Design and Simulation of Filterless Optical Networks: Problem Definition and Performance Evaluation

Émile Archambault, Daniel O'Brien, Christine Tremblay, François Gagnon, Michel P. Bélanger, and Éric Bernier

***Abstract*—Filterless optical networks based on advanced transmission technologies and passive optical interconnections between nodes offer a lower-cost alternative to optical networks based on active photonic switching. A design and simulation platform is proposed for studying these novel network architectures and looking at their performance characteristics. Simulation results are presented for three reference network topologies, along with a comparative cost and performance study of active photonic and passive filterless optical network solutions.**

***Index Terms*—All-optical networks; Network architectures; Optical network design and planning; Routing and wavelength assignment algorithms**.

I. Introduction

Recent advances in optical transmission and electrical compensation technologies have stimulated the exploration of novel optical network architectures. A passive wide area network (WAN) solution, called the filterless optical network, which eliminates or minimizes the active photonic reconfigurable component count and uses passive splitters and combiners for interconnecting the fiber links, has been proposed recently as a cost-effective and reliable alternative to active optical switching network solutions [1]. In this paper, a filterless optical network design tool is proposed and validated on a number of network topologies. Filterless solutions are presented and discussed, along with a performance evaluation and comparison of active switching and filterless optical networks in terms of cost and wavelength utilization.

The paper is organized as follows. In Section II, the filterless network concept is presented. In Section III, a filterless network design and simulation (FNDS) tool is proposed and illustrated in a solution example. In Section IV, filterless solutions are proposed for two other network topologies. Finally, in Section V, the performance and cost characteristics of the proposed filterless solutions are compared with those of active photonic solutions.

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É. Archambault (e-mail: emile.archambault@cegep-rimouski.qc.ca), formerly with the École de technologie supérieure, 1100 rue Notre-Dame Ouest, Montréal, Québec H3C 1K3, Canada, is now a member of the staff of the Cégep de Rimouski, 60 rue de l'Évêché Ouest, Rimouski, Québec G1L 4H6, Canada.

D. O'Brien, C. Tremblay (e-mail: christine.tremblay@etsmtl.ca), and F. Gagnon are with the Department of Electrical Engineering, École de technologie supérieure, 1100 rue Notre-Dame Ouest, Montréal, Québec H3C 1K3, Canada.

M. P. Bélanger (e-mail: mbelange@ciena.com) is with Nortel Networks (now Ciena Corporation), 3500 Carling Avenue, Nepean, Ontario K2H 8E9, Canada.

É. Bernier (e-mail: eric.bernier@canarie.ca), formerly with Nortel Networks, 3500 Carling Avenue, Nepean, Ontario K2H 8E9, Canada, is now with CANARIE Inc., 110 O'Connor Street, Ottawa, Ontario KIP IA4, Canada.

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II. Filterless Network Concept

The filterless network concept was first introduced in [1]. In current optically agile WAN architectures, the agility is delivered at the network nodes. Our proposal, which takes advantage of recent transmission technology breakthroughs, such as advanced modulation formats, electronic dispersion compensation [2], and tunable transceivers, is based on the premise that the need for agility can now be provided by wavelength tuning at the transmitter and wavelength discrimination at the receiver, in much the same way as agility is achieved in radio networks. Filterless networks essentially offer a passive broadcast medium in which passive optical splitters and combiners are used for interconnecting fiber links. This passive optical network architecture eliminates or minimizes the number of active photonic switching elements in the optical line system. As shown in the case study presented in [1], the resulting network architecture reduces the installed first cost of the network at the expense of greater wavelength utilization. It can also be expected to bring about other significant advantages,

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such as ease of maintenance and reconfigurability, as well as good resilience and multicast capabilities.

A filterless network is based on the construction of a set of fiber links that optically connect all nodes to each other by using passive optical splitters and combiners added at some nodes. The resulting filterless physical topology, and therefore network connectivity, depends on the splitter and combiner configuration at each node. A set of interconnected fibers form a fiber tree, which is the filterless physical layer extension of the light-tree concept defined in [3]. A light tree is established within a single fiber tree as a function of the unicast or multicast traffic between network nodes.

