Scaling Optical Networks Using Full-Spectrum Spatial Switching

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***Abstract*—Accommodating sustained exponential traffic growth in optical networks requires scaling the spatial dimension using space-division multiplexing. Numerous uncoupled spatial channels may be realized by activating multiple parallel fibers or cores in multicore fibers. A multiplicity of uncoupled spatial channels will render the granularity provided by multiple wavelength channels less essential in enabling optical switching. In this paper, we investigate a possible paradigm shift in optical node architectures, in which nodes based on wavelength-selective switching are replaced by those based on simple spatial switching. We compare spatial switching of full-spectrum superchannels to wavelength switching of uncoupled spatial superchannels, considering the evolution of traffic over time. Our results show that spatial switching may achieve more efficient scaling than wavelength switching in roughly 10 to 17 years, depending on the traffic growth rate assumed.**

***Index Terms*—Optical Networks, Wavelength-Division Multiplexing, Space-Division Multiplexing, Optical Switching.**

I. Introduction

For almost three decades, wavelength-division multiplexing (WDM) has been the key technology for supporting the exponentially increasing data traffic in core optical networks. To date, network upgrades have been mainly based on activation of additional wavelength channels within a single fiber. However, the capacity of single-mode fibers (SMFs) is limited. As the routed throughput exceeds the capacity of a single SMF provided by the entire spectrum, the deployment of space-division multiplexing (SDM) - either in multiple SMFs, multi-core fibers (MCFs), or multi-mode fibers (MMFs) - is inevitable [1]–[4].

While utilizing spatial channels, to keep the complexity of SDM switching nodes at an acceptable level, one approach proposed is the wavelength switching (WS) of spatial superchannels [5]–[7]. On the other hand, the sustained exponential increase in data rates shall render the fine granularity and flexibility provided by wavelength channels less essential. A promising option may be to replace wavelength switching (WS) with spatial switching (SS), which allocates a spectral superchannel individually for a source-destination pair. When implemented for full-spectrum in uncoupled spatial channels, SS can substantially reduce the complexity of a networking node, as the wavelength-dependent components in reconfigurable add-drop multiplexers (ROADMs) can be replaced by simple optical cross-connects (OXCs). Network robustness can be enhanced by eliminating interfering wavelengths that originate at different sources. In addition, SS can increase the spectral efficiency by utilizing the spectrum more efficiently and enable full-spectrum nonlinear compensation, which is not possible in WS, since nonlinearly interfering neighboring channels may be routed from/to different source or destination points.

Various spectral and spatial utilization strategies have been studied for scaling of SDM networks. Khodashenas et al. presented several spectral and spatial allocation schemes including WS, without addressing full-spectrum SS [8]. Similarly, Siracusa et al. studied resource allocation algorithms for SDM networks [9], [10], and mentioned full-spectrum SS. Marom et al. presented a detailed overview of node architectures in SDM networks [11], [12]. Switching nodes with only SS were presented, but the issues related to dynamic traffic were not studied. A similar approach was followed by Klonidis et al. in [2]. Arik et al. studied the impacts of spectral and spatial aggregation in [1], addressing the scalability of SDM networks using analytical derivations of the required number of components and the routing power. Shariati et al. evaluated different switching paradigms for SDM networks [13], but did not analyze full-spectrum SS. Rottondi et al. investigated spectrally- and spatially-flexible SDM architectures [14], but only focused on WS. Muhammad et al. adapted the concept of optical white boxes (or known as architecture on demand) to SDM [15], yet without examining full-spectrum SS and WS of spatial superchannels. The concept of filterless networks has also been investigated in SDM networks with MCFs. In [16], Muhammad et al. proposed to eliminate signal splitting in the node ingress, but allowed the coupling of signals from different cores. Saridis et al. demonstrated experimentally in [17] the transmission performance of connections routed in heterogeneous MCFs based on filterless node architectures. The performance of SDM in data centers for several switching architectures was evaluated by Fiorani et al. in [18]. The paper analyzed full-spectrum spatial switching, but only for a fixed number of spatial channels.

