Authors' accepted manuscript.
Article accepted for publication in the *Journal of Optical Communications and Networking*.
Version of record will be available at: https://opg.optica.org/jocn/home.cfm

Cost and Energy Efficient Filterless Architectures for Metropolitan Networks

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Received 01 February 2023; revised 18 June 2023; accepted 06 July 2023; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

The network operators are forced to find cost and energy efficient solutions for networks supporting new and emerging services with strict latency and ultra-high-capacity requirements. A disruptive approach for delivering network agility in a cost and energy efficient manner is employing filterless optical networking based on broadcast-and-select nodes and coherent transceivers. The filterless network concept has been widely studied for terrestrial and submarine applications. In this paper, we investigate performance of filterless optical networks in metropolitan core and aggregation networks where agility is required due to service dynamics, customer changes and service flexibility requirements. We compare our results with a conventional metro network based on active switching. The results show that filterless metro network based on a hierarchical structure similar to its active switching counterpart has comparable installed first cost and spectrum usage at 11 Tb/s of total traffic, as well as a cost and wavelength consumption advantage of 19.5% and 16%, respectively, at 107 Tb/s of total traffic. These results confirm that the filterless architecture is an attractive alternative for metro network deployments. © 2023 Optica Publishing Group

http://dx.doi.org/10.1364/JOCN.99.099999

1. INTRODUCTION

The ceaseless traffic growth and the competitive telecommunications market necessitate re-thinking network architectures for profitable operation. To reduce the network cost while efficiently maintaining capacity growth, network operators are examining novel solutions that also ensure flexible service support. Today's networks support flexibility at all levels including agile wavelengths, which brings significant operational expenditure (OpEx) benefits. Agility at the wavelength level refers to the reconfigurable wavelength routing. In today's optical networks, wavelength agility is provided by active switching elements such as reconfigurable optical add-drop multiplexers (ROADMs) [1]. In order to improve the profitability, one can eliminate or minimize the number of active photonic reconfigurable elements in optical line systems [2]. This can be realized thanks to the technological advancements in coherent transmission such as electronic impairment compensation, tunable transmitters and coherent receivers, which makes it possible to implement the filterless network concept.

In our previous work, we have shown that agility can be realized by employing the filterless concept in terrestrial networks [3-5] and submarine networks [6-8] with some trade-offs. A key benefit of this option is that it offers an intrinsically gridless passive architecture making it inherently suitable for elastic optical networking. Consequently, filterless solutions are being explored, with some deployments, by network operators, for application in regional and core networks. In fact, filterless optical networks have been trialed and deployed in Europe since 2012 [9,10]. The previous studies indicate strong potential of filterless networks to support flexible and cost-efficient core and submarine networking solutions. However, their suitability in the rapidly evolving metro segment where agility is required due to service dynamics, customer changes and service flexibility requirements has not been analyzed thoroughly and requires further examination. Metro optical networks are currently under pressure as a consequence of the exponential traffic growth generated by residential, enterprise and data center (DC) services such as media streaming, Virtual Private Network

