Spectrally and Spatially Flexible Optical Networks: Recent Developments and Findings

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ABSTRACT

Space division multiplexing (SDM) has been proposed as the ultimate solution to address the capacity crunch of optical transport networks. The efficient utilization of SDM requires some forms of spatial integration which is expected to bring huge cost savings for the deployment of SDM-based optical networks. Spatially integrated components with different characteristics have been largely explored and demonstrated for the realization of SDM networks, including; transmission media, transceivers with sophisticated digital signal processing (DSP) units, amplifiers, and ultimately optical switching nodes which are the key elements for the realization of transparent optical networks exploiting SDM technologies. As a consequence, in contrast to the currently deployed optical networks based on standard single mode fibers (SSMF), the next generation of optical networks exploiting SDM technologies can be realized utilizing various kinds of transmission media and the other corresponding elements. However, due in part to the physical properties of different components, their complexity, and the technology limitations not all of them meet the economic feasibility and a desired level of network-wide performance. Therefore, careful analysis should be done revealing the most appropriate and cost-effective solutions. In this work, we review the recent developments and findings which pave the way for a simplified and efficient implementation of the spectrally and spatially flexible optical networks.

Keywords: space division multiplexing, optical networking.

1. INTRODUCTION

As the traffic increases, the expansion in the space dimension becomes the only futureproof solution able to provide the expected capacity. In addition, any alternative solution like the expansion of the operating spectrum or the increase of the spectral efficiency can be included in a spatially expanded infrastructure [1]. The key point though is to reduce the overall cost and power consumption by offering some form of spatial integration. This integration is seen today in the development of multi-core fiber (MCF) and few mode fiber (FMF) media, multi-port amplifiers, tidily packed transceiver PICs and efficient low loss mux/de-mux elements. However, individual component integration is not sufficient to exploit the full potential of SDM networks; from the fiber infrastructure to the optical switching nodes. Therefore, primarily due in part to the emergence of different flavors of integrated solutions for every component, in addition to the component-level design optimization, for a particular use-case and network segment, a component selection procedure and a software-based optimization are required in order to obtain a compelling solution with network-wide superior performance and financial benefits.

In this paper, we review the possible solutions for the realization of spectrally-spatially flexible optical networks [2][3]. We approach the problem from a networking perspective and discuss the benefits and drawbacks of different implementations in order to reveal that a component selection procedure is a must for a successful deployment of future SDM network. Additionally, we discuss the areas where software-based optimization can further enhance the performance of SDM networks.

2. FROM INDIVIDUAL COMPONENTS TO NETWORK ARCHITECTURES

The fundamental concept of SDM relies on placing numerous spatial channels in a single fiber structure aiming at manufacturing an integrated fiber carrying manifold channels in a denser, lighter, and more cost-effective cable [4]. Even though many SDM fiber options with different number of cores/modes have been developed for the future SDM networks, for the purpose of our discussions, we categorize SDM media in three groups, according to whether they have 1) uncoupled/weakly-coupled spatial dimensions (cores, modes or parallel fibers), 2) strongly coupled spatial dimensions, or 3) sub-groups of strongly coupled spatial dimensions (Fig. 1a). Therefore, unlike the current infrastructure which is solely based on single mode fibers (SMF)s, an SDM network can be realized in different ways considering the type of deployed fibers. In addition, due to the availability of a single spatial dimension (i.e. just the spectral domain over SMFs), the optical switching functionality of the current infrastructure is limited to wavelength switching granularity. However, due to the availability of several spatial dimensions with different levels of inter-mixing of information among them, different strategies are required to transparently switch spectral content in an SDM network [5]. These strategies may support wavelength switching, space switching, or full/fractional wavelength-space switching. Considering these restrictions, three SDM switching strategies have been identified which strongly correlate with the SDM fiber categories defined above; independent switching (Ind-Sw), fractional joint switching (FrJ-Sw), and joint switching (J-Sw), in order of decreasing flexibility and increasing hardware efficiency. Ind-Sw supports full space-wavelength granularity, FrJ-Sw supports fraction space full wavelength granularity, and J-Sw supports solely wavelength granularity (Fig. 1c). In other words, these switching strategies support varying spatial and spectral switching granularities. The spatial granularity is related to the grouping of the spatial resources, whereas the spectral granularity depends on the channel baud rate and the spectral resolution supported by WSS. These switching strategies have significant impact on the network-wide performance of an SDM network in terms of resource utilization [6-8].