Replacing WS by full-spectrum SS would be an important paradigm shift in optical networking, given the extensive efforts in wavelength-based component technologies and net-

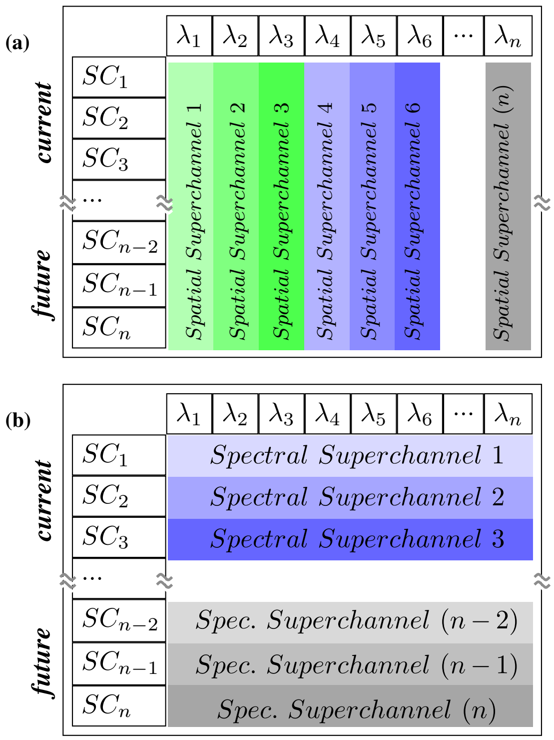

Fig. 1. Current and future example of link occupation with (a) wavelength switching of spatial superchannels and (b) full-spectrum spatial switching. In the figure, SC denotes spatial channel and λ denotes wavelength channel.

working algorithms to efficiently utilize wavelength degrees of freedom. An important open question is when SS might be more favorable than WS. Given the current volume of data traffic, implementing full-spectrum SS in today's networks would result in activation of a large number of cores with very low utilization, which is inefficient from an economic viewpoint. However, as the data traffic evolves and network utilization increases, SS shall become more efficient. The main contribution of this paper is to compare the efficiency of WS of spatial superchannels and full-spectrum SS options over a 20-year time frame, and investigate the cross-over points where SS may become preferable to WS. To our knowledge, this is the first time that full-spectrum switching is investigated, with a focus on the evolution over time.

The rest of the paper is structured as follows. Section II explains the switching architectures investigated in the paper. Section III presents the dynamic allocation techniques for scaling optical networks. Section IV describes the simulation setup and results for time evolution of optical networks. Lastly, Section V presents the conclusions.

II. Wavelength switching vs. spatial switching

The main concepts behind WS of spatial superchannels and full-spectrum SS are summarized in Figs. 1a and 1b, which show utilization of spatial channels and wavelength channels between two nodes.

We define a spatial superchannel (see Fig. 1a) as a collection of signals multiplexed in all available different spatial channels that are transmitted, routed, switched and received as a unit. In this paper, we assume spatial multiplexing in uncoupled spatial channels, which may be in separate SMFs or separate cores in an uncoupled-core MCF. Each spatial channel supports two polarizations. In the context of elastic optical networks, a spatial superchannel may have a variable bandwidth, and may be generated by a single carrier or multiple subcarriers. Even if the spatial dimensions are uncoupled, it is desired to switch all spatial modes as a unit to lower the complexity of switching nodes [7] [5].

Analogously, we define a spectral superchannel as a collection of signals multiplexed in all different wavelength channels, as shown in Fig. 1b. In spatial multiplexing with uncoupled spatial dimensions, such as in bundles of parallel fibers, the entire spectrum can be considered as a spectral superchannel, and transmitted, routed, switched and received as a single entity.

In today's networks, the number of supported wavelength channels (e.g., ≈ 100 for 100 Gbps channels) is much higher than the number of spatial channels. Current traffic volumes favor WS to provide full networking flexibility while fulfilling the required transmission capacity. As the traffic volume increases and new spatial channels are activated, the effectiveness of WS will be reduced. Efficient spectrum utilization techniques, such as defragmentation and elastic superchannels, may extend the applicability of WS [8]. Yet, such techniques will have a minor impact eventually, since in a scenario of exponential traffic increase, utilization of the entire spectrum by a source-destination pair is a natural trend.