Wavelength blockers can be added as extra components in a filterless solution to reduce the number of wavelengths needed to meet traffic demands. These wavelength blockers create islands of transparency in the network and allow wavelength reuse at strategic locations. Unlike the light-trail mesh networks introduced in [4], many fewer splitters and combiners are used, and wavelength blockers are optional in filterless networks. Splitters and combiners are placed only at strategic locations at the fiber connection stage, which further reduces cost and corresponding physical impairments. Furthermore, all fiber trees are optically isolated from each other and can thus be treated independently when physical impairments and wavelength assignment are considered.

Figure 1(b) shows a filterless solution example for a subset of the German network [5] with 7 nodes and 11 pairs of optical fiber links illustrated in Fig. 1(a). In Fig. 1(b), each fiber tree is represented by a different line pattern. A total of 3 fiber trees and 16 passive optical dividers were used to interconnect all the network nodes. In this example, a connection between node A and node D can be set by using the light tree represented by the black solid lines, and a number of wavelengths can be assigned depending on the traffic demand between these two nodes.

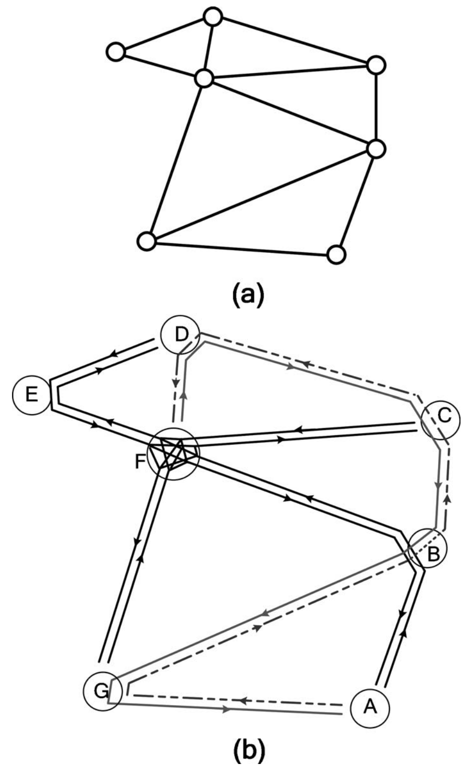

Fig. 1. A subset of the German network [5]: (a) Network topology (7 nodes, 11 links, 690 km diameter); (b) three-fiber-tree filterless network solution. Each fiber tree is represented by a different line pattern. The longest fiber tree is 1214 km. A total of 16 passive optical splitters and combiners are used for link interconnection.

III. Filterless Network Design Tool

The filterless network design problem can be partitioned into two parts: (1) establishment of the fiber connections and (2) routing and wavelength assignment (RWA) according to traffic demand. The first step is critical, since it defines the network's physical connectivity, which determines the RWA solution possibilities. As described in [1], a filterless optical network can be represented by a graph, and a filterless virtual topology design problem (including parameters, constraints, variables, and optimization objective) can be defined.

Fiber connection and RWA algorithms have been developed for solving the filterless network design and planning problem. The algorithms were integrated into a filterless network design and simulation (FNDS) tool developed in a MATLAB environment. For a given network physical topology and traffic matrix, this tool makes it possible to determine a fiber connection matrix and to perform the RWA for all connection requests. Various solutions can be obtained, depending on the specific optimization parameters (number of wavelengths, number of fiber trees, number of passive optical dividers, etc.). The main network characteristics can be further extracted from the simulation results and used for performance analysis.

In the first step, a fiber connection algorithm is used for interconnecting the nodes by using optical splitters and combiners without creating closed loops that would generate laser effects in the optically amplified links. It is assumed that the tunable transceivers are equipped with electronic dispersion-compensating modules. The only physical layer impairment considered in the fiber connection algorithm is the system's reach, which sets a maximum distance for any root-leaf combination in a fiber tree. The objective is to establish a set of fiber trees that not only satisfies all the connection requests, but ensures that all the nodes can be physically connected. This flexibility is essential in case additional connection requests are required after the initial set of fiber trees has been constructed. Given the problem's complexity, a genetic algorithm adapted from previous work [6] was used to explore the extremely large search space, in order to find optimal or at least near-optimal fiber-tree solutions among a population of candidates. Fitness values are attributed to these candidates, which are based on the network's total connectivity and the average connection length.

