Architecture on Demand Design for High-Capacity Optical SDM/TDM/FDM Switching


Abstract—Reconfigurable optical add/drop multiplexers (ROADMs) are key elements in operators’ backbone networks. The breakthrough node concept of architecture on demand (AoD) permits us to design optical nodes with higher flexibility with respect to ROADMs. In this work, we present a five-step algorithm for designing AoD instances according to some given traffic requests, which are able to support subwavelength time switching up to wavelength/superchannel/fiber switching. We evaluate AoD performance in terms of power consumption and number of backplane optical cross-connections. Furthermore, we discuss trade-offs involved in the migration from a fixed to a flexible grid with regard to the optical node size, capacity, and power consumption. We compare several ROADM architectures proposed in the literature with AoD in terms of power consumption and cost. We also study different technologies for enhancing the scalability of AoD. Results show that AoD can bring significant power savings compared to other architectures while offering a throughput of hundreds of terabits per second.

Index Terms—Optical architectures; Routing; Switching.

I. INTRODUCTION

In the last decade, Internet traffic has been growing fast over recent years due to the emergence of new bandwidth-hungry services supported by new broadband access technologies, both wireless and based on the fiber-to-the-x paradigm. Network operators’ infrastructure must support this increasing bandwidth demand while maintaining reasonable levels of quality of service, reliability, and power consumption in all segments of their network (access, metro, and core). Toward this end, network operators are attempting to overcome this challenge by increasing their electronic infrastructure and deploying new transmission and switching equipment. However, this solution may pose future interconnection issues on backbone optical networks and may increase operators’ operational expenditure (OPEX) and global CO₂ emission. Enabling flexible-grid spectrum allocation [1,2] has been devised as the solution for handling both legacy low bitrates and future high-speed superchannels exploiting the available bandwidth in already-deployed optical fibers. Therefore, future optical nodes will require us to support variable channel bandwidths in a flexible-grid manner to achieve higher spectral efficiency. Despite the existence of several proposals of node architectures, mainly based on spectrum selective switches (SSSSs), the architecture on demand (AoD) approach is motivated by the two following observations.

On the one hand, recently proposed optical node architectures present several limitations. Figure 1(a) shows the usual reconfigurable optical add/drop multiplexer (ROADM) based on a broadcast-and-select configuration [3–5], for which different architectures were proposed. ROADMs are usually dimensioned by $N$ input/output ports (i.e., degree) to provide connectivity with other ROADMs in the network and $L$ add/drop ports [i.e., transponder (TPND) or client interfaces] for lightpaths with a local source or destination. These architectures offer the so-called colorless/directionless/contentionless (C/D/C-less) features: Colorless means that transponders are not associated with a specific wavelength, directionless implies that transponders are not associated with a specific input or output port of the node, and contentionless means that wavelength contention inside the node is eliminated. Interestingly, C/D/C-less capabilities reduce the need for manual intervention by a technician compared with the first generations of ROADMS [6]. However, they still present three major drawbacks. First, they offer a limited flexibility, since they are usually based on a hard-wired arrangement of devices, which prevents their upgradeability and their adaptation to new network requirements. Second, they also lack scalability in providing a per-service granularity (i.e., degree, port, wavelength, or band). In particular, these architectures are constrained by the number of required devices and by their port count. Third, the nonadaptable nature of ROADMs implies high power consumption. Indeed, some components of these systems contribute to power consumption regardless of the traffic variations or network requirements (e.g., common equipment in the case of ROADMs [7] or optical/electrical/optical devices in some optical cross-connect architectures [8]).
The major contributions in this paper are 1) a five-step based synthesis algorithm to automatically design and configure AoD instances supporting subwavelength time-switching requests, 2) a performance analysis in terms of power consumption and number of backplane optical cross-connections, and 3) the study of different technologies for enhancing the scalability of AoD. Conclusions are presented in Section VII.

II. RELATED WORK

In this section we review related work of ROADM architectures and previous works on AoD.

A. ROADMs

Optical networks have experienced an enormous evolution over the past 30 years [6]. Thus, ROADMs are key elements in optical networks, their design has been the source of numerous studies in the recent literature. The majority of the related works investigate different architectures for achieving colorless, directionless, and, more recently, contentionless (C/D/C) features. Even if the design of ROADMS that guarantees C/D/C is outside the scope of this work, it is worth mentioning the most relevant works on this topic.

The first reference to the colorless feature was made by Basch et al. in [13], and the directionless feature was firstly referred to by Kaman et al. in [14]. The majority of the works since then address a feasibility and scalability comparison of different ROADM alternatives in terms of cost or optical impairments. Among them, [15] can be considered as the first work using this comparison approach. In particular, [15] analyzes the scalability of several ROADM architectures composed of 3D-MEMS, wavelength blockers, and wavelength selective switches (WSSs). In [16], different architectures are compared in terms of estimated cost considering the use of WSSs and optical 3D-MEMS switches. Similarly, in [5] six ROADM architectures composed of couplers/splitters, multiplexers and demultiplexers [(DE)MUXs], WSSs, and optical switches are compared in terms of optical impairment and hardware size. In addition, the architectural solutions that guarantee contentionless performance are also discussed. Finally, Gringeri et al. in [4] survey ROADM architectural trends for CDC features.

A notable breakthrough for the ROADM design has been the introduction of the planar-lightwave-circuit-based multicast switch (MCS) [17]. The MCS provides broadcast-and-select functionality by means of a first stage of $N^1 \times M$ splitters connected to a second stage of $M^1 \times N$ switches in a relatively small hardware footprint. Different works have analyzed the use of MCSs to guarantee completely contentionless performance [18,19]. It is also worth mentioning recent works that analyze different trade-offs between WSS-based and MCS-based ROADMs in terms of optical impairment, cost, and power consumption [20,21].

All the works previously referred to propose ROADM node architectures based on a hard-wired connection of devices. Therefore, all the reported architectures may present scalability, flexibility, and power consumption drawbacks.
B. Architecture on Demand

The optical node concept of AoD was introduced by Amaya et al. in 2011 [9]. Since then, experimental demonstrations have shown that AoD offers complex optical processing functionalities that are outside of the scope of this work. First, in the case where an optical signal requires amplification (e.g., due to through losses), an EDFA module can be added to the particular AoD instance [22]. Second, AoD can include spectrum defragmentation modules to avoid possible wavelength contention issues. That is, when two signals from different inputs that are at the same spectrum slot request the same output, a wavelength conversion operation must be applied to one of them [23]. More recently, AoD has also been experimentally demonstrated in a software-defined networking scenario [24] and in a multitechnology/multirate metropolitan/edge scenario [25].

AoD has been shown to provide considerable gains in terms of scalability [11], power consumption [12], and resiliency [26]. The work done in [11] and [12] by the same authors is extended here 1) presenting a five-step synthesis algorithm for AoD that supports subwavelength time-switching requests, 2) including a performance analysis in terms of power consumption and number of backplane optical cross-connections, and 3) studying space division multiplexing (SDM) and wide available spectrum alternatives to enhance the scalability of AoD in terms of supported throughput.

