Establishment of Dynamic Lightpaths in Filterless Optical Networks

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Abstract—In this paper, we study the performance of dynamic routing and wavelength assignment (RWA) in filterless optical networks. These types of broadcast and select networks benefit from breakthroughs in advanced transmission technologies for replacing optical filters and active photonic switching devices, such as wavelength selective switches, with passive optical interconnections between nodes, creating passive optical light trees. We introduce an RWA scheme for establishing passive optical lightpaths in a filterless context and managing unfiltered channels at intermediate egress nodes, which, by propagating downstream of the terminating nodes, participate in wavelength usage and increase the risk of wavelength exhaustion. Simulation results are presented for six network topologies, along with the performance evaluation of active photonic and filterless optical network solutions with static and dynamic RWA schemes. We show that the performance of the proposed scheme depends on the average degree of node connectivity.

Index Terms—All-optical networks; Dynamic routing; Optical control plane; Physical layer aware routing; Routing and wavelength assignment algorithms.

I. INTRODUCTION

The widespread popularity of Internet applications, such as video on demand, high definition television, and intelligent mobile phone applications, leads to the growth of network complexity and traffic demand. Current all-optical wavelength routed networks rely on wavelength selective switch (WSS)-based reconfigurable optical add–drop multiplexers and offer lightpath switching capability for transferring IP packet switching loads in the optical layer. These key components allow dynamic, per wavelength reconfigurability for the efficient management of traffic variations, but at the expense of higher capital cost and dependence on the International Telecommunication Union (ITU) spectral grid.

The filterless optical network concept was first introduced on the premise that breakthroughs in transmission technologies and digital signal processing could support agility by ingress and egress nodes equipped with tunable transceivers and frequency selective coherent receivers, respectively [1]. Filterless network solutions have been proposed for regional and core network topologies and compared to active photonic switching solutions from the point of view of cost and performance; the results show that filterless networks represent a cost-effective, reliable, and energy-efficient alternative to WSS-based networks [2–4].

Indeed, in a filterless network, passive optical splitters and combiners offer link interconnection between nodes and local add–drop, and the resulting broadcast and select network consists of a set of passive light trees in which frequency selective filters and active photonic switching devices (WSSs) are replaced by less expensive passive components.

The bandwidth granularity of the photonic layer is typically equal to the wavelength capacity (e.g., 10 Gbps), which is in stark contrast to that of the IP packet layer. In classical WDM networks, a tributary client signal is provisioned as an optical carrier, and this carrier is only shared by the ingress and egress nodes, leading to potential resource underuse and operational constraints.

Filterless optical networks provide three features to reduce these operational constraints and increase agility. First, colorless and gridless abilities are enabled, thanks to the removal of wavelength selective filters. Second, the setup time for path establishment in a filterless network can be expected to be potentially simpler and shorter than in active photonic switching networks, since only end nodes need to be configured. Third, the passively add function of intermediate nodes is a key enabler for light-trail communications, as first proposed in [5], and for multilayer routing, which allows tributary client signals to be passively and dynamically aggregated into an optical carrier along the path, following the traffic grooming concept [6].

The main constraint in a filterless network lies in the presence of unfiltered channels propagating all the way to the terminating nodes of a filterless light tree as a result of the passive drop and continue feature of a filterless node. The concept of unfiltered channels, as well as their

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performance impact in filterless networks, has been described and analyzed in [2]. Unfiltered channels impact the management of wavelength contention and increase the risk of the available wavelengths on a route being exhausted, preventing the establishment of a new connection.

Both offline and online routing and wavelength assignment (RWA) make it possible to handle connection requests. In an offline or static algorithm, solving the RWA problem is based on a previously known traffic matrix. In contrast, an online or dynamic approach creates routes based on the network’s available resources and is more suited to situations in which traffic is unpredictable [2].

In this paper, we propose a dynamic RWA scheme for optical path establishment in filterless networks. We show its performance when applied to six network topologies in terms of blocking probability, wavelength usage, and number of unfiltered channels. In particular, the dynamic RWA scheme is compared with static filterless and active photonic switching RWA solutions obtained from the Filterless Network Design and Simulation (FNDS) tool [2,3] and NetCalc Optical Planner 3.1, respectively.

