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DESIGN OF ADVANCED OPTICAL NETWORKS BASED ON THE FILTERLESS CONCEPT

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CONCEPTION DE RESEAUX OPTIQUES AVANCÉS
BASÉE SUR LE CONCEPT DE SANS FILTRE

Zhenyu XU

RÉSUMÉ

Le trafic Internet mondial continuera à croître à une très grande vitesse dans les années à venir. Pour répondre à cette exigence et ce défi, la capacité des réseaux optiques a augmenté de façon significative au cours des dernières années en s’appuyant sur l’avancement de la technologie du multiplexage en longueur d’onde (WDM en anglais).

Les opérateurs de réseaux concentrent régulièrement sur la réduction des coûts opérationnels et l’augmentation de l’efficacité de transmission afin de déployer des réseaux optiques agiles plus rentables et plus efficaces spectralement. La résilience des réseaux est également une préoccupation majeure pour les opérateurs de réseaux étant donné que une énorme perte pourrait être causée par une petite défaillance de nœud ou de liaison dans les réseaux optiques à ultra haut débit.

Le concept des réseaux sans filtre a été proposé comme une méthode plus simple et plus rentable de fournir l’agilité du réseau par rapport aux réseaux photoniques actifs basés sur commutateurs sélectifs en longueur d’onde (WSS en anglais). Ce concept est basé sur la prémisse que l’agilité et la reconfigurabilité des réseaux optiques peuvent être obtenues en utilisant des transmetteurs accordables et des récepteurs cohérents aux terminaux de réseau, comme les réseaux radio.

Une solution du réseau sans filtre est obtenue en résolvant le problème d’interconnexion de liaison en fibre optique. Ensuite la solution obtenue est caractérisée par un ratio de protection inhérent. Dans cette thèse, nous proposons une stratégie de protection dédiée sur la couche optique pour les réseaux sans filtre en assurant une protection à 100% pour toutes les connexions dans la topologie sans filtre. La consommation de longueur d’onde des solutions sans filtre protégées est évaluée en résolvant le problème de routage et assignation de longueur d’onde (RWA en anglais). Les résultats de simulation montrent que les solutions des réseaux sans filtre protégées peuvent être réalisées avec un coût plus rentable que son homologue actif tout en gardant la consommation de longueurs d’onde à un niveau comparable.

Le réseau optique à grille flexible est une méthode prometteuse pour améliorer l’efficacité et la flexibilité spectrale car la largeur de bande passante d’un canal peut être attribuée à une demande spécifiquement, selon la condition de capacité et distance. Dans cette thèse, nous présentons le concept des réseaux optiques sans filtre à grille flexible, qui combine les avantages des architectures des réseaux sans filtre et des réseaux a grille flexible. Nous proposons à la fois une optimisation linéaire en nombres entiers (ILP en anglais) et des méthodes heuristiques pour résoudre le problème de routage et assignation du spectre (RSA en anglais) pour les réseaux optiques sans filtre à grille flexibles. Les solutions sans filtre à grille fixe et flexible sont comparées en termes de consommation spectrale et les avantages de la défragmentation du spectre périodique sont également quantifiés par des simulations.

Mots-clés : Réseaux optiques à grille flexible, réseaux sans filtre, résilience, RSA, RWA, WDM

DESIGN OF ADVANCED OPTICAL NETWORKS BASED ON THE FILTERLESS CONCEPT

Zhenyu XU

ABSTRACT

Global Internet traffic will continue to grow at high speed in the forthcoming years. To meet this requirement and challenge, the capacity of optical core and regional networks has increased significantly over the past few years by leveraging the wavelength division multiplexing (WDM) technology.

Telecommunications network providers have been steadily focusing on reducing their operational costs and increasing the transmission efficiency so as to deploy more cost-effective and spectrally efficient agile optical networks. Failure survivability is one of network operators' major concerns considering that enormous losses could be caused by one small node or link failure in actual ultra high capacity optical networks.

The filterless network concept has been proposed as a simpler and more cost-effective method to deliver network agility compared to conventional wavelength selective switch (WSS) -based active photonic switching networks. This concept is based on the premise that the need for network agility and reconfigurability can be provided by using tunable transmitters and coherent receivers at the network edge terminals, as in radio networks.

A filterless network is devised by solving the fiber link interconnection problem, and then the resulting solutions are characterized by an intrinsic protection ratio. In this thesis, we propose a 1+1 dedicated optical-layer protection strategy for filterless networks in an effort to provide 100% protection for any connection within the topology. The wavelength consumption of protected filterless solutions is evaluated by solving the routing and wavelength assignment (RWA) problem. The simulation results show that the survivable filterless network solutions can be more cost-effective than its active counterpart while keeping the number of used wavelengths at a comparable level.

Elastic (flex-grid) optical networking is a promising solution to improve spectral efficiency and flexibility since channel bandwidth can be assigned to a traffic demand dynamically, according to its capacity and distance requirements. In this thesis, we present the concept of elastic filterless optical networks, which combines the advantages of filterless network architectures and flex-grid networking. Besides, we propose not only an mathematical optimization method based on an integer linear programming (ILP) formulation but also more computationally efficient heuristic methods to solve the routing and spectrum assignment (RSA) problem in the elastic filterless optical networks. The performance in terms of spectrum utilization and cost for fixed- and flex-grid filterless solutions are compared and the benefits of periodical spectrum defragmentation are quantified through simulations as well.

Keywords: Elastic optical networks, filterless optical networks, routing and wavelength assignment (RWA), routing and spectrum assignment (RSA), survivability, Wavelength division multiplexing (WDM)

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LIST OF ABREVIATIONS

ASE	Accumulated Spontaneous Emission
BLSR	Bidirectional Line-switched Ring
BPSK	Binary Phase Shift Keying
BW	Bandwidth
CD	Chromatic Dispersion
C/D/C	Colorless, Directionless, and Contentionless
CO-OFDM	Coherent Optical Orthogonal Frequency-Division Multiplexing
CoWDM	Coherent Optical Wavelength Division Multiplexing
CPF	Colored Passive Filter
DEMUX	Demultiplexer
DP-QPSK	Dual Polarization-Quadrature Phase Shift Keying
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-doped Fiber Amplifier
FEC	Forward Error Correction
FNDS	Filterless Network Design and Simulation
GA	Genetic Algorithm
GMPLS	Generalized Multiprotocol Label Switching
ILP	Integer Linear Programming
IP	Internet Protocol
ITU-T	International Telecommunication Union Telecommunication Standards Sector

LCoS	Liquid Crystal on Silicon
LSP	Label-switched Path
MEMS	Microelectromechanical System
MILP	Mixed-Integer Linear Programming
MPLS	Multiprotocol Label Switching
MUX	Multiplexer
OAWG	Optical Arbitrary Waveform Generation
O-E-O	Optical-Electrical-Optical
OFDM	Optical Orthogonal Frequency-Division Multiplexing
OOK	On/Off Keying
OTN	Optical Transport Network
OXC	Optical Cross-Connect
PCE	Path Computation Element
PDL	Polarization-dependent Loss
PMD	Polarization Mode Dispersion
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RMLSA	Routing, Modulation Level and Spectrum Allocation
RSA	Routing and Spectrum Assignment
RWA	Routing and Wavelength Assignment
SDH	Synchronous Digital Hierarchy

SDN	Software Defined Networking
SNR	Signal-to-Noise Ratio
SONET	Synchronous Optical Network
SSS	Spectrum Selective Switch
TDM	Time Division Multiplexing
TS	Tabu Search
UPSR	Unidirectional Path-switched Ring
WAN	Wide Area Network
WB	Wavelength Blocker
WDM	Wavelength Division Multiplexing
WRON	Wavelength-Routed Optical Network
WSS	Wavelength Selective Switch

INTRODUCTION

Global Internet traffic driven by the popularity of mobile devices, bandwidth-intensive applications (e.g., Netflix, Hulu, YouTube, Facebook etc.), data centers, and cloud-based services will continue to grow at extremely high speed in the coming years (Cisco, 2013). To meet this requirement, the capacity of optical backbone and metro networks has increased significantly over the past few years by leveraging on advances of wavelength division multiplexing (WDM) technology (Mukherjee, 2006). On the other hand, the revenues of network operators have not followed the same pattern. To address this imbalance, carriers have been steadily focusing on reducing their operational costs and at the same time increasing the transmission efficiency so as to deploy more cost-effective and spectrum-efficient optically agile networks.

0.1 Filterless Optical Networks Concept

In current active photonic switching networks, agility and flexibility are provided by wavelength selective switches (WSS)-based reconfigurable optical add-drop multiplexers (ROADM) (Collings, 2013; Strasser & Wagener, 2010) or optical cross-connect (OXC) at intermediate nodes, whereas the hardware requirements are rather intense to realize these capabilities even though the number of fiber ports is relatively small. In the light of this context, the filterless optical network concept has been proposed as a simple and cost-effective method to deliver network agility on the scale of wide area network (WAN) and regional networks. This passive network architecture is based on the premise that the need for agility and reconfigurability can be provided by using tunable transmitters and coherent receivers at the network edge terminals, similarly to radio networks. In the resulting architecture, active switches and colored components used for signal switching and local signal add-drop are replaced by passive optical couplers. This network architecture is also considered as a promising approach for Software Defined Networking (SDN) (Goth, 2011; Gringeri, Bitar, & Xia, 2013). Furthermore, the passive gridless architecture of filterless networks makes them naturally suitable for elastic optical networking, as the current fixed-grid dense WDM (DWDM) line systems can be upgraded to flexible ones without the need to replace the switching and filtering devices at intermediate nodes. Thus, in filterless networks, the gridless operation can be achieved at almost no cost without having to deploy gridless WSS, which are at present significantly more expensive than fixed-grid ones.

0.2 Survivability in Filterless Optical Networks

Resilience and survivability against potential node or link failures is always a major concern of network operators, considering that enormously economic loss could be caused by one small failure in actual ultra high capacity optical transport networks. The network protection can be realized in optical layer and/or its client layer. The filterless network solutions are characterized by an *intrinsic protection ratio*, which can be defined as the percentage of source-destination (s-d) node pairs connected by at least two link-disjoint paths among all the s-d node pairs in the network without any specific consideration for resiliency. The intrinsic protection ratio of a given filterless network solution is fully determined by the configuration of sets of interconnected optical fibers referred to as *fiber trees* (Christine Tremblay et al., 2013). This ratio could be lower than 100% as it is not always possible to guarantee that all s-d node pairs are covered by two edge-disjoint fiber trees. Therefore, some traffic demands may have only one single lightpath available in the network, and consequently, cannot be protected in the case of a link or node failure. Hence, the problem of providing protection against fiber link failures in a filterless outside plant needs to be addressed, similarly to the conventional active switched photonic networks.

0.3 Paradigm of Elastic Optical Networking

Based on DWDM technology, current wavelength-routed optical networks (WRON) use a fixed 50/100-GHz International Telecommunication Union Telecommunication Standards Sector (ITU-T) frequency grid (ITU-T, 2012) to offer high transmission capacity. Facing the ever-increasing interest of superchannels (i.e., a unified channel of data rate in the Terabit per second range) (Bosco, Curri, Carena, Poggiolini, & Forghieri, 2011) as well as the variations in the capacity required by different applications, it is unlikely to keep using the conventional

WDM systems with fixed channel spacing for long-haul transmission. The paradigm of flexible optical networking (also referred to as elastic, flex-grid and gridless networking in the literature) (Gerstel, Jinno, Lord, & Yoo, 2012; Jinno et al., 2009; Patel, Ji, Jue, & Wang, 2012; Roberts, Beckett, Boertjes, Berthold, & Laperle, 2010) has emerged as a promising solution to provide enhanced spectral efficiency and flexibility. The migration from fixed-grid to flexible grid paradigm has opened a gate to bring new potential architectural possibilities to optical networking design. According to ITU DWDM frequency grid definition (ITU-T, 2012), the center wavelength and bandwidth of the optical channels in elastic optical networks can be configured on the fly for end-to-end traffic demands of different data rates to optimize the spectrum requirements of individual channels. In the resulting configuration, a specific amount of channel bandwidth can be assigned dynamically to an end-to-end demand according to the capacity and distance conditions. An important and challenging design and planning problem is generally referred to as *routing and spectrum assignment* (RSA). The RSA problem can be defined as finding a proper lightpath for each end-to-end traffic request and assigning a set of continuous spectral resources with the objective of minimizing the overall spectrum consumption, while maintaining the spectrum contiguity and spectrum continuity constraints. Some key enabling technologies to realize elastic optical networks include multicarrier-based flexible transponders and flexible spectrum selective switches (Roberts et al., 2010).

0.4 Contribution of the Thesis

0.4.1 Protection Strategy for Filterless Optical Networks

In the first part of this thesis, we study the survivability problem in filterless optical networks. To achieve a survivable filterless solution with 100% protection ratio (i.e., at least two link-disjoint paths could be found for all s-d node pairs in a filterless architecture), we present a 1+1 dedicated optical-layer protection strategy, referred to as Inter-tree Protection Path strategy (Xu Zhenyu et al., 2014), based on the deployment of wavelength blockers (WBs) and/or colored passive filters (CPFs) at some selected network nodes, as well as an algorithm for their placement, and propose an efficient heuristic algorithm for solving the *routing and spectrum assignment* (RWA) problem in the survivable filterless optical networks. We validate the performance of proposed survivable filterless solutions in terms of wavelength consumption and cost for a number of physical network topologies by comparing them with WSS-based active photonic switching counterparts. The numerical results show that the filterless network solutions with 100% protection ratio obtained by using this method is much more cost-effective than its active counterpart while keeping the wavelength usage at a comparable level.

0.4.2 Elastic Filterless Optical Networks

Considering all previous work regarding the filterless network remains in the context of standard rigid ITU frequency grid (i.e., 50-GHz channel spacing), in the second part of this thesis, we introduce a new concept of elastic filterless optical networks, which combines the benefits of broadcast-and-select node structure in filterless networks with the spectrum efficiency and flexibility of elastic networking. In the third part of this thesis, we then present computationally efficient algorithms for the elastic filterless optical networks. An integer linear programming (ILP) formulation and two algorithmic methods, greedy and genetic algorithm based heuristic, are devised to solve the RSA problem in the elastic filterless optical networks with realistic traffic data. Elastic and fixed-grid filterless solutions are compared in terms of spectrum utilization and the benefits of periodical spectrum defragmentation is quantified through numerical results.

0.5 Organization of the Thesis

The content of this thesis is summarized based on our published and submitted journal papers. The remainder of this thesis is organized as follows. In Chapter 1, we review the literature including virtual topology design problem in WRON, the related work of elastic optical networking, and previous work in filterless optical networks design. In Chapter 2, we address the survivability issue in filterless optical networks. An inter-tree protection path strategy is proposed to achieve fully protected filterless solutions and solve the RWA problem in the resulting filterless architecture with a heuristic algorithm. In Chapter 3, we introduce the concept of elastic filterless optical networks and evaluate its performance compared to fixed-grid filterless network solutions. In Chapter 4, we investigate the RSA problem in the elastic filterless optical networks and solve the problem with an ILP-based optimization as well as metaheuristic algorithms for finding optimal spectrum utilization. Finally, we conclude the thesis and point out some future work.