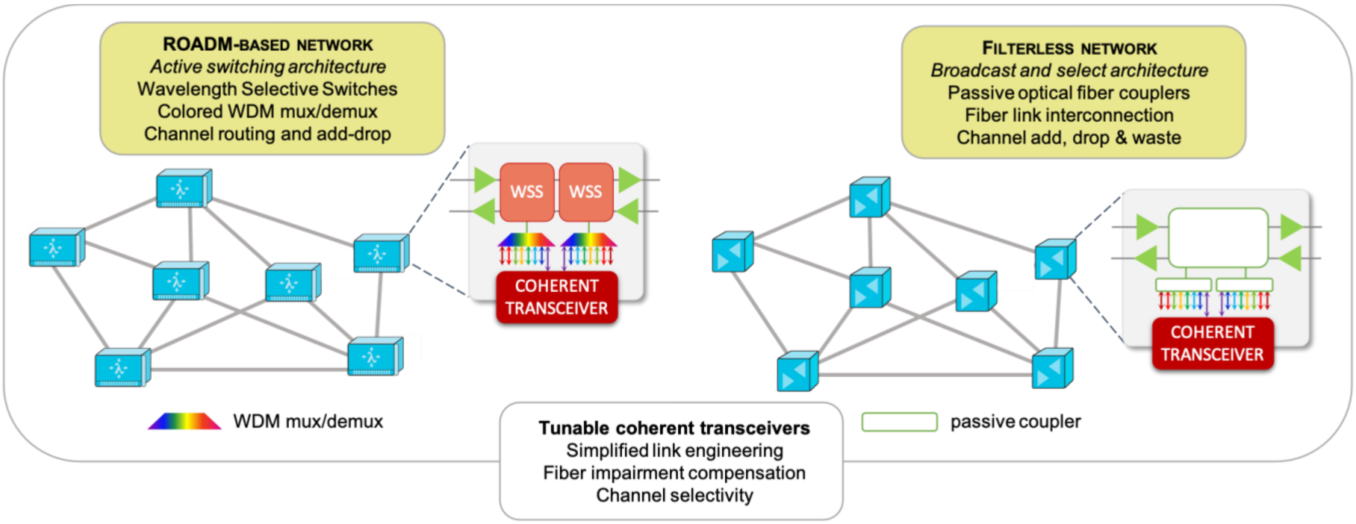


Fig. 1. Contrasting ROADM-based and filterless network architectures.

(VPN), Internet, as well as wireless 4G, 5G and beyond networks.

In [11], we performed a preliminary investigation of the significance of filterless solutions in the metro environment by comparing a ROADM-based and an equivalent filterless solution based on the same 3-layer hierarchical structure. It was shown that the cost of this particular filterless metro solution was comparable to the cost of a conventional metro solution. In [12], we proposed an additional single-layer filterless solution more suitable for broadcast transmission in passive fiber trees.

In this paper, we extend the work presented in [12] by introducing a three-layer filterless solution and conducting a comparative analysis of the cost, wavelength usage and power consumption of both single-layer and 3-layer filterless network solutions and their ROADM-based counterparts in a multi-period scenario. Based on the results, we discuss the benefits and trade-offs of filterless metro networks.

The paper is organized as follows. Section II summarizes the concept and advantages of filterless networks in core applications. In Section III, we propose filterless architectures for a metropolitan network scenario. A comparative analysis of filterless and conventional active switching solutions in terms of cost, wavelength usage and power consumption is carried out in Section IV. Finally, Section V provides concluding remarks on the suitability of filterless architectures in metro applications.

2. FILTERLESS NETWORKING CONCEPTS

Filterless and active switching network architectures are contrasted in Fig. 1. Currently, reconfigurable optical networks are built with ROADMs utilizing active wavelength selective switch (WSS) elements. The filterless network architecture, first introduced in [2], utilizes the characteristics of coherent optical transmission to deliver network agility at lower cost compared to the ROADM based approach. Unlike ROADM-based architectures, where reconfigurability is realized via active photonic switching elements at selected network nodes, filterless networks rely on tunable edge nodes equipped with coherent transponders to deliver reconfigurability, and deploy passive optical splitters and combiners at network nodes. The optical fiber links interconnected by passive splitters and couplers form a set of passive fiber trees. The absence of active switching and filtering components results in a broadcast-and-select network. The edge terminals perform wavelength selection by adjusting the frequency of the local oscillator in tunable coherent transceivers and filtering the desired signal in baseband.

The system benefits of filterless optical networks are many-fold. The removal of WSSs translates into simplified optical line systems with lower cost, footprint, and power consumption, as demonstrated in [5,6,8]. This simplification also improves robustness to hardware and software malfunctions and improves the network reliability performance by increasing the mean time between failures (MTBF) [13]. In addition, the absence of filters makes filterless networks intrinsically gridless and thus inherently suitable for elastic optical networking and innovations such as dynamic spectrum allocation. Moreover, colourless node operation is possible since terminals can access all Dense Wavelength Division Multiplexing (DWDM) wavelengths and select the specified channels. The broadcast nature of filterless optical networks implies the innate support of multicast traffic. Other benefits include easy network planning, and fast connection establishment [14]. By allowing the traffic from higher protocol layers to be handled more easily and cost-effectively in bulk at the wavelength layer compared to active switching nodes, the passive channel bypass and add-drop functionality at filterless nodes is a key enabler for multilayer networking. Moreover, simpler impairment-aware routing in filterless networks makes software-defined networking (SDN) control more straightforward [15].

Filterless network solutions have been proposed initially for terrestrial and submarine applications [4,5,16-20]. As expected, it was shown that the replacement of switching and filters in core network nodes by simple passive fiber couplers leads into significant cost savings. Similar cost studies carried out on undersea network topologies have shown reductions of 30-44% in terminal costs and 11-12% in line equipment costs when compared to conventional submarine network solutions based on ROADMs deployed at the cable landing stations only [6-8,19]. Application of filterless architecture in metropolitan networks has also been proposed first in [11] and studied further in [12,22-25,26]. A tutorial on filterless optical networks can be found in [27].

