Semi-filterless Optical Network

A Cost-efficient Passive Wide Area Network with Effective Resource Utilization

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Abstract

Two novel passive wide area network (WAN) approaches, filterless and semi-filterless optical networks, utilizing advanced optical coherent transmission and electrical compensation technologies are introduced. These approaches are able to eliminate or reduce the use of expensive active photonic reconfigurable components by interconnecting nodes with passive components. The resulting networks are more cost- and energy-efficient, as well as more reliable, compared to the networks based on active optical switching.

Beside the advantages which filterless optical networks offer, they suffer from broadcasting characteristics. A single wavelength goes further than the intended destination node and consequently any assigned wavelength can only be used once in a given fiber tree.

Addressing the drawback of the filterless approach, semi-filterless optical networks introduce passive wavelength filters at some selected nodes. Such an approach can improve resource utilization, because placing filters at some predefined nodes prevents signals from going further than their intended destination and the broadcast nature of the purely filterless approach can be limited.

This thesis project proposes an efficient algorithm to design a semi-filterless optical network. Moreover, a simulation tool for filter placement and wavelength assignment has been developed in order to validate the devised algorithm. Performance evaluation, done by using this tool, confirms that a properly designed semi-filterless optical network can provide a significant reduction in resource usage, while keeping the deployment cost as low as the filterless network.

Sammanfattning

Två nya passiva Wide Area Network (WAN) metoder, filterlösa och delvis-filterlösa optiska nätverk, använder avancerad optisk koherent transmission och elektriska tekniker ersättning införs. Dessa metoder kan eliminera eller minska användningen av dyra aktiva fotoniska omkonfigurerbara komponenter genom att sammankoppla noder med passiva power kopplingar (delare / kombinerarna). De resulterande nätverken är mer kostnads-och energieffektiv, samt mer tillförlitlig, jämfört med nät baserade på aktiv optisk koppling.

Filterlösa optiska nät använder avstämningen på sändarna. Dessutom kan de använda våglängden diskriminering mottagarna för att välja specifika våglängder, som tilldelats den avsedda destinationen noden (noder). Kombinera dessa egenskaper med ett passivt optiskt nät ökar flexibiliteten genom att undanröja eller minimera antalet aktiva fotoniska omkopplingselementen på bekostnad av större våglängd användning.

Utvidga denna filterlös strategi genom att använda passiv våglängdsfilter på vissa utvalda noder resulterar i en delvis-filterlös optiska nät, kan ett sådant tillvägagångssätt bättre resursutnyttjande. Med utnyttjande av filter och deras icke-broadcast egendom, kan sändningen natur rent filterlös tillvägagångssätt begränsas. Placering filter på vissa fördefinierade noder hindrar signaler från att gå längre än den avsedda destinationen.

Denna avhandling föreslår en effektiv algoritm för att konstruera en delvis-filterlös optiskt nätverk. Dessutom har ett simuleringsverktyg för filter placering och våglängd uppdrag tagits fram för att validera fram algoritmen. Utvärdering av prestanda, göras med detta verktyg, bekräftar att en rätt utformad delvis-filterlös optiska nätverk kan ge betydande minskning av resursanvändningen jämfört med filterlös nätverk, samtidigt som alla fördelar med en passiv WAN.

Acknowledgements

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1. Introduction

Due to the tremendous growth of network traffic over the Internet, the telecommunications industry has been experiencing challenging times over the past several years. Among the different types of network architectures that are available to telecommunications operators, fiber optical networks offer nearly unlimited bandwidth for the foreseeable future. Furthermore, the deployment costs of optical networks are as economical as copper networks[1]. Fiber optical networks are divided into two major categories: actively switched and passively split.

Actively switched photonic network utilize active elements. Individual wavelengths are switched into separate paths for routing specific information to different destinations. In this type of networks the optical signal can be terminated at the destination node, without being broadcasted over the whole network. Due to the use of active components the costs of an actively switched network are higher than passive network architectures.

Passive networks reduce the usage of electronic components, and do not provide any switching capabilities. In filterless optical networks, a signal is broadcasted via a fiber tree that contains both the source and destination nodes. All of the traffic from the source node is transmitted through fiber links and passes through splitters leading to all of the directly connected nodes. Similarly, the traffic propagates to the next set of directly connected neighbors. By taking benefit of cost-efficient passive components, the deployment cost of the network is reduced at the expense of greater wavelength usage.

This thesis proposes a novel passive wide-area network architecture: a semi-filterless optical network. Such a network architecture can provide efficient wavelength utilization, while reducing the deployment costs. Beside an efficient algorithm which has been introduced, we have implemented a simulation tool in order to validate the proposed algorithm.

1.1. Motivation and related work

Passive networks can be an attractive scheme for a network operator. They are more cost-effective as well as more reliable than the networks based on active optical switching. In contrast with active networks, a passive approach utilizes only cost-efficient passive components at intermediate nodes which have inherently lower failure rates. The failure of optical network components results in transmission losses.

Recent progress in optical transmission and electrical compensation technologies has stimulated the exploration of novel approaches in optical network architectures. An electrical equalization scheme is proposed in [2], which provides the ability to compensate for arbitrary amounts of dispersion and other linear channel effects in direct detection systems. The implementation complexity grows linearly with dispersion, which can be extended to compensate for arbitrary amounts of dispersion. Linear pre-compensation can be combined with non-linear pre-distortion to address optical nonlinearities. These methods move complexity out of the optical path and hence can make equipment based on silicon less expensive.

Filterless and semi-filterless optical networks are introducing a new generation of passive optical networks into core and metropolitan area networks. Both of these approaches result in reliable, cost-effective, and energy-efficient networks. These two approaches take advantage of recent transmission technology breakthroughs, such as advanced modulation formats, electronic dispersion compensation and tunable transceivers [3] which perform wavelength tuning at the transmitter and wavelength discrimination at the receiver.

Despite the significant advantages of the filterless optical network[2, 3], it suffers from a constraint on wavelength reuse due to its broadcast nature resulting in wavelengths being transmitted further than their intended destinations. Consequently, any assigned wavelength can only be used once in a given fiber tree. As a result, in order to satisfy the same traffic demands filterless networks always require more wavelengths than the approaches based on active optical switching.

To address this issue, the concept of semi-filterless optical networks was proposed in [4] as an improvement and extension of the filterless networks. This approach improves the wavelength utilization while still providing a lower deployment cost than when using active optical switching.

1.2. Outline

This thesis introduces a design for semi-filterless architecture. Moreover, a semi-filterless optical network design tool which performs routing and wavelength assignment has been proposed. The main objective of the tool is to efficiently design a semi-filterless optical network which can achieve high wavelength utilization while keeping the deployment costs low. The results are validated on a number of network topologies and confirm that a properly designed semi-filterless optical network can offer a significant reduction of the number of wavelengths compared to the filterless approach.

This thesis project was done as a part of a joint project between KTH, École de technologie supérieure ETS, and Ciena Corp. Utilizing the results of active networks and filterless networks acquired from the ETS, a comparison of costs and wavelength utilization in optical networks based on active switching, filterless, and semi-filterless approaches has been made. These results can be useful in both metropolitan/regional networks and core networks. As mentioned earlier, the main objective of this thesis project was to minimize the investment costs of deployment and keep the number of wavelengths required as low as possible, by using no more than a predefined number of filters.

The remainder of this thesis is organized as follows:

Chapter 2 gives some background about passive optical core networks, including both filterless and semi-filterless approaches. This chapter also compares filterless and semi-filterless architectures.

Chapter 3 illustrates the proposed semi-filterless network design tool. In this chapter, we have explained how our devised algorithm performs wavelength assignment and filter placement.

Chapter 4 presents different network case studies and the results obtained from the proposed design tool. The 7-node subset of the German, 10-node Italian, and 17-node German networks have been used as sample case studies.

The final chapter concludes the thesis and suggests the future work for continuation of this project.

2. Filterless versus Semi-filterless Optical Networks

Two novel types of passive optical core network architectures, filterless and semi-filterless optical networks, have been proposed. The concept of filterless optical network was first introduced in [3]. A filterless network design and simulation (FNDS) tool was proposed in [2], which provides performance and cost analysis along with a comparison with other types of network architectures, e.g. active photonic network. The results have shown that a filterless optical network reduces the deployment cost of the network considerably at the expense of requiring more wavelengths.

The semi-filterless concept was proposed in [4] as an extension of the filterless approach. Introducing some filters can mitigate the drawback of the filterless network and provide more efficient wavelength utilization. This novel solution introduces passive filters into the network and utilizes their non-broadcast characteristic to improve wavelength utilization.

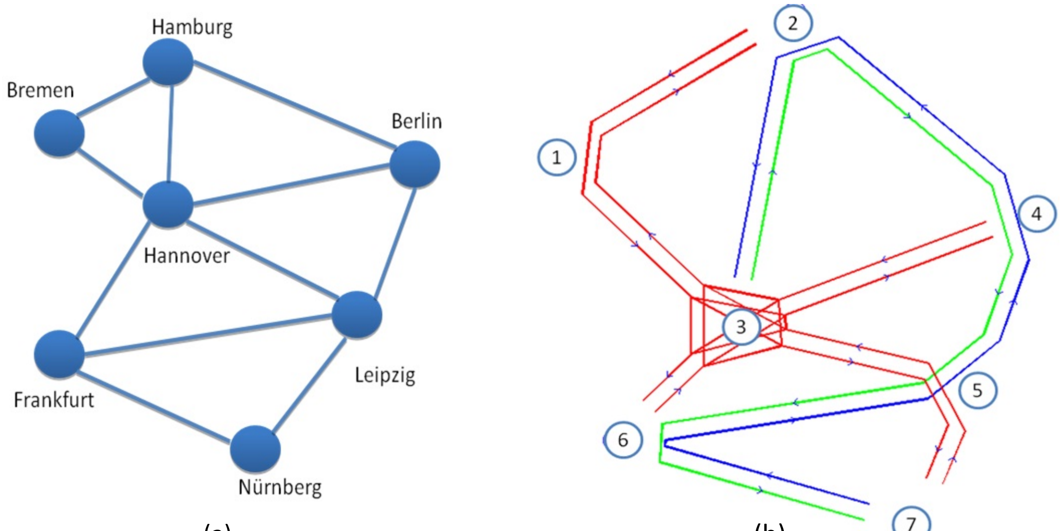
In the following of this chapter, filterless and semi-filterless optical networks and their characteristics have been explained. Furthermore, design phases of these passive optical networks have been illustrated.

2.1. Filterless optical network

Design and construction of a filterless network is based on a set of fiber links which are connected by passive splitters and combiners. The architecture provides at least one optical path between each node pair [2] and is expected to offer the following significant advantages [3]:

1. Eliminating or reducing the usage of active photonic switching elements.
2. Reducing initial deployment costs.
3. Ease of maintenance and reconfigurability, good resilience, and multicast capability.

Figure 1 shows a 7-node German network with a possible fiber interconnection. Figure 1(a) represents the network topology of the German network with 7 nodes, 11 links, and 690 km diameter; while Figure 1(b) illustrates a possible fiber interconnection with three fiber trees. The different fiber trees are shown with different colors. A total of 16 passive optical splitters and combiners are used for link interconnection. As represented in this figure, the filterless network structure provides connectivity between each two nodes.



(a) (b)

Figure 1: (a) 7-nodeGerman network and (b) one example of a fiber tree design for a filterless optical network

Due to the broadcast nature of a filterless optical network, a single wavelength goes further than the intended destination node. Consequently any assigned wavelength can only be used once in a given fiber tree. As a result, a filterless network always requires more wavelengths in order to satisfy the same set of traffic demands than an active optical switching network.

Figure 2 illustrates the broadcast nature and wavelength reuse constraints of a filterless optical network. The figure shows a simple optical network with 5 nodes and a set of fiber links forming a fiber tree (which is shown by the red lines). Each node may have number of contacts (combiners and splitters). Combiners are called outgoing contacts while splitters are incoming contacts. Two lightpaths, LP1 and LP2, support network traffic demands. Lightpath LP1 provides a path between node1 and node2 (blue dashed line). As a result of the broadcast property, the signal of lightpath LP1is sent from node 1 to node 2 and to the neighbors of node 2 in the fiber tree, thus nodes 3, 4, and 5 receive the wavelength as well (represented by black dashed lines). Therefore, the wavelength of lightpath LP1 cannot be assigned to lightpath LP2 (which is represented by blue solid line). Additional information about passive optical networks is provided in section 2.3.

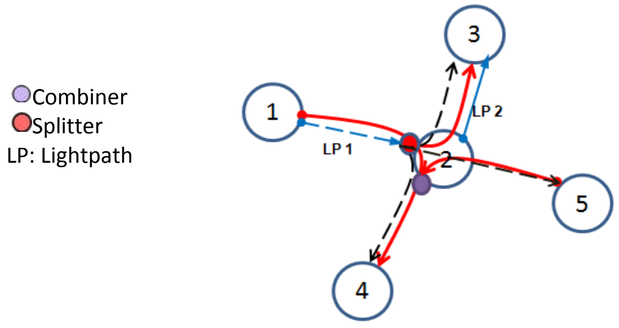


Figure 2: Wavelength reuse constraint in filterless optical network

To address this issue, we propose the concept of semi-filterless optical network as an improvement to the filterless network. Details of this concept are given in the next section.

2.2. Semi-filterless optical network

Semi-filterless optical network is proposed as an extension of filterless optical networks [5]. By introducing passive colored components, e.g., fiber Bragg gratings (FBG), red/blue filters, etc., at some selected nodes in the fiber tree, this approach takes advantage of non-broadcast property of filters in order to eliminate or reduce the wavelength reuse constraint. A semi-filterless network improves wavelength utilization at a relatively low deployment cost. Moreover, adding filters can help to reduce crosstalk between different wavelength-division multiplexed channels and decreases physical impairment.

Figure 3 illustrates the impact of adding filters to a simple optical network. Placing a filter before the splitter of Node 2 (destination of the lightpath LP1) prevents the wavelength of LP1 from propagating farther, i.e., it bounds the broadcast domain of LP1. The major benefit of this approach is that we can decrease the total number of wavelengths required to meet traffic demands. In the filterless approach, we cannot use the same wavelength for LP1 and LP2, so 2 wavelengths are required to meet traffic demands. But in the semi-filterless approach, these two lightpaths can be served by a single wavelength.

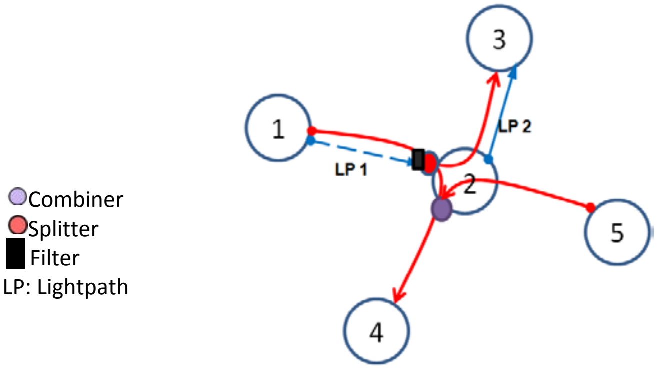


Figure 3: A Semi-filterless optical network

2.3. Passive wide area network design

In a passive optical network design, the following main constraints should be taken into consideration:

1. Wavelength-continuity constraint:
   In the absence of wavelength conversion, a lightpath operates on the same wavelength across all fiber links which it traverses.
2. Wavelength reuse constraint [2]:
   This constraint occurs when two lightpaths share common link(s) throughout their

paths. It results in a conflict between related wavelengths. Consequently, this constraint forces an assignment of different wavelengths to the different lightpaths.