CHAPTER 1

BACKGROUND AND RELATED WORK

1.1 Overview of Wavelength-Routed Optical Networks

With the considerable advancement of WDM (Mukherjee, 2006) technology in recent years, current WDM optical fiber transmission systems are capable of offering a tremendous amount of transmission capacity on a single fiber-optic link (Bennett, Kuang-Tsan, Malik, Roy, & Awadalla, 2014; Essiambre, Kramer, Winzer, Foschini, & Goebel, 2010; Roberts et al., 2010). Wavelength-routed WDM networks, which typically utilize OXCs or WSS-based ROADMs at core nodes to manage the signal switching/routing and local add-drop functions, have been widely deployed in optical long haul and metro networks, which are mostly based on the mesh and ring topologies. An overview of typical core, metro (or metropolitan), and access optical networks is illustrated in Figure 1.1. The nodes shown in this figure are connected by optical links, which consist of multiple fiber pairs. Most of the traffic collected from individual business and homes in the access network is hubbed into carrier's central office located in the metro network. Then the traffic from the metro network is further aggregated into the core network, which interconnects different cities and areas and spans hundreds to thousands of kilometers between nodes.

In backbone (core) networks (see Figure 1.1), the optical signals between source nodes and destination nodes can be kept entirely in the optical domain throughout their end-to-end routes without optical-electrical-optical (O-E-O) conversion at intermediate nodes in order to avoid expensive electronic switching and processing within the nodes, such networks are referred to as all-optical wavelength-routed networks. Wavelength conversion technology (Mukherjee, 2006; Ramamurthy & Mukherjee, 1998; Yoo, 1996) can be used at intermediate nodes of WDM networks to improve the efficiency of wavelength usage by converting the data arriving on one wavelength from an ingress port into another wavelength at an intermediate node and forward it to an egress port. The all-optical connections between source-destination node pairs are called lightpaths (Chlamtac, Ganz, & Karmi, 1992). Figure

1.2 illustrates the lightpath establishment in a wavelength-routed optical core network. In the example shown in Figure 1.2, three lightpaths (e.g., between node [A, E], [B, D], and [A, C], each with a specific wavelength (λ)) are created in a mesh topology, where the access nodes represent end users equipped with a set of (tunable) transponders and optical switches (e.g., ROADM/OXC) in the mesh topology are responsible of routing ingress light signals to their desired egress links.

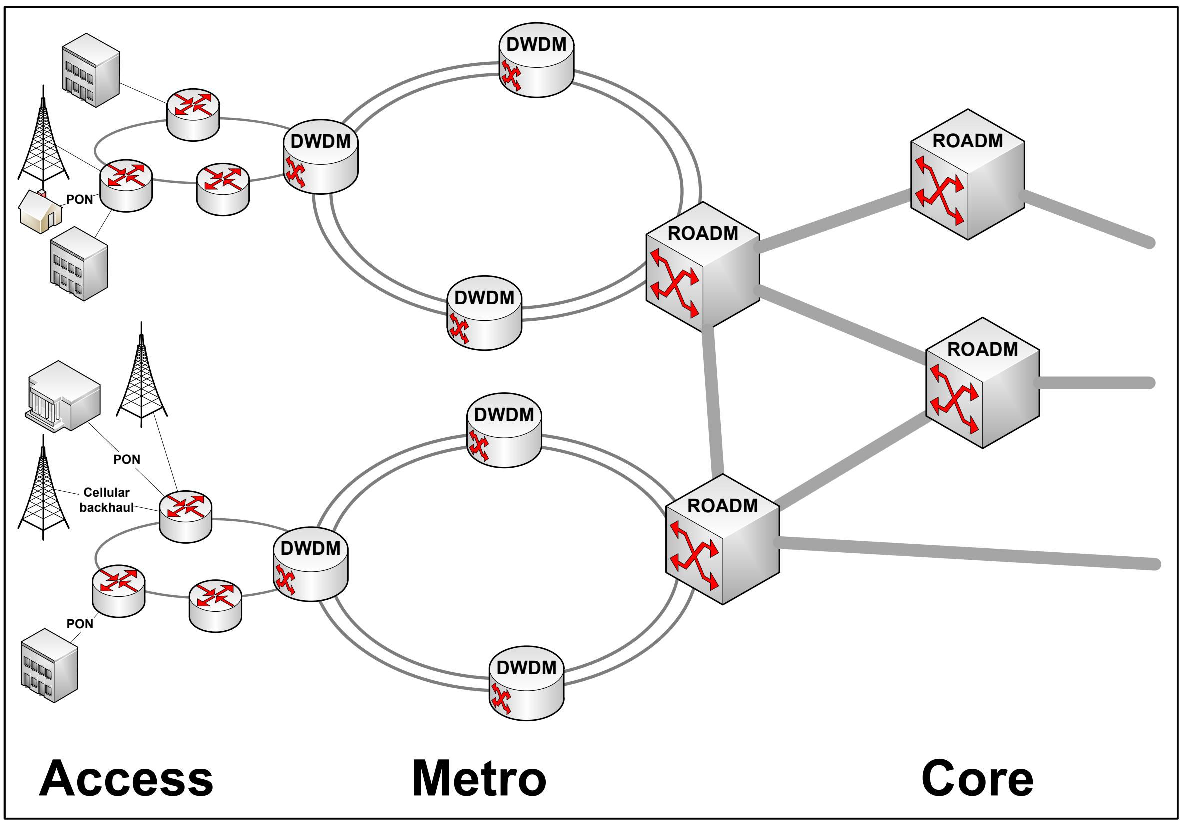


Figure 1.1 An overview of core, metro and access optical networks. In this illustrated example, the mesh architecture is deployed in core networks and the ring architecture is deployed in the metro networks. ROADM (reconfigurable optical add-drop multiplexer), DWDM (dense wavelength-division multiplexing)

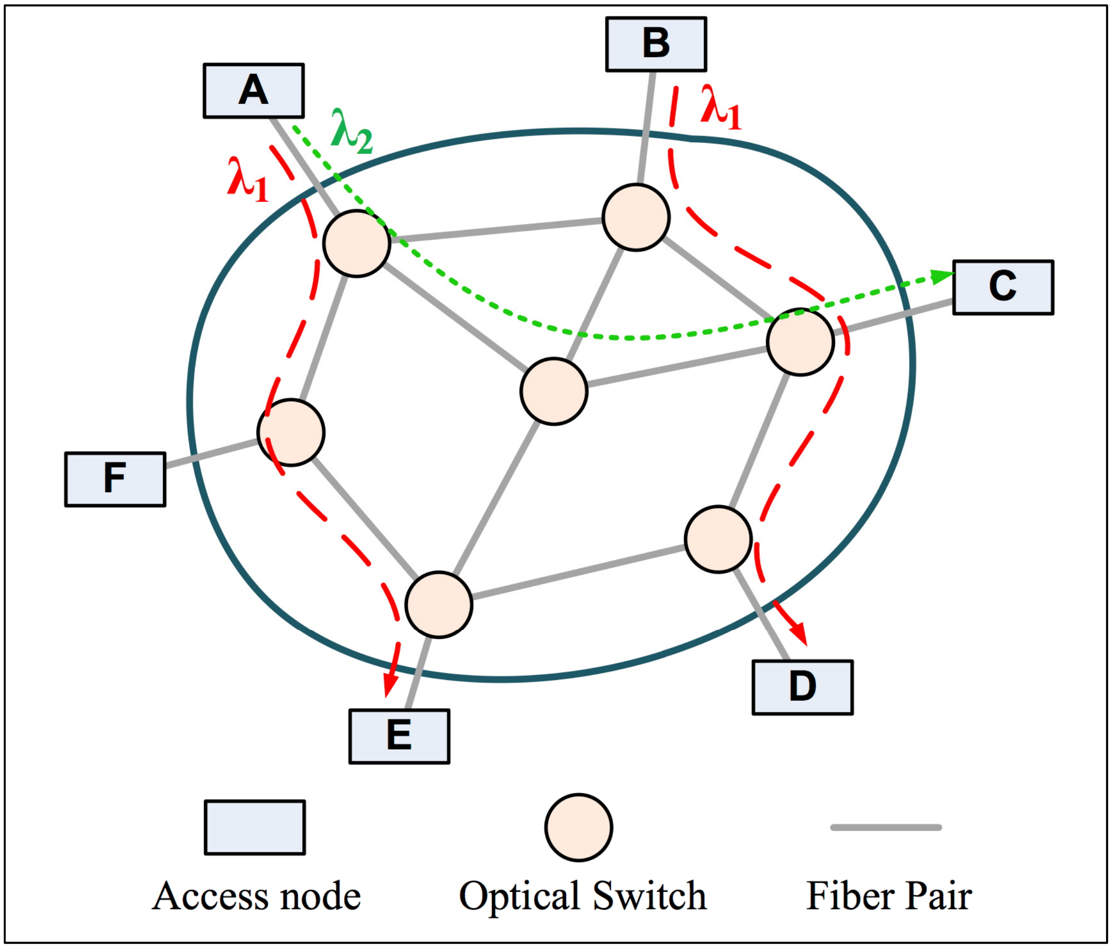


Figure 1.2 An illustration of lightpath establishment in a wavelength-routed optical network
Retrieved from Mukherjee (2006, p. 356)

1.1.1 Routing and Wavelength Assignment Problem

One of the challenges in planning the wavelength-routed optical networks (WRON) is to develop efficient approaches for solving the routing and wavelength assignment (RWA) problem, which can be further classified into static or dynamic RWA problem depending on the type of given traffic scenario that is considered in the problem. The RWA problem has been intensively studied in the literature (Banerjee & Mukherjee, 1996; Hui, 2000; R. Ramaswami & Sivarajan, 1995), and it can typically be transformed into a *graph-coloring problem* (Mukherjee, 2006), where each node in an auxiliary graph represents a lightpath demand in the network and two nodes are connected by an undirected edge if their corresponding lightpaths share a common physical fiber link. The goal of the graph-coloring problem is to color all nodes of the auxiliary graph such that no two adjacent nodes have the same color. Due to the NP-completeness of the RWA problem (Chlamtac et al., 1992), it is generally decomposed into two sub-problems, Routing (R) and Wavelength Assignment (WA), which are solved sequentially by well-studied heuristic algorithms (Hui, 2000; Mukherjee, 2006). The static RWA problem, where a set of lightpaths demands is scheduled in advance in the form of a traffic matrix, has been studied in (Banerjee & Mukherjee, 1996; Christodoulopoulos, Manousakis, & Varvarigos, 2008; R. Ramaswami & Sivarajan, 1995). Possible optimization objectives of the problem can be minimizing the number of required wavelengths (called as min-RWA problem) or maximizing the served traffic given a limited number of wavelengths (called as max-RWA problem) (Jaumard, Meyer, Thiongane, & Yu, 2004).

In this thesis we assume that no wavelength conversion is available at intermediate nodes. This assumption implies that one same wavelength must be used for one connection throughout its lightpath. The problem of static RWA in WRON can be defined as follows.

Given a network topology G (V, E) with a set of nodes V and a set of links E, a set of lightpath traffic demands must be accommodated on the network. For each lightpath demand between an s-d node pair, we need to determine the route over which the lightpath is established and assign an available wavelength to this lightpath. Without the wavelength conversion capability at intermediate nodes, the same wavelength must be used throughout fiber links passed by the lightpath, which is referred to as the *wavelength continuity constraint*. Consequently, two different wavelengths must be assigned to two lightpaths that share a common fiber link. The objective of the problem is typically to minimize the total wavelength consumption on all fiber links for the given traffic.

A number of ILP formulations and heuristic approaches have been proposed in the literature (Banerjee & Mukherjee, 1996; R. Ramaswami & Sivarajan, 1995) to solve the static RWA problem. Optimal solutions can be obtained by the ILP approach, however, due to the problem's complexity and computational intensity, optimization with the ILP formulation may become computationally intractable (Hopcroft, Motwani, & Ullman, 2007) for large-sized networks (e.g., more than 8 network nodes). This is because the number of variables and constraints, leading to the computational time, increase quickly with the increase of network size, thus it causes the problem intractable in large networks. For large-sized networks, a number of efficient heuristic methods have been proposed to solve the RWA problem in a reasonable time. However, only suboptimal results can be achieved with the heuristic algorithms. There is a tradeoff between the optimality of obtained results and the computational time.

In the dynamic RWA problem, where random lightpath demands arrive on the fly and with certain amount of holding time, we need to choose one of available routes for each arriving lightpath demand and assign an available wavelength to it. The objective is to minimize the blocking probability or to maximize the number of accommodated demands for limited wavelength resources. A lightpath demand is blocked when there is no available wavelength can be assigned across all fiber links of its route.

1.1.1.1 Formulate the Static RWA Problem as ILPs

In the survey of RWA problem (Hui, 2000; Mukherjee, 2006), two most often studied methods of ILP formulation for the static RWA problem with two different objective functions have been presented: 1) the minimization of the flow in each link, which can be considered as equivalent to the problem of minimizing the number of wavelengths (referred to as min-RWA); 2) the maximization of the number of established connections for a given number of wavelengths (referred to as max-RWA).

1.1.1.2 Heuristics for Solving the Routing Subproblem

To reduce the complexity of combined RWA problem, the RWA problem can be divided into the routing subproblem and the wavelength assignment subproblem and they are solved separately. We first review three effective heuristics for solving the routing subproblem that have been studied in the literature.

1) Fixed routing

One pre-determined routing path is calculated offline for each lightpath demand between an s-d node pair. Typically, the shortest routing path is used for simplification and best performance in terms of latency. The lack of flexibility is a major drawback of this method, as the routing path is fixed and it will possibly lead to high wavelength consumption and network blocking probability.

2) Fixed-alternate routing

To improve the performance of the fixed routing approach, fixed-alternate routing algorithm is proposed, where each demand may have several candidate routing paths. In this approach, each demand attempts to establish a connection by sequentially choosing one routing path from the candidate routing paths. The commonly used criteria for ordering these candidate routing paths include according to the physical distance, number of fiber link segments passed by the routing path or other user-defined metrics.

3) Adaptive routing

In this method, the routing path for each s-d demand is selected dynamically, according to the network state when the demand is served. For example, the network state can be defined as the total cost for establishing current connection or the least congested path. The network state is updated each time when a new connection demand has been served, which requires extensive coordination of the network control plane. There is a tradeoff between the network performance and the computational complexity in this approach.

1.1.1.3 Heuristics for Solving the Wavelength Assignment Subproblem

The wavelength assignment subproblem has been well studied in the literature and the following heuristics have been proposed for solving the problem in single-fiber networks: 1) Random, (2) First-Fit, (3) Least-Used, (4) Most-Used, (5) Wavelength Reservation, and (6) Protection Threshold. We will briefly review these heuristics here in this section, more details of these heuristics can be found in (Hui, 2000; Mukherjee, 2006).

1) Random wavelength assignment (R)

This approach randomly chooses one wavelength among all available wavelengths and assigns it to a current demand.

2) First-Fit (FF)

In this scheme, all wavelengths are numbered. Each demand searches for an available wavelength from the lower-numbered wavelength to the higher-numbered one, and the first available wavelength will be assigned to a current demand.

3) Least-Used (LU)

This heuristic always selects the wavelength that is the least used in the network, in the hope of balancing the load among all the wavelengths. The usage of wavelength can be defined as wavelength × link.

4) Most-Used (MU)

Contrary to the LU, MU selects the most used wavelength in the network.

5) Wavelength Reservation (Rsv)

Rsv keeps a wavelength on a specified link for a traffic demand, usually a multi-hop demand. Therefore, this heuristic only reduces the blocking probability for multi-hop demands.

6) Protection Threshold (Thr)

In this scheme, a single-hop demand (i.e., a connection traverses only one fiber link) is assigned a wavelength only if the number of available wavelengths on the link is at or above a given threshold. It should be noted that, both Rsv and Thr heuristics are utilized jointly with other heuristic to achieve a better performance.

The performance of above heuristics in terms of the wavelength consumption can be ordered as follows: LU < R < FF < MU (Hui, 2000).