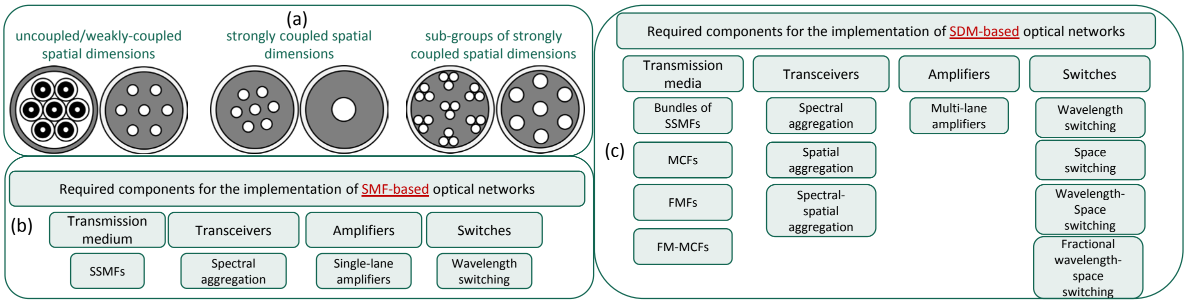

Figure 1: (a) SMF-based networks; (b) SDM-based networks; (c) Different categories of optical fibres.

Ind-Sw can be realized by means of a node architecture such as the one shown in Fig. 2(left) for a route-and-select ROADM configuration [9]. It is composed of a number of conventional wavelength selective switches (WSSs), one per spatial dimension, degree and ingress/egress port. Commercially available 1×5, 1×9 or 1×20 WSSs can be employed since the port count is not a limiting factor in this case. The selection of one or another WSS realization will depend on a number of factors, such as the required ROADM operation (e.g. whether "spatial LC" are allowed) and the nodal degree – i.e. the number of available directions – of the network nodes. Core switching is an alternative term referring to spatial LC when MCFs are discussed. FrJ-Sw and J-Sw make necessary a redesign of the WSSs. They are configured to operate as $S\times(I\times O)$ WSSs, i.e. they direct I input ports, each carrying S spatial modes/cores, toward O output ports using spatial diversity. This has the implication that for large S, WSSs with very high port count (HPC) are required. By making use of spatial group WSSs, the FrJ-Sw and J-Sw paradigms enable reducing the number of necessary WSSs to $2\cdot\lceil S/G\rceil$ and 2, respectively, per degree, as illustrated in Fig. 2 (center and right), but the required port count increases by a factor of G and S, respectively.

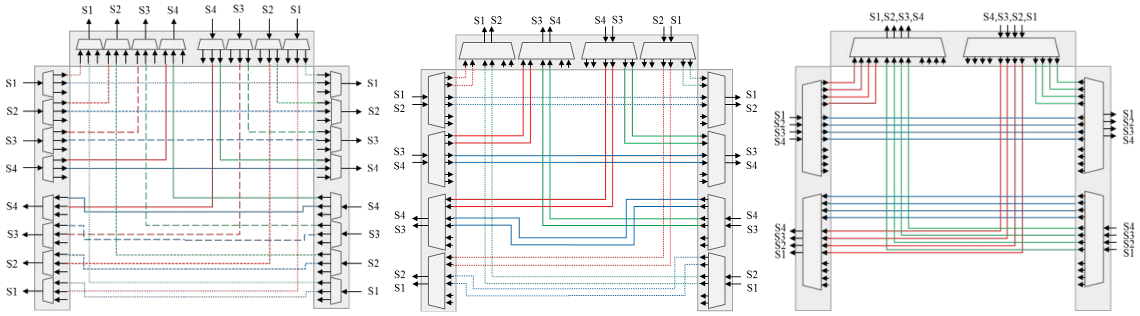

Figure 2. Switching of spatial and spectral channels under different granularities, for a four spatial dimension, degree three node. Left: Space-wavelength granularity, center: fraction space/full wavelength granularity, right: wavelength granularity.

In contrast to Ind-Sw which has the highest flexibility in routing, in J-Sw the spectrum assignment is limited to a single connection across all spatial dimensions within a spectral slice, with the consequent drawback that the unused spatial dimensions at a certain spectral slot cannot be allocated to other demands [6]. While the choice of switching technology can restrict the routing flexibility (given that the coarse granularity of J-Sw and FrJ-Sw penalizes the network spectral occupancy), it can also boost the economic feasibility of SDM solutions [10]. For instance, J-Sw and FrJ-Sw allow the use of joint DSP at different degrees, which can lead to cost and power consumption savings of integrated receivers in SDM networks [10]. Add/drop modules (not shown in Fig. 2), depending on the chosen add/drop module/transponder technology, can allow for several degrees of operational flexibility: they can be colorless, directionless and/or contentionless. Colorless, directionless, contentionless (CDC) ROADM architectures are based on multicast switches or $M\times N$ WSSs. For more details on CD(C) ROADM architectures for SDM networks, see [9]. J-Sw is compatible with any type of SDM fibers, while FrJ-Sw and Ind-Sw are fiber-dependent. Alternatively, bundles of SMFs and weakly-coupled MCFs are compatible with all switching paradigms, while coupled MCFs and FMFs require a particular type of switching paradigm (J-Sw).