Two different cases should be taken into consideration. First, as mentioned earlier, when two lightpaths share a common link throughout their paths, different wavelengths should be assigned. Another case occurs when two lightpaths do not share a common link, but the wavelength continuation in a lightpath can affect the other one. This case is called a parent-child constraint and it is illustrated in Figure 2 and Figure 3. The two lightpaths LP1 and LP2 do not share a link, but if they use the same signal, the continuation of LP1 collides with LP2. To address this issue, the semi-filterless architecture adds a filter at node 2 to avoid collision.

3. Laser effect constraint:
   Fiber loops should be avoided. Because amplifier gain through the fiber links produces a laser effect. Figure 4illustrates the laser effect which is created in a closed loop of a filterless network.

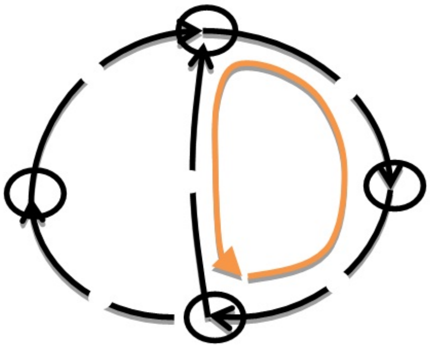


Figure 4: Laser effect in filterless optical network

4. The fiber-tree length constraint:
   The only physical layer constraint which defines the maximum fiber-tree length for any leaf–root combination.

Considering these constraints, design of a passive wide area network includes the following parts described in sections 2.3.1 to 2.3.4:

2.3.1. Fiber link interconnection

The first step is critical, since it defines the network’s physical connectivity which impacts the routing, wavelength assignment, and filter placement possibilities. The objective of this step is to establish a set of fiber trees that not only satisfies all the connection requests, but also ensures that all the nodes can be physically interconnected. [2].

The structure of a passive optical network consists of one or more fiber trees. A fiber tree is a set of interconnected fibers which provides connectivity between nodes in the network. Node interconnection is done by passive couplers (splitters/combiners) without creating closed loops. Often, couplers are manufactured to have only one input or one output. A coupler with only one input is referred to as a splitter while a coupler with only one output is called a combiner. Signal power received on an input port of a splitter is split between output ports. Signals received from input ports of a combiner are combined as the sum of the signal powers to its output port.

2.3.2. Routing

The objective of this step is to find a proper route for each request within a fiber tree in the optical network. The results from this step are transferred to a conflict graph, where the nodes represent the network's traffic demands. The wavelength assignment phase utilizes the obtained conflict graph to assign wavelengths to all traffic demands.

In filterless networks, a lightpath is a directional path between two nodes utilizing a single wavelength on all links along this path. Effective establishment of lightpaths is crucial, because they are the basic building blocks of passive optical networks.

2.3.3. Wavelength assignment

Considering the level of congestion between lightpaths within a fiber tree in the network, a suitable wavelength among the many possible choices is assigned for each lightpath so no two lightpaths which can affect each other share the same wavelength.

A set of lightpaths and a limited number of wavelengths are input data to the wavelength assignment problem. The objective of a solution to this problem is to assign a wavelength to each lightpath, in a manner that efficiently utilizes the resources of the network. (i.e. number of WLs, etc.)

The wavelength assignment process is accomplished as a graph coloring problem. Routing results are reflected to 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 or the continuation of one lightpath collides with another lightpath (parent-child constraint), forcing an assignment of different colors (or wavelengths).

2.3.4. Filter placement

This step is only done in semi-filterless networks as the main focus of the semi-filterless network design. Adding one or more passive colored components, e.g., fiber Bragg gratings (FBG), red/blue filters, etc., improves wavelength utilization by bounding the propagation of a wavelength.

Finding the best places for filters is crucial, as it impacts the wavelength reuse possibilities in the network. The main objective is to decrease the number of required wavelengths. In order to fulfill this objective, first we need to find a fiber tree within a filterless network with the maximum number of used wavelengths. A possible decrease in the number of required wavelengths in this fiber tree results in a decrease in total number of required wavelengths in the network. Hence, a node within this fiber tree can be the best place to put filter(s). In order to utilize the dropped signal's wavelength more efficiently, we try to place filter(s) as close as possible to the root of the fiber tree. Hence, the wavelength may be used by a greater number of lightpaths within the fiber tree.

3. Semi-filterless Network Design Tool

This chapter describes the filterless design and simulation (FNDS) tool. As an extension of the FNDS tool, the devised semi-filterless network design tool is described.

3.1. Filterless Network Design Tool

The filterless network design scheme is presented in Figure 5. The first step provides the input parameters taking the constraints into account. Utilizing information in the first step, a loop-free fiber interconnection design is established. The purpose of this step is to establish a set of fiber trees that not only satisfies all the connection requests, but ensures that all the nodes are physically connected. In the next step, routing is performed by selecting the shortest path for each connection. Finally wavelength assignment is done as a graph coloring problem, where nodes represent the network traffic demands. According to the network singularity constraints, conflicts exist between connections when there is at least one common link in their paths or the continuation of one lightpath collides with another lightpath (parent-child constraint). As a result, different wavelengths should be assigned to the conflicted lightpaths.

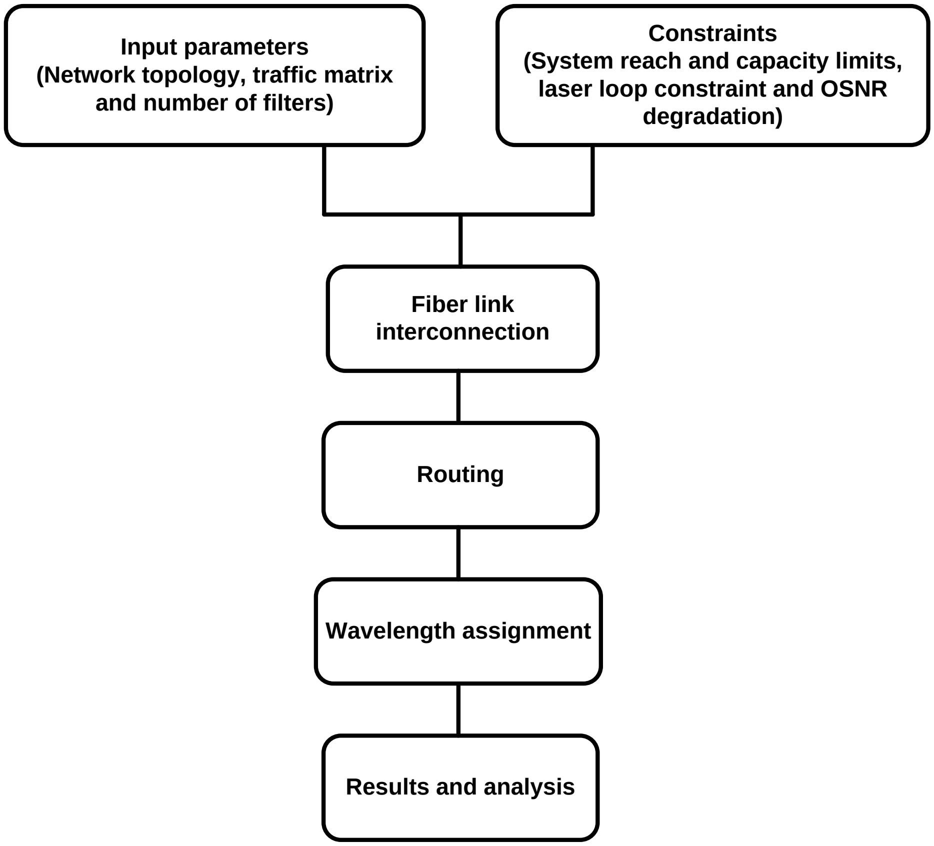


Figure 5: Filterless network design tool

Figure 6 shows a simple network with its related conflict graph which is used during the wavelength assignment phase of filterless network design and simulation tool. Two lightpaths LP3 and LP4 share a common link. Due to the wavelength reuse constraint, two different wavelengths are assigned to these two lightpaths. Another case leading to a conflict between two lightpaths is the so-called parent-child constraint. For example, two lightpaths LP1 and LP2 do not have any shared link. But LP1 affects LP2, as the assigned wavelength to LP1 passes the link between node 2 and node 3 after reaching its destination. Hence, we need to use different wavelengths in order to avoid a collision in the link between node 2 and node 3.

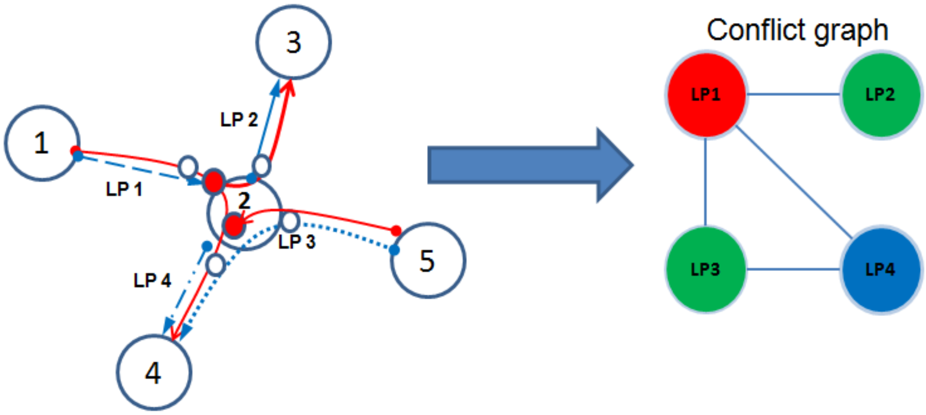


Figure 6: A filterless network and its related conflict graph

The semi-filterless network addresses the parent-child constraint which can help to eliminate or relax this constraint at the expense of a small increase in the deployment cost.

3.2. Semi-filterless Network Design

The semi-filterless design tool is presented in Figure 7. After the fiber connection and routing establishment phases, filter placement is done jointly with wavelength assignment in a consequent mode.

Extending the filterless approach by adding filters at some selected nodes can decrease the number of required wavelengths. Filter placement can be more helpful if the major share of the constraints between lightpaths is of a parent-child format.

For a given network physical topology and traffic matrix, this tool determines a fiber connection matrix, performs routing, wavelength assignment and filter placement for all connection requests.

As an extension of the filterless network, semi-filterless optical networks can also take advantage of advanced modulation formats, electronic dispersion compensation and tunable transceivers to provide agility at network nodes and interconnect the nodes with passive splitters/combiners. Therefore, the schemes of physical link interconnection and lightpath routing used in the filterless optical network can be adapted to the semi-filterless approach as well (The fiber link interconnection and routing algorithm were provided by the project contributors from the École de technologie supérieure ETS).The main focus of the thesis is filter placement and wavelength assignment in order to improve wavelength utilization.

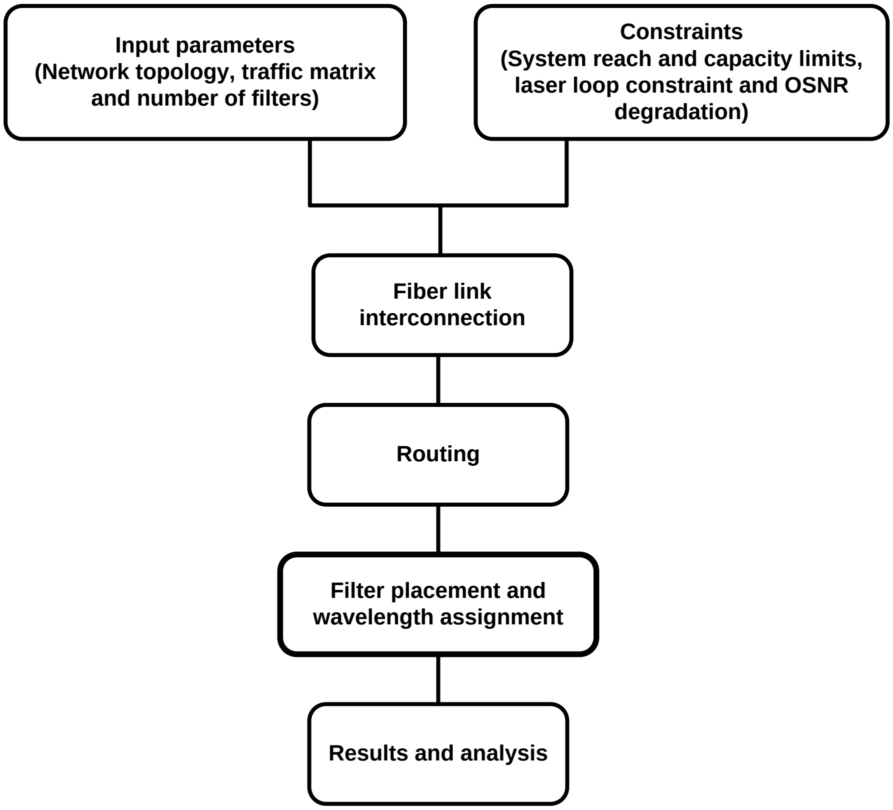


Figure 7: Semi-filterless network design tool

Similar to the filterless network, wavelength assignment is accomplished as a graph coloring problem. To perform the filter placement, we proposed a heuristic algorithm with the objective of minimizing the number of required wavelengths by placing a pre-determined number of passive filters at some selected nodes to drop signals. The dropped wavelengths can be reused by a lightpath in the same fiber tree starting at or after the node equipped with the filter. Due to the impact of filter placement on relationships within the conflict graph and the wavelength assignment phase, these two phases should be performed jointly. So after each filter placement in the fiber tree, we need to update the conflict graph based on the possible decrement in dependencies in order to do a correct wavelength assignment.

Figure 8 presents a flow chart of the proposed heuristic algorithm for filter placement and wavelength assignment. At the starting point of this chart, the wavelength assignment problem is solved by the existing algorithm in [2] for the filterless case. Furthermore, the values for two variables *#filter* (number of filters) and W_{max} (maximum number of required wavelengths) are initialized. The variable *#filter* is equal to the number of available filters to be placed in the network. The variable W_{max} is equal to the maximum value among numbers of required wavelengths in different fiber trees in the optical network.