The paper is organized as follows. In Section II, we present the filterless network transmission line and node model. Section III is devoted to the description of a control plane for filterless optical networks. In Section IV, specific concepts of filterless networks are discussed. Finally, in Section V, a dynamic RWA scheme is proposed for filterless networks and its performance is compared with static RWA schemes in filterless and active photonic switching networks. Blocking probability, wavelength usage, and the number of unfiltered channels are studied in particular. This study helps us realize that, as the degree of node connectivity increases, both static and dynamic RWA schemes in filterless solutions exhibit good performance in terms of wavelength usage and the number of unfiltered channels.

II. FILTERLESS NETWORK MODEL

A. Filterless Network Concept

In filterless networks, the replacement of wavelength selective filters and switches with passive optical splitters and combiners, achieving passive fiber optical interconnections between nodes, has been enabled by breakthroughs in tunable and coherent transponders, making possible the delivery of agility by end nodes. In fact, wavelength tuning at the transmitter, wavelength selection at the receiver, and the absence of configuration at intermediate nodes make the agility in filterless networks analogous to the agility in radio networks. As a consequence of the minimization of the number of active filters and switches, filterless networks reduce capital expenditure while ensuring reduced power dissipation, at the expense, however, of greater wavelength usage [3,4].

Filterless networks can also provide other advantages, such as better robustness to faults occurring in active components (e.g., WSS), passive multicast capabilities for enhanced traffic grooming, and simplified establishment of generalized multiprotocol label switching (GMPLS) multilayer label switched paths. The remaining part of this paper will address our claims regarding simplified path establishment of multipoint to multipoint connections and connections with different granularities (e.g., wavelength, time slots) in a filterless network.

B. Filterless and Active Optical Transmission Lines

The paradigm difference between a filterless and a WSS-based active optical transmission line rests on two main points, as shown in Fig. 1. First, a filterless solution proposes the minimization of wavelength selective filters and active switches. (Note that passive optical splitters and combiners implement the passive local add–drop function in a colorless fashion, which helps to reduce operational constraints related to the colorless, directionless, and gridless concepts [8].) Second, filterless networks exploit recent breakthroughs in digital signal processing and electronically compensated dispersion. As a result, legacy optical dispersion compensation modules are no longer required.

A filterless transmission line consists, then, of a sequence of optically amplified fiber links interconnected through passive optical splitters and combiners. Intermediate nodes support the drop and continue and passively add functions. It follows, therefore, that every node in the transmission line has access to any lightpath. Consequently, a filterless network is an embodiment of broadcast and select networks. The corresponding losses of the replaced WSS switches let us determine a maximal nodal degree of connectivity. We then estimate that the splitting/combing ratio should be limited to 8, corresponding to a maximal loss of about 9 dB.

C. Filterless Node Model

A filterless network is assembled from a set of passive fiber trees constructed following the abovementioned
principles. The resulting network architecture and the number of fiber trees depend on the passive optical splitter and combiner configuration at each node, as shown in Fig. 2.

Figure 2(a) shows a filterless solution example for a 7-node subset of the German network topology [9], in which 3 passive fiber trees are proposed for interconnecting the 7 nodes and 11 bidirectional fiber links. The expanded view of node B (degree 4) in Fig. 2(b) shows the internal configuration of the node.

Any change, addition, or removal of the fiber interconnections translates into a change in network architecture. For example, in node B, if A–C and C–A link interconnections are added, then a two-fiber-tree filterless network solution is obtained.

It is important to mention that, in active switching architectures, once the WSSs are configured and provisioned, they can perform any port interconnection. In contrast, a filterless passive configuration corresponds to only one passive interconnection pattern. Unused ports make any topological change or upgrade in a network possible (in terms of evolution), without requiring replacement of the passive devices, which could lead to network outages.

Moreover, switches can be dynamically reconfigured and may maintain a view of how their ports are interconnected. In filterless nodes, however, while fiber link interconnections are made statically, passive devices provide no means to automatically discover how the passive interconnections are made, and there is no facility provided to probe any topological inconsistency. As a result, filterless networks need to rely on extra features to achieve automatic discovery of internal node configuration and link interconnections.