Even though the fiber infrastructure and switching nodes are key elements in determining the resource allocation strategies for an SDM network, the resource aggregation in establishing a lightpaths is determined by end-to-end transceivers [11]. In contrast to current SMF-based, where spectral aggregation is the only available option resulting in the realization of spectral super-channel transceivers, there two more alternatives based on spatial aggregation as well as spectral-spatial aggregation which can be employed in SDM based networks.

Figure 1c summarizes all alternatives in component level upon which an SDM network can be deployed. Therefore, it becomes far more complex to find the most appropriate solution for every use-case in comparison with the current infrastructure based on SMFs (Fig. 1b). Additionally, due to the various characteristics of above mentioned technologies, different networking-level strategies shall be developed to capture their capabilities and restrictions.

3. DISCUSSIONS

In this work, we mainly focus on the impact of switching strategies and WSS technologies on the performance of SDM networks. We consider two WSS technologies for handling of the SDM switching paradigms in the performance evaluations: 1) the current WSS realization, 2) WSS technology with a factor-two resolution improvement [8]. The performance investigation has been carried out considering several traffic profiles, showcasing the feasibility of the proposed solutions for different segments of the Internet backbone, where alternative aggregation policies are applied [7]. The investigation has shown that the performance of all switching paradigms converges as the size of the traffic demands increases (applicable for example in inter-datacentre communications where high aggregation level of traffic is applied), but finer spatial and spectral granularity can lead to significant performance improvement for small traffic demands (typically seen in regional part of networks or likely to be found in the front-haul/back-haul convergence point of the transport network supporting the 5th generation of mobile networks). Additionally, it has been shown that considering the current WSS technology, even though exploiting switching nodes with finer spectral switching granularity significantly improves the performance of J-Sw for small values of traffic, as the load increases, the performance of all switching paradigms reduces due to the less efficient utilization of spectrum arising from a lower amount of occupied spectrum containing actual traffic compared to the required guard band for the WSSs [8]. Then it has been demonstrated, by utilizing WSSs with improved resolution which require 50% less guard band, the performance of switching paradigms in the case of large values of traffic can be improved by a factor of two at the expense of a 25% increase in the switching infrastructure cost. Furthermore, we found out, irrespective of the WSS resolution, large values of spectral channel width are more beneficial for large values of traffic, and consequently spectral switching granularity must be adaptable to the traffic size in order to achieve a globally optimum spectrum utilization in an SDM network, for which spectrally flex-grid ROADMs and bandwidth-variable transceivers are a requirement. Therefore, we draw a concrete conclusion that even though the idea behind SDM can be somehow orthogonal to the one behind the elastic optical networking (EON) paradigm, where intelligently managing the resources was proposed to cope with the forecasted traffic increase and variability, we should emphasize that, in a long-term horizon, not only will EON or SDM revolutionize the Internet backbone but also their combination.

The emerging Spectrally-Spatially Flexible Optical Networking (SS-FON) solutions will become a reality following the development of new technologies (mainly transceivers and ROADMs) capable of manipulating all spectral and spatial resources, and flexibly assigning them to serve the incoming connections in a resource efficient and cost-effective way, in which INSPACE project has played a key role in developing the switching node solutions for the envisioned ROADMs [2]. At the end of the day, even though the deployment of SDM networks utilizing coupled multi-core fibres (MCFs) and few mode fibres (FMFs) may not happen in a near future, due to the huge complexity of the MIMO processing units [12] (and the consequent footprints) and the lack of such fibres in the ground, the developed switching nodes have been demonstrated to well operate with bundles of the standard single mode fibres already available in the ducts. Therefore, we envision an early deployment of the developed switching nodes with the use of bundles of SSMFs, as the developed solutions can bring down the cost of the optical switching nodes significantly, making them feasible solutions to be deployed as early as a couple of parallel SSMFs will be required to support the traffic increase.

Furthermore, our studies related to the cost benefits of INSPACE proposed solutions showed that, after the transceivers, the second most costly element is the A/D nodes (consisting of WSS and multicast switch modules) [10]. Our analysis showed that the most cost-effect SDM ROADM architecture is the one which i) maximizes the number of available A/D ports, and ii) does not heavily increase the port count of pass-through WSSs [9]. It has also shown that joint-switching based ROADMs are more cost effective than those implementing independent and fractional joint switching. We anticipate that the cost reduction due to the switching infrastructure as well as the possibility of using integrated spatial super-channels transceivers will prove joint switching as potential candidates for SDM networks. Therefore, utilizing INSPACE proposed solutions, 50% savings can be realized in the development of the optical express units of the ROADMS. Moreover, significant savings can be achieved by adopting the ROADM architectures proposed in the framework of the INSPACE, where the prototyped HPC 1×N WSSs and envisioned $M \times N$ WSSs will be used in the cost-effective development of A/D units of the ROADMS.

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