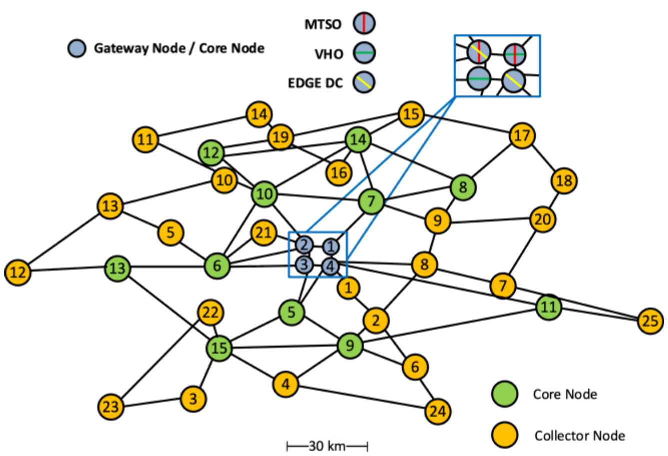


Fig. 2. Metropolitan optical network topology composed of 25 collector nodes, 15 core nodes and 4 gateway nodes. [12,32]

Spectrum consumption in filterless networks has been studied extensively [4-8,16-21,28]. The results show that fixed-grid filterless network approaches can consume 10-50% more spectrum than ROADM-based solutions, depending on the physical topology and traffic load. The higher spectrum consumption is mainly due to the signal splitting mechanism into the passive filterless branches of a fiber tree, and the broadcast transmission from the source to the destination nodes where unfiltered signals are not terminated and propagate beyond the destination nodes. Additional 20-30% savings in spectrum consumption are possible through flex-grid operation which can be achieved at minimal upgrade cost in filterless networks [5,18]. Multi-band transmission using an unamplified L-band system has also been proposed to increase the capacity of metro filterless networks [29].

The presence of these unfiltered signals magnifies wavelength or spectrum consumption, as the spectral resources occupied by these channels cannot be reused for other connections. The extra wavelength consumption issue can be alleviated by adding wavelength blockers (or colored fixed passive filters) in optimal locations between fiber trees. This hybrid approach, referred to as semi-filterless networks [30,31], offers reduced propagation of unfiltered channels between the nodes.

In addition, a programmable filterless network architecture can be realized by combining filterless transmission with programmable optical switches, thus making filterless networks more flexible 19. By adapting the node architecture to the network traffic, the programmable filterless networks can reduce splitting ratios and the resulting optical losses, as well as reduce the spectrum waste.

As shown in previous studies, filterless solutions are most suitable for networks with a small number of nodes (≤ 10-12) and size (with respect to system transmission reach), as well as relatively high average connectivity (≥ 0.8) and high average nodal degree (≥ 3.0) [3-8,16].

Encouraged by these properties and by the evolution of metropolitan networks we are investigating application of filterless networks in metropolitan areas. A preliminary comparison in terms of wavelength and power consumption of a single-layer filterless and ROADM-based network solutions was presented at IEEE FNWF 2022 [12]. In the following sections we extend the preliminary work by considering a three-layer filterless solution and performing a comparative performance analysis with their ROADM-based counterparts in terms of cost, wavelength and power consumption.

3. CONSIDERED METRO AND AGGREGATION NETWORKS ARCHITECTURES

A. ROADM-based metropolitan network

An example of ROADM-based metropolitan optical network for the transport business of an incumbent service provider is shown in Fig. 2. The network topology (based on a North American city of about 5 million population such as Atlanta, GA) consists of 60 Tier 3 end office nodes (EOs) which are connected directly to adjacent pairs of 25 Tier 2 collector nodes (CollNs), then to 15 Tier 1 core nodes (CNs) and 4 gateway nodes (GNs) using diverse paths [12]. The 60 EOs (not shown in Fig. 2 for the sake of simplicity) are located at the suburban edge where the access systems and wireless sites collect and distribute services to the clients. For traffic replication and protection considerations, each CollN is connected to 2 CNs, each CN is connected to 4 other CNs as well as to the 4 GNs, either directly or via another node. The traffic leaving the metro network and destined to the core network pass by the GNs. Two video hub offices (VHO), as well as two edge data centers (DCs) and mobile telephone switching offices (MTSOs) are co-located at GNs.

The ROADM-based solution is composed of three layers for CollN-CN, CN-CN and CN-GN interconnection, respectively. The layers are interconnected through electronic multiplexers at inter-layer nodes. Coloured channel mux/demux (fixed filters) and WSS-based ROADMs are commonly deployed at all nodes. Optical amplifiers are used at the terminal sites for intranode loss compensation but, given the short distances at play, no line amplifier is used. The total lit distance is 1813.3 km (i.e., 237.6 km for the CollN-CN layer, 692.7 km for the CN-CN layer and 21.6 km for the CN-GN layer). Within each layer, traffic between node pairs is interconnected using a ROADM.