III. CONTROL PLANE FOR FILTERLESS NETWORKS: IMPLEMENTATION PROPOSAL

A. Description of the Control Plane

A filterless node includes control components to implement an automated control plane. A path computation element (PCE)-based centralized control plane has been proposed for filterless networks [7]. First, it implements a path computation client (PCC) to enable communications with a PCE every time a route needs to be computed. It also implements an optical connection controller (OCC) to support conventional GMPLS signaling (RSVP-TE), advertising (OSPF-TE), and management (LMP) protocols. This process is discussed more fully below.

A reliable control plane is required to perform automated functions, such as lightpath establishment and release, resource management, as well as fiber break detection and recovery. To create this plane, we propose that an out-of-band wavelength dedicated to an optical supervisory channel (OSC) is filtered in each node port, as shown in Fig. 3.

This is mandatory so that, in the case of a misconfigured node, the control plane is still able to operate and detect an error, such as a laser loop harming the procedure on the supervisory channel.

Another advantage of filtering the OSC is that its wavelength is released such that it can be reused by dedicated optical devices (represented by *** boxes in Fig. 3) which are inserted at every filterless node and referred to as OSC controllers. These devices are used to detect the fiber interconnections, as shown in Fig. 3(b), allowing a filterless node to discover its own passive internal connection pattern. The discovery mechanism works as follows: In a round robin fashion, the node selectively turns on one of the OSC controllers and reads the power received by the other OSC controllers. Should any of these OSC controllers detect a received signal, the node deduces that there is an interconnection between the port turned on by the OSC controller and the OSC controller port detecting a signal. The set of interconnections is determined by turning on one OSC controller after another. This information can then be stored in a local database and flooded to the PCEs via a link state protocol such as OSPF.

In conventional active photonic switching networks, the out-of-band OSC is filtered in the same way as any channel of the data plane. In contrast, in filterless networks, the OSC could remain unfiltered, like the rest of the channels, leading to the creation of an optical bus hundreds of kilometers in length. In this case, nodes along the fiber tree
would need to perform complex frame collision detection for their control messages. Thus, OSC filtering is a practical way to simplify operations in filterless networks and limits the concept of filterlessness to the data plane.

This helps maintain an out-of-band signal to monitor the network while keeping the data plane within the conventional filterless definition. In that sense we could argue that the “filterless” part of these optical networks only applies to the data plane, which remains unfiltered. Moreover, the OSC channel is filtered in the usual way as performed in conventional WSS-based networks.

From this, it is clear that a control plane for filterless networks acts in much the same way as it does in (filtered) active photonic switching networks and that no supplementary extension to the GMPLS procedures and protocols is expected. It is worthwhile to mention that, as a consequence, the filtered out-of-band OSC channel helps create a control plane for filterless networks in which the discovery and the flooding mechanisms act in the same way as those in active photonic switching networks.

B. PCE Implementation

A PCE is a device capable of performing constraint-based route computation from a network view, based on the premise that it is a key component of GMPLS multi-layer and multidomain networks.

We propose to exploit dedicated PCEs as building blocks of the control plane, because they can integrate constraints that are specific to filterless networks, such as the unfiltered channels and the passive interconnection layout, as well as the backward and forward ports as defined in [2], in their route computation and validation, while reducing the performance degradation of the node’s processors.

In [2], a static RWA approach was used to study the performance of a filterless optical network. It implemented a genetic algorithm to solve the problem of fiber interconnection placement and a tabu search algorithm to address the static RWA problem. This strategy is based on complete knowledge of a traffic matrix and the maximization of performances. We propose a dynamic RWA algorithm that attempts to maximize network resources while establishing lightpaths for random connection requests. A load balancing strategy helps to prevent a few fiber trees from being preferred over others. Unlike similar approaches, such as lightpath length minimization, this strategy avoids preference being accorded to a fiber tree for a given pair of source/destination nodes and reduces the blocking probability arising from wavelength exhaustion.

Figure 4 shows a control plane for filterless networks consisting of two specialized PCEs, as in [10], performing RWA computation and validation, and a set of nodes implementing OCC in order to achieve path signaling and resource advertisement. The first component, called RWA-PCE, provides the function of optimal route computation. The state of the lambda layer is important, as it is capable of performing wavelength assignment and of handling wavelength contention. The second component, an impairment-aware PCE (IA-PCE), addresses physical impairment validation and needs to be fully aware of the physical layer constraints, as described in [7].