1.1.1.4 General Framework for Optical Networks Design

A general optimization framework for the formulation of optical networks design (Dutta & Rouskas, 2000; Leonardi, 2000; Mukherjee, Banerjee, Ramamurthy, & Mukherjee, 1996) has been summarized by (Degila & Sanso, 2004) as shown in Table 1.1.

This table classifies the functional measures in modeling a topological design and an optimization problem for optical networks. For example, given a network physical topology, a traffic matrix, and a routing scheme (1-3 in Table 1.1), the virtual topology design problem can be classified into maximization or minimization problem (4-5 in Table 1.1) with the objective of finding optimal virtual topology and routing solutions (13-14 in Table 1.1), while satisfying certain constraints (8-12 in Table 1.1). Associated functional metrics are listed in the third column of the table.

1.1.2 Light-tree and Optical Multicasting

In this section we review the concept of light-tree and the problem of multicasting in WDM networks. Optical multicasting is a bandwidth-efficient solution for the transmission of information from one source to several destinations in a one-to-many fashion, such as audio/video conferencing, and media streaming applications.

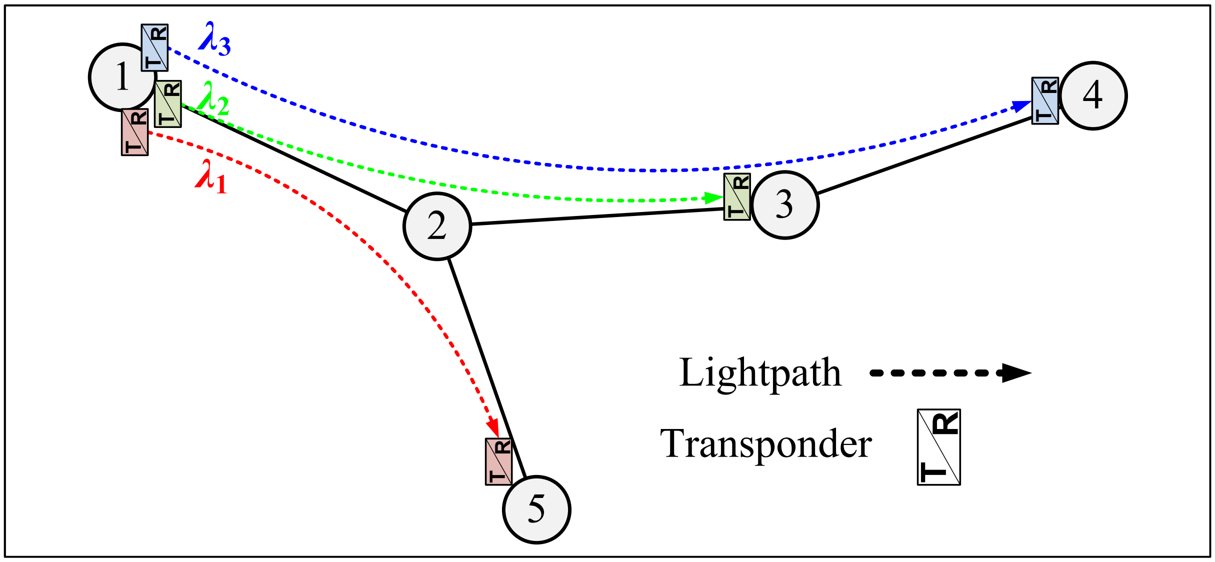
Table 1.1 General functional measures optimization framework for the topological design for optical networks
Retrieved from J. R. Degila *et al*. (2004, p. 29)

		Functional Measures
Given	1. Network physical topologies/System specifications 2. Traffic matrix 3. (Routing scheme)	
Objectives	4. Maximization	a. Total external traffic b. One-hop traffic
	5. Minimization	c. Maximal congestion d. Average weighted intermodal distance e. Mean delay
Variables	6. Flow	f. Portions of traffic over links
	7. Link	g. Lightpath-fiber indicators h. Lightpath-fiber-wavelength indicators
Constraints	8. Virtual structure	i. Virtual node degree j. Lightpath hop or length limitation
	9. Flow	k. Flow conservation l. Flow delay
	10. Coupling constraints	m. Flow-lightpath n. Lightpath-wavelength o. Wavelength-fiber
	11. Wavelength constraints	
	12. Variables range	p. Binary variables q. Positive real variables
Find	13. Virtual topologies 14. (Routing scheme)	

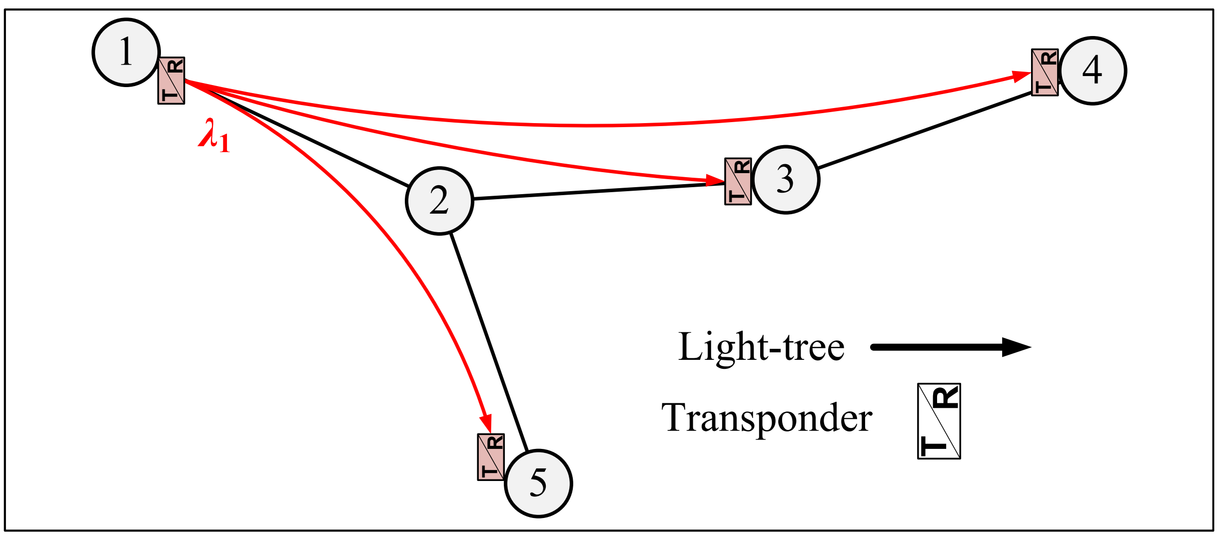
1.1.2.1 The Concept of Light-tree

A light-tree, proposed by (Sahasrabuddhe & Mukherjee, 1999), is a point-to-multipoint logical connection in a WDM optical network. As a generalization of a lightpath, a light-tree can be considered as a set of several lightpaths originating from a same source node. The benefits of a light-tree based topology compared to a lightpath-based topology lie in the support for not only unicast traffic (such as end-to-end lightpath demands), but also multicast and broadcast traffic because of its inherent point-to-multipoint logical structure. A comparative example between the lightpath and light-tree based virtual all-optical wavelength connections is illustrated in Figure 1.3. For instance, if we need to accommodate the traffic between nodes [1-3], [1-4] and [1-5], three lightpaths with different wavelengths and six transponders (i.e., two transponders per lightpath) are required in the lightpath solution (as shown in Figure 1.3(a)). Alternatively, we can broadcast the traffic by creating one virtual light-tree connection from node 1 to node 3, 4 and 5, passing through node 2, with only one wavelength and four transponders (i.e., one deployed at the source node 1 and three at the destinations node 3, 4 and 5, respectively) to carry the traffic (as shown in Figure 1.3(b)), assuming that the capacity of one wavelength in the light-tree is sufficient to support the total traffic. We can see from this example that the number of wavelengths and transponders can be reduced, and consequently leading to lower cost in light-tree based topology compared to the lightpath-based topology.

On the other hand, the benefits of deploying light-trees come at expenses of deploying multicast-capable wavelength routing switches (MWRS) (Sahasrabuddhe & Mukherjee, 1999) at certain nodes and requiring additional optical amplification in the network to maintain the optical signal power level without transmission errors. The multicast functionality in the MWRS (as shown in Figure 1.4) can be described as follows: First an incoming signal is demultiplexed and only the wavelength that needs to be duplicated (e.g., λ_b in Figure 1.4) is split by an optical power splitter; Then the output of the splitter is send to an optical switch (OSW shown in Figure 1.4), which routes different copies of the signal to their destination ports. The extra costs of MWRSs and optical amplifiers can be balanced by the savings of significantly reduced number of transponders at terminal nodes.



(a)



(b)

Figure 1.3 Comparative illustration of virtual connections produced by the lightpath (a) and light-tree (b) all-optical wavelength channel

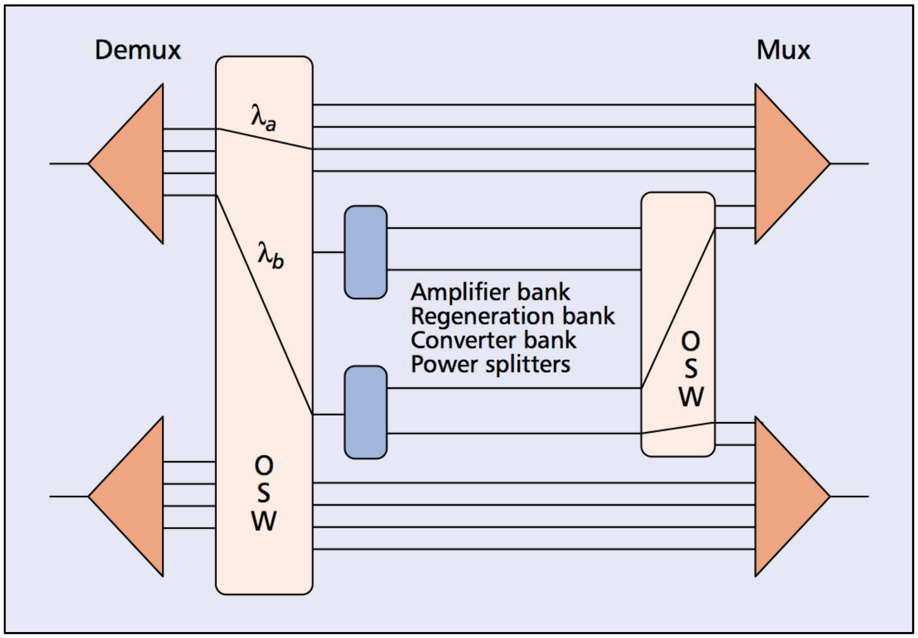


Figure 1.4 A multicast-capable wavelength-routing switch
Retrieved from J. He *et al.* (2002, p. 10)

In (Sahasrabuddhe & Mukherjee, 1999), the authors formulated the light-tree-based optimum virtual topology design problem as a mixed-integer linear programming (MILP), and the simulation results showed that the light-tree-based virtual topology has superior performance in terms of the average packet hop distance and number of opto-electronic components compared to lightpath-based virtual topology.

1.1.2.2 Multicasting in WDM Networks

The paper of (Jingyi, Chan, & Tsang, 2002) surveys the problems of multicasting in three types of WDM networks: 1) broadcast-and-select, 2) wavelength-routed, and 3) optical burst-switched WDM networks.

Table 1.2 summarizes the major issues and corresponding solutions of multicasting in these three types of WDM networks. In a broadcast-and-select WDM network, network nodes are connected by passive broadcast-enabled components (e.g., passive star couplers), and the signal stays in the optical domain from a source node to a destination node. The main problem in the broadcast-and-select networks is the coordination/scheduling of the transmissions because of the presence of contentions in such resource-shared networks. Such contention may occur when more than one transmitters want to use the same wavelength channel at the same time. Therefore, efficient multicast scheduling algorithms are highly necessary to avoid this problem.

Table 1.2 Summary of multicasting in three types of WDM networks
Retrieved from J. He *et al.* (2002, p. 3)

WDM networks		**Application areas**	**Major issues for multicasting**	**Approaches**
Broadcast-and-select		LAN, MAN	Contentions in the shared-media and shared-channel environment	Multicast Scheduling Algorithms (MSAs)
Wavelength-routed	Mesh	WAN	Limitations in • number of wavelengths • wavelength conversion capability • light splitting capability	Multicast Routing and Wavelength Assignment (MC-RWA)
	Ring	LAN, MAN, WAN	Limited number of wavelengths	
Optical burst-switched		WAN	Overheads of the control packets and guard bands	Sharing schemes

In a wavelength-routed WDM network, a light-tree is created for each multicast demand. The main challenge in such networks is solving the multicast routing and wavelength assignment problem where we need to route the light-trees and determine the wavelengths to be assigned to these routes.

In an optical burst-switched WDM network, a control packet used for establishing a connection and resources reservation is sent prior to the transmission of a data burst. As a part of the data packet, guard bands are needed for each burst to mitigate the timing jitters when passing intermediate nodes. Hence, besides the challenge of establishing light-trees, reducing the overheads of the control packets and guard bands has been a primary objective for multicasting in such networks.

1.1.3 Advancements in Wavelength-Routed Optical Networks and Enabling Technologies

In this section we briefly review some advances and enabling technologies in the wavelength-routed optical networks. We first look at the ROADM architecture in long-haul DWDM networks and then review the advances of high-capacity optical transmission systems.

1.1.3.1 ROADM Architecture

As a major part of core node in long-haul DWDM networks, ROADM supports all-optical signal switching and wavelength channel cross connecting through software control. The current generation of WSS-based ROADM primarily uses two architectures: broadcast-and-select and route-and-select node architecture (Collings, 2013; Strasser & Wagener, 2010). The broadcast-and-select ROADM (as shown in Figure 1.5) uses a single WSS and passive splitter in each ROADM node degree. The passive splitter broadcasts all signals onto its output ports, and desired signals are then selected at each WSS input port. On the other hand, the route-and-select ROADM (as shown in Figure 1.6) uses two WSSs in each ROADM node degree. The required signals are selectively transmitted from one WSS to the other.