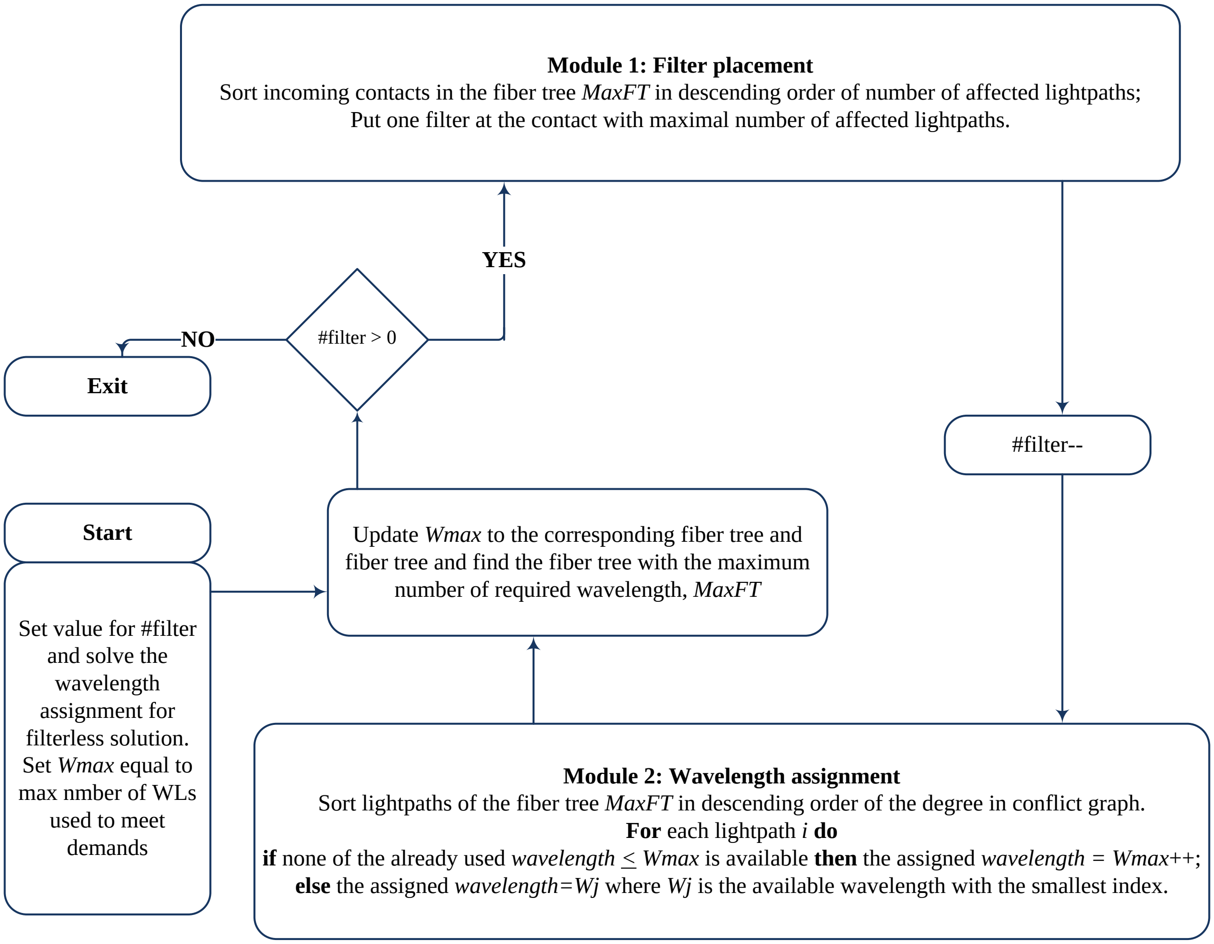


Figure 8: The proposed heuristic for filter placement and wavelength assignment

The whole process consists of several iterations equals to the number of filters. In each round, two modules, called filter placement and wavelength assignment, are executed. In the filter placement module, a fiber tree with the maximum number of required wavelengths is selected. Then, one filter is placed at the incoming contact with the maximal number of affected lightpaths in that fiber tree. In this way, a large number of edges in the related conflict graph can be removed which implies a potential decrease in the number of assigned wavelengths. After the filter placement module, the remaining number of filters decreases by one.

A greedy algorithm proposed in [6] is applied to the wavelength assignment module. In each iteration, only the fiber tree with the newly placed filter is considered for wavelength re-assignment. A conflict graph is generated accordingly and the wavelengths are assigned to the lightpaths according to the descending order of their degree.

4. Case Studies

We have implemented our heuristic scheme in C++ and tested it on several different network topologies: 7-node subset of the German network,10-node Italian network, and 17-node German network [2]. Figures 9, 10, 11, 12, 13, and 14 depict the network topologies and a sample fiber interconnection of these networks. The fiber trees are shown in different colors. These topologies are selected as they provide a good range of network case studies. Furthermore, the traffic considered in these networks is non-uniform for the 7-node German network and uniform for 10-node Italian and 17-node German networks.

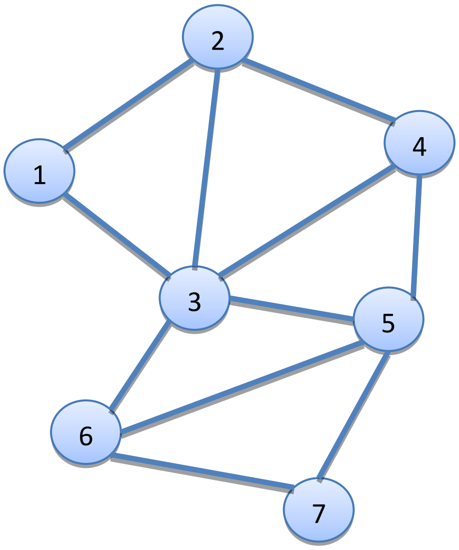


Figure 9: The7-node German network topology

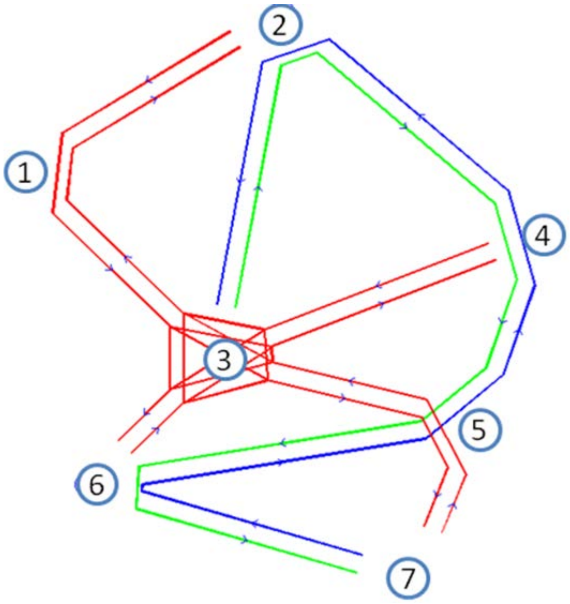


Figure 10: A sample fiber interconnection for 7-node German network

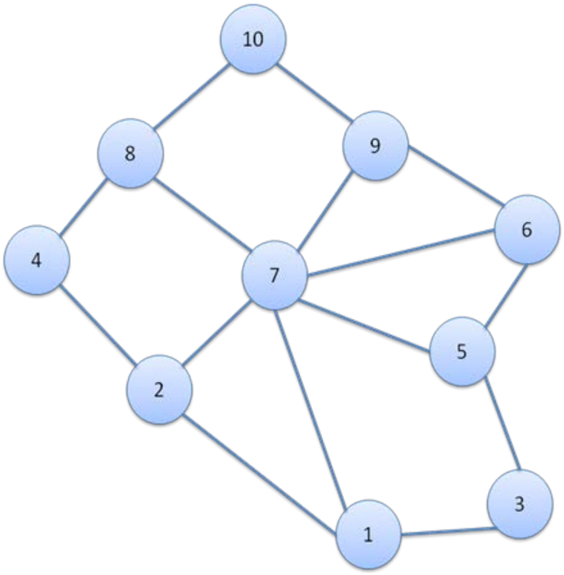


Figure 11: The 10-node Italian network topology

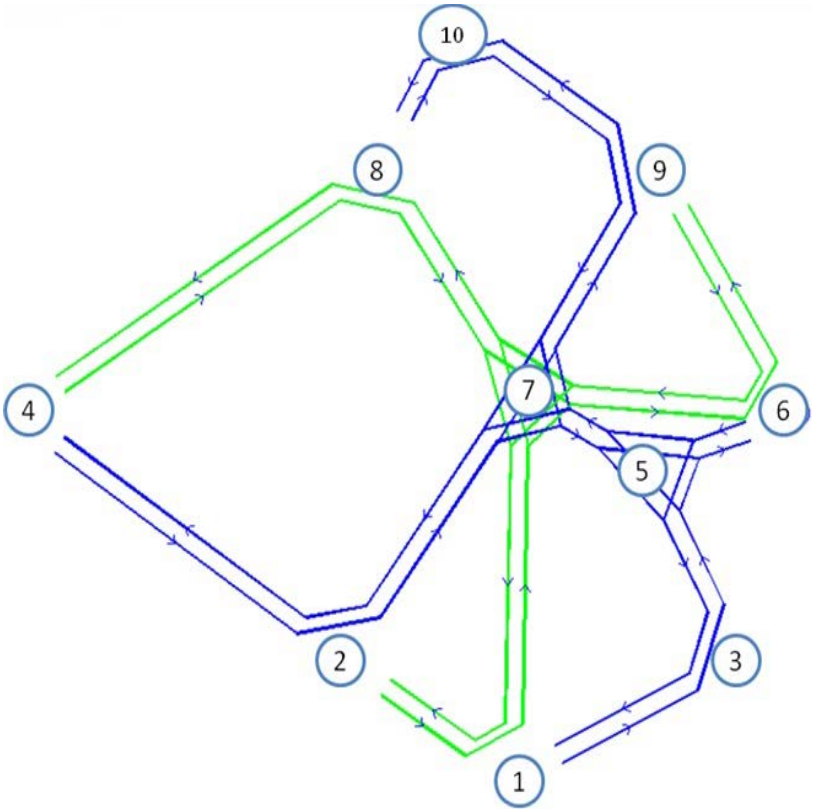


Figure 12: A sample fiber interconnection for 10-node Italian network

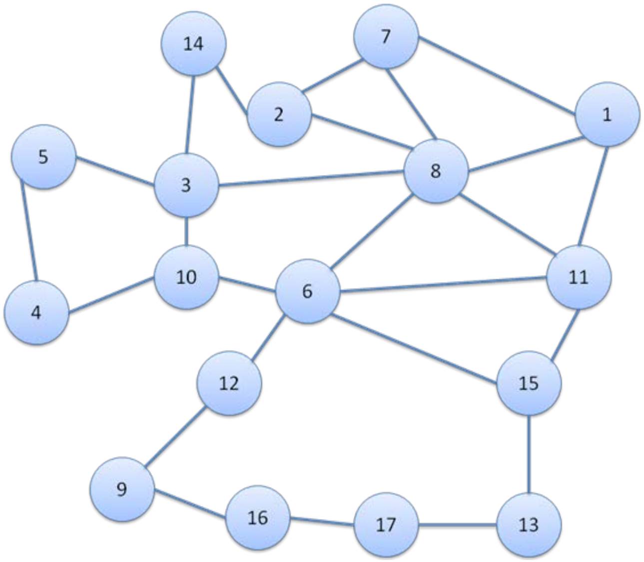


Figure 13: The 17-node German network topology

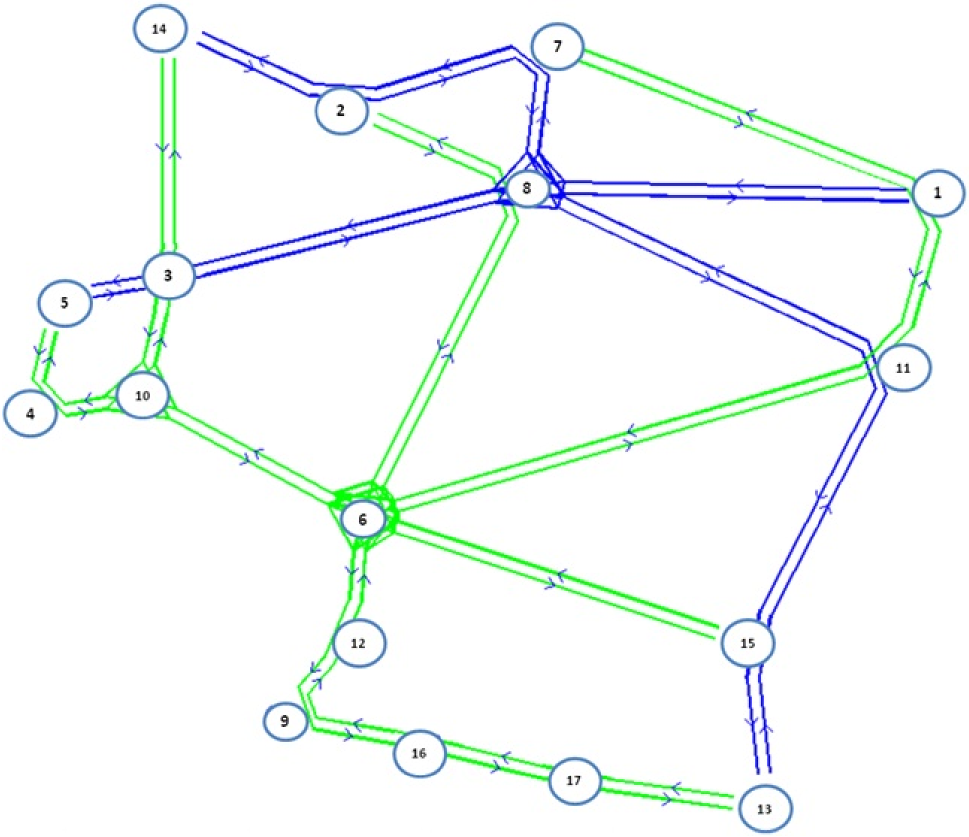


Figure 14: A sample fiber interconnection for 17-node German network

The active photonic networks considered in this study are based on wavelength-selective switch (WSS) devices, which perform per wavelength routing in the optical domain. To achieve full switching capability, we assumed that a WSS was required for every fiber connected to nodes.

The results of the active photonic solution were considered as a benchmark for our comparison with the results obtained from our network design tool.

4.1. 7-node German network

These case studies consist of an optical network with 7 nodes, 148 demands, and different numbers of fiber trees (ranging from 3 to 7). As was mentioned earlier, all of the traffic for these case studies was non-uniform. The results of running our design tool on these case studies with different numbers of fiber trees are as follows:

1) German network (7 nodes, 3 fiber trees, 148 demands)

This case study has three fiber trees. By placing filters in this network, the number of required wavelengths is decreased from 38 to 34; which is the saturation point for this case study. This means that despite further increases in the number of filters, we cannot decrease the total number of required wavelengths. As a result, the total number of wavelengths in the semi-filterless case is decreased to 89 percent in the filterless case.

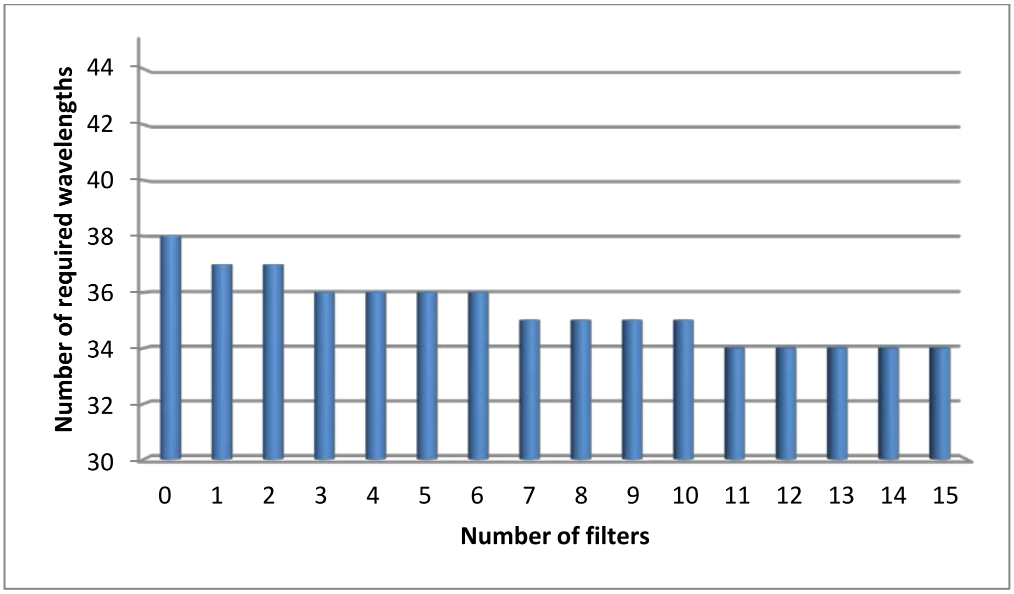


Figure 15: Number of wavelengths vs. number of filters, German network with 3 fiber trees

2) German network (7 nodes, 4 fiber trees, 148 demands)

By placing filters in this sample topology, we can decrease the number of required wavelengths by 5. It means that before placing filters in the network, we needed 40 wavelengths to meet traffic demands; while after placing filters, we can decrease number of required wavelengths to 35. However, additional filters cannot improve wavelength utilization any further. As a result, the total number of required wavelengths in the semi-filterless case is 87.5 percent of filterless case.