We will focus on WS and SS separately, although their joint implementation is possible and may be advantageouos in intermediate regimes [1]. For WS, we assume that nodes are capable of jointly routing all spatial channels at a specific wavelength, as a single spatial superchannel, as in [5] [7]. For SS, we assume that the nodes are capable of jointly routing all wavelength channels as a single spectral superchannel, such as using simple OXCs for switching between fiber cores.

III. Dynamic allocation techniques

We classify spatial or spectral superchannels into "available" or "allocated". Available superchannels have all its channels unused. An available superchannel becomes allocated if one of its channels is used to accept an incomming traffic demand.

The resource allocation algorithm for WS of spatial superchannels is depicted in Fig. 2a. First, the algorithm checks if there is an existing allocated spatial superchannel between the desired source-destination pair with available capacity, i.e., unused spatial dimensions. If there is, the request is accepted on this capacity. Otherwise, routing and wavelength assignment is performed using the shortest path and first-fit algorithm to allocate a new spatial superchannel. This process may be repeated for K shortest paths if the first attempts fail. If this process is successful, the request is accepted in the

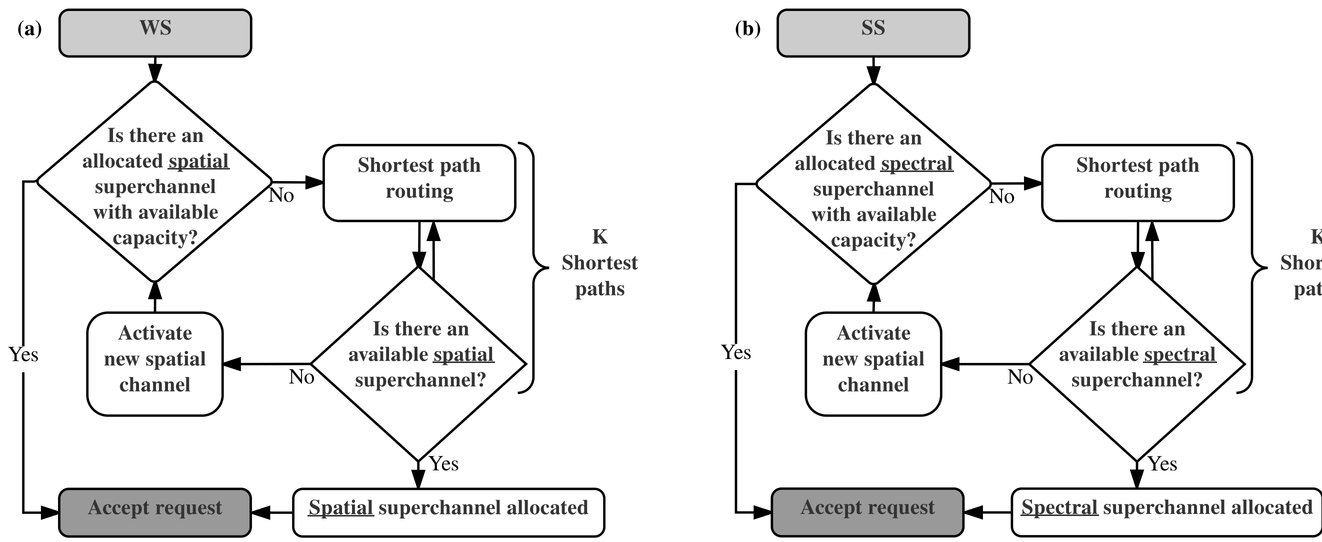

Fig. 2. The resource allocation algorithms are shown in (a) for WS, and (b) for SS.