III. AoD AND TRAFFIC REQUEST MODELS

We focus on a multidimensional fiber, superchannel, wavelength, and time switching scenario where a high-layer network control plane provides the switching requests of the input signals. In the case of fiber switching, all the signals corresponding to a specific input port are sent toward a destination output, without any spectrum operation. In the case of wavelength channels occupying a single spectrum slot, optical processing is performed by means of fixed-grid array waveguide grating (AWG)-based (DE)MUXs or liquid-crystal-on-silicon-based SSSs [27]. We also allow superchannel switching, in which a set of contiguous spectrum slots are used to accommodate high-speed channels, e.g., 400 Gbits/s, 1 Tbit/s, and beyond. Time switching allows us to implement subwavelength time-sliced channels, in which many channels are multiplexed on the same wavelength in time, according to a predefined time division multiplexing (TDM) scheme. In the case of time switching operation, the signal on a wavelength corresponding to a particular time slot is sent to the destination output, without changing its temporal position. We assume that all the all-subwavelength time-sliced channels are fully synchronized. Note that a time slot duration of 18 μs was shown to be experimentally feasible in [23].

Inspired by the AoD implementation of Fig. 1(b), we developed a three-stage logical model, where the use of a module by an optical signal is considered as an AoD stage.

An optical signal fed into an input port can be switched via the optical backplane either toward an output port or toward a module. If a module is chosen, its output(s) is switched again via the optical backplane either toward an output port or toward a successive module. This process can be repeated for up to three modules, i.e., passing through three stages. The output of the third module is always switched via the optical backplane toward an output port. Note that this three-stage model enables most of the required functionalities of current state-of-the-art elastic optical node architectures. In [10], Amaya et al. describe and analyze four different elastic optical node architectures: “broadcast and select” (two stages), “spectrum routing” (two stages), “switch and select with dynamic functionality” (three stages), and AoD. At least two stages are needed to provide wavelength switching toward different destinations: demultiplexing and multiplexing. Moreover, if additional functionality is required (e.g., time switching), then three stages are sufficient. This fact motivates our choice of considering architectures with at most three stages.

Figure 2 depicts the logical model of the AoD node, in which the input ports are connected to the output ports either just through the optical backplane or through one, two or three stages. Let N denote the degree of the architecture, i.e., the number of input and output ports. For instance, when input signals require both spectrum and time switching, the first stage performs spectrum routing by means of DEMUXs or SSSs, the second stage performs time switching by means of 10 ns piezoelectric lead lanthanum zirconate titanate (PLZT) [28] switches, and the third stage couples or multiplexes the output signals when needed.

Let W be the number of available spectrum slots per fiber, for example, W = 96 for C-band dense wavelength division multiplexing (DWDM) systems with channel spacing of 4 × 12.5 GHz or W = 48 for spacing of 8 × 12.5 GHz [29].

The request set defines the switching requests, which can be any of the following:

![AOD logical model](image-url)
A fiber that must be switched from an input to an output port.
A fixed-grid wavelength that must be switched from an input to an output port.
A superchannel that must be switched from an input to an output port.
A subwavelength time-sliced channel that must be switched from an input to an output port, without changing its timeslot.

We assume that the request sets are feasible, i.e., no output contention is experienced: At most one fiber/wavelength/superchannel must be destined for each output. In the case of subwavelength switching, for each output at most one wavelength must be associated with each timeslot.

A. AoD Backplane Architectures

In order to support heterogeneous traffic requests that may require different types of optical processing (e.g., space/frequency/time switching as in [32]), there is need of an optical backplane with a high port count. However, available commercial 3D-MEMS optical switches offer up to 320 ports [30] (i.e., two fiber terminations per port: transmit and receive), thus limiting to this maximum the number of backplane cross-connections of the AoD instances and the number of pluggable building modules. Therefore, several optical backplane switches must be interconnected together to overcome this limitation. Relevant to the backplane architectures and the synthesis of AoD instances, we consider the following two definitions:

- **Supported** cross-connections are the optical ports available in the AoD optical backplane (i.e., plug-in optical interfaces) for inputs, outputs, adds, drops, and modules.
- **Required** cross-connections refer to the set of optical circuits to be established in the AoD optical backplane to properly satisfy a given request set. These optical circuits can be described by pairs of input and output ports according to the request set.

To better understand these definitions, note that when a single optical switch is considered as an optical backplane, the number of supported cross-connections coincides with the port-count size of that switch. For instance, 320 cross-connections are supported by an optical backplane built with a single 3D-MEMS optical switch of 320 ports [30]. However, when several switches are interconnected together to compose a larger optical backplane (i.e., using a certain amount of switches’ ports for their interconnectivity), the number of supported cross-connections is lower than the sum of all the switches’ ports. By construction, the required cross-connections must be lower than or equal to the supported cross-connections in order to enable the synthesis of AoD instances. Indeed, the required cross-connections derive from the dynamic use of AoD and are the outcome of the enhanced synthesis algorithm (E-SA, see Section IV).

In the following, we review two backplane architectures reported in [31].

On the one hand, Fig. 3(a) depicts the first architecture, providing a simple approach to solving the backplane port count limitation issue, where \( y_U \) optical switches of \( k \) ports are connected in a unidirectional fashion. In more detail, the \( N \) input ports of AoD are connected to the first optical backplane switch. Successive optical backplane switches are connected using \( N \) ports up to the last \( (y_U) \) optical backplane switch, at which all the output ports are connected. Note that optical signals are constrained to pass through all the optical backplane switches. This configuration offers a number of supported cross-connections equal to

\[
X_U = y_U k - N(y_U - 1).
\]

Note that for this backplane architecture the number of backplane switches \( y_U \) must be set in a resource dimensioning study carried out before AoD is deployed and used. Once \( y_U \) is set and AoD is operating, the connection of additional backplane switches compromises already established optical links through AoD.

On the other hand, Fig. 3(b) depicts the expandable backplane architecture, where \( y_E \) optical backplane switches of \( k \) ports are bidirectionally connected. The \( N \) input and output ports of AoD are connected to the first optical backplane switch and \( 2N \) connections (\( N \) in each direction) are set between successive backplane switches. Once AoD is operating, this architecture uses the optical backplane switches in an incremental manner, since switches near input and output ports are the first ones to be completely used. Therefore, this expandable backplane architecture allows us to tailor \( y_E \) to the traffic request and the connection of additional backplane switches without compromising already established optical links through AoD. This configuration offers a number of supported cross-connections equal to

\[
X_E = y_E k - 2N(y_E - 1).
\]

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\[
X_E = y_E k - 2N(y_E - 1).
\]
Table I details the number of supported cross-connections for both backplane architectures, considering $X_U$ and $X_E$ according to Eqs. (1) and (2), respectively, for $N = 20$ and $k = 320$; the latter value is equal to a commercially available 320-port 3D-MEMS switch [30]. The adaptable nature that characterizes the expandable backplane architecture allows us to increase in a stepwise fashion the number of backplanes $y_E$ ($\leq 5$ in this example) to satisfy the required cross-connections. This offers a clear benefit for resource dimensioning purposes, since additional optical backplane switches may be turned on only when required. On the other hand, for certain values of supported cross-connections (e.g., $1160 \leq X \leq 1220$ and $1440 \leq X \leq 1520$), a higher number of backplane switches is required by the expandable composition compared to the unidirectional backplane composition. Indeed, the unidirectional architecture offers more supported cross-connections for a given number of backplane switches due to the lower number of ports used to interconnect them. However, the unidirectional case requires a preliminary backplane dimensioning study in order to set a constant number of switches $y_U$.

