WSSs with $3 \times (1 \times 5)$ –i.e. 18– ports for FrJ-Sw, and 24 WSSs with 1×5 ports for Ind-Sw. This leads to a far lower number of WSSs required by J-Sw and FrJ-Sw, which should bring the network cost down significantly especially as the number of spatial dimensions increases. However, increasing the port count affects the WSS cost, so it is necessary to evaluate whether the reduction in the number of ports can compensate for the increase in the WSS cost. To do that, we have taken into account the cost of commercial LCoS-based 1×9 and 1×20 WSSs and, based on [7] and our analysis in the framework of the EU project INSPACE, we have estimated the cost of WSSs with port counts higher than 20. Using the cost of a 1×9 WSS as a reference, the 1×20 WSS cost is 1.5 and we have observed that the HPC-WSS cost per port ranges between 0.10 and 0.15. In the following, for simplicity and without affecting the results and conclusions, we will assume an average value of 0.125.

3. Simulation environment and assumptions

The Telefónica Spain national network [8], representative of a typical national-scale backbone network in Europe, consists of 30 nodes (average/max. nodal degree 3.7/5) –14 of which are transit nodes with add/drop capabilities– and 56 bidirectional links (average length of 148 km). The network is characterized by a quite heterogeneous traffic matrix with 84 demands between two subsets of 7 transit nodes. The heterogeneous nature of the traffic matrix is the consequence of demands being mostly exchanged between highly populated transit areas and Madrid/Barcelona (more than 70% of the total traffic flows are from/to Madrid), where the Internet exchange points are located. This leads to the existence of $\sim 30\%$ of *hot links* (i.e. links with more than twice the average spectrum utilization per link in the network), $\sim 20\%$ of *underutilized links* (i.e. links with $< 1/3$ the average spectrum utilization per link in the network) and $\sim 50\%$ of *moderately utilized links*.

To address the problem of the limited fiber resources, the utilization of already-installed and unused SMFs is likely to be the most natural and cost-effective option for near-term realizations of SDM networks. Having this in mind, we implemented an RSMSA algorithm consisting of a diverse routing computation element (a k -fixed alternate shortest path with maximal disjoint links for each source-destination pair [9]) and a resource allocation module in which spatial and spectral resources are assigned to traffic demands in the form of spatial super-channels (Sp-Ch) –i.e. demands are spread across all SMFs over a given spectral slice–, following a first-fit strategy, starting from the shortest path and the lowest indexed spatial/spectral resource. In order to alleviate the problem of the *hot links*, we implemented a load-balancing engine including a *request-breakdown* element (which breaks up connections larger than the capacity of one spatial Sp-Ch, i.e. the number of SMFs in the bundle). The load-balancing engine distributes big demands proportionally over *underutilized* and *moderately utilized* links when the shortest paths between end-nodes become very congested. Above all, the selection of best path and the most adequate spatial/spectral resources to establish a connection is carried out by a simulated annealing meta-heuristic optimization tool equipped with a multi-starting-point generator to avoid local minima thus yielding a nearly optimal global spectrum utilization [10].

Regarding the transmission technology, single carrier (SC) multi-line rate (MLR) systems have been considered in order to find a good compromise between transmission reach and spectral efficiency. The available modulation formats are dual-polarization (DP) – BPSK, QPSK, 8QAM and 16QAM, with maximum transmission reach calculated by means of the Gaussian Noise (GN) model of nonlinear interference in coherent (Nyquist) WDM systems [11].