C. Functions of the Control Plane and Proposed RWA Strategy

Capitalizing on the concepts described above, that is, a control plane based on a filtered OSC and a PCE, filterless networks can support the four main features of a dynamic optical control plane [6], including 1) automated self-inventory and spreading of resources and adjacency data; 2) automated connection management, establishment, and release; 3) efficient operation and traffic shifting during maintenance procedures; and 4) self-healing or resiliency, consisting of recovery in the case of failure.

The focus of this paper is on automated connection management. Relevant data are gathered that minimize the routing cost of the path to be established. These data comprise traffic engineering information and physical layer impairment (PLI) constraints.

The objective of a fast, efficient, holistic RWA scheme is to improve the speed of path establishment and achieve optimal conservation of the resources disseminated over the network.

Our proposed RWA strategy, which consists of RWA-PCE and IA-PCE, is the following:

- RWA-PCE: proposes K filterless fiber trees and chooses the first available channel for each of them.
- IA-PCE: elects the optimal fiber tree, based on the fact that the received optical signal-to-noise ratio meets the requirements of a service layer agreement, by using a worst-first strategy.

IV. DYNAMIC LIGHTPATH ESTABLISHMENT CONCEPTS IN A FILTERLESS NETWORK

A. Bootstrapping

Before establishing new lightpaths, a node must be registered in the network and its passive internal configuration must be validated. This is achieved by means of a bootstrap procedure, thanks to the control plane, which
helps to prevent a network from collapsing if a misconfigured new node creates a laser loop when inserted into an existing topology. Another issue is possible channel collisions caused by the control plane during lightpath establishment because of a discrepancy between its own view of the topology and the real passive link interconnections.

Because collisions occur only at the egress port, where the passive interconnections are made, every time a topology change needs to be performed, during maintenance, or whenever a node is to be bootstrapped or revalidated, it is important that the topology be validated first before the fiber is connected downstream of the passive optical combiner. This prevents any potential collision from occurring when the control plane allows the new topology, which in turn improves the efficiency of the operation.

B. Link Interconnection Discovery and Advertising

Filtering the OSC at the ingress port leaves the associated wavelength free to be reused inside the node. This feature helps the node to determine the link interconnection pattern in the absence of active components. Figure 3 illustrates this approach using an out-of-band channel. In the first step, the node lights one of its ingress ports in a round robin manner and probes its egress ports to determine whether power is being received—that is, a connection is detected—or not. The node is then able to build a view of its inner topology and advertise it to the control plane. Conventional means, such as LMP, help outdoor link connections to be gathered between nodes. This conjugate knowledge helps the network to automatically discover the layout of the filterless trees.

C. Management of Unfiltered Channels

The drop and node architecture of filterless nodes generates unfiltered channels propagating from egress nodes to the fiber tree end node. In Fig. 5(b), a lightpath established between nodes 1 and 2 still propagates to node 4, which locks the related wavelength and participates in increasing both the blocking probability and the wavelength usage. If improperly managed, a newly established lightpath could cause the unwanted outage of existing backward connections.

In the case of a collision, the control plane needs to take into account the lightpath itself, as in active photonic switching networks, as well as the related unfiltered channels. Figure 5(b) shows the result. A new lightpath established between nodes 1 and 2 may interrupt the existing one between 3 and 4. The wavelength locked in by this latter lightpath must not be reused.

In active photonic switching networks, two disjoint lightpaths may use two instances of the same wavelength, as in Fig. 5(a), without interruption, because active photonic switching devices can block wavelengths at the egress node and guarantee collision avoidance.

Since collisions cannot be prevented by intermediate nodes, the control plane must implement procedures to avoid them. This implies several considerations. First, in a distributed signaling scheme (that is, using the RSVP protocol), path and reserve messages are exchanged over the passive fiber tree and not simply over the future lightpath, as would have been the case with active photonic switching solutions. Each node communicates with each other via the OSC, and conventional IP routing and addressing models can be used to pass all RSVP-TE messages around the various nodes. The label semantics, the session and sender/receiver address, and so forth can be handled similarly, and it is the implementation of the PCE that handles the differences with respect to conventional networks. In a filterless optical network, without electrical regeneration or wavelength conversion at some nodes, there is no switching (either optical or electrical) involved and the RESV message is used to lock the wavelength at all nodes along the fiber tree.