Fig. 3 shows the network traffic scenario considered in this

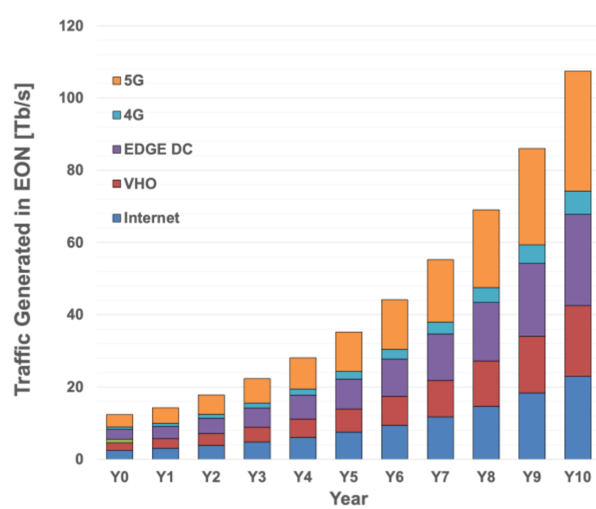


Fig. 3. Network traffic scenario considered in this study. [12]

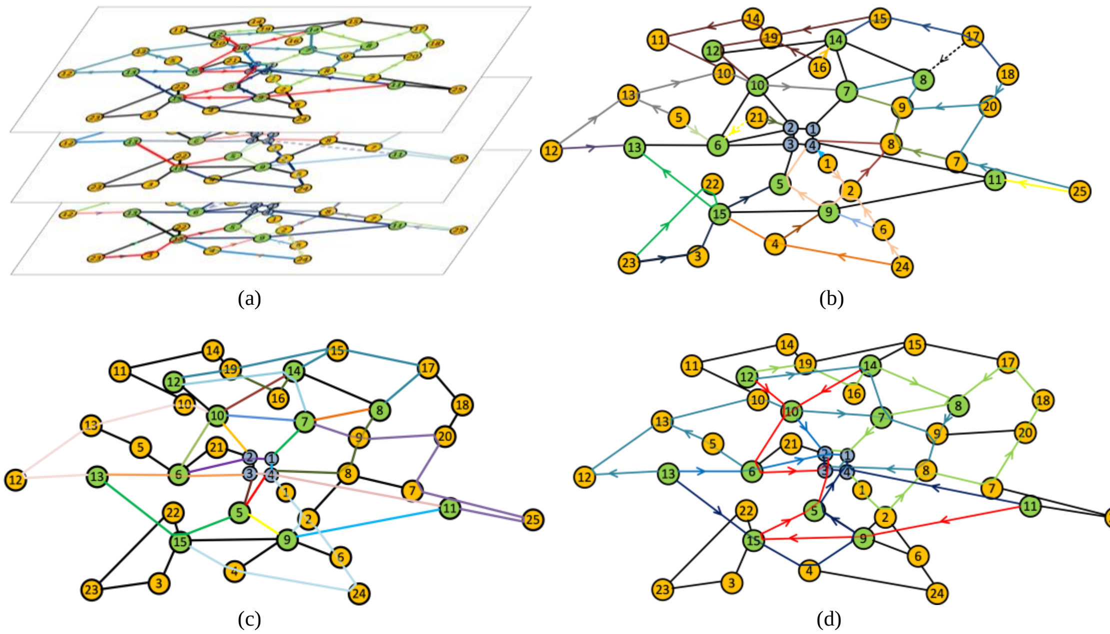


Fig. 4. Three-layer filterless network solution example (a) for interconnecting the collector nodes to the core nodes, layer 1 (b), the core nodes, layer 2 (c), and the core nodes to the gateway nodes, layer 3 (d).

study. The network traffic originates from services delivered to residential, business, and wireless 4G and 5G clients. Traffic volumes are derived from an end user consumption perspective considering the following:

- Residential: busy hour loading, linear and on-demand entertainment video dominant services (VHO);
- Small, medium and large enterprise: virtual private network (VPN) and Internet services (Wired Internet);
- Very large enterprise: DC traffic (Edge DC);
- Wireless voice and data (4G and 5G).

The total volumes of traffic in Fig. 3 are obtained by summing the different traffic types at the EOs. A uniform yearly growth of 25% is assumed for all services over the 10 growth periods considered in this study [33]. Note that the same growth factor has been applied to VHO traffic although growth is likely to be much slower due to service substitution by streaming entertainment. The overall impact on traffic volumes is inconsequential to the study.