In the second step, routing is performed by selecting the shortest path for each connection. The wavelength assignment process is finally accomplished as a graph coloring problem with a Tabu search metaheuristic adapted from previous work [6]. Routing results are transposed into a conflict graph, where nodes represent the network's traffic demands. According to the wavelength singularity constraint, conflicts exist between connections when there is at least one common link in their paths, forcing an assignment of different colors (or wavelengths).

As a result, the FNDS tool provides filterless network solutions for performance and cost analysis, along with comparisons with other network architectures.

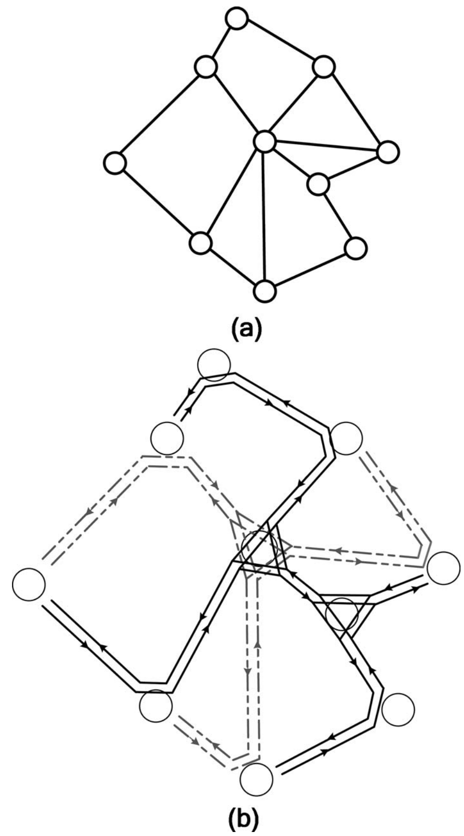

Fig. 2. The Italian network [7]: (a) Network topology (10 nodes, 15 links, 830 km diameter); (b) two-fiber-tree filterless network solution. The longest fiber tree is 1230 km. A total of 18 passive optical splitters and combiners are used for link interconnection.

IV. Proposed Filterless Network Solutions

To validate the filterless network concept and to test the FNDS tool, simulations were conducted on three different network topologies. The filterless network solutions were compared to active photonic network solutions, in terms of network cost, wavelength utilization, average demand length (latency), and average number of fiber link segments per demand.

Three network topologies were considered in this work: the 7-node subset of the German network (Fig. 1), the 10-node Italian network [7] (Fig. 2), and the 17-node German network [5] (Fig. 3). These topologies cover a good range of networks, with 15 links and a diameter of 830 km for the 10-node Italian network and 26 links and a diameter of 951 km for the 17-node German network.

Figures 2(b) and 3(b) show the filterless solution examples obtained with the FNDS tool for the 10-node and 17-node network topologies, respectively. In both cases, two fiber trees were used for interconnecting all the nodes in the network. Assuming a uniform traffic matrix between nodes (e.g. 1 wavelength for every possible connection), 25 and 88 wavelengths were used in the 10-node and the 17-node network, respectively.

The proposed filterless network solutions satisfy the following constraints.

1. The laser loop constraint: no closed loop is allowed in interconnecting the nodes with splitters and combiners, in order to avoid laser effects.
2. The fiber-tree length constraint: the maximum fiber-tree length for any leaf–root combination was limited to 1500 km, which represents a realistic reach value for a long-haul WDM transmission system.
3. The wavelength utilization constraint: for wavelength assignment, filterless solutions that minimize the number of wavelengths used were chosen.