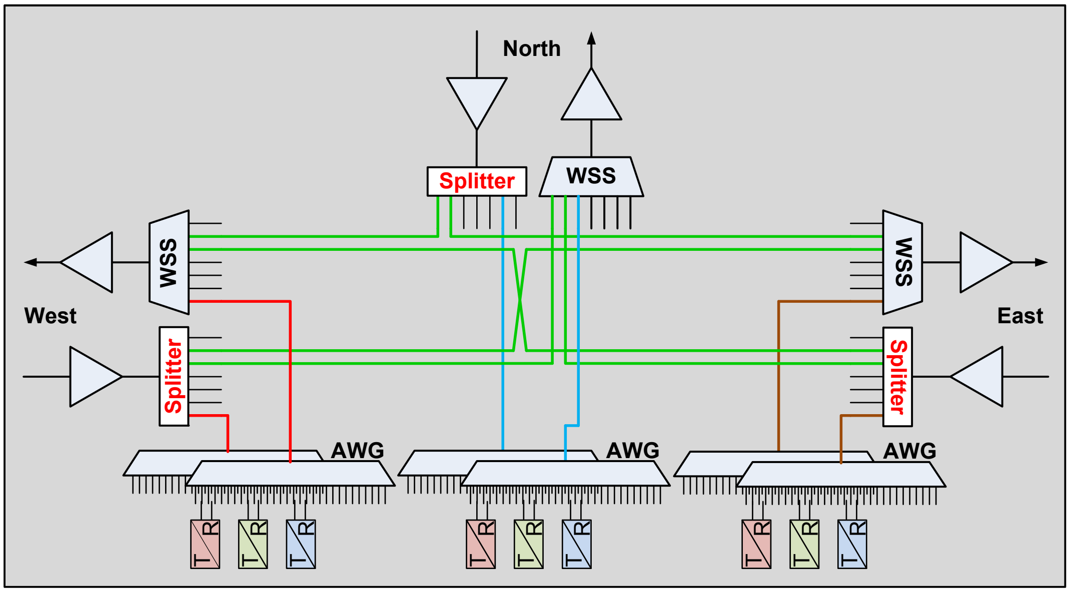


Figure 1.5 An example of broadcast-and-select ROADM node architecture
Retrieved from B. Collings (2013, p. 67)

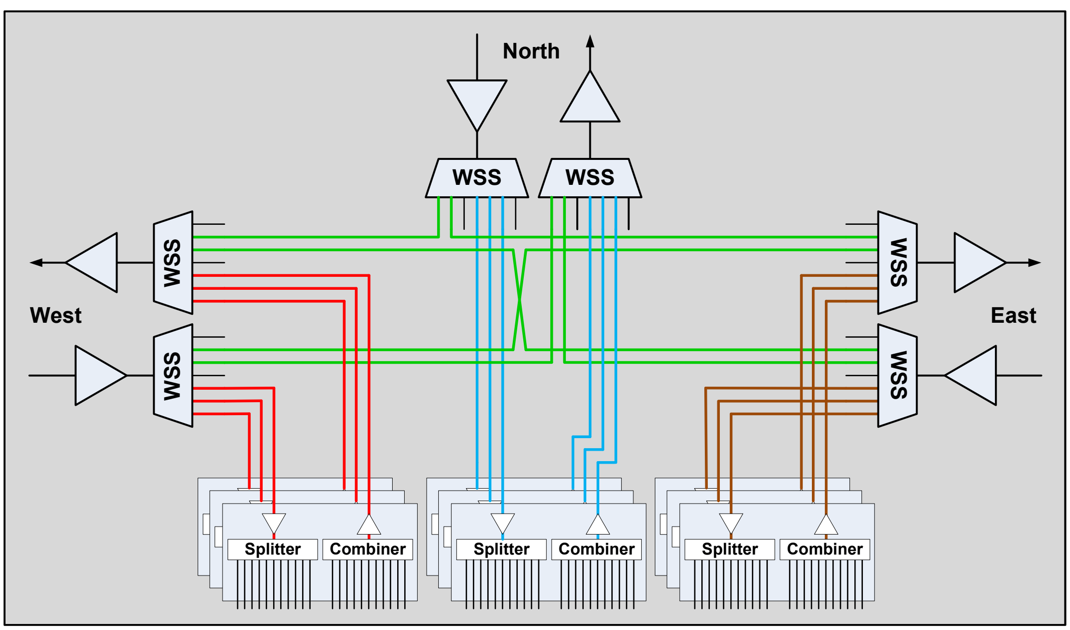


Figure 1.6 An example of route-and-select ROADM node architecture
Retrieved from B. Collings (2013, p. 68)

The tradeoffs between these two ROADM architectures are summarized in Table 1.3 (Filer & Tibuleac, 2014). Benefits of broadcast-and-select architecture lie in lower optical and electronic complexity, cost, and energy consumption because it requires only one WSS per input port. For these reasons, the passband narrowing effect when cascading ROADMs is higher in the route-and-select architecture than broadcast-and-select one, causing higher OSNR penalties. On the contrary, a major downside of the broadcast-and-select architecture is the lower isolation on the blocking ports due to crosstalk. Another limitation of the broadcast-and-select architecture is insertion loss, which scales with the number of ports, whereas this loss is constant regardless of port count for the route-and-select scheme. We can see clearly that the disadvantages of the broadcast-and-select architecture are advantages for the route-and-select one, and vice versa.

The cascading of ROADMs in DWDM networks leads to significant optical bandwidth reduction and in-band crosstalk within the receiver bandwidth (Filer & Tibuleac, 2014). The results of a comparative study (Filer & Tibuleac, 2014) of above two ROADM node architectures in 120 Gb/s dual polarization quadrature phase shift keying (DP-QPSK) transmission showed that the broadcast-and-select ROADM architecture is preferred for node degrees less or equal to nine owing to lower system penalties, and route-and-select ROADM architecture for higher node degrees because of its fixed insertion loss and increased isolation.

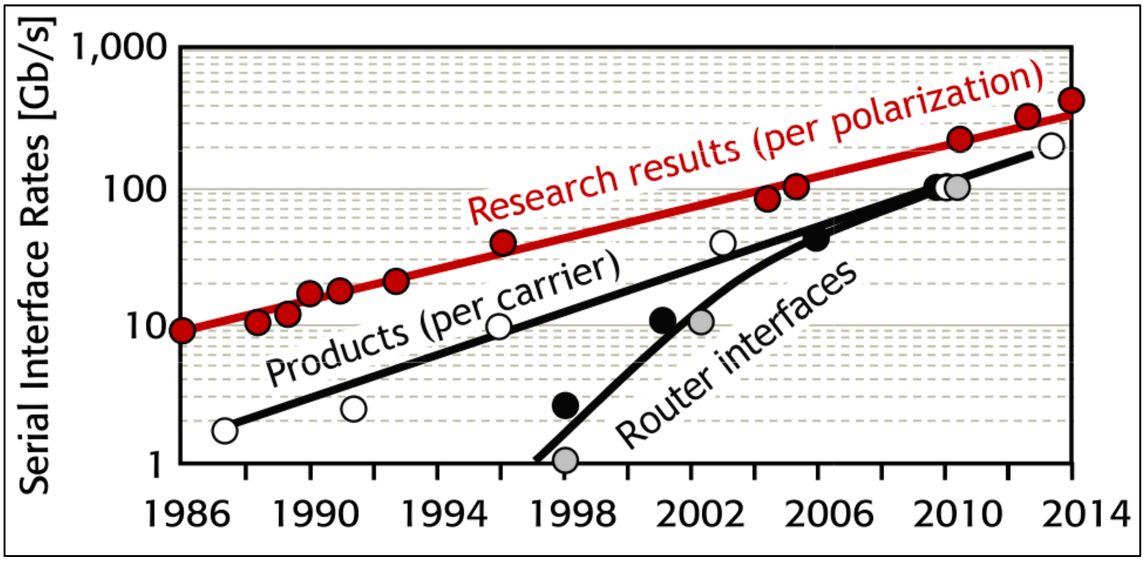
Next generation ROADM requires Colorless, Directionless, and Contentionless (C/D/C) capabilities at the add/drop switch ports for dynamic wavelength switching (Feuer & Woodward, 2012; Jensen, Lord, & Parsons, 2010). The true flexibility of the next generation of core node structure is to enable the wavelength tunability of each optical transponder installed on the ROADM (colorless), to enable the wavelength add/drop from any direction (directionless), and to allow multiple copies of the same wavelength on a single add/drop port (contentionless) (Gringeri, Basch, Shukla, Egorov, & Xia, 2010). With the increase of network traffic, more efforts have been made for designing C/D/C flexible grid ROADM architecture (Egorov, 2013; Way, 2012) to improve spectral utilization and support multicarrier or superchannel transport. Compared to basic ROADM architectures, the C/D/C enabled ROADMs will bring more flexibility into next generation optical networks at the expense of higher node complexity and increased costs.

Table 1.3 Comparison of broadcast-and-select and route-and-select ROADM architecture Summarized from M. Filer *et al*. (2014, p. 2)

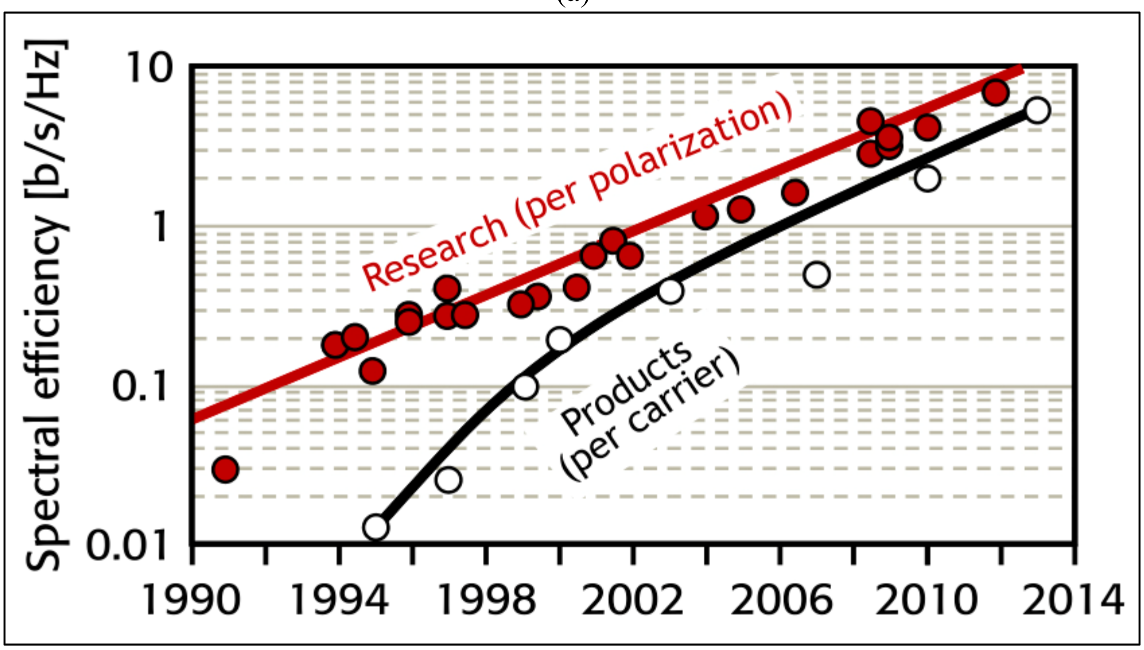
	Pros	**Cons**
Broadcast-and-select **ROADM**	1. Reduced cost 2. Reduced power consumption 3. Reduces optical and electronic complexity 4. Smaller BW-narrowing effect	1. Reduced isolation (higher crosstalk) 2. Insertion Loss scales with node degree
Route-and-select **ROADM**	1. Superior isolation (lower crosstalk) 2. Insertion Loss fixed regardless of node degree	1. Increased cost 2. Increased power consumption 3. Increased optical and electronic complexity 4. Larger BW-narrowing effect

1.1.3.2 High-capacity Transmission

The single-channel capacity has been increased from 10 Gb/s to 400 Gb/s and beyond in the last two decades by leveraging significant technical advancements of modulation and multiplexing (Liu & Chandrasekhar, 2014; Roberts et al., 2010; Roberts et al., 2009), which include the following aspects: 1) symbol rate, 2) bits per symbol, 3) polarization multiplexing, 4) multiple frequency carrier, and 5) spatial multiplexing. Advances of coherent detection and digital signal processing (DSP) are indispensable for the improvement of transmission distance and impairment tolerance over conventional direct detection. Furthermore, forward error correction (FEC) (Nelson et al., 2012) with high coding gain has been extensively applied to further extend the reach of high-capacity optical transport systems. The system capacity can be increased by multiplexing channels by means of the DWDM transmission technology. The scaling trend of single channel capacity and WDM system spectral efficiency in research and commercial products is illustrated in Figure 1.7.



(a)



(b)

Figure 1.7 Historic serial bit rate capacity (a) and WDM system spectral efficiency (b) scaling in research and products. Optical transmission products (white), research demonstrations (red), router interfaces (black), and Ethernet standards (gray) Retrieved from P. J. Winzer (2014, p. 25)

Figure 1.7(a) shows commercially available serial interfaces (e.g., SONET (synchronous optical network)/SDH (synchronous digital hierarchy), and OTN (optical transport network)) (white circles) and router interfaces (black circles). Gray circles in Figure 1.7(a) represent related Ethernet standards. Research demonstrations of single-channel data rates are denoted by green circles. In the last decade, the modulation format underwent a transition from simple on/off keying (OOK) using direct detection to QPSK, 16-QAM using coherent detection, and the highest commercially available single-channel data rate has reached around 200 Gb/s. The increasingly closing gap between commercial single-channel data rates and pioneering transmission research will force the usage of an increasing level of optical parallelization (Winzer, 2010), requiring denser photonic integration. The growth of WDM system capacity is beneficial for creating transport networking with lower cost. However, this trend has not been sufficient to meet the requirement of fast traffic growth. As shown in Figure 1.7(b), a trend of changing slope of the WDM research and commercial capacity growth has been observed, going from 2.5 dB around the year 2000 to a present value of ~0.8 dB per year. The limitation comes from i) the practical penalties due to technical difficulties in implementing high-level modulation formats at high interface rates, and ii) several fundamental considerations, such as the fundamental Shannon limit and spectrally efficient modulation formats ask for higher signal-to-noise ratios (SNRs).

1.1.4 Elastic Optical Networking

To meet the requirement of ever increasing traffic growth, the concept of elastic optical networking has been proposed as a promising architecture to enable the network efficiency and flexibility. In this section we review the concept and related network optimization problems. Some key enabling technologies to realize the elastic optical networks are also presented.

1.1.4.1 Concept of Elastic Optical Networking: Fixed-grid vs. Flex-grid

For the sake of standardization of the transmitters employed in dense wavelength division multiplexing (DWDM) systems, the 50 GHz ITU spectral grids (ITU-T, 2012) divide the optical spectrum range of 1530–1565 nm (referred to as the C-band) and 1565–1625 nm (referred to as the L-band) into fixed 50 GHz spectrum slots. For such channel spacing on a fiber, the central frequencies of the transmitters in THz are defined as: $193.1 + n \times 0.05$, where n is an integer. With the commercialization of 100-Gb/s-based transmission systems in recent years, which are still compatible with 50 GHz ITU grids, more and more interests have been focused on a data rate beyond 100 Gb/s. Meanwhile, it is likely that such data rates higher than 100 Gb/s will not fit into this fixed 50-GHz configuration, especially for long distance transmissions.

The paradigm of elastic optical networking, also referred to as flexible, flex-grid, or gridless optical networking in the literature (Gerstel et al., 2012; Gringeri et al., 2010; Jinno, 2013; Jinno et al., 2009; Palkopoulou et al., 2012; Patel et al., 2012; Roberts et al., 2010), has been proposed as a promising solution to offer superior spectral efficiency and flexibility for the superchannels and varied data-rate transmission (compared to traditional WDM transport operated at 10 Gb/s on a rigid 50-GHz channel spacing). According to the ITU DWDM frequency grid definition (ITU-T, 2012), the flexible DWDM grid is sliced into frequency slots occupying certain amount of frequency range (e.g., a granularity of 6.25/12.5/25 GHz), and the channel bandwidth in elastic optical networks will be tailored for traffic demands with different data rates to optimize spectral efficiency of individual channels. Here, the channel bandwidth consisting of a set of continuous frequency slots is assigned to a demand from its source node to the destination node along a physical route. For the flexible DWDM grid with 12.5-GHz slot width, the allowed central frequency in THz can be defined as: $193.1 + n \times 0.00625$, where n is an integer. Any combination of frequency slots is allowed as long as no two frequency slots overlap (ITU-T, 2012). A comparison between legacy WDM system with rigid frequency grid and optical orthogonal frequency-division multiplexing (OFDM)-based elastic optical networking is illustrated in Figure 1.8.

As we can see in Figure 1.8, the elastic optical networking enables spectrally efficient accommodation of variable data rates (e.g., sub-wavelength and super-wavelength shown in Figure 1.8) owing to the feature of flexible bandwidth allocation. Compared to the elastic scheme, current WDM optical networks with rigid frequency grid cause inefficient frequency spacing for lower data rate signals. Consequently, bandwidth saving can be achieved with the elastic optical networking (e.g., a variation of 100 G can be added in the elastic scheme for given spectral resources shown in Figure 1.8.).