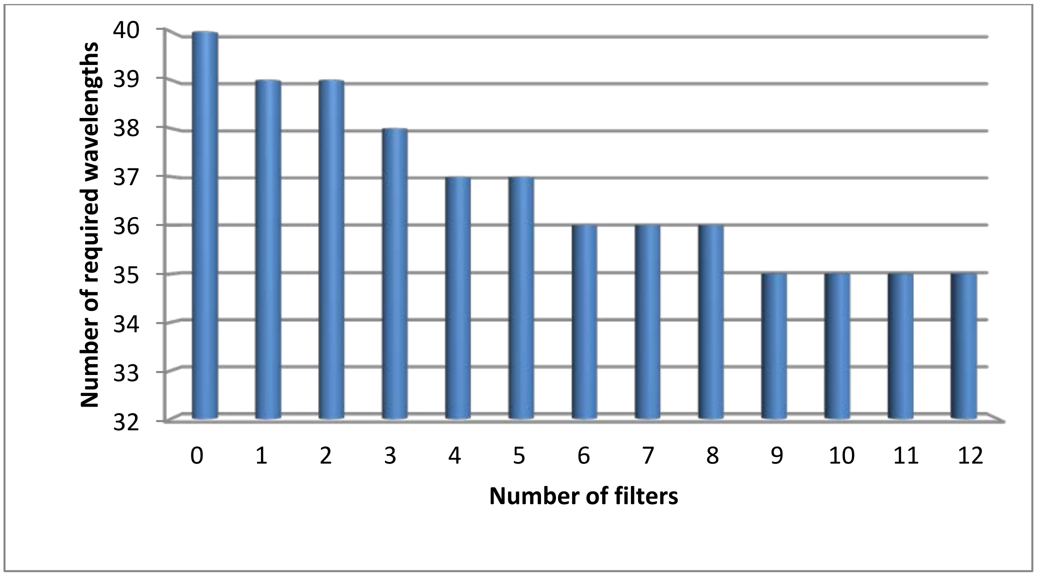


Figure 16: Number of wavelengths vs. number of filters, German network with 4 fiber trees

3) German network (7 nodes, 5 fiber trees, 148 demands)

In this example, we have a 7 node case study with 5 number of fiber trees. By placing filters in the network, the required number of wavelengths is decreased from 44 to 36. Hence, the total number of wavelengths in the semi-filterless case is decreased 18 percent in comparison with in the filterless case.

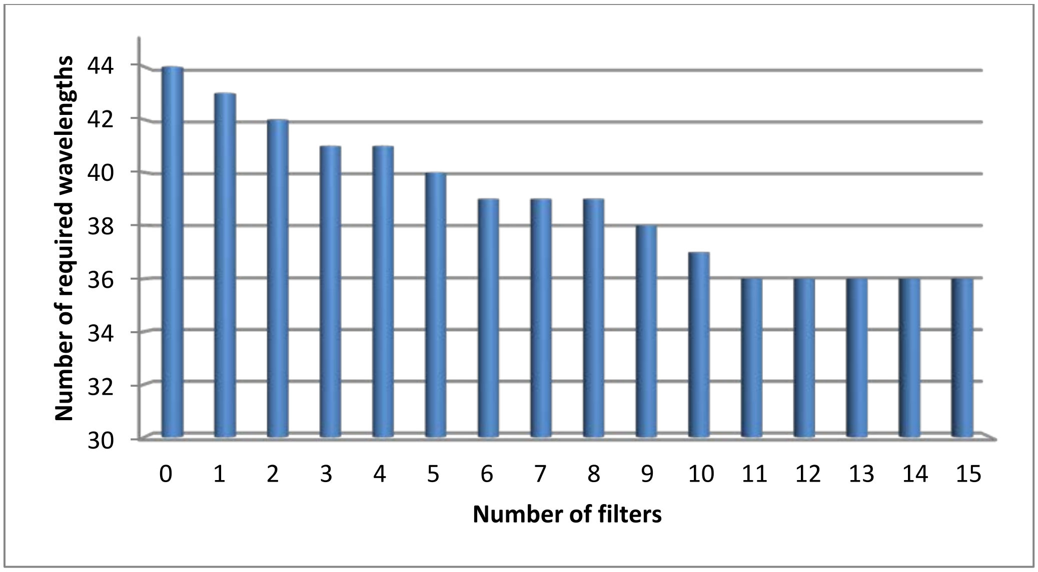


Figure 17: Number of wavelengths vs. number of filters, German network with 5 fiber trees

4) German network (7 nodes, 6 fiber trees, 148 demands)

This sample network has 6 fiber trees. By using 42 wavelengths in filterless case, it meets 148 traffic demands. However, placing filters decreases the total number of required wavelengths to 31. Hence, it causes 26 percent reduction in the required number of wavelengths in compare with of filterless case.

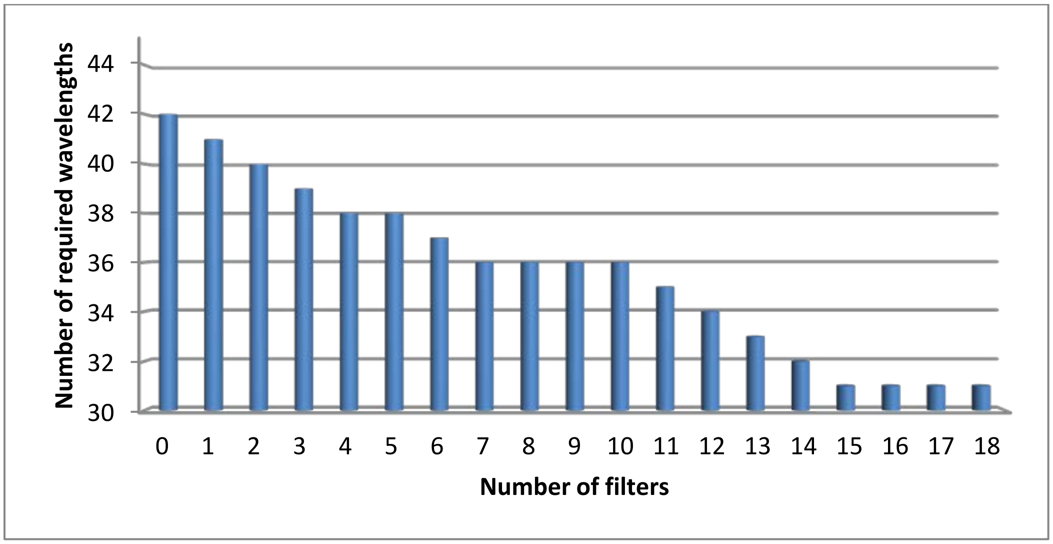


Figure 18: Number of wavelengths vs. number of filters, German network with 6 fiber trees

5) German network (7 nodes, 7 fiber trees, 148 demands)

In this sample topology of German network by using 7 fiber trees and 43 number of wavelengths, 148 demands are covered. By placing filters in this network, the number of required wavelengths is decreased from 43 to 36. As a result, the total number of required wavelengths in semi-filterless case is 84 percent of filterless case.

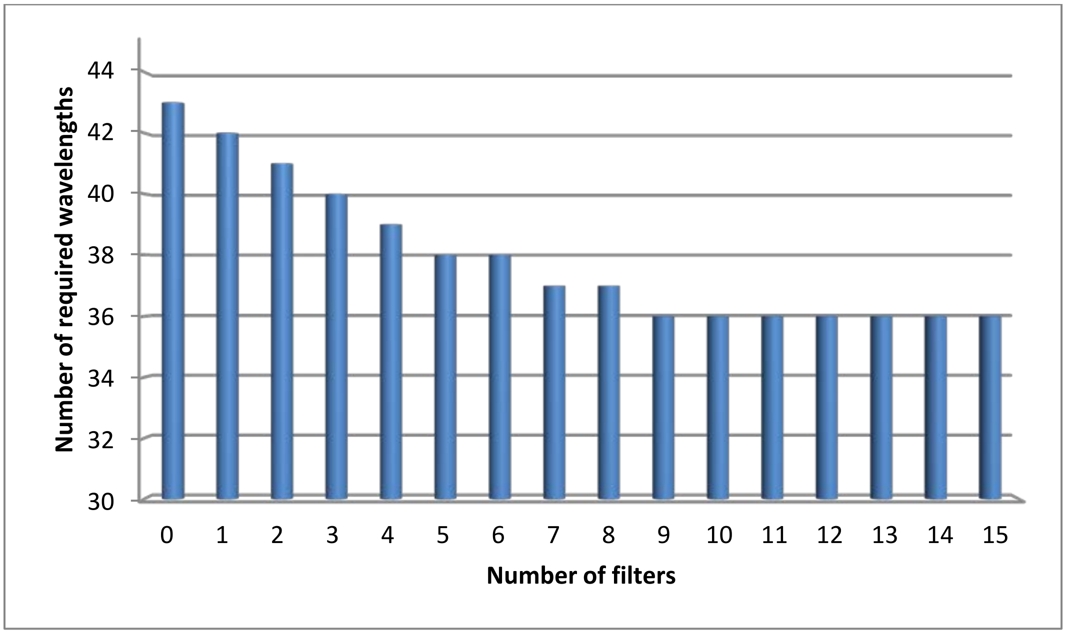


Figure 19: Number of wavelengths vs. number of filters, German network with 7 fiber trees

Summary of German 7 node cases

Figure 20 shows the number of wavelengths needed as a function of the number of fiber trees for the German 7 node cases.

By analyzing the results, we have figured out that distribution of demands among more fiber trees could improve the performance of the proposed solution. As it is illustrated in the Figure 20, utilizing more fiber trees and distribution of demands improves the results achieved from semi-filterless design tool.

Furthermore, balanced distribution of traffic among fiber trees improves the performance of the tool considerably. For example, the traffic in the sample network with 6 fiber trees is distributed evenly. Hence, placing filters could noticeably decrease the number of required wavelengths in comparison with other case studies.

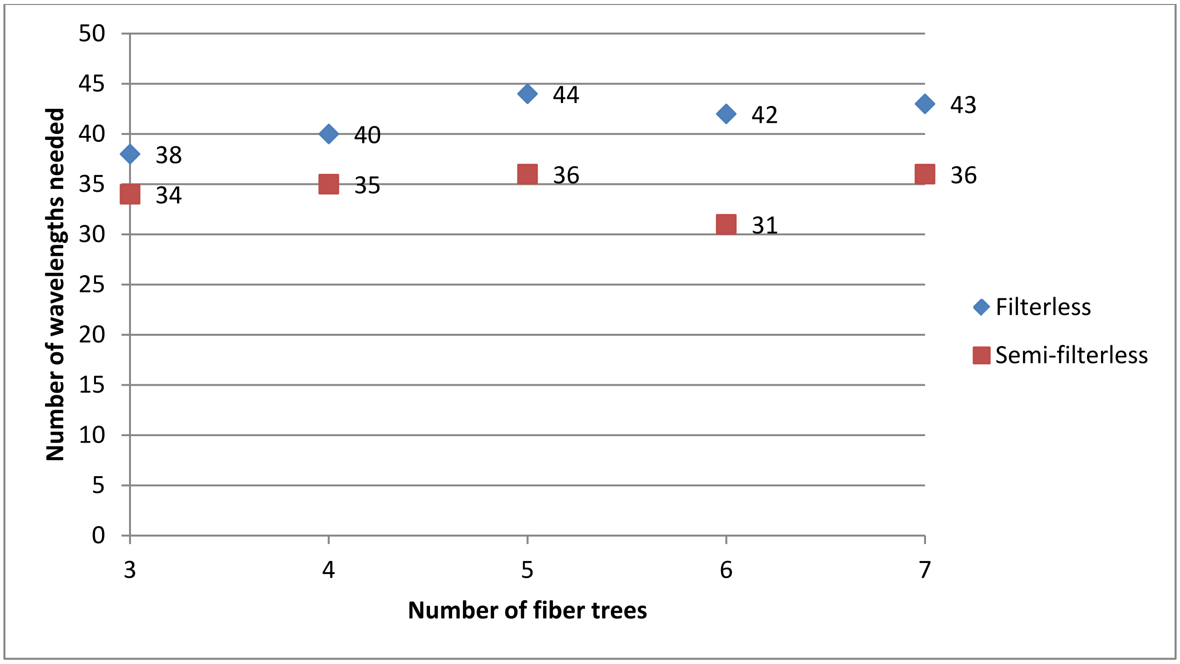


Figure 20: The number of wavelengths needed as a function of the number of fiber trees in the 7-node German networks

4.2. 10-node Italian network

These case studies consist of an optical network with 10 nodes, 90 demands, and different number of fiber trees ranging from 1 to 4. All the traffic utilized in these sample topologies is symmetric. The results of running our design tool on these case studies are as follows.

1) Italian network (10 nodes, 2 fiber trees, 90 demands)

The first sample of the Italian network has two fiber trees. All 90 lightpaths pass through the fiber trees. Before placing filters in this network, we need 29 wavelengths to meet traffic demands. By placing filters, the total number of required wavelengths is decreased to 22. However, the network becomes saturated at this point. Consequently, the total number of required wavelengths in semi-filterless case is 75 percent of filterless case.

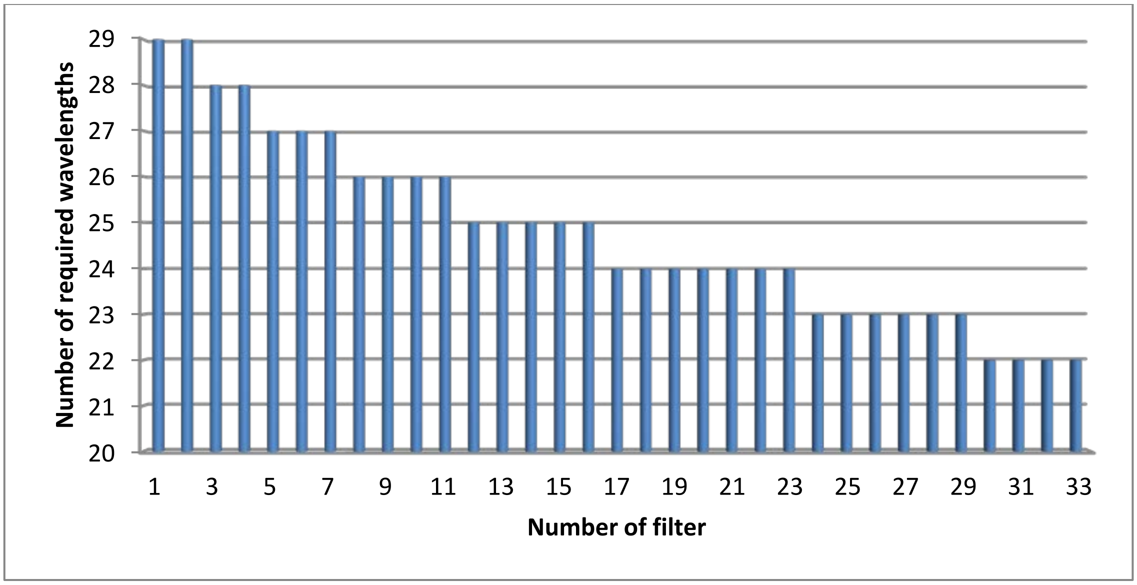


Figure 21: Number of wavelengths vs. number of filters, Italian network with 1 fiber trees

2) Italian network (10 nodes, 4 fiber trees, 90 demands)

In this case study, 90 demands are distributed in four fiber trees. By putting filters in the fiber trees, the total number of required wavelengths is decreased from 21 to 12. As a result, the total number of required wavelengths in the semi-filterless case is decreased 48 percent compared to the filterless case.