B. Three-layer filterless solution

A 3-layer filterless solution for the metro network example is shown in Fig. 4. The solution is composed of three layers, each comprising a set of passive edge-disjoint fiber trees (represented in different colors). Based on capacity demand and fiber topology, the fiber trees are created using passive optical splitters and combiners by taking into account the network connectivity, laser loop and 20 spans x 20 km system reach constraints [3]. As for the ROADM-based solution, the layers are interconnected via electronic multiplexers at the inter-layer nodes. The first layer, shown in the bottom of Fig. 4a and Fig. 4b, interconnects the 25 collector nodes to the 15 core nodes. The second layer (Fig. 4c) interconnects the core nodes for traffic replication purposes. Finally, the five fiber trees shown in the top layer of Fig. 4a and Fig. 4d connect the core nodes to the gateway nodes. The ingress/egress nodes in the filterless solution are equipped with passive colorless power combiners/splitters for channel add/drop as well as optical amplifiers for compensation of power loss in splitters and fibers.

This filterless solution was obtained in a non-optimized manner by re-using the same network segmentation (layering strata) and connectivity constraints as in the ROADM-based solution. This approach, although not the best suited for the filterless case, was used to compare two network architectures delivering similar traffic connectivity.

C. Single-layer filterless solution

In this section, we consider the filterless solution based on lower network connectivity proposed in [12], which is more suitable for the passive broadcast transmission than the previously

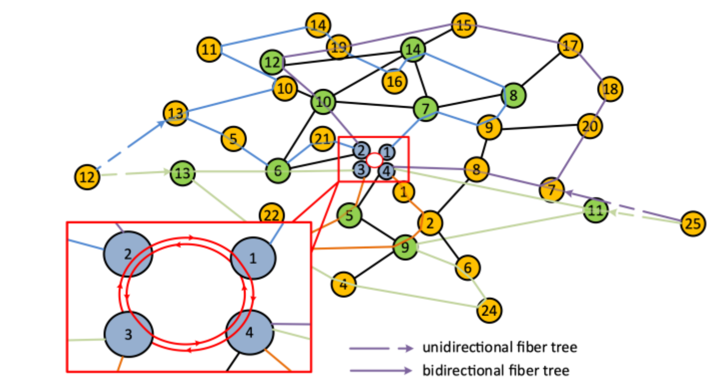
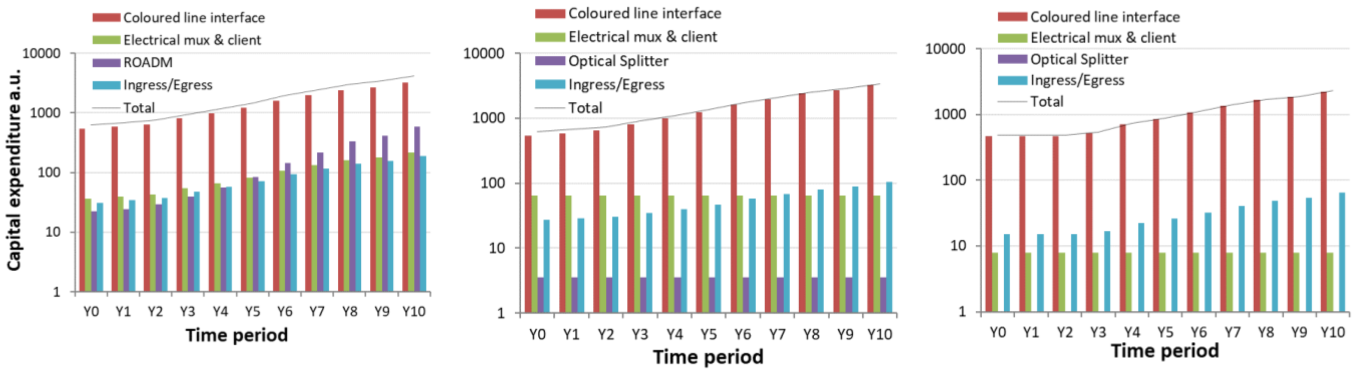


Fig. 5. Single-layer filterless network solution based on lower connectivity constraints, compared to the ROADM-based and 3-layer filterless solution. Each CN and each CollN is connected to 4 GNs, and the 4 GNs are interconnected [12].