The expandable backplane composition offers two additional advantages compared to the unidirectional composition. First, given a number of backplane switches used in both compositions, i.e., by setting $y_E = y_U \geq 2$, the expandable case permits an arbitrary utilization order of the building modules that belong to different backplane switches, whereas in the unidirectional case this would not be possible. Second, more than one backplane switch can be connected to the backplane switch with the input and output ports in order to compose a treelike expandable backplane. These solutions may present different reachabilities (i.e., number of backplane switches that the optical signals need to go through) of the building modules that belong to different backplane switches while supporting the same number of cross-connections as Eq. (2), which corresponds to the expandable composition of Fig. 3(b). However, these treelike-based architectures may be equivalent from a performance point of view to the ones considered in this work; otherwise, their possible advantages are limited. Their investigation is left for future work.

In the remainder of the paper we consider the expandable backplane composition due to the highlighted benefits. Therefore, by rearranging Eq. (2), the number of backplane switches $y_E$ can be obtained from the number of required cross-connections $X > 2N$ as

$$y_E = \lceil (X - 2N)/(k - 2N) \rceil. \quad (3)$$

### TABLE I

<table>
<thead>
<tr>
<th>No. of Switches</th>
<th>Expandable</th>
<th>Unidirectional</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>320</td>
<td>320</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
<td>620</td>
</tr>
<tr>
<td>3</td>
<td>880</td>
<td>920</td>
</tr>
<tr>
<td>4</td>
<td>1160</td>
<td>1220</td>
</tr>
<tr>
<td>5</td>
<td>1440</td>
<td>1520</td>
</tr>
</tbody>
</table>

**B. Example of an AoD Instance**

Consider the request set shown in Fig. 4(a), referring to a scenario with $N = 4$ ports and $W = 5$ spectrum slots, with corresponding wavelengths $\lambda_1, \ldots, \lambda_5$. We assume that for the subwavelength channels (denoted as TDM 1,2,3), two slots are present in the frame. The numbers in the figure denote the destination port; in the case of subwavelength channels, the pair of numbers denotes the destination port for odd and even slots, respectively, as shown in detail in Fig. 4(b). The considered request set consists of a heterogeneous traffic scenario with six fixed-grid wavelength channels, three subwavelength channels, and two superchannels.

Figure 5(a) shows the logical model of a possible AoD configuration satisfying the request set shown in Fig. 4. Channels at input port 1 are fed to a $1 \times 4$ SSS to allow flexible spectrum switching, thereby supporting the superchannel. All the channels at input port 2 must be switched to output port 4; thus, a single cross-connection is set to the third stage, bypassing stages 1 and 2. Two DEMUXs are placed at the first stage of inputs 3 and 4, since channels need to be demultiplexed. At the second stage, two PLZTs are placed to provide the fast time-switching functionality required by inputs 1 and 4, considering a possible reuse of the PLZT optical switch. Note that in this example, the number of hardware devices (modules) required is 9 and the number of cross-connections is 20, since 13 cross-connections are required for inter-stage connections, 7 to connect both the 3 inputs to the first stage and the 4 outputs to the corresponding modules (or inputs).

Figure 5(b) shows an AoD implementation (i.e., a schematic of how devices and cross-connections are set and devices are attached to the optical backplane) for the request set shown in Fig. 4. For simplicity, only the modules used are shown. To improve adaptability to future request sets, idle ports of a module are connected to the backplane switch, even if they are unused for the current request set. The process required to choose each building module for each position (i.e., the architecture design) according to the request set is explained in the following section.
IV. Enhanced Synthesis Algorithm for AoD

We propose the E-SA executed at the AoD controller to compute the AoD design based on a given feasible request set. E-SA (whose flow chart appears in Fig. 6) is divided into five steps: Four steps perform switching functionalities from coarser to finer granularities (i.e., at fiber, superchannel, wavelength, and subwavelength levels), and the fifth step couples signals from different sources.

In more detail, given a request set, the first step checks the destination of all signals from each input. In the case that they are all destined to the same output, a cross-connection is set [e.g., input port 2 in Fig. 5(a)].

The second step checks the presence of superchannel requests for each input. If superchannel requests are found, an SSS is placed and a possible reuse of cross-connections is considered (due to the SSS arbitrary bandwidth switching capability); otherwise, the required connections are placed [e.g., input port 1 of Fig. 5(a)].

The third step checks the presence of fixed-grid wavelength channels to be switched for each input. It may reuse SSSs and connections that have already been placed. Otherwise, a DEMUX and the required cross-connections are set up. For the example shown in Fig. 5(a), in this step a cross-connection is set for the wavelength channel at $\lambda_2$ at input 1 with destination output 1, and two DEMUXs with the required cross-connections are set for input ports 3 and 4.

The fourth step checks the presence of subwavelength time-sliced channels for each input. In such a case, a possible reuse of already placed SSSs, DEMUXs, and cross-connections is considered. Otherwise, a DEMUX is placed if needed. Subsequently, a possible reuse of already placed PLZTs is considered to provide time switching toward the same two required outputs. In the case where the two destinations of the subwavelength time slices are not being addressed by an already placed PLZT, a new PLZT is placed to perform time switching between the two required outputs.

The fifth step couples at each output the signals from different sources. This proposed E-SA outperforms our previous synthesis algorithm presented in [11], because it supports subwavelength time-sliced requests in the architecture design. Furthermore, unlike the previous version, E-SA computes the coupling of signals required at each output port only once. Indeed, this guarantees a faster execution time while maintaining its complexity $\Theta(N)$.

V. AoD Performance in the C Band

In this section we analyze AoD performance in terms of required backplane cross-connections and power consumption when supporting C band DWDM requests with $W = 96$ spectrum slots, thus considering channel spacing of $4 \times 12.5$ GHz [29]. To this aim, we generate request sets with the following four parameters.
1) The **load** \( P \in [0, 1] \) is the fraction of the requested fixed-grid wavelengths per input over \( W \) (i.e., \( 4 \times 12.5 \) GHz bandwidth channels).

2) The **subwavelength index** \( \sigma \in [0, P] \) is the fraction over \( W \) of the requested wavelengths per input port that contain TDM subwavelength signals. We consider only two possible destinations for each TDM subwavelength signal, and thus we focus on the use of \( 2 \times 2 \) PLZT switches.

3) The **superchannel index** \( \rho \in [0, P] \) is the fraction over \( W \) of requested wavelengths per input port that are randomly aggregated into couples of two adjacent wavelengths (i.e., \( 8 \times 12.5 \) GHz bandwidth channels).

4) The **fiber switch index** \( F \in [0, 1] \) is the proportion over \( N \) of input ports assumed to request fiber switching in the request set. Therefore, all wavelength and superchannel channels of the input are switched to the same output. Conversely, the destination of channels that are not assumed to be fiber switching is set according to a uniform distribution between the output ports. For instance, \( F = 0.25 \) holds for the scenario depicted in Fig. 4, since all channels fed at input 2 need to be switched to output 4.