Finally, the advertisement mechanisms should also provide the means to inform nodes about the existing unfiltered channels. This can lead to an increase of the OSC load, as well as a need for an optimal view of the network resources. The advertising mechanisms specific to filterless networks are beyond the scope of the paper. Extensions for advertising will be required as a consequence of this architecture. However, the fact that the control plane is filtered does not alter the legacy way of managing the network. As a result, in a filterless network, the flooding mechanism is the same, but an extension will be required to advertise the link interconnections.

Fig. 5. (a) Lightpath establishment in an active photonic switching network. The two disjoint lightpaths (1–2 and 3–4) can use the same wavelength (λ1). RSVP message exchange is performed along the path. (b) Lightpath establishment in a filterless network. The control plane needs to be aware of the unfiltered channel propagating through the passive tree (dotted line). In this case, the two disjoint lightpaths must use two different wavelengths (λ1, λ2) in order to avoid the unfiltered channel from the backward connection causing a collision with a forward connection. In a distributed signaling scheme, RSVP messages must be exchanged along the entire passive tree, outside the path, in order to avoid collision with unfiltered channels.
1) Backward and Forward Port Handling: The PCE-based centralized control plane can deal with backward and forward port handling, as long as an efficient routing and wavelength algorithm is used.

In active photonic switching solutions, an available wavelength is determined by producing the complementary of the concatenation of the busy wavelengths at every egress port through which the future lightpath passes. The same process can be performed in each passive filterless tree by taking into account the backward and forward ports of the source port of the future lightpath, as shown in Fig. 6.

Indeed, in Fig. 6, if port 2 is the ingress port of a new connection, the busy wavelengths of both port 1 and port 3 must be considered: port 1, because unfiltered channels resulting from backward connections may occur, and port 3, since the new lightpath may, in turn, generate an unfiltered channel prone to interrupting existing forward connections. Consequently, ports 1 and 3 are labeled backward and forward ports, respectively.

Backward and forward ports are located in the same fiber tree and lock in available resources that are not necessarily in the future lightpath. Their knowledge helps the control plane avoid using a wavelength that could involve a collision once it is considered as an unfiltered (unused) channel.

To detect backward and forward ports for a given ingress port, we used a two-step algorithm in a depth-first search fashion. The algorithm needs the view of the physical topology, along with knowledge of the interconnections of each nodal link.

In the first step, starting from the emitting port considered, the algorithm finds the remote receiving port, and then, thanks to the knowledge of the corresponding nodal link interconnections, it can build a set of backward ports by including the emitting ports connected to this remote receiving port via fiber link interconnection. This step is repeated recursively for each of these emitting ports until all the leaves of the filterless tree have been reached.

The second step is similar to the previous one. Starting from each of the backward ports, the algorithm covers the filterless fiber tree toward its root. This helps to find branches combined backward from the considered port.

2) RWA in Filterless Light Trees: The control plane simulator for filterless networks includes the PCE embedding the algorithm to detect the backward and forward ports, which is a key component for the RWA in the lightpath establishment process.

Once the egress and ingress nodes are determined for the new lightpath to be established, the PCE finds the available filterless fiber trees. Since the number of fiber trees is smaller than the number of potential routes in an active photonic switching network, the PCE is able to produce the complete list of available filterless fiber trees and is not restricted to proposing the K best candidates.

Fiber trees are then validated in a load balancing strategy, which means that the PCE evaluates the wavelength usage in each of the available filterless fiber trees and then seeks the least used tree that is physical layer compliant.

The rules of the wavelength assignment process are the following:

- The PCE cannot use a busy wavelength in the new lightpath, that is, one being used by an existing connection. This is the classical case encountered in active photonic switching networks.
- The PCE cannot use a wavelength that could cause or be involved in a collision if it becomes an unfiltered channel or the future lightpath is crossed by an unfiltered channel. This feature keeps the connections in a filterless network healthy but comes at the expense of greater wavelength usage.
- The PCE should, if possible, avoid using a wavelength if the connection becomes an unfiltered channel that collides with an existing unfiltered channel, because of physical layer considerations.

In summary, wavelengths are assigned using a first-fit strategy among the set produced, thanks to the complementary of the concatenation of the busy wavelengths of all backward and forward ports.