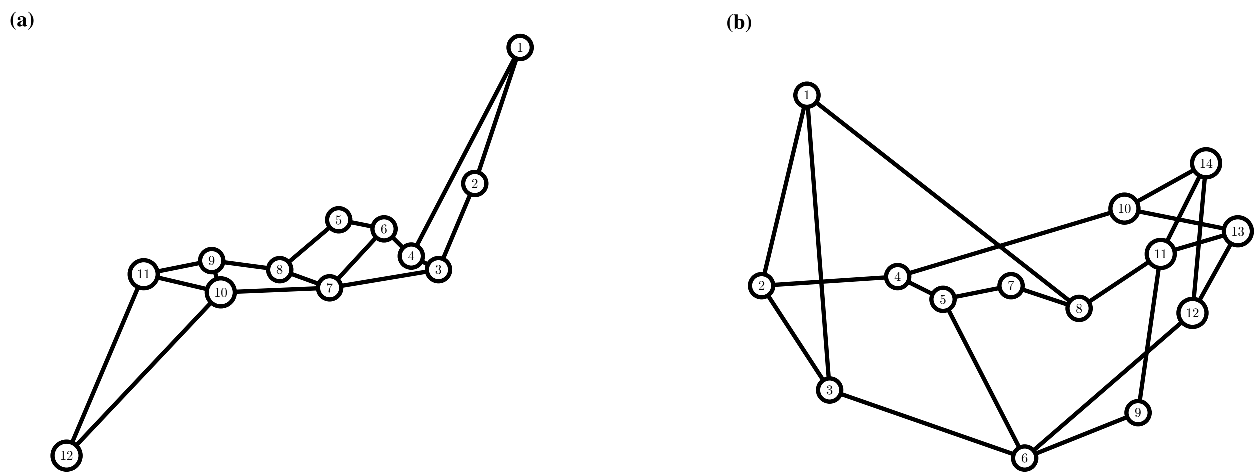

Fig. 3. Simulated network topologies: a) Japan Photonic Network (JPN12); b) National Science Foundation Network (NSFNET).

new spatial superchannel. Otherwise, a new spatial channel is activated at all network links, and the algorithm restarts, to accept the incomming request.

The resource allocation algorithm for full-spectrum SS is depicted in Fig. 2b. The algorithm starts by verifying if there is an allocated spectral superchannel with available capacity between the desired source-destination pair. This may represent, for example, a dedicated fiber with unused wavelengths. If there is, the incoming connection is accepted on this empty capacity. Otherwise, after shortest-path routing, an unused spatial channel is searched. This process may be repeated for K shortest paths. If this search is successful, a spectral superchannel is allocated in the unused spatial channel. Otherwise, a new spatial channel is activated at all network links, and the algorithm restarts, to route and allocate a new spectral superchannel and accept the incomming request.

IV. Simulation of Time Evolution

We evaluate WS of spatial superchannels and full-spectrum SS based on a discrete event-driven simulation where incremental traffic is generated without removing provisioned connections. Simulated networks are designed to have no blocking, since an additional spatial channel is activated at all network links whenever there is not sufficient capacity to accommodate a new request. We assume an optical spectrum of 4.8 THz (as 96 $\times$ 50-GHz frequency slots). Connection requests are allocated at 100 Gbps over a single 50-GHz slot. The maximum number of shortest paths $K = 3$ is chosen. Data traffic is assumed to be uniformly distributed between all source-destination pairs. Wavelength conversion is not supported. The capacity installed in the first year was set to 3 Tbps, and increased annually according to compound annual growth rates (CAGRs) of 30%, 40% or 50%. This is in line with the Cisco Visual Networking Index [21], that forecasts CAGRs ranging from 20% to 50% for different grographic re-