4. Results and discussions

In this section, we compare different SDM switching alternatives in a network planning scenario for the Telefónica Spain national network assuming bundles of 12 SMFs across all links as a near-term SDM solution. In the first part of the study, we selected the average occupied spectrum per link per fiber as a quantitative

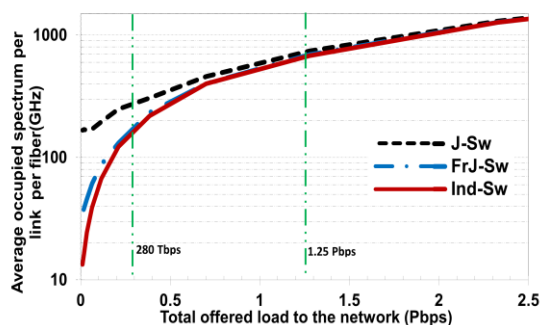


Fig.1(a). Average occupied spectrum per link per fiber.

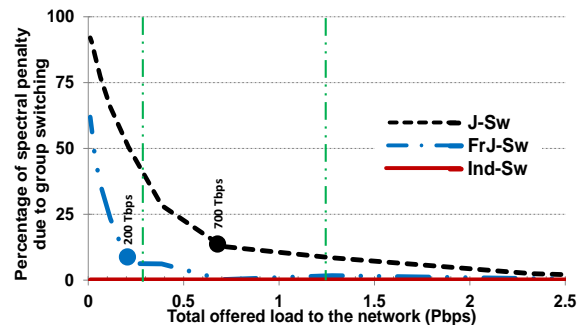


Fig.1(b). Percentage of spectral penalty due to group switching.

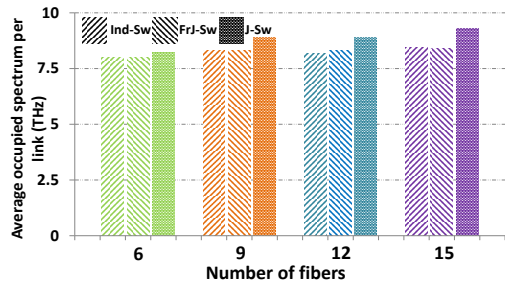


Fig.2. Average occupied spectrum per link for Ind-Sw, FrJ-Sw and J-Sw, considering different numbers of fibers for total offered load to the network equal to 1.25Pbps

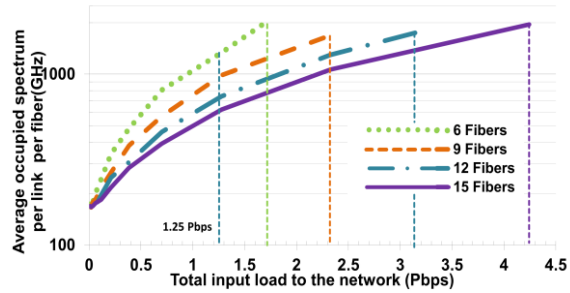


Fig.3. Average occupied spectrum per link per fiber for different number of fibers in a bundle of fiber with J-Sw in terms of total offered to the network.

network performance metric. Fig. 1(a) presents the key result of the study, where the performance of J-Sw and FrJ-Sw is seen to converge to that of Ind-Sw. When the total offered load to the network exceeds 280Tbps and 1Pbps, the performance of FrJ-Sw and J-Sw, respectively, becomes similar to that of Ind-Sw, which is the scenario with the most flexibility at the switching level and therefore the best performance.

Fig.1(b) presents an alternative visualization of Fig.1(a) in terms of the percentage of spectral penalty (defined as the amount of extra occupied spectrum due to the coarse switching granularity of FrJ-Sw and J-Sw which does not contain actual traffic). Inflection points in the performance of FrJ-Sw and J-Sw are observed at total offered loads of 200 Tbps and 700 Tbps, respectively, from where the spectral penalty of FrJ-Sw and J-Sw reduces significantly. Fig. 1(b) also illustrates that the spectral penalty of FrJ-Sw and J-Sw becomes negligible compared to Ind-Sw for total offered loads in excess of 600 Tbps and 1Pbps, respectively.