V. Performance Analysis of the Proposed Implementation

In this section, we compare the performance of the proposed control plane and dynamic RWA scheme with the performance results presented in [2] for a static filterless RWA scheme and corresponding active photonic switching network solutions obtained by using NetCalc Optical Planner 3.1.

A. Presentation of the Control Plane Simulator

A control plane simulator for filterless networks has been developed in Java for studying the performance of the proposed approach. The simulator implements the concepts discussed above. The path sequence operations are as follows:

- The user specifies in real time the ingress and egress nodes for the path to be established using the point-and-click concept.
- The request is sent to the PCE to perform RWA based on the path establishment demand.
The RWA algorithm probes all the passive filterless trees, which enables the ingress node to reach its egress peer. (Note that this step is not limited to evaluating the K best candidates, as in other heuristics.)

The RWA algorithm performs the two-step algorithm for every filterless tree discovered, in order to create a list of backward and forward ports, based on the assumption that it has a view of the entire topology, including the passive fiber link interconnections.

The RWA algorithm concatenates all the busy ports for each of the ports on the above list, so that no unavailable wavelength needs to be considered, as explained earlier in the discussion of the collision avoidance concepts.

The RWA algorithm uses its filterless link validator tool [11] to implement PLI-aware routing and to reject any candidate that does not satisfy the required quality of service for the lightpath to be established.

The simulator evaluates the wavelength usage of the remaining passive filterless trees and retains the least congested fiber tree. Then, via explicit routing objects in RSVP messages, the resources can be locked between the ingress and the egress nodes, regardless of the need to advertise any intermediate node.

The simulator operates over “precomputed” filterless network solutions. In other words, it assumes that the filterless tree layout is already set over a given network topology. Estimated algorithm time and space complexity are $O(V^2)$ and $O(V^2/E)$, respectively, where $V$ is the number of links and $E$ the number of nodes, assuming a local state is kept up to date whenever wavelengths are used and released:

- A depth-first search algorithm is applied to select the available fiber tree and then to compute the amplified spontaneous emission (ASE) noise over the lightpath to be established.
- A first-fit approach is applied over the available wavelengths in the spectrum. Time and space complexity are here considered related to a constant.

Note that filterless light trails, even though enabled by the simulator, are beyond the scope of this paper.

### B. Performance Evaluation of Reference Networks

Table I summarizes the six reference regional and core network topologies used in this study and illustrated in Fig. 7:

- A 7-node subset and the 17-node German networks, with meshed topologies and an average degree of connectivity of 3. These are useful for validating the principles of dynamic RWA schemes for network loads of two different intensities.
- The 11-node East US and the 17-node Californian networks, with ringed topologies and an average degree of connectivity close to 2. These constitute a good counterpart to the two preceding networks.

The total available optical spectrum considered in the simulations was 88 wavelengths with 50 GHz spacing in the C-band. The network diameters ranged from 690 to 1924 km, which corresponds to medium sized countries. The maximum fiber-tree length was limited to 1500 km, which is a realistic value for long haul WDM transmission systems.

Table II provides a comparison between the static and dynamic RWA schemes for each of these reference networks. It gives the sum, for each unidirectional fiber link, of the unfiltered channels that are not part of a connection, as described earlier in this paper. As active photonic switching networks have no unfiltered channels, a good filterless solution and associated control plane must be capable of mitigating the formation of these channels in order to avoid performance degradation. The objective here

<table>
<thead>
<tr>
<th>Network Topology</th>
<th>Number of Links</th>
<th>Average Nodal Degree</th>
<th>Diameter in km</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-node German</td>
<td>22</td>
<td>3.14</td>
<td>690</td>
</tr>
<tr>
<td>10-node Italian</td>
<td>30</td>
<td>3.00</td>
<td>830</td>
</tr>
<tr>
<td>17-node German</td>
<td>52</td>
<td>3.06</td>
<td>951</td>
</tr>
<tr>
<td>8-node European</td>
<td>24</td>
<td>3.00</td>
<td>1393</td>
</tr>
<tr>
<td>11-node East US</td>
<td>24</td>
<td>2.18</td>
<td>1924</td>
</tr>
<tr>
<td>17-node Californian</td>
<td>40</td>
<td>2.25</td>
<td>1027</td>
</tr>
</tbody>
</table>
is the total number of unfiltered channels

The simulator provides the complete status of the wavelength consumption on a per link basis, for instance, the number of wavelength channels used in lightpaths and unfiltered channels. The number of unfiltered channels shown in Table II is the total number of unfiltered channels in all the links for a given network solution.