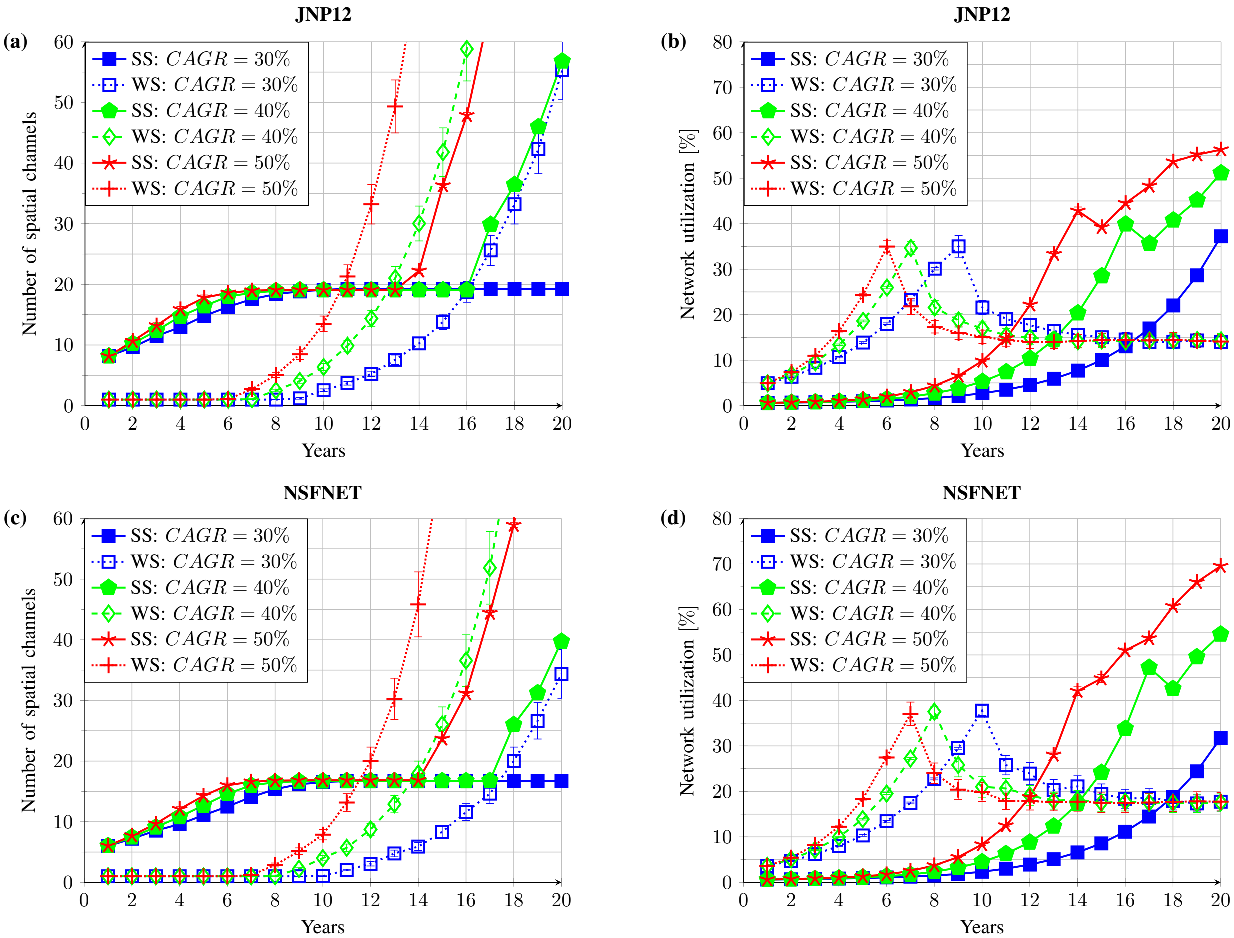

Fig. 4. Time evolution of the number of spatial channels (Figs. 1a and 1c), and of the amount of network utilization (Figs. 1b and 1d), for the JNP12 [19] (first row) and NSFNET [20] (second row) networks. The compound annual growth rate (CAGR) was set to 30%, 40% and 50%.

gions. Simulations are performed for the two optical transport network topologies shown in Fig. 3: (*i*) the National Science Foundation Network (NSFNET) [20], comprising 14 nodes and 21 bidirectional links; and (*ii*) Japan Photonic Network (JNP12) [19], with 12 nodes and 17 bidirectional links. Two metrics are evaluated in an annual basis: the total number of active spatial channels, and the amount of network utilization U, defined as:

$$U = \frac{\sum_{i=1}^{n} E_i}{N_\lambda \cdot N_{sc} \cdot E_g}$$

where n is the number of generated requests, E_i is the number of hops traversed by request i, N_λ is the number of frequency slots supported by each spatial channel, N_{sc} is the total number of activated spatial channels and E_g is the number of edges in the network graph. Each simulation point corresponds to the average of 30 runs. Confidence intervals are calculated according to a confidence level of 95%.

Figs. 4a to 4d show the evolution of the number of activated spatial channels and the network utilization, for the JPN12 and NSFNET networks. Despite the differences between the two topologies, the numerical results show similar trends. WS requires just one spatial channel until some time between years 6 and 9, which is favorable from an economical perspective. The network utilization increases steadily as new wavelength channels are activated, reaching a maximum of 35%. It is important to note that the network utilization is low, because a non-blocking condition is assumed. After the capacity of the first spatial channel is utilized, a second spatial channel is activated and utilization decreases. After this spatial channel is activated, the number of spatial channels grows exponentially. In SS the number of spatial channels also grows exponentially, but in a latter point in time, because of better capacity utilization. Thus, after a period that varies from 10 to 17 years, depending on the CAGR, the utilization of SS surpasses that of WS. This gap may be reduced by more efficient wavelength assignment algorithms and defragmentation techniques, but at the cost of more complex network operation.