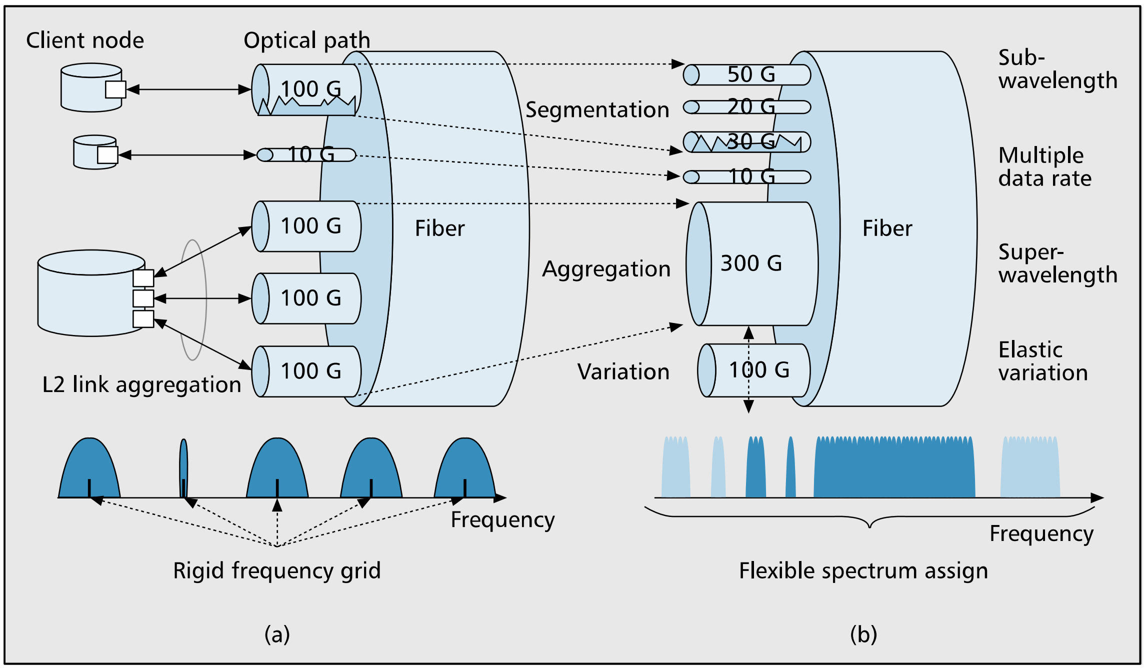


Figure 1.8 Spectrum assignment in OFDM-based elastic optical network. (a) Current WDM system with rigid frequency grid. (b) Flexible spectrum assignment Retrieved from M. Jinno *et al*. (2009, p. 68)

The migration from fixed-grid to flex-grid paradigm has opened a gate to bring innovative architecture options in designing optical networks. In the resulting architecture, different channel bandwidths can be assigned to the traffic demands according to their capacity and distance requirements and the network conditions. To realize the elastic optical networks, elastic transponders and gridless WSSs are enabling elements (Jinno, 2013), seamlessly collaborating with emerging software defined networking (SDN) (Goth, 2011; Gringeri et al., 2013) based on a centralized management and control plane technology. The following sections will provide more detail on related design problem and key enabling technologies.

1.1.4.2 Network Optimization for Elastic Optical Networks

One of the challenges of network optimization for elastic optical networks is effectively provisioning data-rate variable demands and allocating specific amount spectral resources to them while minimizing the spectrum utilization. This adaptive bandwidth allocation problem in an elastic optical network is generally referred to as routing and spectrum assignment (RSA) problem (Christodoulopoulos, Tomkos, & Varvarigos, 2011; Gerstel et al., 2012; Guoying, De Leenheer, Morea, & Mukherjee, 2013; Patel et al., 2012; Talebi et al., 2014; Tomkos, Palkopoulou, & Angelou, 2012). Because the conventional RWA algorithms of traditional WDM networks presented in Section 1.1.1 are no longer directly applicable for solving the RSA problem due to the characteristic of flexible grids and heterogeneous demands (i.e., sub-wavelengths and super-wavelengths), this leads to the introduction of RSA algorithms. Additionally, as more flexibility is allowed by elastic optical networks, new appropriate constraints need to be taken into consideration in the RSA algorithms: 1) Instead of assigning a certain wavelength to each traffic demand, a specific number of contiguous spectrum resources (in terms of frequency slots) that meets the traffic requirement now needs to be assigned to each source-destination demand. This additional constraint is generally referred to as the spectrum contiguity constraint. 2) A guard band consisting of a set of frequency slots may need to be added between neighboring optical channels to mitigate inter-channel interference. 3) The modulation and multiplexing format (e.g., binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM), etc.) can be selected for each traffic demand considering its required data-rate, transparent reach, and physical layer impairments, such RSA problem can be referred to as routing modulation level and spectrum allocation (RMLSA), e.g., in (Christodoulopoulos et al., 2011; Jinno et al., 2010; Palkopoulou et al., 2012). Above additional constraints have to be considered in the RSA problem together with other well-known constraints that have been considered in the RWA algorithms (i.e., in a similar manner as the wavelength-continuity constraint is imposed, the continuity of spectral resources should be guaranteed along the routing path, and no spectrum overlapping is allowed among different connections if they share any fiber links along their physical routes).

The routing and spectrum assignment algorithms can solve the static (also called offline) network optimization problem in a single or multi-period traffic scenario, but also they can be applied to accommodate traffic demands that are dynamically established and released. For dynamic (also called online) and multi-period traffic scenarios, the problem of spectrum fragmentation appears, leading to lower spectral efficiency and higher blocking probability in the dynamic case. Therefore, the development of spectrum defragmentation algorithms is highly necessary.

Similar to the conventional RWA problem, the RSA problem in elastic optical networks can be solved by mathematical optimization methods, such as an integer linear programming (ILP), for small network topology instances due to its complexity and computational intensity. Alternatively, more computationally efficient heuristic approaches can be applied for solving the problem in larger network topologies. In this case optimality can be compromised for the purpose of reducing the computational time.

1.1.4.3 Enabling Technologies for Elastic Optical Networks

Key enabling technologies for realizing elastic optical networks include multicarrier-based elastic transponders (Gerstel et al., 2012; Gringeri et al., 2013; Roberts & Laperle, 2012) and flexible spectrum selective switches (Amaya, Zervas, & Simeonidou, 2013; Gerstel et al., 2012; Gringeri et al., 2010).

1) Multicarrier-based Elastic Transponder
The flexibility of flexible transceivers can be achieved by tuning any of following parameters (Gringeri et al., 2013): 1) modulation format (i.e., BPSK, QPSK, 16-QAM) etc., 2) symbol rate, and 3) number of optical carriers. In order to achieve high capacity and flexible transport in elastic optical networking, new technologies need to be developed by utilizing spectrally efficient multiplexing schemes, such as coherent optical orthogonal frequency-division multiplexing (CO-OFDM) (Shieh, Bao, & Tang, 2008), coherent optical WDM (CoWDM) (Ellis & Gunning, 2005), Nyquist-WDM (Bosco, Carena, Curri, Poggiolini, &

Forghieri, 2010; Bosco et al., 2011), and dynamic optical arbitrary waveform generation (OAWG) (Geisler et al., 2011). Above four multicarrier solutions are illustrated in Figure 1.9. All these technologies are based on combining multiple tightly spaced channels in parallel at low speeds, and they are all capable of utilizing various modulation levels with elastic bandwidth allocations and generation of superchannels offering up to terabit per second transmission capability.

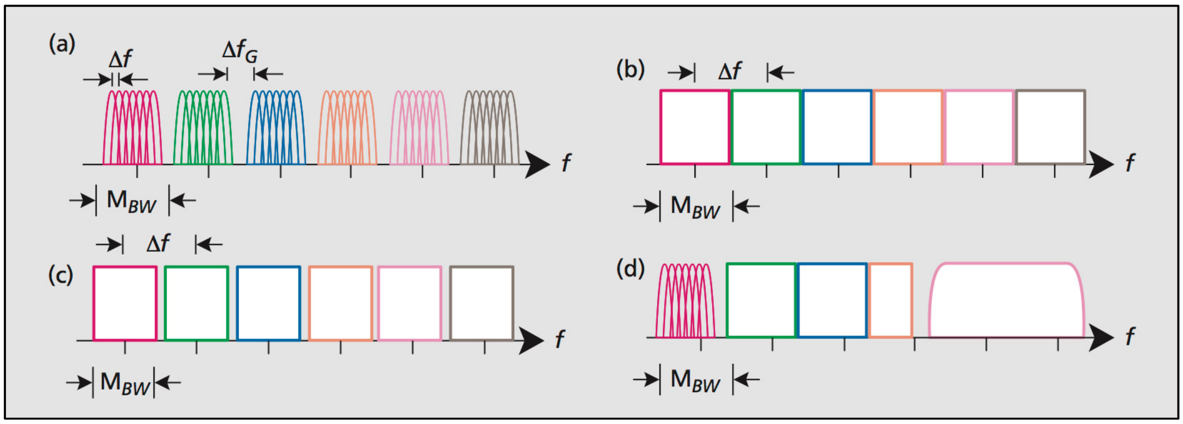


Figure 1.9 Comparison between CO-OFDM, CoWDM, Nyquist-WDM, and OAWG waveform generation: a) CO-OFDM; b) CoWDM; c) Nyquist-WDM; d) OAWG. Δf: subcarrier frequency spacing; Δf_G: frequency spacing between CO-OFDM bands; M_{BW}: modulator bandwidth
Retrieved from O. Gerstel *et al*. (2012, p. s19)

Two multi-carrier-based OFDM solutions have been proposed in literature for optical systems: 1) E-OFDM (Christodoulopoulos et al., 2011; Dischler & Buchali, 2009; Takara et al., 2011; Xiang et al., 2011), where subcarriers are electrically OFDM modulated and assembled into superchannels. 2) CO-OFDM (Chandrasekhar, Xiang, Zhu, & Peckham, 2009; Shieh et al., 2008), where a comb of frequency-locked subcarriers are conventionally modulated at the baud rate of the subcarrier spacing. The spectrum of CO-OFDM solution is shown in Figure 1.9(a), where each modulator generates many low-bandwidth (Δf) subcarriers to form each band, and the orthogonality is satisfied by ensuring a spacing of $\Delta f_G = m \times \Delta f$ for integer values of *m*. The Authors of (Guoying et al., 2013; Talebi et al., 2014) presented a survey on OFDM-based elastic optical network technologies including related key enabling technologies (i.e., the data-rate/bandwidth-variable transponder and wavelength cross-connect design at the node level, RSA, traffic grooming, network survivability, virtualization, network control and management solutions at the network level) and indicated that optical OFDM is a promising technology for high-speed transmission owning to its high tolerance to CD/PMD, high spectral efficiency, and scalability to variable data rates.

The solution of CoWDM as shown in Figure 1.9(b) consists of several tightly spaced subcarriers. The orthogonality between subcarriers is maintained by setting subcarrier symbol rate to the subcarrier frequency spacing. The CoWDM subcarrier bandwidth (~10-40 GHz) is larger than that of CO-OFDM (~100 MHz). Consequently, subcarriers of CoWDM have lower peak-to-average-power ratio with comparable performance to single-carrier systems (Frascella et al., 2010).

In N-WDM (as shown in Figure 1.9(c)) the subcarriers are spectrally shaped so that they occupy a bandwidth close or equal to the Nyquist limit for inter-symbol-interference-free and cross-talk-free transmission (Tomkos et al., 2012).

In the case of OAWG (as shown in Figure 1.9(d)), arbitrary-bandwidth single- and multicarrier channels can be generated, each one them can be in a different modulation format. Lower peak-to-average-power ratios and pre-compensation of CD can be achieved in the scheme because of its customization of generated waveforms (Gerstel et al., 2012).

2) Flexible Spectrum Selective Switch

The introduction of elastic optical networking imposes fundamental changes in ROADM architecture, since current ROADMs are based on fixed-grid WSS using fixed 50/100 GHz channel spacing aligned with the standard ITU-T frequency grid and. The support of elastic spectrum allocation can be realized by replacing current fixed-WSS with flexible spectrum selective switches (SSS) (Amaya et al., 2013). The resulting ROADM architecture (Amaya et al., 2013; Ryf et al., 2005; Sygletos, Tzanakaki, & Tomkos, 2006) is introduced based on liquid crystal on silicon (LCoS) or digital micro electro mechanical systems (MEMS) technology.

1.1.4.4 Control Plane for Elastic Optical Networks

To enable new capabilities of elastic optical networks, an advanced network control plane solution fully supporting adaptive bandwidth allocation is required. The concept of *software-defined networks* (SDN) is a paradigm where a network is operated based on the separation of the data and control planes and a centralized controller is used to control the network activities (e.g., forwarding and switching functionalities). In (Gringeri et al., 2013) the application of an SDN-based control in optical networks that support various transport and switching technologies was reviewed. Both centralized and distributed control planes have their trade-offs and they are likely to coexist in the same network. Authors of (Ben Yoo, Liu, Proietti, & Scott, 2014) studied architecture, protocol, technologies, systems and networking testbed for software defined elastic optical networking. A *path computation element* (PCE) (Farrel, Vasseur, & Ash, 2006), which is considered as a control plane functional component as well as an application, is capable of computing a network path or route based on a network graph and applying computational constraints. In (Casellas, Muñoz, Martinez, & Vilalta, 2013) the deployment and use of PCE as a functional element in the framework of control and management of optical networks and its role in impairment-aware RWA (IA-RWA) and RSA problem were discussed. PCEs are being integrated as functional components in SDN control architecture. In (Cugini et al., 2012) a PCE-based architecture has been deployed and validated on a flexible optical network. The demonstration showed that the PCE is capable of triggering dynamic frequency slot assignment and format adaptation at 100 Gb/s from DP-16QAM to DP-QPSK and driving the dynamic bit-rate adaptation at DP-16QAM from 200 Gb/s to 100 Gb/s.

1.2 Protection Strategies in Optical Networks

In this section we briefly review some existing optical network protection strategies in literature. Optical networks are vulnerable to failures, for instance, fiber cuts, equipment failures, natural disasters, or operational errors, since one single failure could cause huge amount of economic loss, especially when the transmission capacity in a fiber cable has increased significantly in recent years to meet the challenge of rapid growth of global Internet traffic. Therefore, it's essential to consider the protection mechanism as a routine throughout the network design process. The protection scheme can be implemented in optical layer and/or in its client layer. According to the location, the type of resource utilization, and the topology where the protection is implemented, different protection schemes have specific characteristics and applications (R. Ramaswami, K. Sivarajan and G. Sasaki, 2009; Simmons, 2008).

1.2.1 Protection in Optical Layer and Client Layer

A wide variety of protection mechanisms exist in client layers, for example, SONET/SDH, Internet Protocol (IP), multiprotocol label switching (MPLS), and Ethernet networks. The protection scheme in each client layer is designed to work independently of other layers (R. Ramaswami, K. Sivarajan and G. Sasaki, 2009). For example, 1+1, 1:1, 1:*N*, unidirectional path-switched ring (UPSR), and bidirectional line-switched ring (BLSR) protection techniques have been extensively used in legacy SONET/SDH networks. IP networks use "best-effort" and distributed protection scheme. In MPLS networks, the label-switched paths (LSPs) are protected by pre-computed "fast reroute" protection tunnel (i.e., 60 ms carrier grade protection switching time) to bypass the affected node and/or link.