The filterless solution examples assumed an unprotected traffic demand. But, because of the broadcast nature of filterless networks, more than one path can intrinsically exist for routing the traffic between two nodes, which provides a protection path for some of the connection requests. It is interesting to note that the 1+1 protection level (defined here as the ratio of protected demands to the total number of demands in the traffic matrix) was found to be 71%, 47%, and 33% for the proposed 7-node, 10-node, and 17-node network solutions, respectively. Although this aspect has not been fully covered in this study, it can be assumed that extra traffic protection could be provided through complementary fiber trees and extra capacity built in

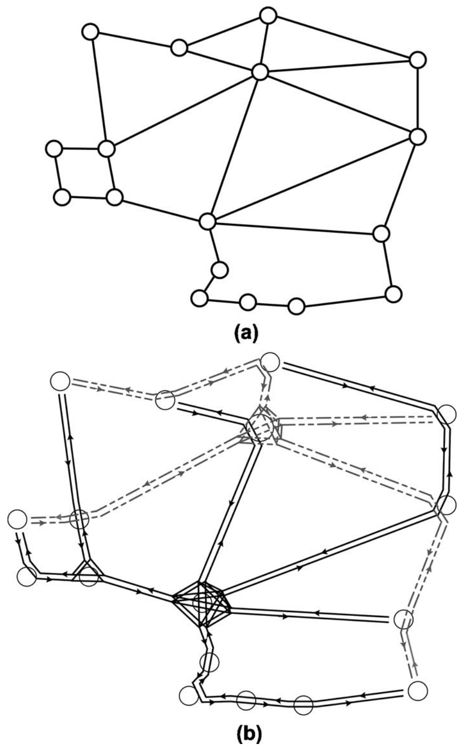

Fig. 3. The German network [5]: (a) Network topology (17 nodes, 26 links, 951 km diameter); (b) 2 fiber-tree filterless network solution. The longest fiber-tree is 1468 km. A total of 52 passive optical splitters and combiners are used for link interconnection.

at nodes. Network migration and growth constitutes another aspect that remains to be explored for filterless networks. At this point, it is assumed that new nodes could be connected to the fiber trees as a filterless network grows, as long as the new connections satisfy the constraints and extra splitters and combiners are planned for connecting new nodes.

V. Performance and Cost Comparison

In this section, the filterless solutions presented in the previous sections are compared with active photonic switching solutions with respect to network parameters and costs.

The active photonic network solutions considered in this study are based on wavelength-selective switch (WSS) devices, which perform per wavelength routing in the optical domain. As shown in previous work [1], these active photonic switching network solutions can be considered a best-case scenario over opaque networks in terms of cost, switching capacity, and latency. To achieve full switching capability, we assumed that a WSS was required for every fiber connected to nodes. A total of D WSSs were thus needed at nodes with a node degree D greater than 2 [8]. Optical amplification (preamplifiers and postamplifiers) was also added to compensate for the WSS insertion loss.

TABLE I
Comparative Study: Added Cost (17-Node German Network)

Network Solution[a]	Extra Components	Quantity	Unit Cost (a.u.)	Total Cost (a.u.)
Active photonic[b]	WSS[c]	38	2.5	95
	Optical amplifiers	76	1.3	98.8
			Total added cost	*193.8*
Filterless	Passive splitters	52	0.02	1.04
			Total added cost	*1.04*

[a]Uniform traffic matrix (one wavelength per connection).

[b]Active photonic solution obtained by minimizing demand length.

[c]One WSS per link (which corresponds to a number of WSS per node equal to the node degree for node degrees greater than 2) and two optical amplifiers per WSS.

A comparative cost study is presented in Table I for the 17-node German network (Fig. 3). In that exercise, only the passive routing cost (using passive optical splitters and combiners in the filterless case) or the active switching cost (using WSS and associated optical amplifiers in the active photonic solution) are considered in the calculation. The unit costs of the devices (indicated in arbitrary units) can be considered to be fairly representative of their relative costs. The total cost obtained for a network solution is referred to as the “added cost.”

The results for the 17-node German network, presented in Table I, show a significant cost advantage for the filterless solution. The added cost in the active photonic solution derives from the use of 38 WSS and 76 optical amplifiers. In the filterless network solution, a total of 52 passive splitters and combiners are used for link interconnection. The added costs were also calculated for the other two reference network topologies considered in this study. The results, pre-

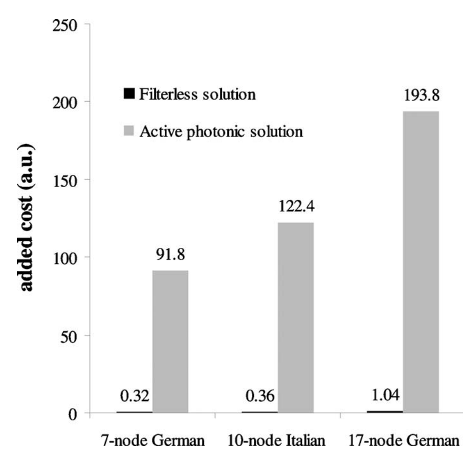

Fig. 4. Cost comparison of filterless and active photonic switching solutions.