By construction, only request sets with \( \rho + \sigma \leq P \) are generated, because wavelength channels can be set either as superchannels (i.e., aggregation of two adjacent wavelengths) or as carrying subwavelength TDM signals, but not both simultaneously.

We focus on an off-line worst-case analysis, according to the following approach. First, we generate at random a feasible request set, based on the above traffic parameters \((P, \sigma, \rho, F)\). Second, starting with an AoD without any preliminary cross-connection, the AoD controller executes the proposed E-SA algorithm to design an architecture that satisfies the request set. Third, as an evaluation phase, we count the required number of optical backplane cross-connections, number of components, and power consumption of the designed AoD instance. We repeat this approach for 1000 different request sets to achieve stable average results, which are reported in the following sections.

### A. Scalability Analysis

We analyze the number of required cross-connections for different types of traffic requests. Note that the number of required cross-connections must always be lower than the optical backplane port count (i.e., supported cross-connections) and thus an indicator of the scalability of the AoD.

**Table II** lists the AoD configurations used for each analyzed parameter.

<table>
<thead>
<tr>
<th>Parameter Analyzed</th>
<th>First Stage</th>
<th>Second Stage</th>
<th>Third Stage</th>
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<tbody>
<tr>
<td>( P )</td>
<td>DEMUX</td>
<td>—</td>
<td>Coupler</td>
</tr>
<tr>
<td>( F )</td>
<td>DEMUX</td>
<td>—</td>
<td>Coupler</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>DEMUX</td>
<td>PLZT</td>
<td>Coupler</td>
</tr>
</tbody>
</table>

**DEMUXs and by the coupling step of E-SA. The maximum number of required cross-connections is**

\[
X_{\text{DEMUX}} = 2N + NW, \quad (4)
\]

which matches our previous calculation in \([11]\).

On the other hand, Fig. 7(b) shows a decreasing number of required cross-connections for traffic requests with increasing aggregation of channels in fiber switching \( F \), given a maximum load \((P = 1)\) and no subwavelength requests \((\sigma = 0)\). We observe a more efficient use of cross-connections, since channels can be aggregated in the first step of E-SA, thanks to fiber switching.

Figure 7(c) shows the number of required cross-connections for request sets with subwavelength TDM signals \( \sigma \), given a maximum load \((P = 1)\) and without fiber switching \((F = 0)\). This type of traffic request exploits the fourth step of E-SA, which uses PLZTs and cross-connections (reusing when possible). However, the maximum number of cross-connections given by Eq. (4), for no subwavelength TDM requests, exceeds thousands of cross-connections. Indeed, the high number of output combinations for each subwavelength TDM request requires a high number of cross-connections and PLZTs, especially for high values of \( N \).

### B. Power Consumption Analysis

To evaluate the power consumption of the synthesized AoD instances, we adopt a realistic power model described by the parameters in **Table III**. The common equipment includes the controller, the cooling fans, and the power supply. The high-speed PLZT switches are built by a switching...
device and a switch driver, with power consumption in the order of a few milliwatts and 8 W, respectively. Hence, only the switch driver contribution is considered. We propose using an incremental power control algorithm that turns on successive switches only when really needed. Note that this algorithm is compatible only with expandable architecture. According to the realistic power model adopted, the consumption of the AoD instance in Fig. 5(b) is 306 W.

Similar to the scalability analysis, we consider the AoD configurations described in Table II for the sensitivity analysis to the parameters $P$, $L$, and $\sigma$, without aggregation of adjacent wavelengths into superchannels (i.e., $\rho = 0$) and with $W = 96$ available spectrum slots per fiber.

Figure 8(a) shows the power consumption as a function of the port load $P$ and the degree of AoD $N$ without fiber switching or subwavelength requests. For this type of traffic request, E-SA computes AoD instances using only, as active components, the common equipment and the backplane switches. We observe an increasing power consumption trend due to the use of additional backplane switches to provide the increasing number of required cross-connections shown in Fig. 7(a). In more detail, for $N = 25$ the number of backplane switches is 2, 4, 6, 8, and 9 for port loads $P = 0.2$, 0.4, 0.6, 0.8, and 1, respectively. This clearly shows the impact on the power consumption of the high number of required cross-connections.

The power consumption decreases, as shown in Fig. 8(b), when the aggregation of channels into fiber switching permits a reduction in the number of backplane switches. Note that these results [as in Fig. 8(a)] are due mainly to the active components being the common equipment and the backplane switches. For instance, for $N = 25$, the number of backplane switches is 9, 8, 6, 4, 2, and 1 for the respective reported fiber switch values. This clearly shows the reduction of the power consumption due to the decreased number of required cross-connections thanks to the aggregation of channels into fiber switching. Note that different power consumption behaviors are observed in Figs. 8(a) and 8(b) depending on $N$ due to the discrete usage of backplane switches. In particular, few increments and decrements of 150 W (i.e., one backplane switch) are observed for $N = 5$, whereas for $N = 25$ more steps (i.e., of two backplane switches) are observed. Additionally, even if DEMUXs are not active devices, it is worth mentioning that $N$ DEMUXs are used under the traffic conditions of Fig. 8(a), whereas a linear reduction in their number is observed in Fig. 8(b) as $F$ increases.

Figure 8(c) shows the power consumption as a function of the subwavelength requests $\sigma$, without fiber switching requests ($F = 0$), with a maximum load ($P = 1$) and with $N$ as a parameter. The AoD instances obtained by the E-SA under these traffic conditions use as active components the common equipment, the backplane switches, and the PLZT switches. Thus, white symbols and dashed lines show the power consumption of the PLZTs used, while the remainder of the power consumption belongs to the common equipment and the backplane switches. For smaller $N$, the power consumption is mainly due to the common equipment and backplane switches. However, as $N$ and $\sigma$ increase, PLZTs become the major contributor to total power consumption. Indeed, note that for this type of traffic request, the number of cross-connections [shown in Fig. 7(c)] increases at a slower pace with respect to the power consumption. Let us consider the number of devices used by the synthesized AoDs for $N = 25$ under the traffic conditions of Fig. 8(c). On the one hand, the number of backplane switches is 8, 10, and 11 for the subwavelength requests $0 \leq \sigma \leq 0.4$, and 12 for $\sigma \geq 0.6$. On the other hand, the number of $2 \times 2$ PLZT switches is 300, 470, 540, 580, and 600 for the subwavelength requests $\sigma \geq 0.2$ (no PLZT switches are used for $\sigma = 0$). We observe a clear increase in the number of both backplane and PLZT switches for low values of $\sigma$ due to the number of possible combinations to be switched toward the $N = 25$ output ports. However, as $\sigma$ increases, i.e., $\sigma \geq 0.6$, the number of remaining outputs that can be used as possible destinations decreases, limiting the increase trend for the numbers of both switches. This behavior is more evident for lower values of $N$, where a constant number of both switches is used above lower values of $\sigma$ (e.g., $\sigma \geq 0.4$ for $N = 15$).