There is a growing interest of implementing protection in optical layer, since the optical protection is provided on the granularity of a wavelength (or a set of wavelengths or a fiber) and it scales gracefully with increasing traffic level (Simmons, 2008). As shown in Figure 1.10, the optical layer in the OTN structure includes the optical channel (OCh) layer, the optical multiplex section (OMS) layer, and the optical transmission section (OTS) layer. Different optical layer protection schemes presented in (R. Ramaswami, K. Sivarajan and G. Sasaki, 2009) include 1+1 OMS protection, 1:1 OMS protection, OMS-DPRing (dedicated protection ring), OMS-SPRing (shared protection ring), 1:*N* transponder protection, 1+1 OCh dedicated protection, OCh-SPRing, OCh-mesh protection, and GMPLS (generalized MPLS) protection.

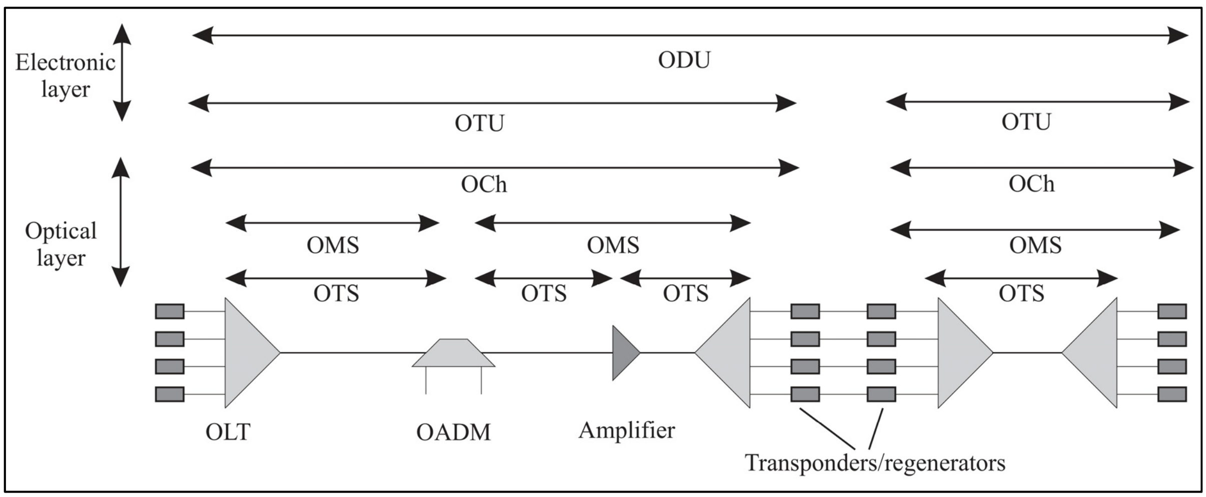


Figure 1.10 Optical layers and electronic layers within OTN
Retrieved from R. Ramaswami *et al*. (2009, p. 478)

Compared to the protection in the client layers, optical layer protection has following advantages and limitations.

Advantages:

- Cost-effective and efficient
- Significant cost savings
- Handle faults more efficiently
- Provide an additional degree of resilience
- Mesh protection requires less protection resources

Limitations:

- Cannot handle all failures
- Trigger the protection based on detecting loss or degradation of optical signal
- Cannot protect part of the traffic
- Longer protection routes

Considering all protection strategies have pros and cons, a solid and effective protection strategy requires seamless cooperation and coordination between different network layers (e.g., IP/MPLS over WDM (Wei, 2002)). A proper implementation of control plane to create a communication channel between multilayers is also essential to realize this task.

1.2.2 Ring vs. Mesh Protection

Protection can be realized in ring topologies and mesh topologies. 1) When a failure occurs in a ring topology, all traffic passing through the failed link or node is routed in the reverse direction of the ring topology to re-establish the connection. 2) In a mesh topology, once the failure occurs, a protection path is established arbitrarily by rerouting on a secondary path, which is generally link-disjoint or node-disjoint with the primary path.

Compared to the ring protection scheme, the mesh protection scheme generally has more freedom on choosing the protection path and requires less spare capacity. However, the mesh protection relies on more sophisticated higher-level control and coordination between nodes.

1.2.3 Link vs. Path Protection

When a failure occurs, link protection searches for a secondary link bypassing only the failed link. Path protection tries to establish a protection path completely link/node-disjoint with working path. For instance, as shown in Figure 1.11, when a failure has been detected between node 2 and 3, in the link protection scheme the traffic is rerouted through links [1-2-5-6-3-4] to bypass failed link [2-3]; on the contrary, in the path protection scheme the traffic is redirected through links [1-7-8-4], which share no common links with the working path [1-2-3-4].

Link protection is generally more capacity-efficient than path protection, since only the failed link of the working path need to be rerouted and therefore may be easier to find available resources within the topology.

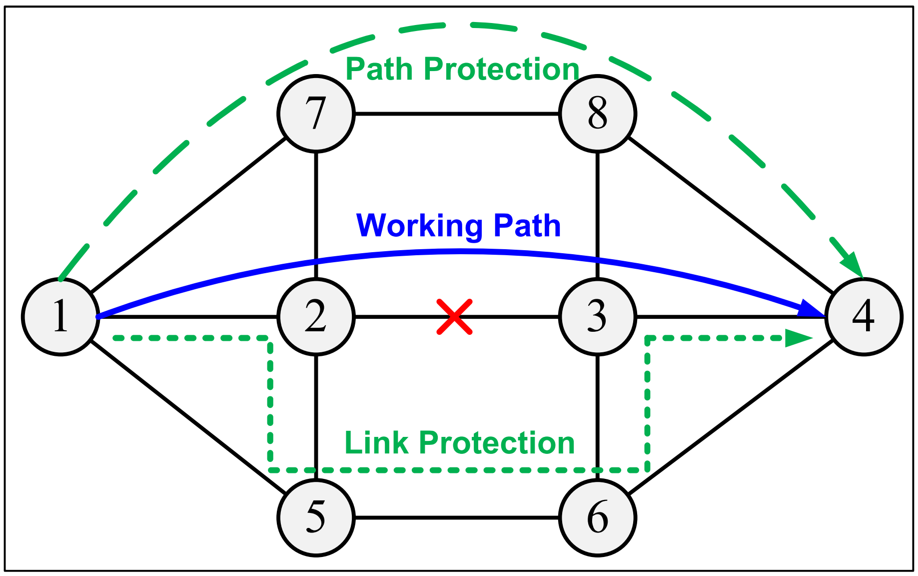


Figure 1.11 Comparison between link and path protection strategies

1.2.4 Dedicated vs. Shared Protection

According to the way of allocating protection resources, we can further classify the protection schemes into dedication protection and shared protection. Well-known dedicated protection schemes include 1+1 and 1:1 protection. The shared protection scheme mostly falls into the category of 1:*N*, or more general form *M*:*N*, where *N* working resource units (e.g., fiber links, transponders, router, lightpath, etc.) share *M* protection units. Apparently, dedicated protection scheme consumes more capacity resources than shared protection scheme, however dedicated protection scheme can respond to the failure quickly without sophisticated coordination and control.

1.2.4.1 1+1 Protection

In the 1+1 dedicated protection scheme, each working path is protected by generally a link and/or node disjoint path. The signal is transmitted on these two paths simultaneously. Once a failure is detected, the traffic is switched to the protection path immediately. The capacity redundancy is intentional in this scheme to improve the protection efficiency. Advantage of this scheme is a quick response to the failure.

1.2.4.2 1:1 Protection

Contrary to the 1+1 strategy, the backup path in the 1:1 dedicated protection scheme is activated only when a failure is detected in the working path. The response time of 1:1 scheme is slower than the 1+1 scheme, since in the 1:1 scheme normally there is a synchronization delay from the detection of the failure to the activation of the protection path.

1.2.4.3 1:*N* (*M*:*N*) Protection

1:*N* protection scheme indicates that one unit of protection resource is shared among *N* working resource units. 1:*N* is a more resource-efficient protection strategy, since the redundancy in the dedicated protection scheme has been largely reduced. Nevertheless, the 1:*N* scheme is more vulnerable in the scenario of multiple network failures. To address this issue, the *M*:*N* scheme has been proposed as a generalization of the 1:*N* protection scheme, i.e., *M* protection resource units are shared among *N* working resource units. The *M*:*N* protection scheme largely increases the robustness when multiple failures occur simultaneously.

1.3 The Filterless Optical Networks

In this section we review the concept of filterless optical networks (C. Tremblay, Gagnon, Châtelain, Bernier, & Bélanger, 2007) and recent work on the design of filterless optical networks. A comparison between conventional and filterless optical line system in terms of required optical node components, physical impairments, and cost is presented. We then review previously developed filterless network design and simulation (FNDS) platform, which has been developed for solving the physical link interconnection and static RWA problem in filterless optical networks. Using the proposed platform, a simple filterless solution of a German 7-node topology is demonstrated as a case study. Finally, we discuss the research problematic of this thesis.

1.3.1 Related Work

The architecture of filterless optical networks (C. Tremblay et al., 2007) has been explored in recent years. In (Christine Tremblay et al., 2013) the filterless network concept based on advanced transmission technologies and passive optical interconnections was presented and resulting filterless solutions obtained using the FNDS tools were analyzed for various network topologies ranging from 690 to 1924 km. The performance in terms of cost and wavelength consumption was analyzed when compared to active photonic switching solutions and the results confirmed the cost-effectiveness and reliability of filterless optical networks as an alternative to the active counterpart. In (Archambault et al., 2010), the filterless network design and simulation (FNDS) tool is developed to solve the physical link interconnection and static RWA problem, and cost-effective filterless solutions achieve comparable wavelength consumption compared to active photonic networks. In (Savoie, Tremblay, Plant, & Belanger, 2010) a filterless analytical link engineering model was developed and validated using the commercial software VPItransmissionMaker^{TM}. In more recent works (Mantelet, Cassidy, et al., 2013; Mantelet, Tremblay, Plant, Littlewood, & Belanger, 2013), the authors proposed path computation element (PCE)-based control plane for the filterless optical networks and studied the dynamic RWA problem.

1.3.2 The Concept of Filterless Optical Networks

Filterless optical networks leverage the breakthroughs of coherent transmission and electronic dispersion compensation technologies (McNicol et al., 2005; Roberts et al., 2009) to offer network agility and cost-effectiveness. Instead of deploying WSS-based ROADM (see Figure 1.5 and Figure 1.6) as in conventional active photonic networks, link interconnection between network nodes and local add-drop are realized by passive splitters/combiners at intermediate nodes. Such passive WAN solution is referred to as the *filterless optical network*. Consequently, this broadcast-and-select architecture uses tunable transponders to adjust the transmitted wavelength at source nodes and coherent receivers to achieve the wavelength selection function at destination nodes, similar to the principle in radio networks (Christine Tremblay et al., 2013). As a promising alternative to the active photonic switching networks, the proposed filterless networks are expected to offer superior performance in terms of cost-effectiveness, robustness, energy efficiency, enabled flex-grid/colorless ability, and multicast capability.

1.3.3 Conventional vs. Filterless Optical Transmission Systems

A comparison between convectional and filterless optical transmission systems is illustrated in Figure 1.12. In a filterless optical transmission system, optical multiplexers (Mux) and demultiplexers (Demux) as shown in Figure 1.12(a) are substituted for passive optical combiners and splitters as shown in Figure 1.12(b). Tunable transponders and DSP-assisted coherent optical receivers are used in the filterless optical transmission systems instead of conventional optical transmitters and receivers based on intensity modulated direct detection (IM-DD) used in legacy optical transmission systems. The resulting filterless architecture removes the dispersion compensation modules (DCMs) along the transmission line, since the physical impairments, such as chromatic dispersion (CD) (up to 50000 ps/nm), polarization mode dispersion (PMD) (up to 100 ps), and polarization-dependent loss (PDL), can be compensated by DSP-assisted receivers at edge terminals (Christine Tremblay et al., 2013).

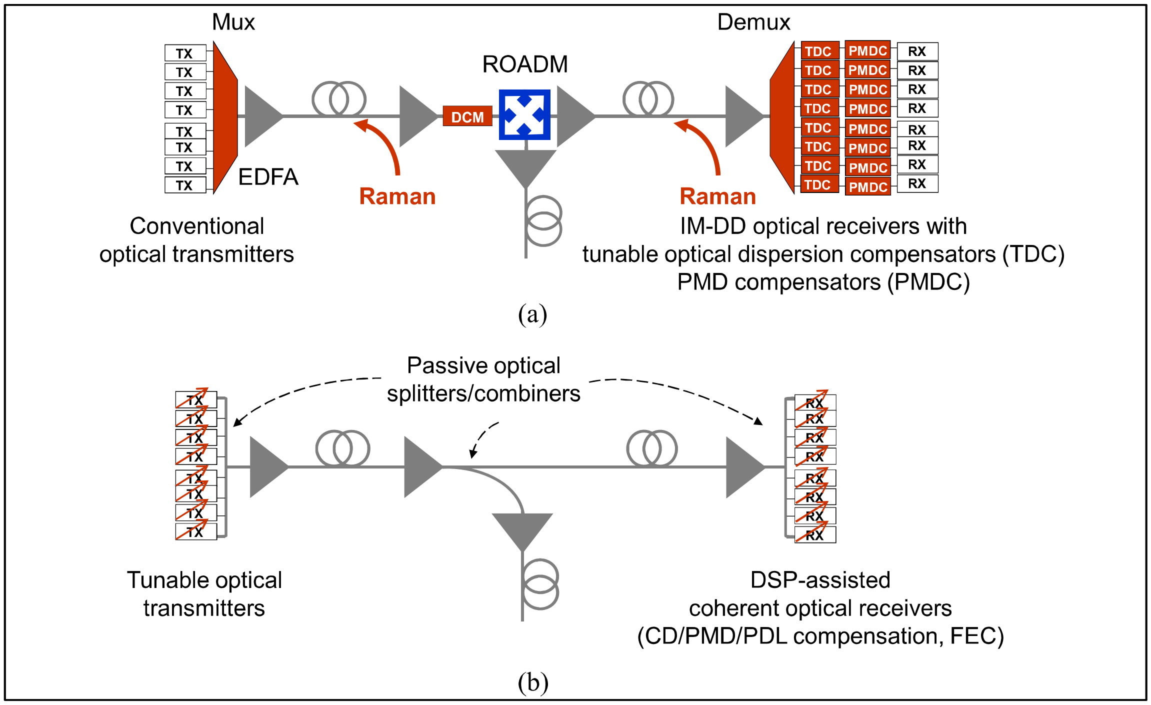


Figure 1.12 Comparison between conventional (a) and filterless (b) optical transmission systems
Retrieved from C. Tremblay *et al*. (2013)

1.3.4 The Filterless Network Design and Simulation Platform

In general, the relevant network design problem of filterless optical networks can be defined as follows. Given a topology $G(V, E)$ with a set of nodes V and unidirectional fiber links E and a set of traffic demands (could be known in advance or dynamically arrived and released), firstly we need to ensure that any two nodes within the topology can be physically connected by fiber links using passive splitters and combiners at some nodes. We refer this problem as *fiber link interconnection problem*. Secondly, we must establish physical path in the topology for each connection request and assign specific spectral resources (such as a wavelength channel) to it, which is referred to *routing and wavelength assignment (RWA)* problem. The objective is to optimize the utilization of spectral resources in all fiber links, while satisfying the following constraints: 1) Laser loop constraint: no closed loop is allowed in interconnecting the nodes with splitters and combiners to avoid laser effects (i.e., accumulated amplified spontaneous emission (ASE) noise). 2) Transmission length constraint: the maximum transmission distance of each connection is limited to 1500km without O-E-O regeneration, which is reasonable value for a long haul WDM system with the consideration of OSNR penalty and the deployment of coherent receivers at edge terminals. 3) Wavelength continuity constraint (see Section 1.1.1).