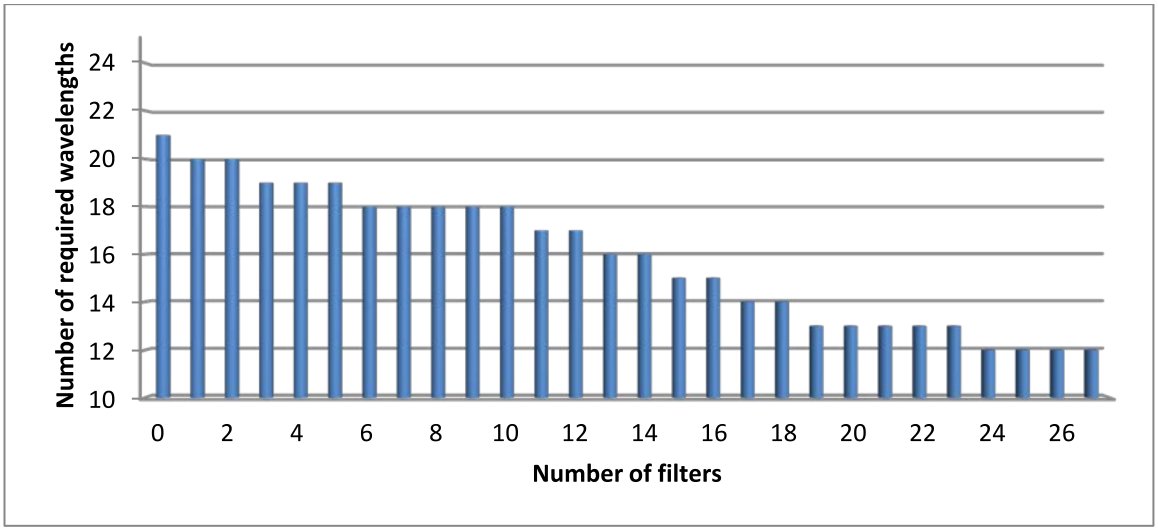


Figure 22: Number of wavelengths vs. number of filters, Italian network with 2 fiber trees

3) Italian network (10 nodes, 6 fiber trees, 90 demands)

In comparison with the previous case study, this topology has 6 fiber tree and the same number of demands. Placing filters in this network, the total number of required wavelengths is decreased from 22 to 13. As a consequence, the total number of required wavelengths in semi-filterless case is 59 percent of the filterless case.

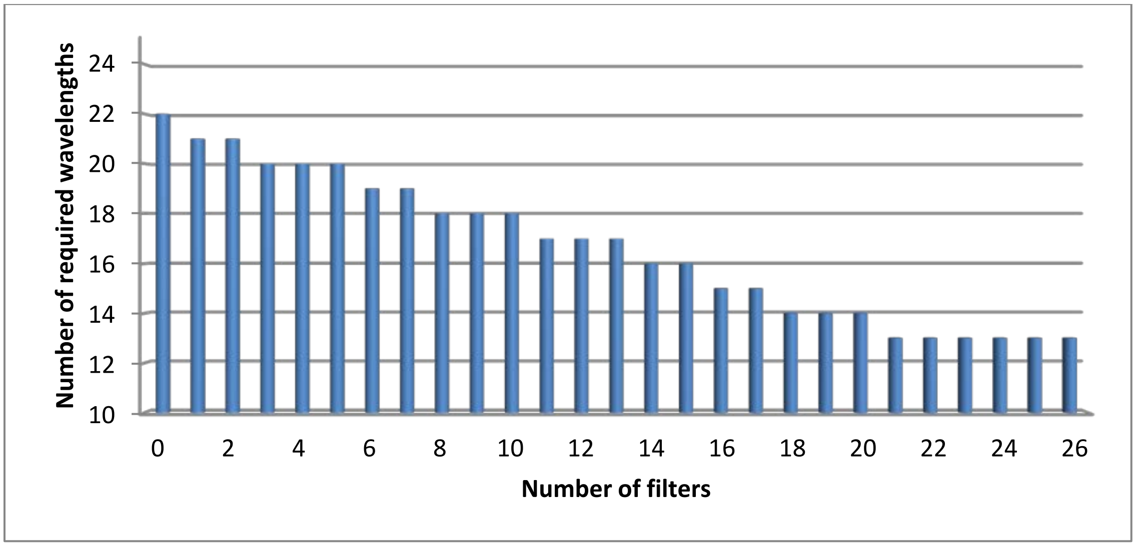


Figure 23: Number of wavelengths vs. number of filters, Italian network with 3 fiber trees

4) Italian network (10 nodes, 8 fiber trees, 90 demands)

This case study illustrates a network with 90 demands which are distributed in 8 fiber trees. After filter placement, the total number of required wavelengths to meet traffic demands has decreased from 23 to 14. Thus, the total number of required wavelengths in semi-filterless case is reduced 40 percent.

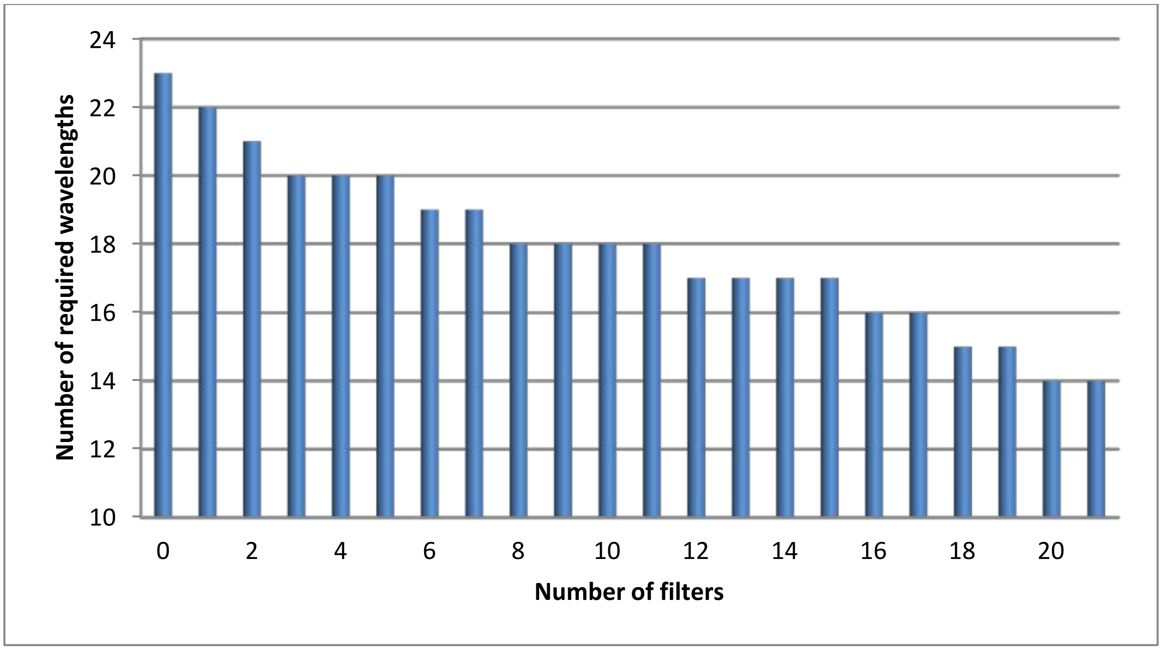


Figure 24: Number of wavelengths vs. number of filters, Italian network with 4 fiber trees

Summary of Italian 10 node cases

Figure 25 depicts the number of wavelengths needed as a function of the number of fiber trees for the Italian 10 node cases. Analysis of the results obtained from the 10-node Italian network case studies represents the impact of balanced demands distribution among fiber trees.

In these sample topologies, the number of fiber trees has been increased. However, major part of network traffic is distributed through limited number of fiber trees. As a result, extending the number of fiber trees could not improve wavelength utilization considerably in these sample topologies.

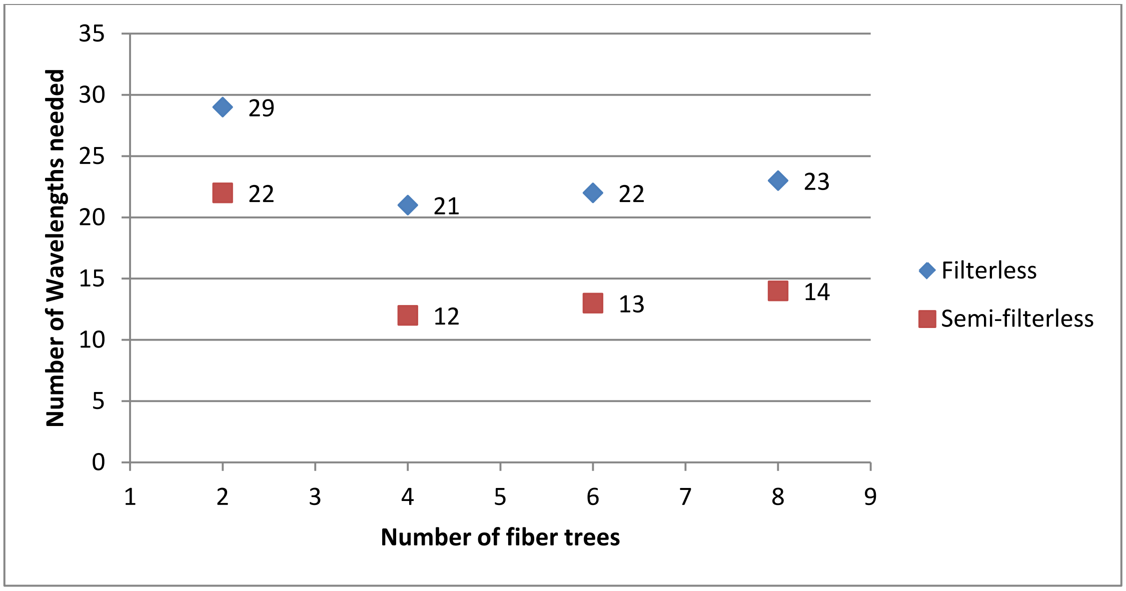


Figure 25: The number of wavelengths needed as a function of the number of fiber trees in 10-node Italian network

4.3. 17-node German network

These case studies consist of an optical network with 17 number of nodes, 272 demands and different number of fiber trees (ranging from 2 to 4). All illustrated sample topologies here are symmetric. The results obtained from our network design tool running these case studies are as follows:

1) German network (17 nodes, 2 fiber trees, 272 demands)

The first sample in 17-node German network has two fiber trees. All 272 lightpaths pass through the fiber tree. Before placing filters in this network, we need 95 wavelengths to meet traffic demands. By placing filters, the total number of required wavelengths is decreased to 76. However the network becomes saturated at this point. Hence, adding 40 filters in the 17-node German network can cause 20 percent reduction of the required number of wavelengths (Figure 26).

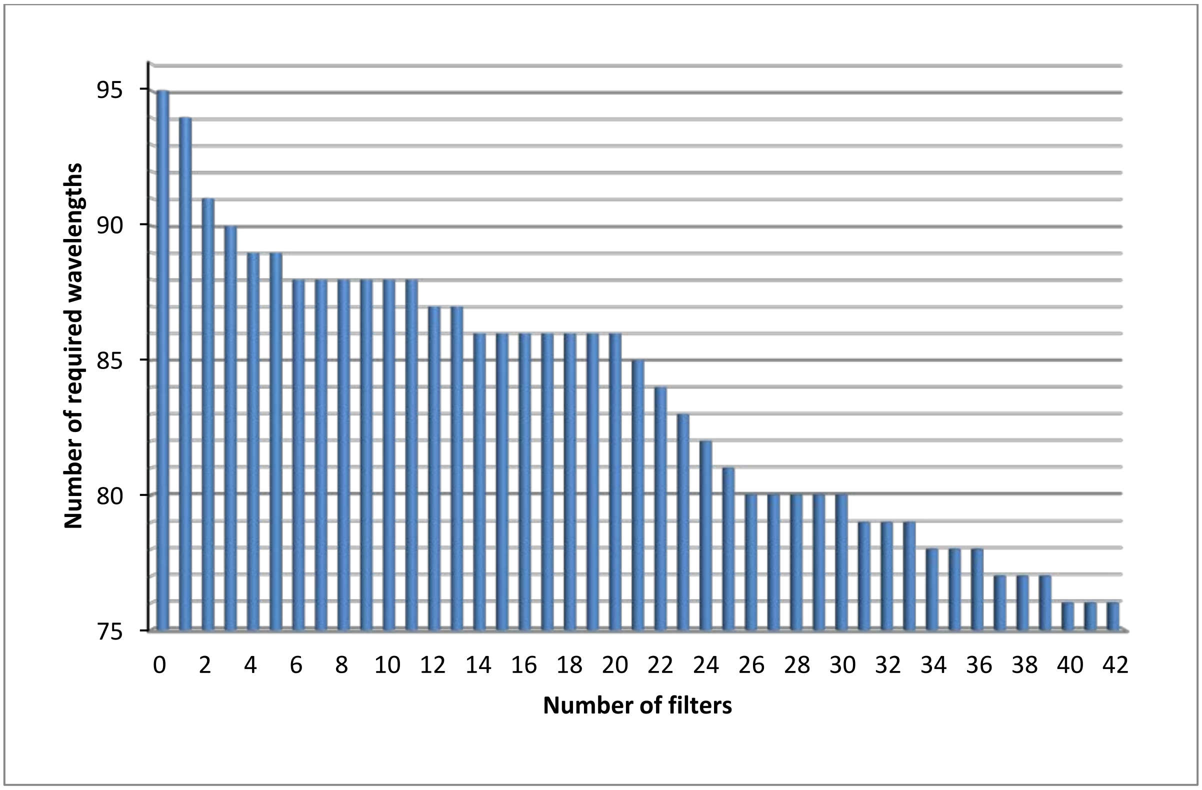


Figure 26: Number of wavelengths vs. number of filters, 17-node German network with 2 fiber trees

2) German network (17 nodes, 2 fiber tree, 272 demands)

This case study illustrates a network with 272 demands which are distributed in two fiber trees. After filter placement, the total number of required wavelengths to meet traffic demands has decreased from 93 to 80. Therefore, the total number of required wavelengths in semi-filterless case is 86 percent of filterless case.