C. Migration Toward the Flexible-Grid Spectrum

We analyze the AoD scalability under traffic requests that aggregate spectrum slots into superchannels, according to the parameter $\rho$. We consider such aggregated traffic as the migration from a fixed-grid spectrum (i.e., with well-defined DWDM 96 fixed-grid spectrum slots of size $4 \times 12.5$ GHz) toward a flexible grid where superchannels are considered as a set of adjacent spectrum slots placed arbitrarily in the spectrum occupying $8 \times 12.5$ GHz. This approach complies with the flexible grid definition given

<table>
<thead>
<tr>
<th>Device</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common equipment</td>
<td>100</td>
</tr>
<tr>
<td>SSS [27]</td>
<td>40</td>
</tr>
<tr>
<td>Fast switch (PLZT) [28]</td>
<td>8</td>
</tr>
<tr>
<td>3D-MEMS (320 ports) [30]</td>
<td>150</td>
</tr>
</tbody>
</table>

TABLE III

CONSUMPTION VALUES

\[ \rho \text{ of adjacent wavelengths into superchannels (i.e., backplane switches. For instance, for high number of required cross-connections. clearly shows the impact on the power consumption of the AoD instance in Fig. 5(b) is 306 W.} \]

\[ \text{Figure 8(a) shows the power consumption as a function of the port load } P \text{ and the degree of AoD } N \text{ without fiber switching or subwavelength requests. For this type of traffic request, E-SA computes AoD instances using only, as active components, the common equipment and the backplane switches. We observe an increasing power consumption trend due to the use of additional backplane switches to provide the increasing number of required cross-connections shown in Fig. 7(a). In more detail, for } N = 25 \text{ the number of backplane switches is 2, 4, 6, 8, and 9 for port loads } P = 0.2, 0.4, 0.6, 0.8, \text{ and 1, respectively. This clearly shows the impact on the power consumption of the high number of required cross-connections.} \]

\[ \text{The power consumption decreases, as shown in Fig. 8(b), when the aggregation of channels into fiber switching permits a reduction in the number of backplane switches. Note that these results [as in Fig. 8(a)] are due mainly to the active components being the common equipment and the backplane switches. For instance, for } N = 25 \text{, the number of backplane switches is 9, 8, 6, 4, 2, and 1 for the respective} \]

\[ \text{reported fiber switch values. This clearly shows the reduction of the power consumption due to the decreased number of required cross-connections thanks to the aggregation of channels into fiber switching. Note that different power consumption behaviors are observed in Figs. 8(a) and 8(b) depending on } N \text{ due to the discrete usage of backplane switches. In particular, few increments and decrements of 150 W (i.e., one backplane switch) are observed for } N = 5 \text{, whereas for } N = 25 \text{ more steps (i.e., of two backplane switches) are observed. Additionally, even if DEMUXs are not active devices, it is worth mentioning that } N \text{ DEMUXs are used under the traffic conditions of Fig. 8(a), whereas a linear reduction in their number is observed in Fig. 8(b) as } F \text{ increases.} \]

\[ \text{Figure 8(c) shows the power consumption as a function of the subwavelength requests } \sigma \text{, without fiber switching requests (} F = 0 \text{), with a maximum load (} P = 1 \text{) and with } N \text{ as a parameter. The AoD instances obtained by the E-SA under these traffic conditions use as active components the common equipment, the backplane switches, and the PLZT switches. Thus, white symbols and dashed lines show the power consumption of the PLZTs used, while the remainder of the power consumption belongs to the common equipment and the backplane switches. For smaller } N \text{, the power consumption is mainly due to the common equipment and backplane switches. However, as } N \text{ and } \sigma \text{ increase, PLZTs become the major contributor to total power consumption. Indeed, note that for this type of traffic request, the number of cross-connections [shown in Fig. 7(c)] increases at a slower pace with respect to the power consumption. Let us consider the number of devices used by the synthesized AoDs for } N = 25 \text{ under the traffic conditions of Fig. 8(c). On the one hand, the number of backplane switches is 8, 10, and 11 for the subwavelength requests } 0 \leq \sigma \leq 0.4 \text{, and 12 for } \sigma \geq 0.6 \text{. On the other hand, the number of } 2 \times 2 \text{ PLZT switches is 300, 470, 540, 580, and 600 for the subwavelength requests } \sigma \geq 0.2 \text{ (no PLZT switches are used for } \sigma = 0 \text{). We observe a clear increase in the number of both backplane and PLZT switches for low values of } \sigma \text{ due to the number of possible combinations to be switched toward the } N = 25 \text{ output ports. However, as } \sigma \text{ increases, i.e., } \sigma \geq 0.6 \text{, the number of remaining outputs that can be used as possible destinations decreases, limiting the increase trend for the numbers of both switches. This behavior is more evident for lower values of } N \text{, where a constant number of both switches is used above lower values of } \sigma \text{ (e.g., } \sigma \geq 0.4 \text{ for } N = 15 \text{).} \]

\[ \text{C. Migration Toward the Flexible-Grid Spectrum} \]

\[ \text{We analyze the AoD scalability under traffic requests that aggregate spectrum slots into superchannels, according to the parameter } \rho \text{. We consider such aggregated traffic as the migration from a fixed-grid spectrum (i.e., with well-defined DWDM 96 fixed-grid spectrum slots of size } 4 \times 12.5 \text{ GHz) toward a flexible grid where superchannels are considered as a set of adjacent spectrum slots placed arbitrarily in the spectrum occupying } 8 \times 12.5 \text{ GHz. This approach complies with the flexible grid definition given} \]

Fig. 8. Power consumption as a function of $P$, $L$, and $\sigma$ for several AoD degrees $N$.
by International Telecommunication Union Telecommunication Standardization Sector (ITU-T) recommendation G.694.1 (i.e., nominal central frequency granularity of 6.25 GHz and slot width granularity of 12.5 GHz). Indeed, the arbitrary spectral placement of wavelength and superchannels is not possible with fixed-grid optical spectrum switching. In particular, arbitrary placement of aggregates of wavelengths (i.e., superchannels) and fixed-grid wavelengths prevents the use of fixed-grid AWG-based (DE) MUXs. Therefore, the arbitrary spectrum switching of SSSs is required [e.g., see input 1 in Fig. 4(a) requiring the SSS].

The second and third columns of Table IV list the decomposition in single wavelength and superchannels for the different values of $\rho$, assuming a maximum load ($P = 1$). For single wavelength channels in a fixed grid with $4 \times 12.5$ GHz slots, dual-polarization quadrature phase-shift keying (DP-QPSK) at 100 Gbits/s is considered, whereas for superchannels in a flexible grid with $8 \times 12.5$ GHz slots, the spectral efficiency of the superchannels is assumed to be twice that of 100 Gbits/s DP-QPSK, thanks to the use of more efficient modulation formats, e.g., DP-16 quadrature amplitude modulation (16QAM). Thus, given the 4.8 THz available in the C band, 96 DP-QPSK channels at 100 Gbits/s are considered for $\rho = 0$. As $\rho$ increases, the number of requested superchannels at 400 Gbits/s increases up to 48 channels for $\rho = 1$ (i.e., full flexible grid). Therefore, the AoD throughput in the flex grid is twice as much compared with the fixed-grid case. The flexible-grid approach may impact the reachable distance by the optical signal [32]. However, we consider suitable a transponder reach of 800 km for the DP-16QAM at a 400 Gbit/s bitrate, whose feasibility is shown in [2].