Note that the number of unfiltered channels propagating over a network depends on the number of connections and the number of nodes per fiber tree, but also on the average degree of connectivity of the network. So, the Californian network produced 55% and 56% more unfiltered channels in static and dynamic RWA schemes, respectively, than the German network, even though they both have 17 nodes and the required 252 path establishments. Table I shows that the former network has a degree of connectivity of two, which is similar to that of a ring topology, whereas the German topology has a degree of connectivity close to three.

The dynamic RWA strategy exhibits good performance in small networks and with a light traffic load (the 7-node German network and the 10-node Italian network, for example). In these cases, the control plane is less able to keep the number of unfiltered channels low relative to an optimal solution, as the number of nodes and paths to be established increase.

Table III presents the wavelength usage, which depends on the number of unfiltered channels and the number of connections to be established. The wavelength usage represents the number of required wavelengths in the C-band to meet the requirements in terms of the number of connections or paths to establish. It corresponds to the number of wavelengths on the busiest link.

Results show that filterless networks exhibit wavelength usages close to those for active photonic switching at typical traffic levels.

In [2], it was demonstrated that the FNDS tool can generate filterless solutions that exhibit an increase in wavelength usage of less than 25% with respect to their active photonic switching counterparts. The performance results obtained by using the proposed dynamic RWA scheme are close to those obtained by using a static RWA approach and presented in previous studies, except for networks with ring-like topologies (11-node East US and 17-node Californian network), which show a greater wavelength usage.

VI. Conclusions and Future Work

In this paper, we introduced a dynamic RWA scheme for passive optical lightpath establishment in a filterless context. Unfiltered channels constitute a key constraint in this scheme and need to be managed properly by a control plane. If they are not, the filterless components have no means for preventing themselves from becoming involved in collisions with backward connections.

The simulation results presented for six network topologies show that the performance of the proposed RWA scheme improves as the average degree of node connectivity increases. This means that mesh networks with a limited number of nodes and moderate traffic levels are better suited for a filterless architecture as the number of fiber trees increases. In turn, the control plane has more choices available for performing routing and decreasing the number of unfiltered channels.

Based on these results, filterless networks can be considered as a promising solution to establish lightpath connections in a faster way, since the intermediate nodes along the path are no longer required to be configured, and the time complexity of the RWA algorithm can be reduced at the expense of slight performance degradation.

Future work includes the exploration of semi-filterless architectures based on passive optical filters placed at strategic locations in the network for minimizing the wavelength consumption and the number of unfiltered channels [12]. A control plane aware of the location of these filters should be able to maintain a view of small clusters with a semi-filterless architecture and to achieve a trade-off between the simplicity and speed of path computation and a reduction in the number of unfiltered channels. Extensions to advertising mechanisms in filterless networks are also planned as part of future work.

<table>
<thead>
<tr>
<th>Network</th>
<th>Number of Connections</th>
<th>Dynamic Wavelength Usage</th>
<th>Static Wavelength Usage</th>
<th>Active Photonic Switching</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-node German</td>
<td>148</td>
<td>34.61</td>
<td>23.75</td>
<td>N/A</td>
</tr>
<tr>
<td>10-node Italian</td>
<td>90</td>
<td>24.15</td>
<td>23.75</td>
<td>22</td>
</tr>
<tr>
<td>17-node German</td>
<td>252</td>
<td>88</td>
<td>88</td>
<td>69</td>
</tr>
<tr>
<td>8-node European</td>
<td>56</td>
<td>21.51</td>
<td>21</td>
<td>N/A</td>
</tr>
<tr>
<td>11-node East US</td>
<td>110</td>
<td>78.2</td>
<td>51</td>
<td>N/A</td>
</tr>
<tr>
<td>17-node Californian</td>
<td>252</td>
<td>88</td>
<td>88</td>
<td>83</td>
</tr>
</tbody>
</table>

*Active photonic switching solutions are used as a reference.
REFERENCES