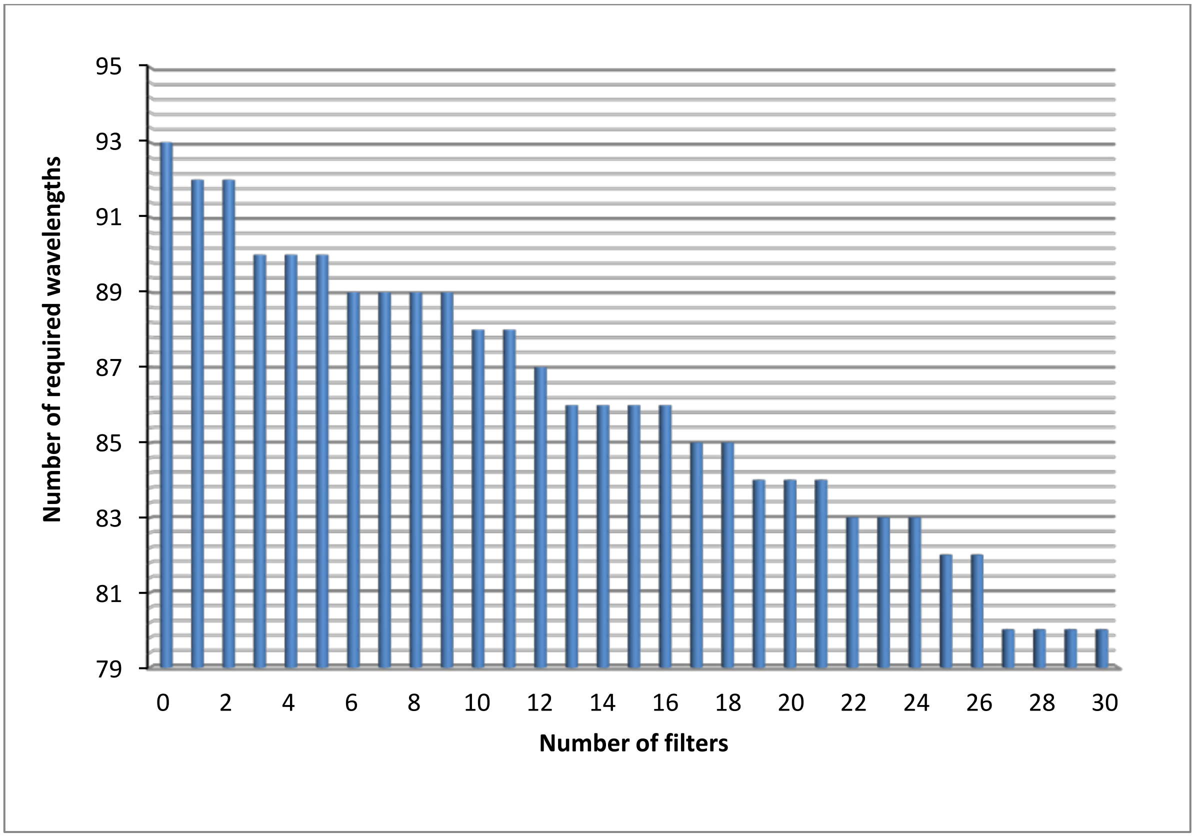


Figure 27: Number of wavelengths vs. number of filters, 17-node German network with 2 fiber trees

3) German network (17 nodes, 4 fiber tree, 272 demands)

This case study illustrates a network with 272 demands which are distributed in four fiber trees. After filter placement, the total number of required wavelengths to meet traffic demands has decreased from 98 to 80. Consequently, number of wavelengths in semi-filterless case is reduced by 19 percent compared to the filterless case. After placing 27 filters, the network reaches its saturation point, meaning that placing more filters is not beneficial.

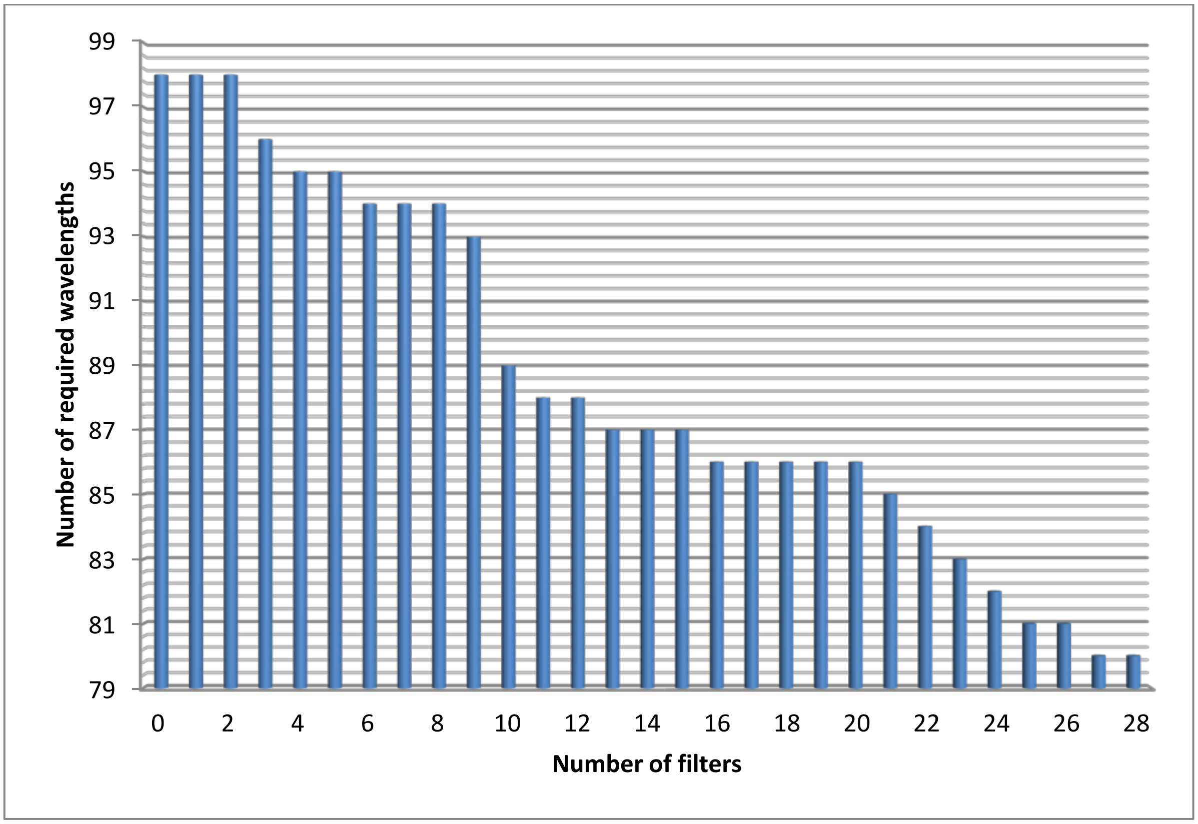


Figure 28: Number of wavelengths vs. number of filters, 17-node German network with 4 fiber trees

4) German network (17 nodes, 4 fiber trees, 272 demands)

This case study illustrates a network with 272 demands which are distributed in four fiber trees. After filter placement, the required number of wavelengths to meet traffic demands has decreased from 107 to 97. Consequently, the total number of wavelengths in semi-filterless case is 90 percent of filterless case.

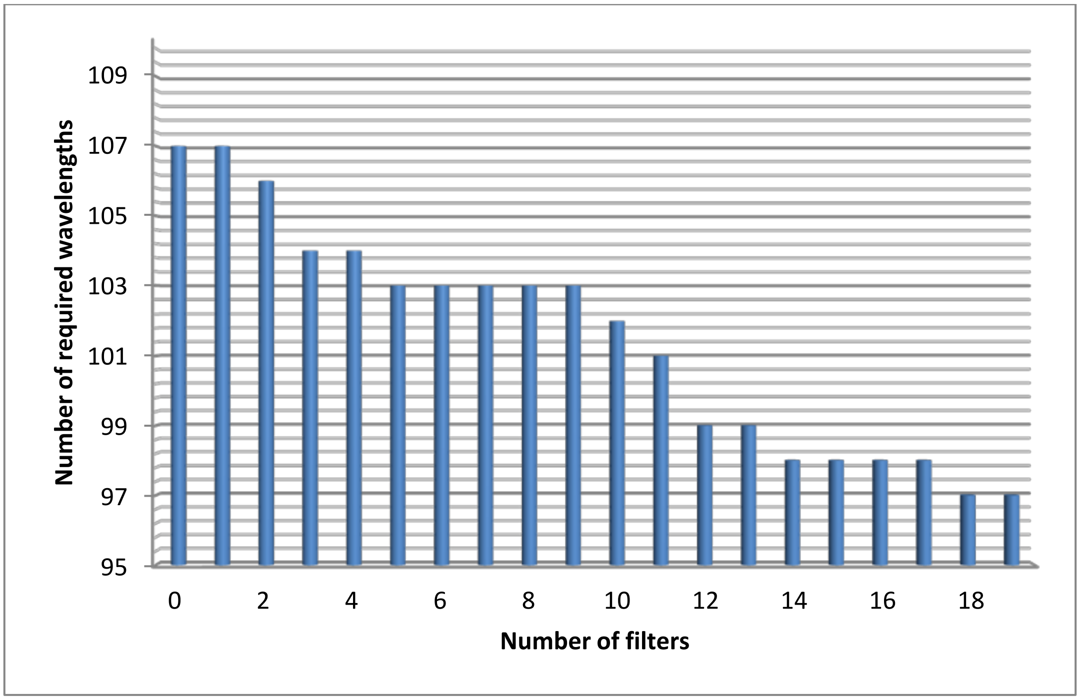


Figure 29: Number of wavelengths vs. number of filters, 17-node German network with 4 fiber trees

Summary of German 17 node cases

Figure 30 depicts the number of wavelengths needed as a function of the number of fiber trees for the German 17 node cases. Distribution of traffic among more fiber trees in the third sample topology improves the results obtained from the semi-filterless network design tool.

The last sample network with 4 fiber trees is an exception, as the network traffic is mainly distributed among limited number of fiber trees. Consequently, extending the number of fiber trees has a low impact on performance of our tool and reducing the number of required wavelengths.

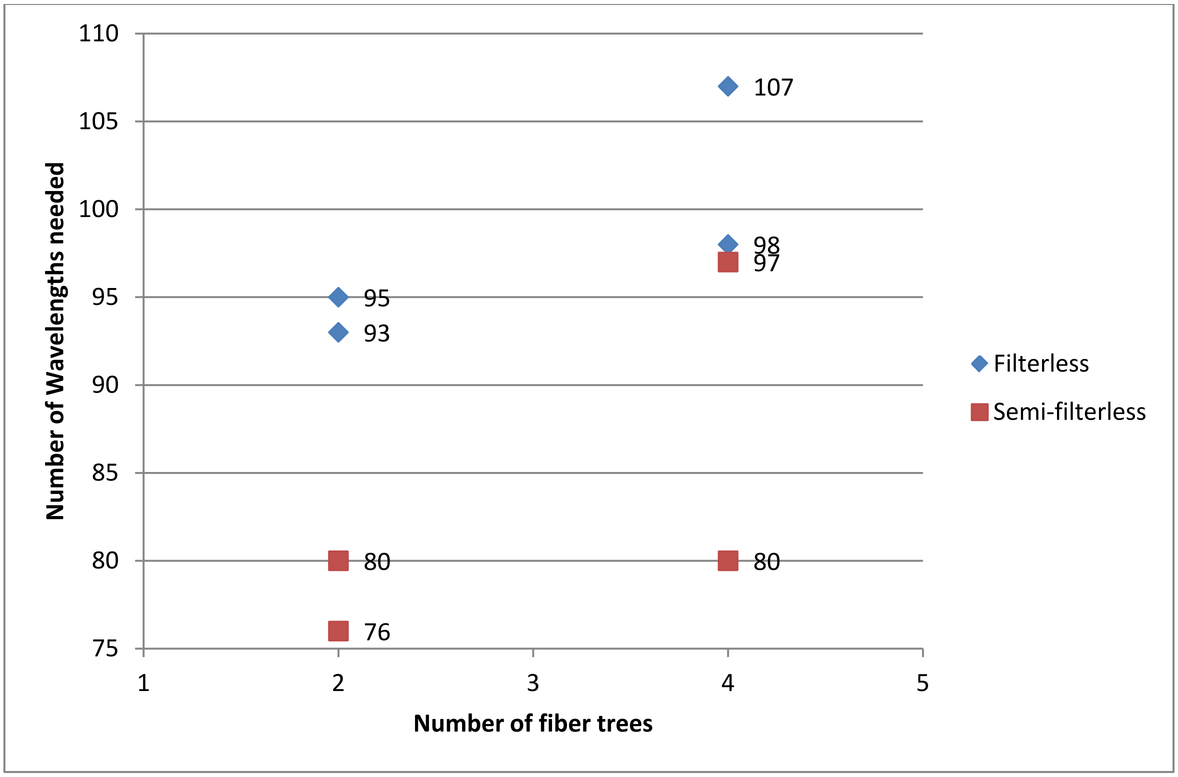


Figure 30: The number of wavelengths needed as a function of the number of fiber trees in 17-node German network

4.4. Demand density

Taking benefits of the semi-filterless network design tool, wavelength utilization in filterless network could be improved. However, the impact of placing filters in various case studies is different. An important factor which can influence the performance of this architecture is demands distribution. It refers to the maximum number of demands in a fiber tree among all available fiber trees.

To figure out the impact of demand distributionon the number of required wavelengths, we run the simulation tool on various 17-node German network case studies with different number of fiber trees and various level of demand distribution. Figure 31 illustrates number of required wavelengths in semi-filterless 17-node German networks as a function of maximum number of demands in one fiber tree. The result indicates that by lowering the density of demands and more balanced demands distribution between all fiber trees, we can decrease the number of required wavelength.

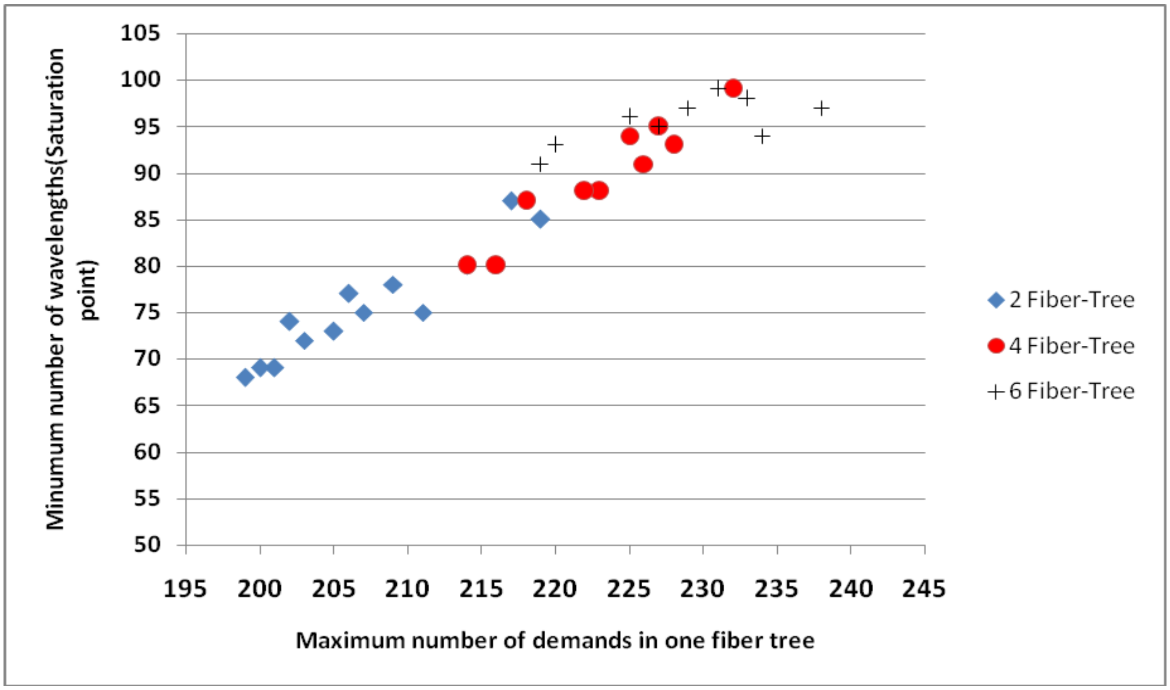


Figure 31: Max number of wavelengths vs. Max number of demands in fiber tree

4.5. Cost comparison

Figure 32 shows the cost comparison of the three considered network scenarios where we assumed relative cost with arbitrary units (a.u.). Moreover, we focus on the cost of nodes, since the link cost is the same for different types of optical networks[5, 8]. The figure depicts that in comparison with optical network based on active switching, both filterless and semi-filterless networks significantly lower costs on nodes, since only passive components are required.