Figure 9(a) shows the number of required cross-connections for AoD with degree $N = 25$, traffic requests with a full load ($P = 1$), no TDM subwavelength signals, and different levels of aggregation in fiber switching $F$ and in superchannels $\rho$. E-SA designs the AoD instances with DEMUXs in the first stage and couplers in the third stage for traffic requests with no aggregation in the superchannels. When wavelengths are aggregated together in the superchannels (as $\rho$ increases), DEMUXs in the first stage are progressively replaced by SSSs. Note that the number of cross-connections is given by Eq. (4) for the fixed-grid scenario ($\rho = 0$) and decreases as the aggregation

$$X_{SSS} = 2N + N^2. \quad (5)$$

which allows a reduction of 75% when all the DEMUXs are replaced by SSSs. The maximum number of cross-connections given by Eq. (5) is an upper bound because in most of the cases a full mesh between input and output ports is not required.

As shown in Fig. 9(b), a reduction of the power consumption is experienced as $F$ increases, since fewer backplane switches are used, thanks to the aggregation of channels due to fiber switching. However, when superchannel requests are introduced ($\rho > 0$), higher power consumption is experienced due to the partial replacement of passive DEMUXs by active SSSs. In particular, for $0.2 \leq \rho \leq 0.8$, the combination of a high number of optical backplane switches (due to the large number of cross-connections required by DEMUXs) and SSSs leads to a higher power consumption compared to either $\rho = 0$ or $\rho = 1$. For $\rho = 1$, the first stage of the AoD node is composed only of SSSs, and three optical backplane switches are used (more precisely, only one for $F \geq 0.35$). Hence, a lower power consumption is experienced with respect to the case $0.2 \leq \rho \leq 0.8$.

We analyze the impact of the degree $N$ on the migration toward a flexible-grid spectrum in terms of required cross-connections in Fig. 10(a), and we report the corresponding power consumption in Fig. 10(b). Figure 10 analyzes AoD instances under traffic requests with a full load ($P = 1$), no TDM subwavelength signals, and different levels of aggregation in superchannels $\rho$ for different values of $N$. We observe similar trends, comparing here the degree of AoD with the aggregation into fiber switching in Fig. 9. However, note that the results reported in Fig. 9(b) correspond to different power consumption values for traffic requests

<table>
<thead>
<tr>
<th>$\rho$</th>
<th>Channels $^a$ Superchannels $^a$</th>
<th>Throughput per Port (Tbits/s)</th>
<th>Throughput in Tbits/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>96</td>
<td>0</td>
<td>9.6</td>
</tr>
<tr>
<td>0.2</td>
<td>78</td>
<td>9</td>
<td>11.4</td>
</tr>
<tr>
<td>0.4</td>
<td>60</td>
<td>18</td>
<td>13.2</td>
</tr>
<tr>
<td>0.6</td>
<td>40</td>
<td>28</td>
<td>15.2</td>
</tr>
<tr>
<td>0.8</td>
<td>20</td>
<td>38</td>
<td>17.2</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>48</td>
<td>19.2</td>
</tr>
</tbody>
</table>

$^a$100 Gbits/s in $4 \times 12.5$ GHz.  
$^b$400 Gbits/s in $8 \times 12.5$ GHz.
with increasing values of aggregation into fiber switching (i.e., the maximum being \( N = 25 \) for \( F = 0 \)), whereas Fig. 10(b) reports the maximum power consumption values for different values of \( N \). Indeed, note that the highest power consumption values correspond to the same traffic requests: \( N = 25 \), \( P = 1 \), \( \sigma = 0 \), \( F = 0 \), and \( 0 \leq \rho \leq 1 \). For \( N = 25 \) and \( \rho = 0 \), nine backplane switches are now used to establish all the required cross-connections by the DEMUXs, whereas only three backplane switches and 25 SSSs are used for \( \rho = 1 \). However, as in Fig. 9(b), for \( 0.2 \leq \rho \leq 0.8 \), the combination of a high number of optical backplane switches and SSSs leads to a higher power consumption compared to either \( \rho = 0 \) or \( \rho = 1 \).

In summary, in our considered scenarios, the migration from fixed grid to flexible grid offers 75% cross-connection reduction and doubles the AoD node throughput while keeping a similar power consumption.

**D. Comparison of AoD With ROADMs**

Here we compare the power consumption and the cost of AoD with other ROADM architectures reported in the literature. To this aim, Table V shows the required number of devices to implement several architectures proposed in the literature. We consider 25% as the add/drop ratio per port. Note that we denote architectures nos. 1–4 with the original numeric IDs of [3]. The C/D/C-ROADM architecture no. 5 reported in [4] is based on the same structure as no. 2.

**TABLE V**

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Active Components</th>
<th>Passive Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arch. #1</td>
<td>SSS 3D-MEMS(^a)</td>
<td>Switch(^a)</td>
</tr>
<tr>
<td>Arch. #2</td>
<td>( N )</td>
<td>( NW/2 )</td>
</tr>
<tr>
<td>Arch. #3</td>
<td>( N )</td>
<td>( NW/2 )</td>
</tr>
<tr>
<td>Arch. #4</td>
<td>( 2N )</td>
<td>( NW )</td>
</tr>
<tr>
<td>Arch. #5</td>
<td>( 2N )</td>
<td>( NW )</td>
</tr>
<tr>
<td>Arch. #6</td>
<td>( 2N )</td>
<td>( NW )</td>
</tr>
</tbody>
</table>

\(^a\)Number of slow switches \( x \) [size].

**TABLE VI**

<table>
<thead>
<tr>
<th>Setup</th>
<th>( P )</th>
<th>( F )</th>
<th>( \sigma )</th>
<th>( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>0</td>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>0.4</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>0.8</td>
<td>0</td>
<td>0.4</td>
</tr>
</tbody>
</table>

1) **Power Consumption Comparison**: Table VI lists different traffic conditions given by \( \{ P, F, \sigma, \rho \} \) and denoted as traffic setups (A, B, C, D, E, F). Note that traffic setups (A, B, C, D) extend the power consumption results presented in Figs. 8 and 10(b). In particular, setup A explores the power consumption of AoD for a fixed-grid wavelength traffic load of 80%. Setups B, C, and D explore the power consumption of AoD for a traffic load of 100% with different fractions of subwavelength, superchannel, and fiber requests, respectively. Finally, setups E and F explore the power consumption of AoD for a traffic load of 100% and with aggregation into superchannel and fiber requests.

Figure 11 compares the power consumption for the different architectures in Table V with AoD under the traffic setups of Table VI. All the considered setups for AoD require a lower power consumption than the architectures proposed in the literature. Furthermore, time switching can be supported in AoD, unlike other architectures. However, when such capability is exploited, a higher power consumption is experienced, as shown by setup C.