TABLE II
NETWORK PARAMETERS FOR FILTERLESS AND ACTIVE PHOTONIC SOLUTIONS

Network Topology	Solution	Average Demand Length (km)	Average No. of Fiber Link Segments per Demand	No. of Wavelengths	Added Cost (a.u.)
7-node German[a]	Active photonic[c]	349	1.51	30 (40)[d]	91.8
	Filterless	374	1.57	37	0.32
10-node Italian[b]	Active photonic	407	2.02	28 (22)	122.4
	Filterless	488	2.27	28	0.36
17-node German[b]	Active photonic	414	2.84	82 (56)	193.8
	Filterless	480	3.16	88	1.04

[a]Traffic matrix in Table 9 of [5], assuming one wavelength per 10 Gbits/s of traffic.

[b]Uniform traffic matrix (e.g., one wavelength per connection).

[c]All active photonic solutions obtained by minimizing demand length.

[d]Number of wavelengths shown in parentheses, obtained through minimizing the number of fiber link segments.

sented in Fig. 4, indicate that filterless network solutions could potentially bring about significant cost savings.

Table II summarizes the network parameters and costs for the filterless and active photonic solutions considered in this study. For this comparative exercise, routing was performed by selecting the shortest path for each demand. This procedure was not completely fair, as active photonic solutions with lower wavelength utilization could be obtained through minimizing the number of fiber link segments, as shown by the numbers in parentheses in Table II. However, the results show that filterless network solutions can compare well with active photonic switching solutions in terms of wavelength utilization.

Simulations carried out on the 7-node German network topology show that the number of wavelengths required to meet a traffic demand corresponding to 3 times the traffic matrix in [5] could be decreased from 105 to 74 by adding 3 wavelength blockers to the network. Further work is required in order to allow the FNDS tool to optimize the number of wavelength blockers and their placement in the network, but this result shows how these optional devices could be used in a filterless network for minimizing wavelength utilization.

VI. CONCLUSION

In this paper, the filterless network concept and a filterless network design and simulation tool were presented and validated on three different network topologies. Filterless network solutions were proposed for the three reference network topologies and compared with active photonic switching solutions from the point of view of cost and performance. The results show that filterless solutions can be found for different network sizes and topologies and that the proposed solutions are cost-effective relative to active photonic switching solutions. Furthermore, the number of wavelengths used in filterless networks can be kept within reasonable limits through optimization and could be potentially lowered by using only a few wavelength blockers. Based on the results of three reference networks, we can conclude that filterless networks could support the same level of traffic as active photonic networks, but at significantly lower cost.

To obtain more realistic filterless network solutions, the design tool needs to be refined in order to include the main physical impairments that can be expected to affect the performance of filterless optical links, e.g. amplified spontaneous emission noise accumulation and passive splitter–combiner insertion loss. To fully demonstrate the robustness of filterless networks and their real-world applicability, further simulation work needs to be carried out using different traffic schemes and levels, as well as more complex network topologies. Network migration and growth, and also traffic protection, are other aspects that need to be explored.

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Émile Archambault was born in Montréal, QC, Canada, in 1979. He received the B.Eng. degree in microelectronics from the Université du Québec, Montréal, QC, Canada, in 2002 and the M.Eng. degree in electrical engineering from the École de technologie supérieure, Montréal, QC, Canada, in 2008. Since 2009, he has been a Professor with the Department of Electrical Engineering, CEGEP de Rimouski, Rimouski, QC, Canada.

Daniel O'Brien was born in Montréal, QC, Canada, in 1989. He is currently working toward the B.Eng. degree in electrical engineering at École Polytechnique de Montréal, Montréal, QC, Canada. He was awarded a Québec Millennium Excellence Award in 2008. Since 2007, he has been working part time with the Department of Electrical Engineering, École de technologie supérieure (ÉTS), Montréal, QC, Canada, focusing on modeling and optimization of wavelength-routed networks. His research interests include NP-complete optimization problems in optical networks and the use of different metaheuristic algorithms.