In the second part of study, we explored the impact of changing the number of SMFs in the SDM bundles across all the links (which also implies changing the size of the spatial Sp-Chs accordingly). In Fig. 2, we show the average occupied spectrum per link as a function of the number of fibers (bundles of with 6, 9 and 15 SMFs) for an exemplary total offered load of 1.25Pbps. All curves follow the same trend as 12 SMFs, which verifies our claim that performance convergence of FrJ-Sw, J-Sw, and Ind-Sw takes place as the total offered load to the network increases. Likewise, in Fig.3 the performance of J-Sw in terms of the total offered load to the network is plotted for all cases under study. We observe that, by taking advantage of larger spatial Sp-Chs (i.e. higher number of SMFs in SDM bundles per link), more traffic can be accommodated in the network, which translates into longer network serviceability. However, we have to state that the total amount of possible offered load to the network is affected by the network topology, the heterogeneity of traffic profile and the placement of hot spots and links.

Finally, in another important contribution of this paper, we also evaluated the cost of the network switching infrastructure under all three SDM switching paradigms according to the premises explained in Section 2. Our results show that Ind-Sw is by far the most costly solution, since its relative network-wide cost is 1344, 2016, and 2688 (as compared to 672, 1008, and 1344 for FrJ-Sw; or 822, 1233, and 1644) for bundles of 6, 9 and 12 SMFs, respectively. This represents a 2x and 1.64x cost increase for Ind-Sw with respect to FrJ-Sw and J-Sw, respectively, regardless of the number of spatial dimensions. Even though FrJ-Sw presents a better performance than J-Sw in terms of both spectral occupancy and cost, we expect that J-Sw, due to possibility of reduced transceiver cost (coming from the use of joint DSP chips common for all spatial sub-channels and the use of a common laser), should lead to cost and power consumption savings in SDM networks since the network CAPEX is dominated by the transceiver cost.

5. Conclusions

We compared the performance of different SDM switching paradigms in terms of spectral occupancy and network switching infrastructure cost, and demonstrated that the spectral occupancy under J-Sw and FrJ-Sw converges asymptotically to that for Ind-Sw, while the switching-related cost can be significantly reduced by using J-Sw or FrJ-Sw.

Acknowledgment: The research leading to these results has received funding from EU ICT INSPACE project under grant agreement N.619732 and the Spanish MINECO SYNERGY project (TEC2014-59995-R).

References

- [1] P. J. Winzer, "Optical networking beyond WDM," in *IEEE Photonics J.* (2012), 4(2), p.647-651.
- [2] P. J. Winzer, "Making spatial multiplexing a reality," in *Nature Photonics* (2014), 8(5), p.345-348.
- [3] D. Marom, et al., "Switching solutions for WDM-SDM optical networks," *IEEE Comm.Mag.* (2015), 53(2), p.60-68
- [4] D. Klonodis, et al., "Spectrally and spatially flexible optical network planning and operations," *IEEE Comm.Mag.* (2015), 53(2), p.69-78
- [5] M. Feuer, et al. "Joint digital signal processing receivers for spatial superchannels," in *IEEE PTL* (2012), 24(21), pp.1957-1960.
- [6] N. K. Fontaine et al., "Heterogeneous space-division multiplexing and joint wavelength switching demonstration," *OFC 2015*, Th5C.5.
- [7] P. Colbourne, et al., "Beyond the C-band: Evaluating the Options," in *PS 2015*, WS3.
- [8] F. Rambach et al., "A multilayer cost model for metro/core networks," in *IEEE/OSA JOCN* (2013), 5, pp.210-225.
- [9] T. Eilam-Tzoreff, "The disjoint shortest paths problem," in *Elsevier Discrete Applied Mathematics* (1998), 85(2), pp.113-138.
- [10] K. Christodououlos et al., "Elastic bandwidth allocation in flexible OFDM optical network," *IEEE/OSA JLT* (2011), 29, pp.1354-66.
- [11] A. Carena et al., "Modeling of the impact of nonlinear propagation effects in uncompensated coherent transmission links," *JLT* 2012