A filterless network design and simulation (FNDS) tool has been developed under a MATLAB environment to solve above filterless network design problem. The fiber link interconnection problem is solved by a genetic algorithm (GA). The RWA problem, is solved sequentially (i.e., routing (R) + wavelength assignment (WA)) by using a GA and Tabu Search (TS) metaheuristic algorithm (Archambault et al., 2010).

1.3.4.1 Fiber Link Interconnection Problem

The objective of the fiber link interconnection problem is to establish full network connectivity in a filterless network by creating a set of edge-disjoint *fiber trees*, each representing a set of interconnected optical fibers and corresponding to a solution to the fiber link interconnection problem. A combination of all created fiber trees spanning all nodes ensures the full network connectivity between any two nodes in the network (i.e., all end-to-end connection is connected by at least one physical route). The resulting broadcast-and-select filterless architecture, and therefore the filterless network connectivity, is created by configuring splitters/combiners at each node. Considering the problem's complexity, the fiber link interconnection problem is solved by a genetic algorithm presented in (Archambault et al., 2010). An example of obtained filterless solution with two fiber trees (i.e., black and gray) is illustrated in the right side of Figure 1.13. The fiber link interconnection problem is subject to the following constraints: 1) Full network connectivity constraint: any two nodes within the network should be physically connected by at least one route. More than one candidate route can be found for certain end-to-end connections in the network owning to the fiber-tree-based filterless architecture. The shortest route is generally referred to the working path, and other routes (excluding the shortest one) will serve as protection paths. Without any consideration of resilience mechanism in the filterless network, the ratio of the number of demands with more than one available candidate routes over the number of total demands is referred to as *intrinsic protection ratio*. 2) Laser loop constraint: since filtering components, which are used to block certain wavelengths in active photonic switching networks, have been replaced by passive splitters/combiners in filterless networks, optical signals are broadcasted at each encountered intersections and continuously propagate along the fiber tree. This node feature is referred to as *drop-and-continue* (Mantelet, Tremblay, et al., 2013). Due to this drop-and-continue filterless node feature, no closed loop is allowed in fiber-tree-based filterless solution to avoid laser effect, which is caused by the accumulation of ASE noise. 3) Transmission length constraint: the maximum transmission reach is limited to 1500km to take into account physical impairments such as CD, PMD, and PDL and avoid O-E-O regeneration. This constraint is satisfied in the FNDS platform by setting the maximum length of fiber tree (i.e., the maximum root-leave distance in a fiber tree) to 1500km.

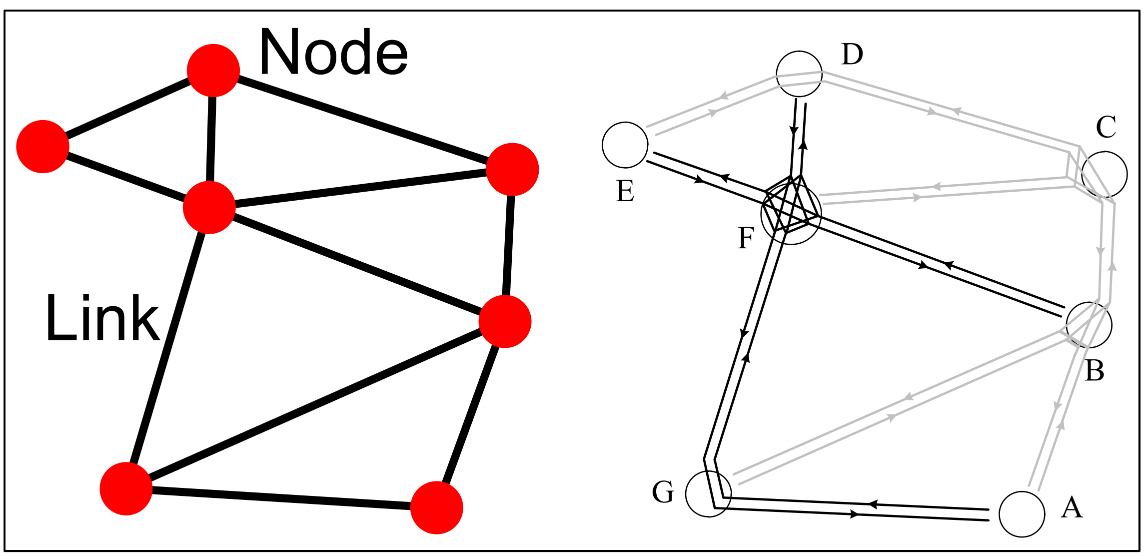


Figure 1.13 A filterless solution example in the German 7-node topology (Archambault et al., 2010) with two fiber trees (gray and black solid line)

1.3.4.2 Static RWA Problem in Filterless Optical Networks

Based on obtained fiber link interconnection solutions, the static RWA problem is solved sequentially in two steps (R+WA). Firstly, the routing (R) subproblem is performed by selecting the shortest path for each connection request. Secondly, the wavelength assignment (WA) subproblem is transformed to a well-known graph-coloring problem (Mukherjee, 2006) and solved by a Tabu Search metaheuristic (O'Brien, Chatelain, Gagnon, & Tremblay, 2008) with the objective of minimizing the maximum number of consumed wavelengths in all fiber links, while satisfying the wavelength-continuity constraint (i.e., for each connection a same wavelength must be used throughout its lightpath and no wavelength overlapping between two connections if they pass through same fiber links). Each wavelength channel in a fixed-grid solution occupies 50-GHz channel spacing and supports a channel capacity of 10 Gb/s.

1.3.5 Case Study: Filterless Network Solution vs. Active Photonic Switching Network Solution

In this Section, we compare the cost and wavelength consumption performance of a filterless solution and an active photonic network solution (referred to as conventional) for a German 7-node network topology, and point out some pros and cons of filterless optical networking when compared to the active counterpart.

The network topology considered is illustrated in Figure 1.14, where each node in the conventional network is equipped with ROADM for signal switching and local add/drop, and on the other hand each node in the filterless network is configured with passive splitters and combiners to for signal broadcasting and local add/drop. The two-fiber-tree-based filterless solution shown in Figure 1.14 has an intrinsic protection ratio of 71%. The traffic matrix is known in advance in a static traffic scenario.

The cost analysis of above two solutions is presented by comparing only the active routing cost (using WSS for signal switching in the conventional case) and passive routing cost (passive signal splitting and combining in the filterless case). In this comparison, the broadcast-and-selection ROADM node structure (see Figure 1.5) is assumed for the conventional network. To achieve full switching capability, the number of WSSs in each node is equal to the nodal degree of that node for any node with a nodal degree greater than 2 (Archambault et al., 2010). For example, in above German 7-node network we have five nodes with a nodal degree greater than 2 (i.e., node B, C, D, F, and G), and total nodal degree for these five nodes are 18, so the number of required WSSs is equal to 18. Additionally, we assume that similar number of optical amplifiers is required in both cases for simplification, so the cost of associated optical amplifiers used to compensate for the insertion loss (WSS or signal splitting) in the active and filterless solutions are not considered.

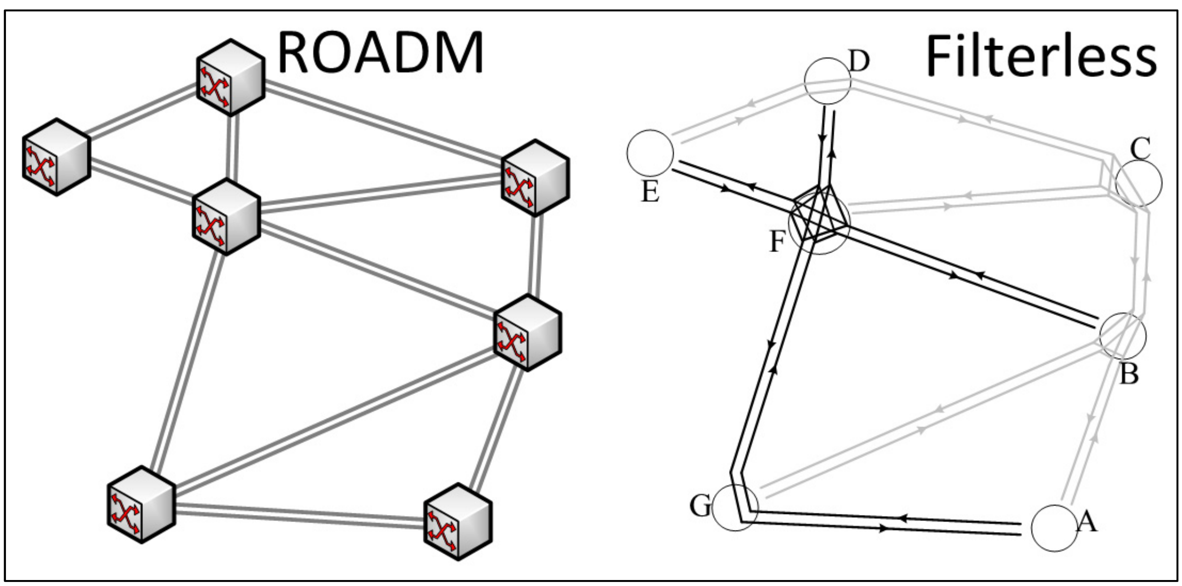


Figure 1.14 Active photonic switching networks based on ROADMs (left) and filterless networks based on two fiber trees (right) for a German 7-node topology

Another performance metric considered in this study is the wavelength consumption for a given traffic matrix. We assume that the channel capacity per wavelength in a 50-GHz channel bandwidth supports traffic of 10 Gb/s. A symmetrical traffic matrix with a total of

1.48 Tb/s traffic is applied for both the conventional and filterless network for a fair comparison. The number of utilized wavelengths in the conventional network is obtained by minimizing the demand length. On the other hand, the result of filterless solution is obtained by solving the RWA problem with the FNDS tool.

The results of performance comparison between the conventional and filterless solution is summarized in Table 1.4. We can see from this table that the filterless solution on the German 7-node network has a comparable performance in terms of average demand length and wavelength consumption when compared to the conventional solution, whereas these performances are achieved with much lower cost in the filterless solution.

Table 1.4 Performance comparison between active photonic switching and filterless solution on the German 7-node network topology

Solution	**Avg. Dem. Length (km)**	**Number of wavelength**	**Added components**	**Unit cost**	**Quantity**	**Added Cost (a.u.)**
Active photonic switching network [a]	349	30	WSS	2.5	18	45
Filterless optical network	353	35 (32) [b]	Passive splitters and combiners	0.02	28	0.56

a. The number of used wavelengths of active network is retrieved from (Christine Tremblay et al., 2013).
b. The result in parentheses is obtained by solving the RWA problem in a joint manner.

On the other hand, the filterless solution has an intrinsic protection ratio of 71% without any consideration of protection strategies, which means that certain demands (e.g., the connection between nodes C and F shown in Figure 1.14) have only one physical route available in the network and they were vulnerable to failures occurred along their routes. Besides, the major concern in the filterless network lies in the presence of unfiltered channels due to the drop-and-continue filterless node feature (Mantelet, Tremblay, et al., 2013), as the wavelengths occupied by them cannot be reused for other connections, which increases the wavelength utilization. That's reason why the number of used wavelengths (shown in Table 1.4) in the filterless network is slightly higher than that of the active network.

1.4 Research Problematic and Conclusions

In this Section, we have reviewed the wavelength-routed optical networks (WRON) and some key enabling technologies in the WRON such as the routing and wavelength assignment, ROADM architectures and high-capacity transmission techniques, and the emerging paradigm of elastic optical networking as a promising solution to achieve spectral efficiency and transmission flexibility. We have also looked over the resilience issue in the WRON and the existing protection strategies in the literature.

In previous work (Archambault et al., 2010; Christine Tremblay et al., 2013; C. Tremblay et al., 2007), the filterless optical networks have been proved to be much more cost-efficient than active photonic networks, while maintaining the wavelength utilization at a comparable level. The major concern in filterless architecture lies in the presence of unfiltered channels due to the drop-and-continue nature of filterless nodes (Mantelet, Tremblay, et al., 2013), where wavelength channels propagate beyond their destination nodes and all the way to the terminal nodes of filterless fiber trees. The existence of these unfiltered signals magnifies the wavelength consumption, as the spectral resources occupied by these channels cannot be reused by any other lightpath connections. In this regard, developing an efficient resource allocation solution is highly necessary to address this concern with an effort to minimize the presence of unfiltered channels, and therefore to optimize the spectral resource utilization. Besides, all existing studies of filterless network architecture have been considering fixed-grid scenarios, i.e., the standard ITU grid with 50 GHz channel spacing supporting 10 Gb/s traffic per wavelength. Facing the rapidly increasing interest in the variations in capacity required by different applications, it is unlikely that long-haul transmission will keep using the conventional WDM systems with such fixed channel spacing. Therefore, there has been increasing interest in considering more spectrally efficient filterless solutions.

Another concern need to be addressed in designing filterless optical networks is the network survivability issue. The filterless network solutions are characterized by an *intrinsic protection ratio*, defined as the percentage of s-d node pairs connected by at least two link-disjoint paths over total number of the s-d node pairs in the given network topology without any specific consideration for resiliency. For most network topologies, this intrinsic protection ratio of a given filterless solution is lower than 100%. Therefore, some traffic demands may have only one single route available, and consequently they cannot be protected in the case of a link/node failure. Hence, the problem of providing dedicated protection mechanism against potential fiber link/node failure in a filterless outside plant needs to be addressed.

CHAPTER 2

ARTICLE I: 1+1 DEDICATED OPTICAL-LAYER PROTECTION STRATEGY FOR FILTERLESS OPTICAL NETWORKS

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Abstract

We propose a dedicated optical-layer protection strategy for filterless optical networks offering a 100% protection ratio by introducing a limited number of wavelength selective components at selected intermediate nodes. A comparison with conventional active photonic switching networks is presented. The results show that the proposed 1+1 protection for

filterless networks exhibits a clear cost advantage at similar wavelength usage compared to active switching solutions.

2.1 Introduction

In order to cope with the growing traffic demand driven mainly by Internet traffic, capacity of optical backbone networks has increased significantly over the past few years. At the same time, the network operator revenues have not followed the same pattern. To address this imbalance, carriers have been steadily focusing on reducing their operational costs and hence looking into deploying more cost-effective optically agile networks. In current active photonic switching networks, agility is provided by reconfigurable add-drop multiplexers based on wavelength selective switches (WSS) at intermediate nodes (Strasser & Wagener, 2010). The filterless network concept has been proposed in (C. Tremblay et al., 2007) as a simpler and more cost-effective method to deliver network agility. This concept is based on the premise that the need for agility and reconfigurability can be provided by using tunable transmitters and coherent receivers at the network edge terminals, as in radio networks (Archambault et al., 2010; Mantelet, Tremblay, et al., 2013; Christine Tremblay et al., 2013; C. Tremblay et al., 2007). In the resulting network architecture, the active switching components at intermediate nodes and the colored components used for local wavelength add-drop are replaced by passive optical splitters and combiners. This results in a cost-effective broadcast and select network architecture that is currently considered as a candidate for software defined networking (Gringeri et al., 2013). Furthermore, the filterless optical network is considered as particularly suitable for submarine applications, which stringently require components with small footprint and low complexity.

A filterless network can be created by placing passive splitters and combiners at some nodes for optically interconnecting all the nodes. A filterless network design tool based on metaheuristics has been developed for solving the fiber link interconnection problem by constructing sets of interconnected optical fibers referred to as *fiber trees* (Archambault et al., 2010). These generated fiber trees are edge-disjoint and some of them may not span all nodes due to the limited connectivity of the network topology. The resulting filterless network architecture, and therefore the filterless network connectivity, depends on the configuration of splitters and combiners at each node.