Notably, the inherent flexibility of AoD permits us to save power compared to other architectures. Power savings depend on the aggregation both into fiber switching and into superchannels. For instance, a more than 60% power consumption reduction is achieved in setup B due to traffic aggregation into fiber switching compared to architecture no. 3. However, as shown in setup D, only 20% of the power consumption reduction is obtained for aggregation into superchannels only. Higher power consumption savings are obtained when aggregation into fiber switching and into superchannels are combined (i.e., 50% and 75% of
power consumption reduction for setups E and F, respectively, depicted with dashed lines).

The ability to switch at different levels (fiber, flex-grid superchannel, and fixed-grid wavelength) reduces the number of required SSS modules and optical switches, saving on their associated power consumption. Therefore, power consumption savings are obtained for AoD depending on the traffic supported (except when time-sliced sub-wavelengths are supported), thanks to the adaptable nature of the architecture. Note that such adaptation to the traffic is obviously not possible with hard-wired ROADMs. Finally, it is worth mentioning that configuration times for AoD and ROADMs are similar due to the use of subsystems with similar configuration times. Therefore, AoD nodes do not present configuration time issues nor penalties compared to ROADMs, and in any case, configuration or synthesis procedures (such as the E-SA in Section IV) are not related to power consumption.

2) Cost Comparison: Table VII lists the cost in arbitrary units for different devices, considering as a reference the price of a 40-channel AWG-based (DE)MUX. The reported costs are based on confidential information given by the different manufacturers. Note that since the PLZT switch is not a mature technology [28], we have considered its cost per port notably higher than for the optical cross-connect (OXC) case based on 3D-MEMS. Similarly, since SSSs are currently targeting research purposes, we have considered their cost 20% higher than the cost of commercially available WSSs. Moreover, we consider that future SSSs will have 25 ports, as current prototypes of WSSs do. The cost of couplers/splitters are not considered in this analysis, since it is negligible compared to the other reported costs.

The costs of the different ROADMs proposed in the literature are obtained according to their number of devices, reported in Table V, and considering $W = 96$ spectrum slots. For the number of OXCs, in the case that the size of the 3D-MEMS (i.e., number of ports) required by the ROADM architecture exceeds 320 (considering commercially available 320-port 3D-MEMS switches [30]), the number of 3D-MEMS switches is obtained by interconnecting switches similarly to the AoD case [Eq. (3)]. Note that Table V shows the number of ports required by the 3D-MEMS switches for the different ROADMs, which is $3NW$ for architecture 1 and NW for architectures 3, 4, and 6.

### TABLE VII

**Cost Values**

<table>
<thead>
<tr>
<th>Device</th>
<th>Cost (a.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUX/DEMUX 40 channels</td>
<td>1</td>
</tr>
<tr>
<td>MUX/DEMUX 96 channels</td>
<td>1.8</td>
</tr>
<tr>
<td>PLZT 2 x 2 ports</td>
<td>2</td>
</tr>
<tr>
<td>WSS 1 x 5 ports</td>
<td>4.5</td>
</tr>
<tr>
<td>WSS 1 x 9 ports</td>
<td>5.5</td>
</tr>
<tr>
<td>WSS 1 x 20 ports</td>
<td>9.5</td>
</tr>
<tr>
<td>OXC 320 ports</td>
<td>55</td>
</tr>
<tr>
<td>SSS 1 x 25 ports</td>
<td>$1.2 \times WSS$</td>
</tr>
</tbody>
</table>

AoD is dimensioned for this cost comparison analysis considering the required devices for a maximum load ($P = 1$) and no aggregation into fiber switching ($F = 0$). Indeed, unlike the power consumption comparison, here we dimension AoD for the cases in which the maximum number of devices are required. In other words, no cost can be saved when devices connected to the backplane are not used due to particular traffic conditions. However, beyond such worst case analyses that take into account previous results for the number of devices, AoD can follow a pay-as-you-grow cost model, since the devices used are correlated with neither the bypass in/out fibers nor the transponders for add/drop traffic. Three different AoD dimensioning cases are considered for this cost comparison:

1) AoD fixed grid: This case considers an AoD deployment in a legacy network with a fixed-grid spectrum of $W = 96$ slots. In particular, it consists of a first stage with a DEMUX per input port, a third stage of couplers, and thus a number of cross-connections [Eq. (4)].

2) AoD flexible grid: Here, we consider an AoD deployment in a future network that has migrated to a flexible-grid spectrum allocation. Therefore, the deployed AoD consists of a first stage with an SSS per input port, a third stage of couplers, and therefore a number of cross-connections [Eq. (5)].

3) AoD sub-λ: This case contemplates an AoD deployment in a long-term future network capable of supporting at maximum 20% of the total traffic containing TDM sub-wavelength requests. The AoD considered in this case consists of a first stage with a SSS per input port, a second stage with a number of PLZTs according to $\sigma = 0.2$ in Fig. 8(c), and a third stage of couplers, which results in a number of cross-connections more than in [Eq. (5)] due to the use of the PLZTs at the second stage.

The number of backplane switches required is obtained according to Eq. (3) for the three considered cases. Similar to the power consumption comparison, we consider 25% as the add/drop ratio per port.

Figure 12 compares the costs for the different ROADM architectures listed in Table V with AoD for the dimensioning cases previously referred. We observe several similarities between the cost comparison and the power comparison in Fig. 11. In particular, architectures nos. 2

![Fig. 12. Cost comparison between AoD and different ROADM architectures reported in the literature.](image-url)
and 5 exhibit the highest cost due to the use of PLZT switches. On the other hand, architecture no. 3 presents the lowest cost among the different ROADMs, achieving a comparable cost to the fixed- and flexible-grid spectrum AoD cases. Moreover, when TDM subwavelength traffic is considered for the deployment of AoD, the overall cost becomes higher than several of the ROADMs considered. Indeed, a similar observation holds for the power consumption when the TDM subwavelength switching capability is exploited by AoD.

The reader may refer to [33] for a more detailed cost analysis on AoD, its comparison against ROADMs, and its impact on network-wide scenarios.

VI. AoD HIGH-CAPACITY ALTERNATIVES

We explore two different scenarios for AoD that supports high-capacity optical switching. In the first scenario, we consider a wide available spectrum that consists of the C and L bands according to the ITU-T recommendation [29]. Indeed, recent developments on Raman-based optical amplifiers permit the use of three additional available spectra compared to traditional EDFA-based amplifiers [34]. In the second scenario, we consider an increment on the spatial dimension exploring the performance of a high-degree AoD node. Subsequently, we compare both spectrum and space high-capacity alternatives. Traffic requests do not contain TDM subwavelength signals.