(a) (b) (c)

Fig. 6. Cost comparison: (a) ROADM-based solution; (b) three-layer filterless solution; (c) single-layer filterless solution.

described three-layer case. Fig. 5 shows the single-layer filterless solution in which each CN and each CollN is connected directly to the 4 GNs at the wavelength level, and the 4 GNs are interconnected. The solution comprises 5 bi-directional fiber trees, created by considering the same laser loop and fiber tree length constraints as for the three-layer case.

4. COMPARATIVE PERFORMANCE ANALYSIS

In this section, a comparative performance analysis of the two filterless solutions and the ROADM-based solution, in terms of cost, wavelength consumption and power consumption, is performed in order to evaluate the potential benefits and trade-offs of filterless metro network architectures. A 60-channel fixed-grid transmission system at 200 Gb/s per wavelength and a link budget enabling 20 spans of 20 km is considered in this study. High-capacity interfaces used in metro applications are evolving from 100 Gb/s and 200 Gb/s to 400 Gb/s, 800 Gb/s and 1.2 Tb/s in the future. 200 Gb/s is a common speed offering; for example, high performance server network interface cards (NICs) are 200G. 200G per channel was selected as a representative capacity in this study. The total client metro traffic is considered over 10 growth periods, as shown in Fig. 2. The unit cost and power consumption values for each component are shown in Table 1. The costs and power consumption values of the network elements are normalized to those of a 200G transceiver.

A . Cost

In this section, the costs of the filterless and ROADM-based metro solutions are evaluated over 10 growth period using the cost data in Table 1. In both the filterless and the filtered solutions, the terminal/ROADM common equipment includes the cost of an electronic switch.

As shown in Fig. 5, the 3-layer filterless solution has lower cost than the ROADM-based solution over all the traffic periods, with a slightly lower installed first cost and a 19.5% cost benefit at period 10. These results contrast with those obtained in our previous studies for regional and core networks in which the cost of the filterless solution was significantly lower than that of a conventional ROADM solution. The origin of the difference in regional and core applications is due to replacement of switching and filtering elements by fiber couplers, as explained in [12]. The cost advantage of the single-layer filterless solution is greater and goes from 21.7% to 45.4% during the growth periods. The key mechanisms behind these savings are the lower number of transceivers and electrical multiplexers, as well as the absence of ROADMs. The cost advantage is obtained in this case at the expense of lower connectivity. Fig. 7 shows the combined cost evolution of all three architectures, where the cost of the single-layer filterless network exhibits the lowest growth rate.

Beside the cost advantages of the filterless (particularly the single-layer) solutions compared to the ROADM-based solution, there are several intrinsic positive features of the filterless solution that need to be considered. For example, the inherent gridless architecture making it ready for flexi-grid operation. Cost benefit can also be expected in the long run due to cost

Table 1. Component cost and power consumption. [12,32]

Component	Unit cost	Unit power	Unit power/λ
200G transceiver	1.000	1.00	1.0000
Electrical mux and client	2.000	1.44	0.0240
ROADM (1×9 WSS)	1.500	1.44	0.0240
EDFA (ingress/egress)	0.800	1.15	0.0192
Mux/demux	0.050	0	0
Splitter/combiner	0.015	0	0

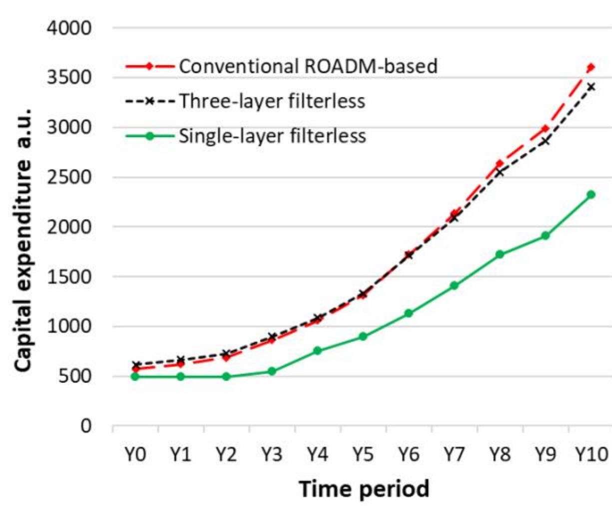


Fig. 7. Evolution of the network costs.