SS requires the activation of several spatial channels in the first years, until all source-destination pairs become interconnected by an exclusive link. After this period, network utilization increases sharply. This effect becomes evident in Figs. 5a (JNP12) and 5b (NSFNET), which show the network utilization achieved by SS and WS as a function of the number of active spatial channels, suppressing the temporal

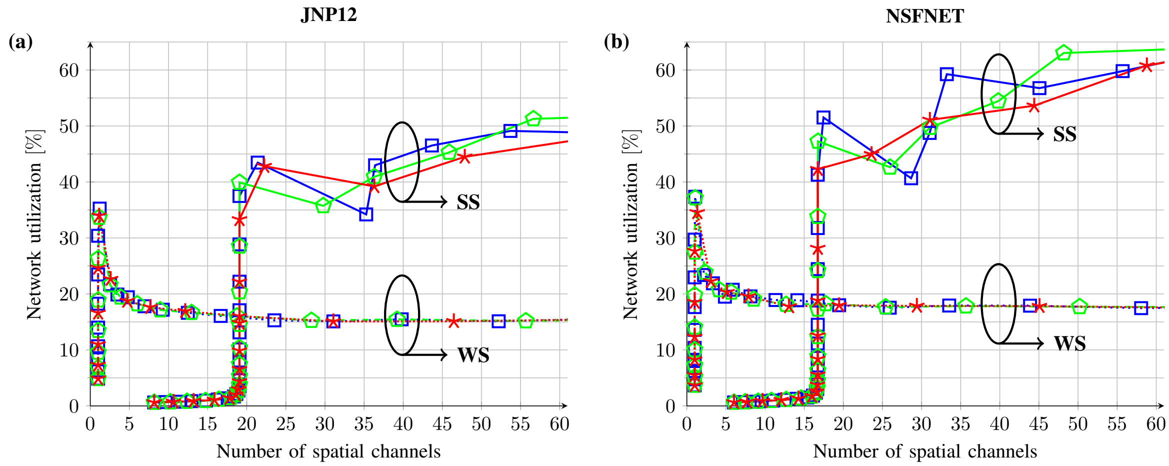

Fig. 5. Network utilization as a function of the the number of spatial channels for the JNP12 [19] (left) and NSFNET [20] (right) networks. The compound annual growth rate (CAGR) was set to 30% (blue squares), 40% (green pentagons) and 50% (red stars).

dependency of previous results. SS utilization grows abruptly after 19 and 16 spatial channels for the JNP12 and NSFNet, respectively, which correspond the quantities needed to bidirectionally connect all source-destination pairs in the network. Such an amount of fiber may be already available in an installed network. Although this approach requires deployment of a large number of amplifiers over the first years, there are important benefits. Switching nodes are simplified by the complete removal of WSSs. In addition, the need for regeneration may be minimized by the reduced node pass-through insertion loss.

V. Conclusion

With the exponential growth of data traffic, it may become inevitable to replace WS by SS to efficiently support increasing throughput. Potential advantages of SS include low-complexity switching by simple OXCs, increased spectral efficiency and simpler network management. Implementation of full-spectrum SS represents a paradigm shift that warrants some study about the best time frame in which to implement it. In this paper, we have studied the time dependence of the network performance for WS of spatial superchannels and full-spectrum SS networks for the estimated traffic growth rates of 30% to 50% per year. We have demonstrated that SS may outperform WS in a time window of 10 to 17 years. Full-spectrum SS can be implemented in legacy networks by activating dark fibers, and replacing WSS-based switching nodes by simple OXCs. Interconnecting all source-destination pairs by an exclusive fiber pair would require the activation of a very high number of amplifiers. However, savings are expected because of simplified switching nodes, and a reduced number of regenerators, as the node insertion loss decreases.

Detailed analysis of node architectures, and networking cost comparison between WS and SS, taking into account the recent progress towards integrated transceivers and amplifiers (e.g. [22]), are important areas for future research.

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