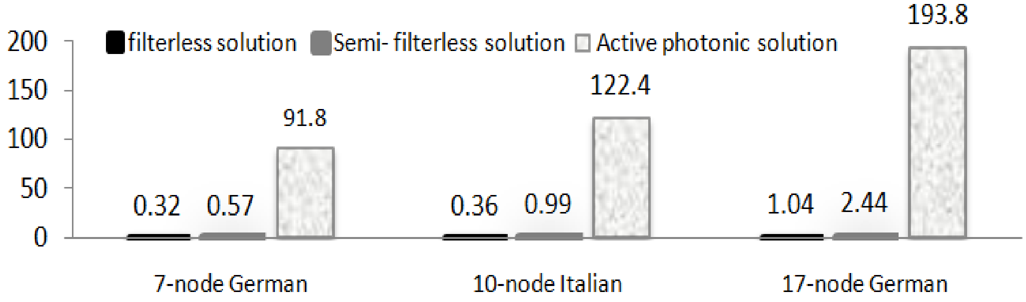


Figure 32: Cost comparison of filterless, semi-filterless, and active photonic switching networks

Table 1 summarizes performance comparison in terms of cost and wavelength usage for all the considered scenarios. It is shown that the semi-filterless network can significantly improve the wavelength utilization at the expense of a minor increase of investment cost [2, 7].

Table 1: Performance comparison of filterless, semi-filterless and active photonic networks

Solutions	7-node German		10-node Italian		17-node German	
	Number of Wavelengths	Cost (a.u.)	Number of Wavelengths	Cost (a.u.)	Number of Wavelengths	Cost (a.u.)
Filterless	37	0.32	28	0.36	88	1.04
Semi-filterless	34	0.57	22	0.99	76	2.44
Active photonic	30	91.8	22	122.4	56	193.8

5. Conclusions and Future Work

This thesis has proposed an efficient algorithm for filter placement and wavelength assignment in semi-filterless network and implemented semi-filterless network design tool which has been validated on different network topologies. In comparison with active switching and filterless optical networks, the semi-filterless approach is a cost efficient alternative as it can achieve high resource utilization as well as low deployment cost. Moreover, the results illustrate that distributing the traffic demands among fiber trees in a balanced way can help to improve the resource utilization in semi-filterless networks.

In order to obtain a comprehensive analysis for both passive and active optical WANs, the plan is to extend the study and evaluate the performance of semi-filterless approach in terms of reliability, flexibility, power efficiency, etc.

6. References

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[7] ‘OASE ("Optical Access Seamless Evaluation”, a large scale Integrated Project funded by the European Commission through the 7th ICT-Framework Programme)’, private communication, 2011.

Appendices

Among our contributions to the project, the following articles have been published:

[1] Sahar Khanmohamadi, Jiajia Chen, Farzad Abtahi, Lena Wosinska, Andrew Cassidy, émile Archambault, Christine Tremblay, Serge Asselin, Paul Littlewood, and Michel Bélanger, "Semi-filterless optical network: a cost-efficient passive wide area network solution with effective resource utilization", in Proc. of IEEE/OSA/SPIE Asia Communications and Photonics Conference and Exhibition (ACP), Nov. 2011. (Furthermore, the article was nominated to the best student paper competition)

[2] Jiajia Chen, Sahar Khanmohamadi, Farzad Abtahi, Lena Wosinska, Zhenyu Xu, Andrew Cassidy, Christine Tremblay, Paul Littlewood, Serge Asselin and Michel P. Bélanger, "Passive Wide Area Network Solutions: Filterless and Semi-Filterless Optical Networks" , in Proc. of IEEE International Conference on transparent Optical Networks ICTON2011, June 2011.

[3] Farzad Abtahi, Cicek Cavdar, Jiajia Chen, Sahar Khanmohamadi, Lena Wosinska, Guillaume Mantelet, Émile Archambault, Christine Tremblay and Michel P. Bélanger, "Optimal Design of Cost- and Energy-Efficient Scalable Passive Optical Backbone Networks", in Proc. of IEEE/OSA/SPIE Asia Communications and Photonics Conference and Exhibition (ACP), Nov. 2012.

Semi-filterless optical network: a cost-efficient passive wide area network solution with effective resource utilization

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Abstract

By utilizing advanced optical coherent transmission and electrical compensation technologies, two novel passive wide area network (WAN) solutions, filterless and semi-filterless optical networks, are able to eliminate the usage of the expensive active photonic reconfigurable components by interconnecting the nodes with passive optical power splitters/combiners and using tunable transceivers. Therefore, they have a potential to be more cost-effective and energy-efficient as well as more reliable than the networks based on active optical switching. In comparison with the filterless approach, the semi-filterless optical network can improve resource utilization by introducing passive wavelength filters at some selected nodes. This paper proposes a semi-filterless optical network design tool for filter placement and wavelength assignment and validates it on a number of network topologies. Performance evaluation confirm that the proper design of semi-filterless optical networks can offer significant reduction of the number of wavelengths needed to support a certain traffic demand compared to filterless networks while keeping all the advantages of the passive WAN solution.

Keywords: Passive wide area network, semi-filterless optical network,filter placement, wavelength assignment

1. Introduction

The exploration of two novel passive wide area network (WAN) solutions, namely, filterless [1, 2] and semi-filterless [3] optical networks has been stimulated by advances in optical coherent transmission as well as electrical compensation technologies. These two novel WAN approaches eliminate the usage of the active photonic reconfigurable component by utilizing passive optical power splitters/combiners, which makes this network architecture more cost-effective and energy-efficient as well as more reliable compared with the networks based on active optical switching.

On the other hand, the filterless optical network [1, 2] suffers from a constraint of wavelength reuse due to its broadcast characteristic resulting in wavelength continuity going further than the intended destination node and consequently any assigned wavelength can only be used once in a given fiber tree.

As a result of this nature, the filterless solution always requires more wavelengths in order to satisfy the same traffic demands than the approach based on active optical switching. To address this issue, the concept of a semi-filterless optical network was proposed in [3] as an improvement and extension of the filterless solution. By introducing passive colored components - e.g., fiber Bragg gratings (FBG), red/blue filters, etc.- at some selected nodes in the fiber tree and utilizing its non-broadcast property to relax the wavelength reuse constraint inherent in the filterless approach, the semi-filterless network, therefore has an advantage to improve the wavelength utilization at a relatively low deployment cost. In this paper, a semi-filterless optical network design tool is proposed and validated on a number of network topologies. A comparison of cost and wavelength utilization in optical networks based on active switching, filterless and semi-filterless approach is provided.

2. Proposed design tool for semi-filterless optical network

The semi-filterless design problem can be partitioned into three main parts (see Figure 1): (1) Fiber interconnection, (2) routing and (3) filter placement and wavelength assignment (WA). As an extension of the filterless solution, semi-filterless optical networks can also take advantage of advanced modulation formats, electronic dispersion compensation and tunable transceivers to provide agility at network nodes and interconnect the nodes with passive splitters/combiners. Therefore, the schemes of physical link interconnection and lightpath routing used in the filterless optical network can be applied to the semi-filterless approach as well. Our semi-filterless design tool uses the efficient fiber connection and routing algorithms as in [1] for the first two steps considering similar input parameters and constraints for network design and planning. In contrast to the filterless solution, in a semi-filterless optical network, passive colored components (e.g., FBG, red/blue filters, etc.) are allowed to be placed at some selected nodes to drop the signal. In this way, the dropped wavelength can be reused for the lightpaths in the same fiber tree starting at or after the nodes equipped with the filter.

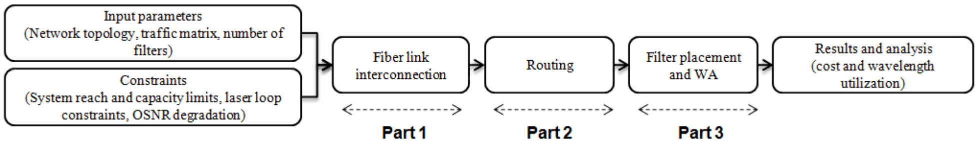


Figure 1.Semi-filterless optical network design tool

Figure 2 illustrates an example for the filterless and semi-filterless networks and the corresponding conflict graph for the wavelength assignment. The correlation between lightpaths [4] is shown in a conflict graph, where an edge represents wavelength clash constraint, i.e. the corresponding two lightpaths are not able to be assigned a common wavelength. Furthermore, we define the contact as the incoming or outgoing port for the nodes. In Fig.2, Node 2 has two incoming contacts, i.e. from Node 1 and 5, and two outgoing contacts to Node 3 and 4. Obviously, it is more efficient to place the filters to drop the wavelength at the incoming contact than at the outgoing contact. The filterless solution showed in Fig. 2 (a) needs at least three wavelengths for all four of the considered lightpaths. However, by introducing a filter at the incoming contact of Node 2 connecting to Node 1 to drop the wavelength signal of LP1 (see Fig.2 (b)), the number of the required wavelengths is reduced to 2.

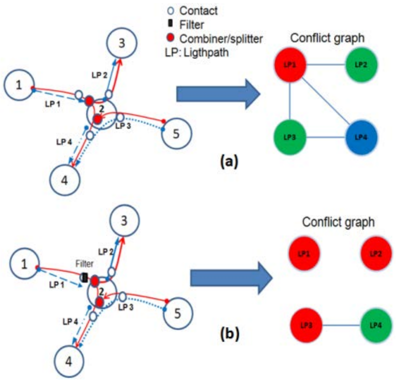


Figure 2. Illustrative example: filterless (a) vs. semi-filterless (b)

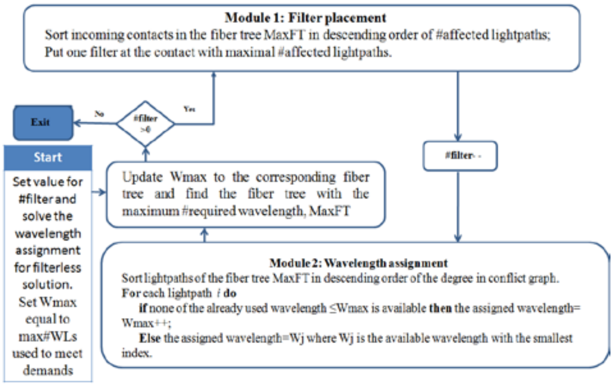
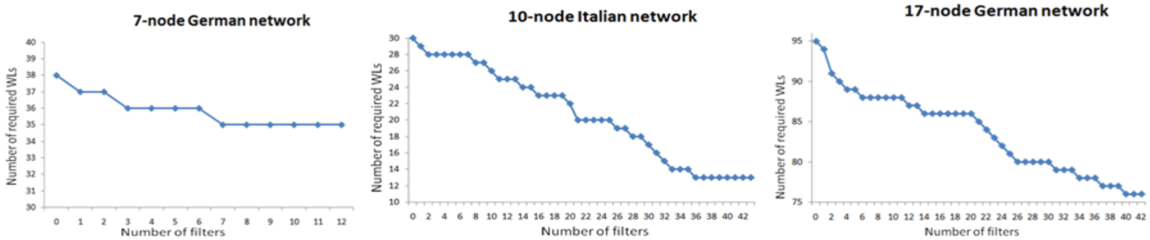


Figure 3.Flow chart of the proposed heuristic for filter placement and wavelength assignment.

The third step of our design tool called filter placement and wavelength assignment (WA) is an important part improving the wavelength utilization. We propose a heuristic algorithm with the objective to minimize the number of required wavelengths by placing a given number of filters. Figure 3 shows the flow chart of our algorithm. The whole process consists of several iterations (whose number is equal to the number of filters). In each round, two modules, called filter placement and wavelength assignment, are preceded. Typically, there are several fiber trees in the network. In the filter placement module, a fiber tree with the maximum number of required wavelengths is selected. Then, one filter is placed at the incoming contact with the maximal number of affected lightpaths in that fiber tree. In this way, a large number of edges in the related conflict graph can be removed which implies the potential of decreasing the number of assigned wavelengths. Furthermore, the greedy algorithm proposed in [4] is applied to the wavelength assignment module. In each iteration, only the fiber tree with the newly placed filter is considered. A conflict graph is generated accordingly and the wavelengths are assigned to the lightpaths according to the descending order of their degree.

3. Performance evaluation

We implemented our heuristic scheme in C++ and tested it on three different network topologies: 7-node subset of the German network, 10-node Italian network, and 17-node German network [1]. Furthermore, for simulation we considered a non-uniform traffic for 7-node German network and a uniform traffic for 10-node Italian network and 17-node German network as presented in [1]. Figure 4 (a-c) shows the number of required wavelengths as a function of the number of filters placed in the network for the considered network topologies. Obviously, the more filters the semi-filterless solution has, the less number of wavelengths is required. However, after a certain point the curve becomes saturated. It means the number of wavelengths is not further reduced by increasing the number of filters placed in the network. The congestion represents the lower bound for the number of required wavelengths. For example, adding 40 filters in the 17-node German network can cause 20 percent reduction of the required number of wavelengths (see Fig. 4 (c)), whereas increasing the number of filters to more than 40 does not improve the wavelength utilization.Besides, it should be noted that the gain on wavelength reduction by introducing the filters is also dependent on the network topologies and traffic matrix. 10-node Italian and 17-node German network, which have uniform traffic, obtain better improvement of wavelength utilization than 7-node German network.



(a) (b) (c)

Figure 4. Number of wavelengths vs. number of filters

Figure 5 shows the cost comparison of the three considered network scenarios where we assumed relative cost with arbitrary units, (a.u.). Moreover, we focus on the cost of nodes, since the cost of link is the same for different types of optical networks. The input data for each relative cost is obtained from [1] and [5]. In comparison with optical network based on active switching, both filterless and semi-filterless solutions have significantly lower cost for nodes since only passive components are required. Table 1 summarizes performance comparison in terms of cost and wavelength usage for all the considered scenarios. It is shown that the semi-filterless network can significantly improve the wavelength utilization at the expense of a minor increase of investment cost.

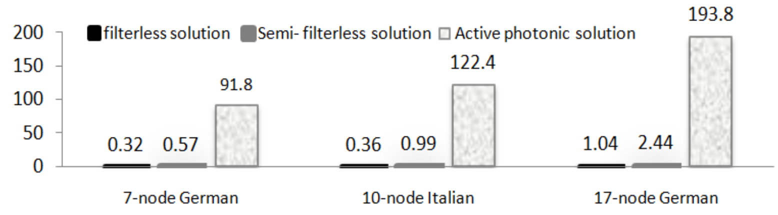
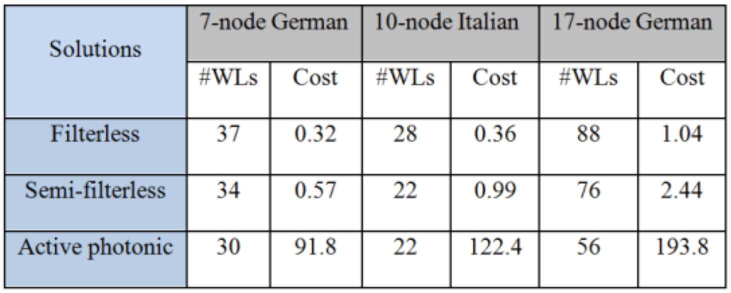


Figure 5. Cost comparison of filterless, semi-filterless and active photonic switching solution



Solutions	7-node German		10-node Italian		17-node German	
	#WLs	Cost	#WLs	Cost	#WLs	Cost
Filterless	37	0.32	28	0.36	88	1.04
Semi-filterless	34	0.57	22	0.99	76	2.44
Active photonic	30	91.8	22	122.4	56	193.8

Table 1: Performance comparison for filterless, semi-filterless and active photonic solutions

4. Conclusion

In this paper, an efficient semi-filterless network design tool has been proposed and validated on different network topologies. In comparison with active switching and filterless optical networks, it is shown that semi-filterless network is a cost efficient alternative with effective resource utilization. In order to obtain a comprehensive analysis for both passive and active optical WANs we plan to extend our study and evaluate other performance parameters, such as resilience, flexibility, power efficiency, etc.