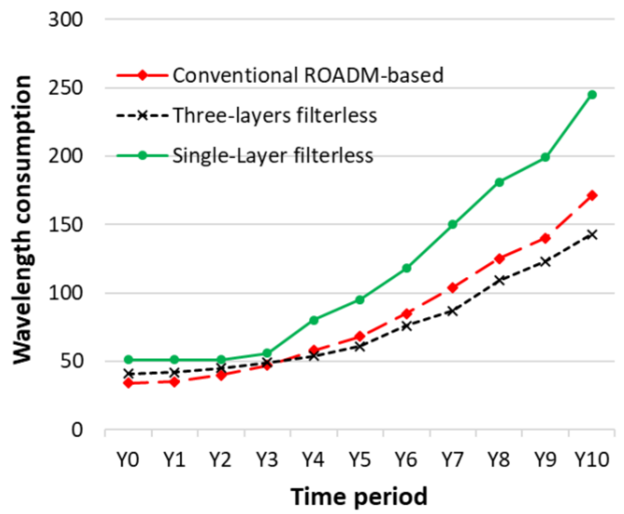


Fig. 8. Evolution of the wavelength consumption.

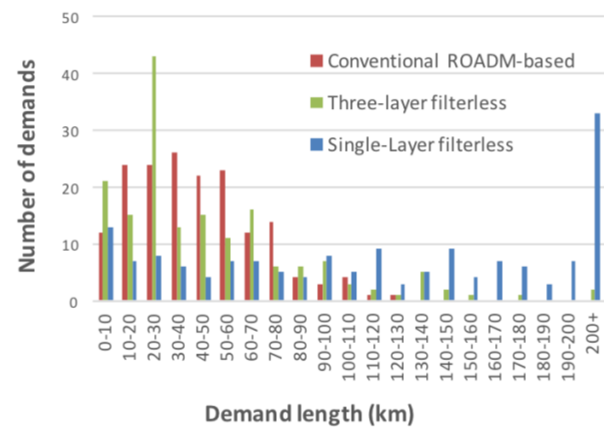


Fig. 9. Histogram of the demand lengths.

efficient support of traffic growth and network upgrades over the years, which can be observed in the results. Further savings on operational costs can arise from the lower power consumption and the lower failure rates of the passive components [12,13].

B. Wavelength consumption

In this section, the wavelength consumption for the ROADM-based and filterless solutions over the 10 growth periods is evaluated. Shortest-path routing over the fiber trees and first-fit wavelength assignment was used for all the demands. As shown in Fig. 8, the wavelength consumption of the 3-layer filterless network and the ROADM-based solutions is similar during the first four traffic periods. In both cases, CN1-CN4 is the highest load link and the average demand length is similar (54.7 km in the filterless case and 46 km in the ROADM-based case). At period 3 (21 Tb/s), the 3-layer filterless solution utilizes only 4% more wavelengths than its active switching counterpart. As the total traffic increases, the 3-layer filterless solution outperforms the ROADM-based approach by 16% at period 10. This can be seen as counterintuitive, but note that the shortest path in the filterless case corresponds to the shortest path along a given fiber tree, resulting in a number of wavelengths which depends on the architecture of the fiber trees. As it can be seen on Fig. 8, the 3-layer filterless solution benefits from a narrower distribution of demand lengths around 20-30 km compared to its ROADM-based counterpart. The majority of short demand length s, compared to the ROADM-based case, explains the advantage of 3-layer filterless approach in terms of wavelength consumption.

On the other hand, the single-layer filterless solution consumes 19% more wavelengths compared to the ROADM-based case at period 0. In this case, CN4-CN3 is the highest load link and the average demand length is 127.6 km. A histogram of the established path lengths for all three analyzed architectures is shown in Fig. 9. The longer path length in the single-layer filterless case leads to a higher total wavelength usage for this solution. Furthermore, the rate of increase of the wavelength consumption for the single-layer filterless solution is higher than for the two other solutions, which makes the single-layer filterless option perform worse at very high traffic levels. The 43% extra wavelength consumption observed for the single-layer filterless solution at year 10 matches with the results of our previous long distance core network studies [3-8,16].