A. Extended Spectrum (C Plus L Bands)

For the first scenario, we consider a wide available spectrum that consists of the C and L bands, leading to $W = 192$ available spectrum slots. Figure 13(a) shows the number of required cross-connections for AoD with $N = 25$, traffic requests with a full load ($P = 1$), and different levels of aggregation in fiber switching $F$ and in superchannels $\rho$. Similar to Subsection VC, AoD instances with DEMUXs in the first stage are synthesized for traffic requests with no aggregation in superchannels, whereas when $\rho$ increases, i.e., wavelengths are aggregated together in superchannels, DEMUXs are progressively replaced by SSSs. We consider a single SSS per input port at the first stage able to switch arbitrarily the entire C and L bands. Similar to the results obtained in Fig. 9(a), the number of cross-connections given by Eq. (4) for the fixed-grid scenario ($\rho = 0$) decreases as the aggregation in fiber switching increases. However, compared with Fig. 9(a), a higher reduction in the number of cross-connections can be observed for high values of aggregation of wavelengths in superchannels ($\rho \geq 0.6$). Indeed, for $\rho = 1$ and $F = 0$, the number of cross-connections has an upper bound given by Eq. (5), which allows a reduction in the number of cross-connections of $86\%$ when all DEMUXs are replaced by SSSs.

Regarding the power consumption of these wide-spectrum traffic requests, we observe in Fig. 13(b) similar trends to those in Fig. 9(b) when $F$ increases. However, when the number of superchannel requests increases, the power consumption is reduced more rapidly than for the $W = 96$ case. Indeed, thanks to the aggregation in superchannels and the arbitrary bandwidth switching capability of the SSSs, we obtain the same power consumption as in Fig. 9(b) for $\rho = 1$.

B. Large Number of AoD Node Degrees

For the second scenario, we explore the AoD performance in terms of required cross-connections and power consumption when E-SA synthesizes high-port-count architectures. To this aim, Figs. 14(a) and 14(b) show the number of required cross-connections and power consumption, respectively, for an AoD node with degree $N = 50$, traffic requests with a full load ($P = 1$), and different levels of aggregation in fiber switching $F$ and in superchannels $\rho$. As before, AoD instances with DEMUXs in the first stage are synthesized for traffic requests with no aggregation in superchannels, whereas when $\rho$ increases, DEMUXs are progressively replaced by SSS-based composed modules.
TABLE VIII
Summary of Different High-Capacity Alternatives

<table>
<thead>
<tr>
<th>Scenario</th>
<th>(\rho)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>(N = 25, W = 96)</td>
<td></td>
</tr>
<tr>
<td>2450 Tbits/s</td>
<td>1295 xc</td>
</tr>
<tr>
<td>1450 W</td>
<td>1730 W</td>
</tr>
<tr>
<td>240 Tbits/s</td>
<td>285 Tbits/s</td>
</tr>
<tr>
<td>(N = 25, W = 192)</td>
<td></td>
</tr>
<tr>
<td>4850 xc</td>
<td>3053 xc</td>
</tr>
<tr>
<td>2800 W</td>
<td>2900 W</td>
</tr>
<tr>
<td>480 Tbits/s</td>
<td>570 Tbits/s</td>
</tr>
<tr>
<td>(N = 50, W = 96)</td>
<td></td>
</tr>
<tr>
<td>4900 xc</td>
<td>2207 xc</td>
</tr>
<tr>
<td>2800 W</td>
<td>4900 W</td>
</tr>
<tr>
<td>480 Tbits/s</td>
<td>570 Tbits/s</td>
</tr>
</tbody>
</table>

We consider that future SSSs will have 25 ports as do current prototypes of WSSs. Therefore, to achieve switching toward 50 different node degrees, we consider a composed module per input port at the first stage, which includes a \(1\times2\) splitter and two SSSs to provide connectivity toward the third-stage modules.

We observe in Fig. 14(a) a linear reduction in the number of cross-connections as the aggregation in fiber switching increases and a drastic reduction when superchannel requests are introduced, similar to the \(N = 25\) and \(W = 96\) case depicted in Fig. 9(a). However, high values of \(\rho\) do not provide an additional reduction in the number of required cross-connections. Indeed, the high degree considered in this case limits the switching capability of the SSSs, because more space than spectrum switching has to be supported. On the other hand, we observe in Fig. 14(b) a notable increase in the power consumption when superchannel requests are introduced. For instance, the use of two SSSs per port (i.e., 100 SSSs total) implies a power consumption of 4000 W for the case without aggregation in fiber switching (\(F = 0\)). Indeed, this poses a severe limitation to high-degree solutions.

C. Trade-Offs Between High-Capacity Alternatives

Table VIII summarizes the different high-capacity alternatives in terms of required cross-connections (denoted as “xc”), required power consumption in watts, and achieved throughput in terabits per second. Results obtained in Subsection VC are also listed for comparison purposes. The reported summary table coincides with the \(F = 0\) curves (no aggregation in fiber switching) of Figs. 9, 13, and 14 in each respective row.

Both wide-spectrum and high-degree scenarios provide twice the throughput compared to the standard AoD limited to the C band and up to 25 node degrees. Furthermore, both high-capacity cases also require almost twice the number of cross-connections and power consumption if compared to the standard AoD configuration when no aggregation into superchannels is requested (i.e., \(\rho = 0\)). Note that for traffic requests with \(0.2 \leq \rho \leq 0.6\), where a combination of wavelengths and superchannels is used, the scenario with the extended spectrum (i.e., C plus L bands) requires more than twice the number of cross-connections and higher power consumption than the standard case. This is due to the high number of wavelengths that need demultiplexing and subsequent multiplexing, which consequently requires a high number of ports, i.e., a larger optical backplane. Nevertheless, as the fraction of superchannel switching increases, the number of cross-connections and the power consumption drop to similar values to the standard AoD case. This reduction is achieved because SSSs utilize a single port to switch multiple wavelengths and superchannels, which is not possible with passive optical (DE)MUXs. Therefore, for the extended-spectrum scenario it is beneficial to implement (de)multiplexing functions using SSS rather than passive wavelength (DE)MUX devices.

The high-degree AoD scenario shows a slight reduction in the number of required cross-connections compared to the extended-spectrum scenario for superchannel switching within the range \(0.2 \leq \rho \leq 0.6\). However, it also implies a higher power consumption, because a larger number of active SSSs are required. Therefore, these results show that the extended-spectrum scenario should be preferred to the high-AoD-degree alternative. Nevertheless, the extended-spectrum scenario requires SSS devices that support both the C and L bands, whereas the high-AoD-degree scenario requires only devices that support the C band.

VII. Conclusions

We studied the power consumption and backplane cross-connection scalability of AoD, supporting TDM subwave-length, wavelength, superchannel, and fiber switching. First, we presented the E-SA to automatically design AoD instances according to the traffic request. Then we reported a scalability and power consumption analysis under different profiles of traffic requests. Furthermore, we showed the benefits of traffic grooming in superchannel switching and the impact of the arbitrary bandwidth switching capability provided by the SSSs at the AoD node level. Our results show that the adaptability of AoD offers significant power saving compared to other architectures, unless power-demanding functionalities (e.g., time switching) are supported. In addition, our results indicate that the AoD worst-case cost is better or comparable to traditional
ROADM architectures. Moreover, its pay-as-you-grow modular and flexible nature (plug-in modules with diverse functionalities) that is disassociated from the degree of architecture provides considerable benefits. Finally, we demonstrated the convenience of enabling additional spectrum switching rather than providing additional space switching, considering SSS devices that support both the C and L bands. In conclusion, the high flexibility offered by AoD brings considerable power efficiency to the optical node while providing a throughput of hundreds of terabits per second.

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