Christine Tremblay received the B.S. degree in engineering physics from Université Laval, Québec City, QC, Canada, in 1984; the M.Sc. degree from INRS-Énergie, Varennes, QC, Canada, in 1985; and the Ph.D. degree (optoelectronics) from the École Polytechnique de Montréal, Montréal, QC, Canada, in 1992. She was a Research Scientist with the National Optics Institute (INO) from 1991 to 1998 where she conducted research on guided-wave optical devices for communication and sensing applications. Between 1998 and 2004, she held senior R&D and technology management positions for several organizations. As Engineering Manager at EXFO and Director of Engineering at Roctest, she was responsible for the development of fiber optic test instruments for the telecommunication and geotechnical markets, respectively. She also served as Product Manager at Nortel for DWDM systems. Since 2004, she has been a Professor with the Department of Electrical Engineering, École de technologie supérieure (ÉTS), Montréal, QC, Canada. Her current research interests include the exploration of novel optical network architectures and the development of monitoring techniques for passive optical networks (PON). At ÉTS, she set up the Laboratoire de technologies de réseaux, an advanced WDM physical layer testbed for studying optical transmission and networking technologies. Dr. Tremblay is a member of the Optical Society of America (OSA) and the IEEE Photonics Society.

François Gagnon received the B.Eng. and Ph.D. degrees in electrical engineering from École Polytechnique de Montréal, Montréal, QC, Canada. Since 1991, he has been a Professor with the Department of Electrical Engineering, École de Technologie Supérieure, Montréal, QC, Canada. He chaired the department from 1999 to 2001 and is now the holder of the NSERC Ultra Electronics Chair, Wireless Emergency and Tactical Communication, at the same university. His research interest covers wireless high-speed communications, modulation, coding, high-speed DSP implementations, and military point-to-point communications. He has been very involved in the creation of the new generation of high-capacity line-of-sight military radios offered by the Canadian Marconi Corporation, which is now Ultra Electronics Tactical Communication Systems. The company has received, for this product, a "Coin of Excellence" from the U.S. Army for performance and reliability. Prof. Gagnon is a recognized leader in research management; he maintains activities with more than 10 companies: Ultra, ISR Technology, Sita, Ericsson, Lipso, Nortel, Bell, Octasic Semiconductors, Sierra Wireless, Boomerang, and IREQ. Prof. Gagnon was awarded the 2008 NSERC Synergy Award (Small and Medium-Sized Companies category) for the fruitful and long-lasting collaboration with Ultra Electronics TCS.

Michel P. Bélanger received the B.Eng degree in electrical engineering from École Polytechnique de Montréal, QC, Canada, in 1979 and the Ph.D. degree in electrical engineering (guided-wave optics) from McGill University, Montréal, Québec, Canada, in 1987. He held R&D positions at École Polytechnique de Montréal and at Canadian Marconi. With the National Optics Institute of Canada, he conducted research into the design and application of guided-wave optical components and diffractive optical elements. After a brief period at Teleglobe working in submarine system engineering, he joined Northern Telecom (now Ciena Corporation) in 1995 as Product Manager for DWDM systems. Later, he moved to the optical development group as a Member of the Scientific Staff. He is currently leading a group developing deployment strategy for coherent, high-capacity, optical systems.

Éric Bernier graduated with Honours B.Eng. and M.Eng. degrees specializing in photonics telecommunication at McGill University, Montréal, QC, Canada, in 2000. As Chief Technology Officer since 2008, Mr. Bernier leads and manages the conception, design, and operation of CANARIE's advanced network infrastructure for research and education. Prior to joining CANARIE Inc., Mr. Bernier held positions of increasing responsibility as a researcher and project manager in the CTO Office at Nortel in Ottawa. During his 8 years with Nortel, Mr. Bernier was involved in managing collaborative projects with several National Research and Experimental Networks. He has led projects with many of CANARIE's peer network organizations and participated extensively in the development of preproduct optical communication systems.