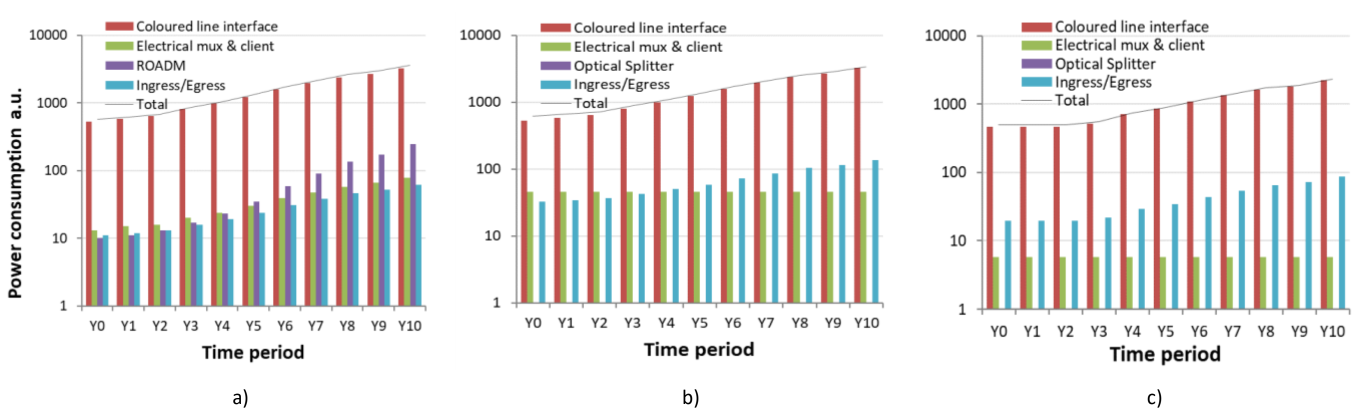


Fig. 10. Comparative power consumption: (a) conventional ROADM-based solution; (b) three-layer filterless solution; (c) single-layer filterless solution.

C. Power consumption

The power consumption of the filterless and ROADM-based solutions is studied in this section. Fig. 10 presents results for the power consumed by each sub-system in each of the considered architectures. In all cases, the colored line interfaces consume the dominant amount of power, whose growth exhibits similar trends as the traffic increases. The three-layer filterless solution exhibits less power consumption to the ROADM-based solution, thanks to the removal of the active switching ROADM elements. The single-layer filterless solution brings additional savings on the power consumed by electrical mux and clients due to the absence of inter-layer nodes and, hence, a lower extent of electronic multiplexing.

Fig. 11 shows the evolution of the power consumption for the three considered network architectures. The power consumption of the 3-layer filterless and ROADM-based solutions is very similar for all the traffic periods, with 6% savings for the filterless case. As expected, the power savings are greater for the simplest (single strata) solution, increasing from 14% to 36% as traffic increases.

5. CONCLUSIONS

In this paper, the feasibility of applying filterless architectures in metropolitan networks has been evaluated.

A case study comparing cost, wavelength and power consumption in a multi-period traffic growth scenario has been carried out. The results show that filterless metro network based on a hierarchical structure and network connectivity similar to its active switching counterpart has comparable installed first cost and spectrum usage (i.e., at 11 Tb/s total traffic in the beginning of the considered time period), while the cost and wavelength consumption advantage of 19.5% and 16%, respectively, can be observed over the 10-year growth period (with maximum of 107 Tb/s of total traffic).

The novelty in this work is more than comparing a ROADM-based nodal implementation with a filterless approach where the simpler implementation comes from exploiting coherent technologies. The paper compares similar (three-layer) ROADM-based and filterless network architectures and also an alternate single-layer implementation well suited to a filterless approach which simplifies implementation.

It is shown that filterless solutions offer an attractive alternative to conventional metro network implementations supporting increasing traffic flows. In large metropolitan cities filterless solutions achieve power and cost savings. While the single layer filterless alternative experiences higher spectrum consumption, the three-layer filterless option has a potential for spectrum savings compared to the ROADM-based option.

In our future work, we will study the impact of revised traffic patterns due to the increasing deployment of edge DCs, which will increase the number of GNs and, consequently, require more meshed connectivity, which effectively increase the number of GNs and are likely to require more meshed connectivity.

Funding Information. National Science and Engineering Research Council (CRDPJ 435362-12), Ciena Corp.

Acknowledgment. We thank Paul Littlewood for his contribution to this work and for insightful comments during the revision.

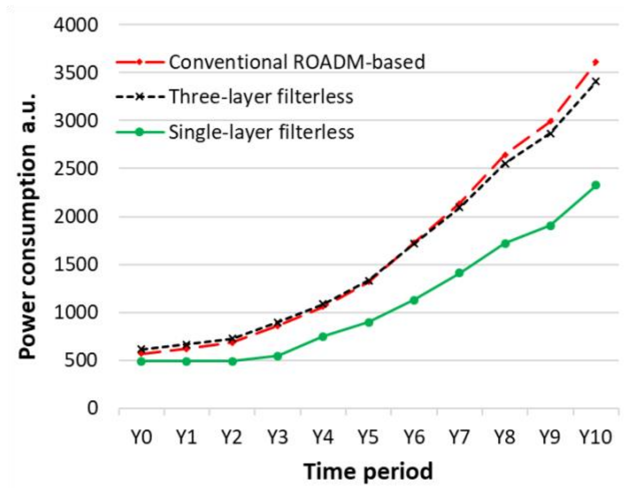


Fig. 11. Evolution of the power consumption.

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