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Passive Wide Area Network Solutions: Filterless and Semi-Filterless Optical Networks

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EXTENDED ABSTRACT

Advances in optical coherent transmission and electrical compensation technologies (such as coherent receiver and forward error correction FEC) have stimulated ideas for novel optical network architectures. Recently proposed passive wide area network solution, referred to as filterless optical network [1-2] eliminates or minimizes the usage of active photonic reconfigurable network elements. In this approach, only the passive splitters and combiners for interconnecting the fiber links are utilized, which makes this network architecture more cost- and energy-effective as well as more reliable compared with networks based on active optical switching.

However, the filterless optical network architecture implies some constraints on fiber interconnection design, maximum fiber-tree length and wavelength reuse due to its broadcast nature. Consequently, filterless solution always requires more resources (i.e. number of wavelengths) compared with the active switched optical networks which are allowed to utilize reconfigurable and coloured components. In order to improve the wavelength utilization while maintaining flexibility of resource allocation, this work extends the idea of filterless optical network by introducing some passive coloured components (e.g., fiber Bragg grating FBG, red/blue filters, etc) to drop local signals at some determined nodes. This approach is referred to as semi-filterless optical network. Furthermore, the semi-filterless solution maintains the passive feature, enabling high reliability and efficiency of cost and energy. Meanwhile, its non-broadcast property at some determined nodes has potential to decrease the transmission impairments and hence relax the constraints on fiber interconnection design and the maximal transparent length, which are strict in the filterless optical network. Our preliminary results confirm the advantages of semi-filterless solution.

Keywords: passive wide area network, filterless optical network, semi-filterless optical network.

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Optimal Design of Cost- and Energy-Efficient Scalable Passive Optical Backbone Networks

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Abstract: We propose an optimization model minimizing number of wavelengths in passive optical backbone networks and obtaining the same resource usage as in networks based on active switching while reducing both cost and power consumption.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.4256) Networks, network optimization; (060.4264) Networks, wavelength assignment

1. Introduction

Benefiting from advanced optical coherent transmission and electronic compensation technologies at the receiver, filterless [1, 2] optical backbone networks (FOBNs) can eliminate the need of active optical switching equipment in the network, using passive components, i.e., power splitters/combiners to interconnect fiber links. Consequently, FOBNs are more cost- and energy-efficient than the networks based on active photonic switching devices. However, due to the broadcasting nature of FOBNs, resource reuse in the network can be very limited and hence the number of wavelengths required to support a certain traffic demand may be significantly higher than in the active networks. To alleviate this problem and keep the advantages of passiveness, the semi-filterless approach (S-FOBN), where passive filters are introduced in some selected nodes, has been introduced in [3, 4]. In this paper we present an optimum solution for both FOBN and S-FOBN by developing an integer linear programming (ILP) model for the wavelength assignment and filter placement problems to minimize the cost. Our cost and power consumption models are more precise compared to [3, 4] where links and transponders were not taken into account.

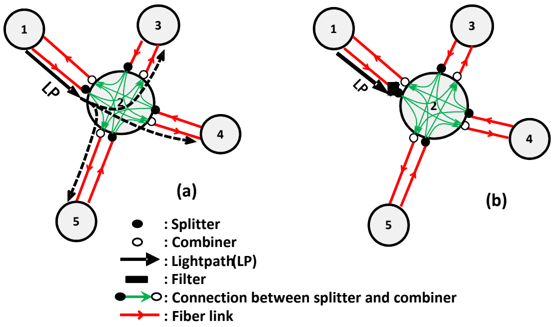

Fig. 1: Illustrative example: (a) FOBN (b) S-FOBN

One of the issues to be taken into account in passive OBNs is the laser effect caused by the amplifier gain in fiber loops, which need to be avoided at fiber interconnection design step [1]. Furthermore, in FOBN any wavelength assigned for a source destination pair can be used only once in a given branch of a fiber tree. Figure 1 illustrates an example of a simple fiber tree for filterless and semi-filterless networks. The directed fiber link from node 1 to node 2 is referred to as a parent of links between node 2-3, 2-4 and 2-5 (see Fig. 1(a)).The green lines inside node 2 represent the connections between splitters and combiners. As can be seen in Fig. 1 (a), without any filters all the lightpaths starting from node 1 and passing the 1-2 link will continue through all the child links, irrespectively if some of the lightpaths are addressed to node 2 and could be dropped there. However, in a semi-filterless network the wavelength of e.g. lightpath LP can be reused in any following child link because it is removed by the one colored passive filter placed in node 2 (see Fig. 1(b)).

The design of passive optical backbone network (OBN) can consist of three steps [1, 4]: (1) Fiber interconnection, (2) routing and (3) wavelength assignment and filter placement (for semi-filterless network). Heuristic solutions are provided in [1, 2] for filterless and in [4] for semi-filterless approaches. In this paper we develop an integer linear programming (ILP) model minimizing number of wavelengths by filter placement in the network and give the optimum solution for S-FOBN. Moreover, in order to get the whole picture we quantified the benefits of the passive OBNs in terms of cost, wavelength usage and power consumption compare to the optical networks based on active photonic switching.

2. Wavelength Assignment and Filter Placement Problem Formulation

In this section, we present an ILP model for the design of S-FOBNs. The objective is to minimize the total number of wavelengths in the network by placing a given amount of passive filters in the selected nodes. Note that this model can also be used to optimize the number of wavelengths in FOBNs by setting the number of filters in the model equal to 0. The problem formulation and ILP model is shown below.

- Given:

D: the set of demands along with their routing information. w: minimum number of wavelengths for each link.

G (N, E): the physical topology consisting the set of nodes *N* and set of fiber links *E* where $l \in E$ denotes one fiber link. *NF*: the number of filters that need to be placed. P_l: the set of parent links of *l* where $P_l \subset E$ and p is used to index the parent links i.e., $p \in P_l$. $K_{p,l}$: the set of demands which is routed through p but not *l* where $K_{p,l} \subset D$. $T_{p,l}$: the set of demands which is routed through *p* and ended before *l* where $T_{p,l} \subset D$.

- Find:

$X_{n,l}^{\lambda}$: is 1 if demand *n* is routed through link *l* on wavelength *λ*.

C_n^{λ} : is 1 if *λ* is used for demand *n*.

F_n^{λ} : is 1 if one filter is placed in destination node of demand n working on wavelength *λ*.

W^{λ} : is 1 if wavelength *λ* is in use.

WL: total number of wavelengths used in the network.

Minimize WL

- Subject to

$$\sum_{n\in D} X_{n,l}^{\lambda} + \sum_{n\in K_{p,l}} X_{n,p}^{\lambda} + (\sum_{n\in T_{p,l}} X_{n,p}^{\lambda} - \sum_{n\in T_{p,l}} F_n^{\lambda}) \le 1 \quad \forall\ l \in E, p \in P_l, \lambda \in w \tag{1}$$

$$\sum_{n\in D} X_{n,l}^{\lambda} + X_{e,p}^{\lambda} - F_e^{\lambda} \le 1 \quad \forall\ l \in E, e \in T_{p,l}, p \in P_l, \lambda \in w \tag{2}$$

$$\sum_{n\in D} X_{n,l}^{\lambda} + \sum_{n\in K_{p,l}} X_{n,p}^{\lambda} \le 1 \quad \forall\ l \in E, p \in P_l, \lambda \in w \tag{3}$$

$$C_n^{\lambda} \ge F_n^{\lambda} \quad \forall\ n \in T_{p,l}, \lambda \in w, p \in P_l, l \in E \tag{4}$$

$$\sum_{\lambda\in w} F_n^{\lambda} \le 1 \quad \forall\ n \in T_{p,l}, p \in P_l, l \in E \tag{5}$$

$$\sum_{\lambda\in w} \sum_{n\in T_{p,l}} F_n^{\lambda} = NF \quad \forall\ p \in P_l, l \in E \tag{6}$$

$$\sum_{\lambda\in w} X_{n,l}^{\lambda} = 1 \quad \forall\ n \in D, l \in E \tag{7}$$

$$C_n^{\lambda} \le \sum_{l\in E} X_{n,l}^{\lambda} \quad \forall\ n \in D, \lambda \in w \tag{8}$$

$$C_n^{\lambda} \ge X_{n,l}^{\lambda} \quad \forall\ n \in D, l \in E, \lambda \in w \tag{9}$$

$$X_{n,l}^{\lambda} = X_{n,p}^{\lambda} \quad \forall\ n \in D, \lambda \in w, l \in E, p \in P_l \qquad \text{where destination node of } p \text{ is source for } l \tag{10}$$

$$\sum_{\lambda\in w} C_n^{\lambda} = 1 \quad \forall\ n \in D \tag{11}$$

$$W^{\lambda} \ge X_{n,l}^{\lambda} \quad \forall\ n \in D, l \in E, \lambda \in w \tag{12}$$

$$\sum_{\lambda\in w} W^{\lambda} = WL \tag{13}$$

In order to reuse wavelengths and avoid conflicts, constraints (1-3) are considered, where (1) and (2) are checking the possibility of having filters in the parent links and constraint (3) ensures wavelength conflict avoidance, when there is no possibility to place filter in the parent links. Constraints (4-6) guarantee that only one filter can be utilized for one demand and its filtered wavelength can be reused for the other demands. Constraint (7) ensures that each demand can use only one wavelength. Constraints (8-11) are employed for wavelength continuity. Finally, constraints (12) and (13) are used to calculate wavelength usage.

3. Results

To evaluate the proposed ILP formulation we performed a set of simulations on different networks. As an example, we present the results for 10-node Italian network with a uniform traffic matrix1 with a set of 90 demands each of which has granularity of 10Gbps. The results obtained for other networks show similar benefit achieved by our optimization as the ones presented here for the Italian network. Figure 2(a) shows the results of wavelength usage as a function of the number of optimally placed passive filters. It can be seen that a significant reduction of number of wavelengths required to support the considered traffic demand is obtained by applying passive filters. The number of wavelengths needed is decreasing with increasing number of passive filters up to the certain point. Then, the curve is saturated, which means that placing more filters in the network will not further reduce the number of wavelengths. This is giving important information for the network provider regarding the number of filters that is beneficial to deploy. For the Italian network the maximum wavelength reuse can be attained with 12 filters. Figures 2(b-d) provide a performance comparison in terms of wavelength utilization, cost and energy consumption for the three considered network approaches, i.e. filterless, semi-filterless and active photonic networks. Since ILP solution always finds the optimum value of number of wavelengths for semi-filterless approach, it proves that it is possible to reach the same level as in the active photonic case by placing a small number of filters. The results shown in Fig. 2(c-d) demonstrate that the filterless and semi-filterless networks have significantly lower cost and power consumption compared to the active photonic networks.

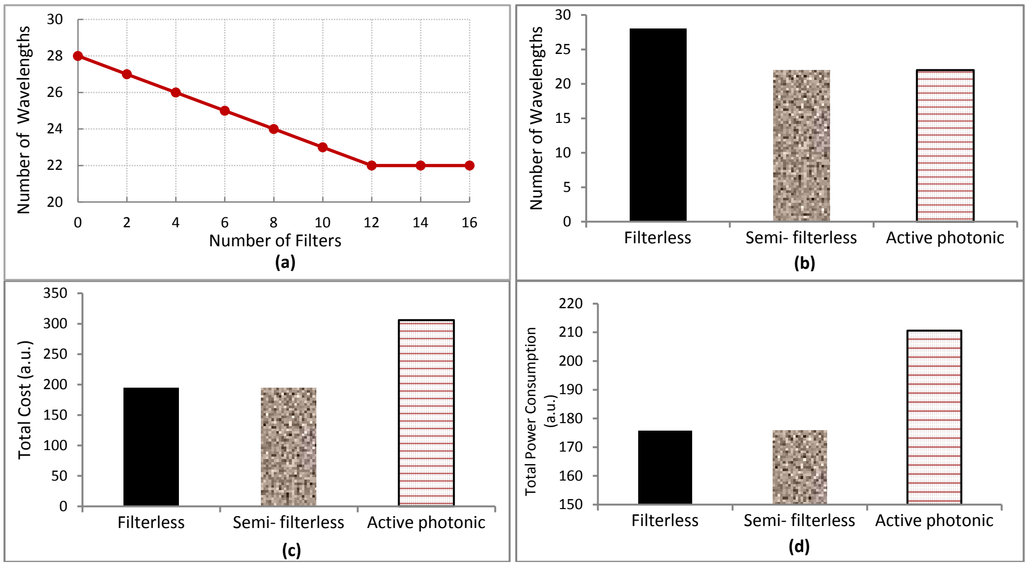

Fig. 2: (a) Number of wavelengths vs. number of filters in passive OBN and performance comparison for filterless, semi-filterless and active photonic solutions in terms of (b) number of wavelengths, (c) cost and (d) power consumption

We used the following models for the cost and energy consumption by considering the normalized values for the components which are shown in Tab. 1. In the formulations (14-17) N indicates number of specific devices while C and P represent cost and power consumption of corresponding devices, respectively. In passive OBNs we considered transponders with electronic dispersion compensation module (T-eDCM) and single stage (SS) optical line amplifiers (OLA) while in active architecture we used transponders without eDCM (T-no-eDCM) together with dual stage (DS) OLAs, due to longer transmission distance and higher impairment in passive OBNs.

- Active photonic:

$$Total\ Cost = N_{T-no-eDCM}.C_{T-no-eDCM} + N_{WSS}.C_{WSS} + N_{OLA}.C_{DS} \quad (14)$$

$$Total\ Power\ Consumption = N_{T-no-eDCM}.P_{no-eDCM} + N_{WSS}.P_{WSS} + N_{OLA}.P_{DS} \quad (15)$$

- Passive (filterless and semi-filterless):

$$Total\ Cost = N_{T-eDCM}.C_{eDCM} + N_{Cou}.C_{Cou} + N_{OLA}.C_{SS} + N_{F}.C_{F} \quad (16)$$

$$Total\ Power\ Consumption = N_{T-eDCM}.P_{no-eDCM} + N_{OLA}.P_{SS} \quad (17)$$

Tab. 1: Normalized values for cost and energy consumption in arbitrary unit (a.u.) [5]

Component		Cost*	Power Consumption**
Coupler(Cou)		$C_{cou}=0.02$	$P_{cou}=0$
Filter(F)		$C_{F}=0.035$	$P_{F}=0$
Optical Line Ampilifier(OLA)	Single-Stage	$C_{SS}=1.3$	$P_{SS}=1.3$
	Dual-Stage	$C_{DS}=2.6$	$P_{DS}=1.8$
Wavelength Selective Switch (WSS)		$C_{WSS}=2.5$	$P_{WSS}=0.9$
10 G Transponder with eDCM (T-eDCM)		$C_{T-eDCM}=1.2$	$P_{T-eDCM}=1$
10 G Transponder without eDCM (T-no-eDCM)		$C_{T-no-eDCM}=1$	$P_{T-no-eDCM}=0.9$

* Normalized to the cost of T-no-eDCM. **Normalized to the power consumption of T-eDCM.

Filterless and semi-filterless line systems also exhibit lower power dissipation, thanks to the electronic dispersion compensation capability of the tunable receivers, which allows using single-stage optical amplifiers except at equalization sites. Calculations made for Italian network topology (80-km spans and two equalization sites) indicate savings of about 22% for optical links equal to the network diameter.

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