These filterless network solutions are characterized by an *intrinsic protection ratio*, defined as the percentage of source- destination (s-d) node pairs connected by at least two link-disjoint paths among all the s-d node pairs in the network without any specific consideration for resiliency. The intrinsic protection ratio of a given filterless network solution, which is fully determined by the fiber tree configuration, could be lower than 100% as it is not always possible to guarantee that all s-d node pairs are covered by two edge-disjoint trees (Christine Tremblay et al., 2013). Therefore, some traffic demands may have only a single route available, and consequently, cannot be protected in the case of a link failure. Hence, the problem of providing protection against fiber link failures in a filterless outside plant needs to be addressed, similarly to the conventional active switched photonic networks.

In this paper, we propose a 1+1 optical-layer protection strategy for filterless networks. Protection paths are set up by using wavelength selective components placed at selected nodes for interconnecting the fiber trees. Fully protected filterless solutions with 100% protection ratio (e.g., at least two link-disjoint paths could be found for all the s-d node pairs in the network) are proposed for a number of physical network topologies and compared with WSS-based active photonic switching counterparts. The results show that the filterless network solutions with 100% protection ratio obtained by using this method can be much more cost-effective than its active counterpart while keeping the wavelength usage at a comparable level.

2.2 Inter-tree Protection Path Strategy

Each filterless network solution generated by the design tool is characterized by a single value for the intrinsic protection ratio. The intrinsic protection ratios of filterless network solutions are presented for several physical topologies in Figure 2.1 (Christine Tremblay et al al., 2013). The intrinsic protection ratio of all tested network topologies except the EuroCore 11 (4-edge-connected) is less than 100% because it is not possible to find two edge-disjoint spanning fiber trees and cover each s-d node-pair. It can be seen that the intrinsic protection ratio of a filterless network solution correlates strongly with the filterless network connectivity, which is defined as $2k/n(n-1)$, where k is the number of fiber link interconnections and n is the number of nodes. This strong correlation suggests that the protection ratio of a filterless network could be increased by improving the filterless network connectivity. In this section, we propose a protection strategy to achieve a 1+1 dedicated optical-layer protection with a 100% protection ratio in filterless networks.

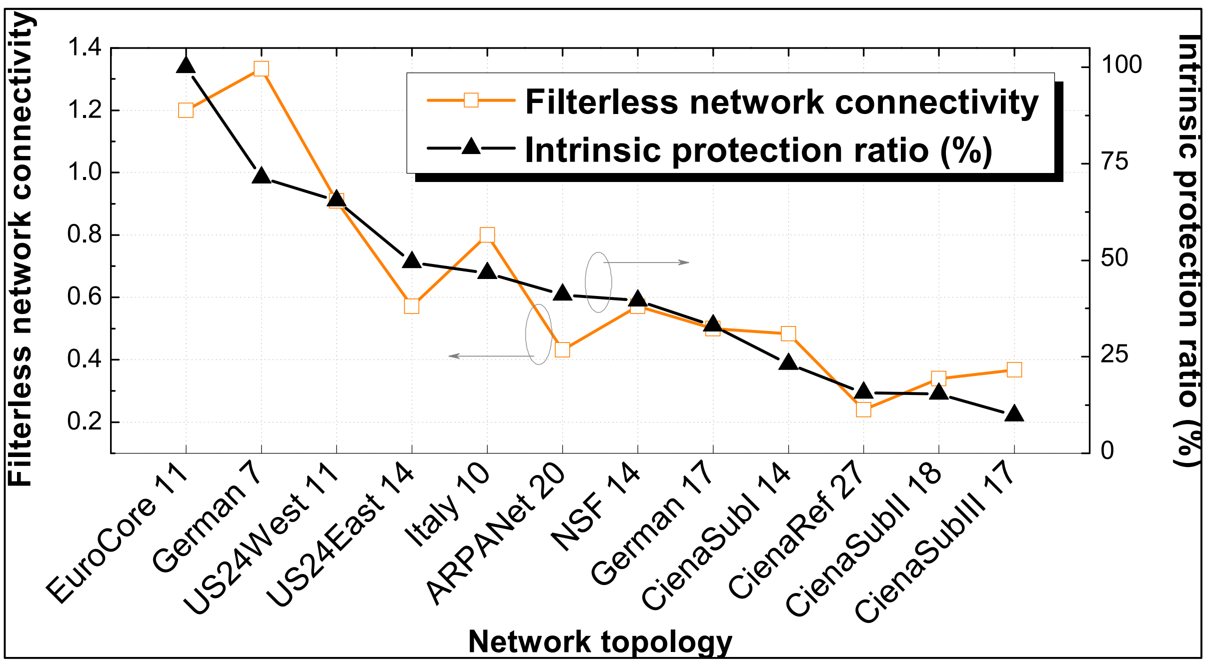


Figure 2.1 The intrinsic protection ratio vs. the filterless network connectivity. The intrinsic protection ratio (solid triangles) of filterless solutions correlates extremely well with the filterless network connectivity (squares) for different types of network topology (Chatelain, Belanger, Tremblay, Gagnon, & Plant, 2009)

The basic principle of the proposed protection strategy is to create extra protection paths by introducing a minimum number of wavelength blockers (WBs), referred to as *inter-tree WBs*, at some intersecting nodes between edge-disjoint fiber trees.

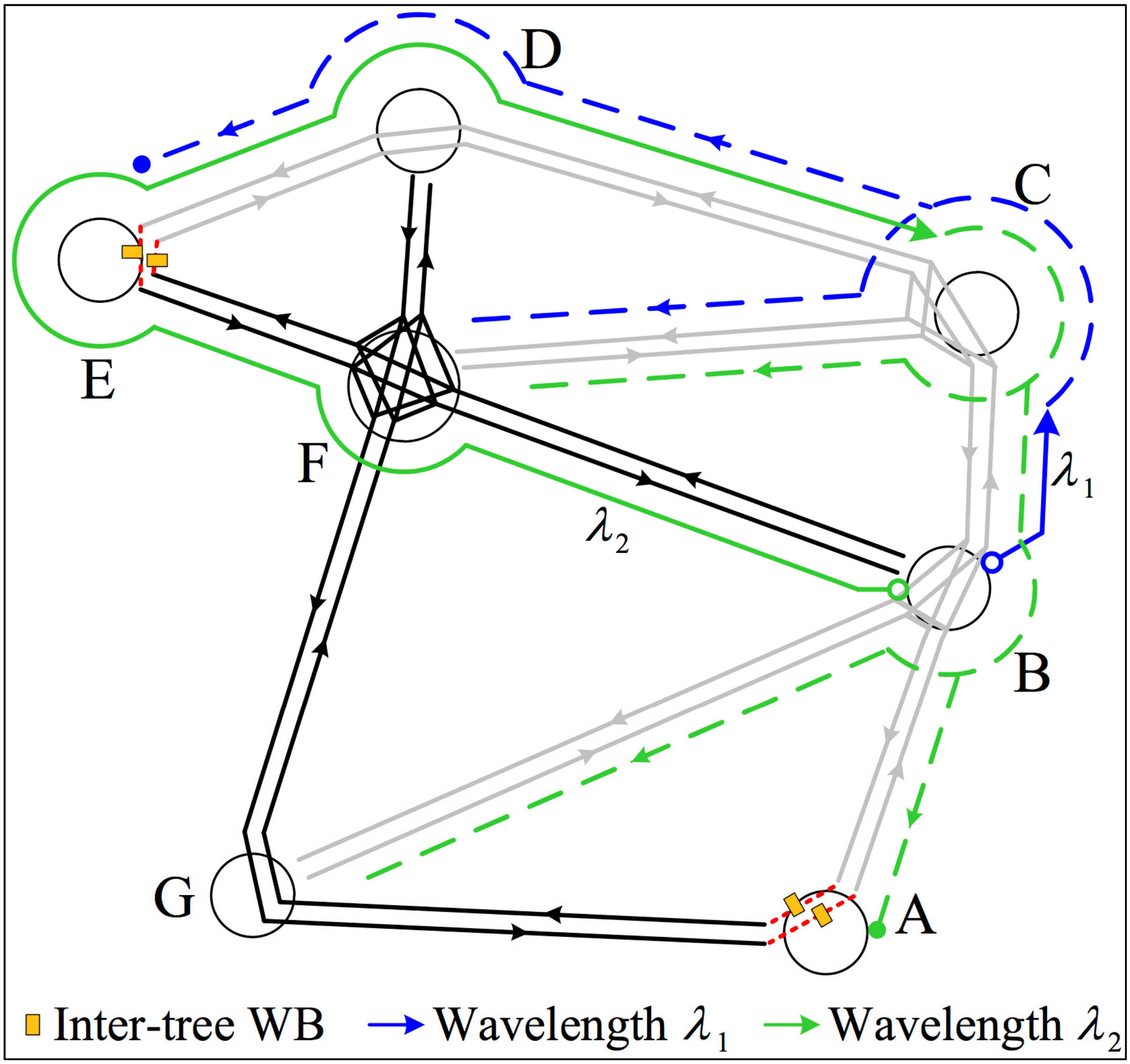


Figure 2.2 WB-only protection scheme on G7. WB-only protection scheme illustrated on a filterless solution for a 7-node subset of German network (G7) (Archambault et al., 2010) composed of two fiber trees (black and gray solid lines, respectively). Unfiltered wavelength λ_1 and λ_2 are marked by dashed lines

Figure 2.2 illustrates the WB-only approach with an example of a filterless solution for a 7-node subset of German network (G7). This filterless solution composed of two edge-disjoint fiber trees (represented by the black and gray lines, respectively) has an intrinsic protection ratio of 71%. In this example, the protection ratio is increased to 100% by placing two pairs of inter-tree WBs (one per direction) at intersecting nodes A and E between two trees. In the resulting 1+1 protected solution, all s-d pairs are connected by two link-disjoint paths. For example, for the B-C node pair, there is only one path [B-C] (marked in blue) in the original filterless solution. A protection path [B-F-E-D-C] (represented in green solid line) is created by placing an inter-tree WB at node E. Inter-tree WBs can also prevent the wavelengths from passing from one fiber tree to another, thus preventing conflicts between connections using the same wavelength in two different (independent) fiber trees. The blocking function of the WB is depicted in Figure 2.2, where the wavelength λ_1 in one fiber tree (gray line) is blocked by the WB at node E and hence can be reused in the second fiber tree (black line) for another traffic demand, whereas the wavelength λ_2 carrying crossing-tree traffic passes the WB at node E and then is blocked by the WB at node A to relieve the wavelength continuity.

Given the problems complexity, the inter-tree WB placement problem is solved through a heuristic algorithm (see flowchart in Figure 2.3). The objective is to ensure that all traffic demands are protected by using a limited number of wavelength selective components. In the first step, link-disjoint protection paths are provided for each s-d node pair by adding inter-tree WBs to an existing unprotected solution. Two different routing methods are considered for inter-tree WB placement: shortest path and lowest node complexity, respectively. The shortest path minimizes the length of the protection paths, while the least node complexity minimizes the number of inter-tree WBs by selecting the inter-tree configuration with the lowest node degree amongst all the instances.

In the second step, the laser loops introduced by the inter-tree WBs are removed by placing a minimum number of WBs (referred to as *intra-tree WBs*) in the fiber trees. WBs present the advantage of being wavelength reconfigurable (Christine Tremblay et al., 2013), but fixed colored passive filters (CPFs), such as fiber Bragg gratings (FBG) or red/blue filters, can also be used as a more cost-effective alternative (Chen et al., 2011). Two protection schemes have been considered: 1) based only on WBs, referred to as *WB-only* solution; and 2) a hybrid solution, using both WBs and CPFs, referred to as *WB+CPF*.

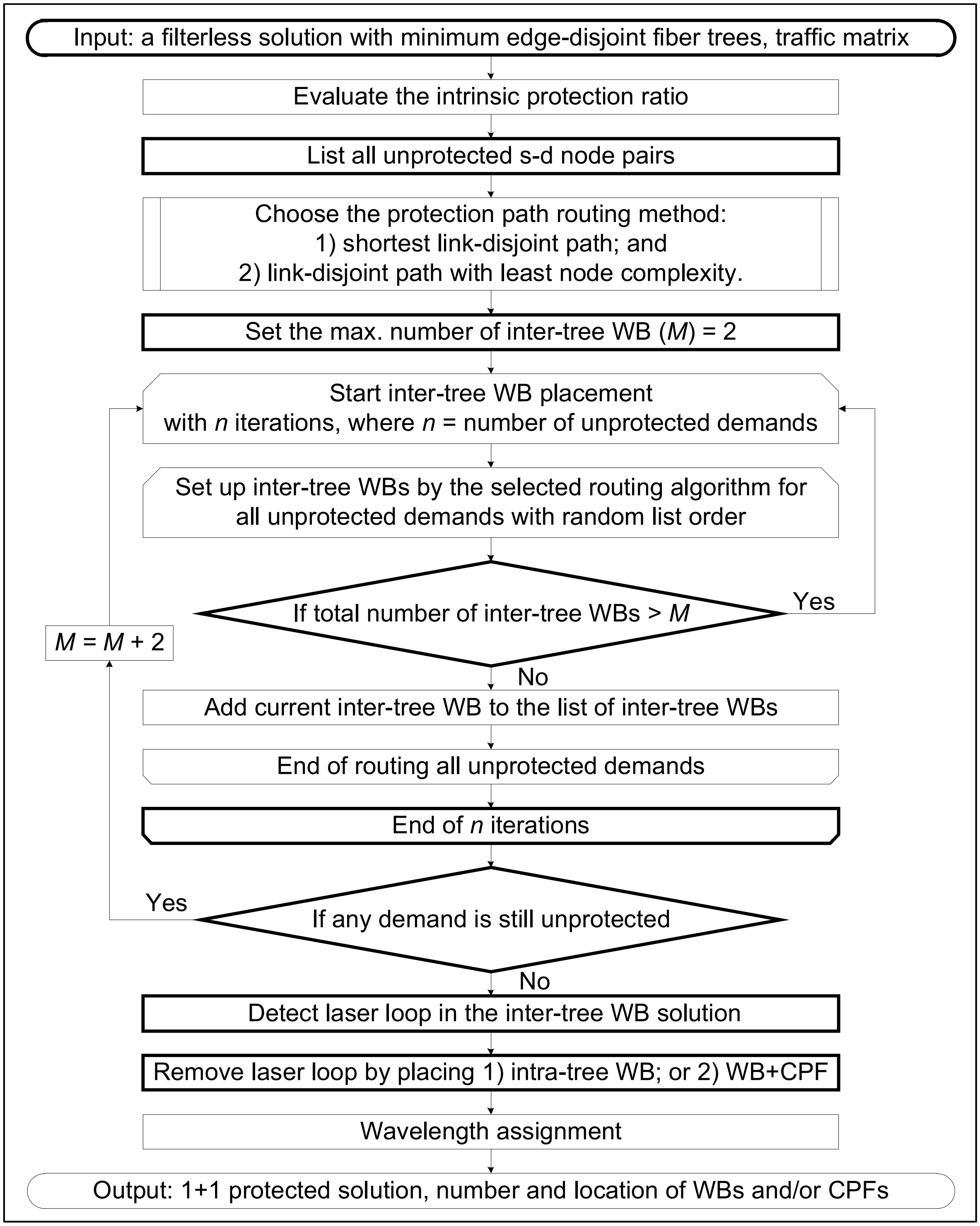


Figure 2.3 Flowchart of RWA heuristic algorithm for survivable filterless solutions. Proposed RWA heuristic algorithm for providing 1+1 protected solutions through inter-tree WB placement

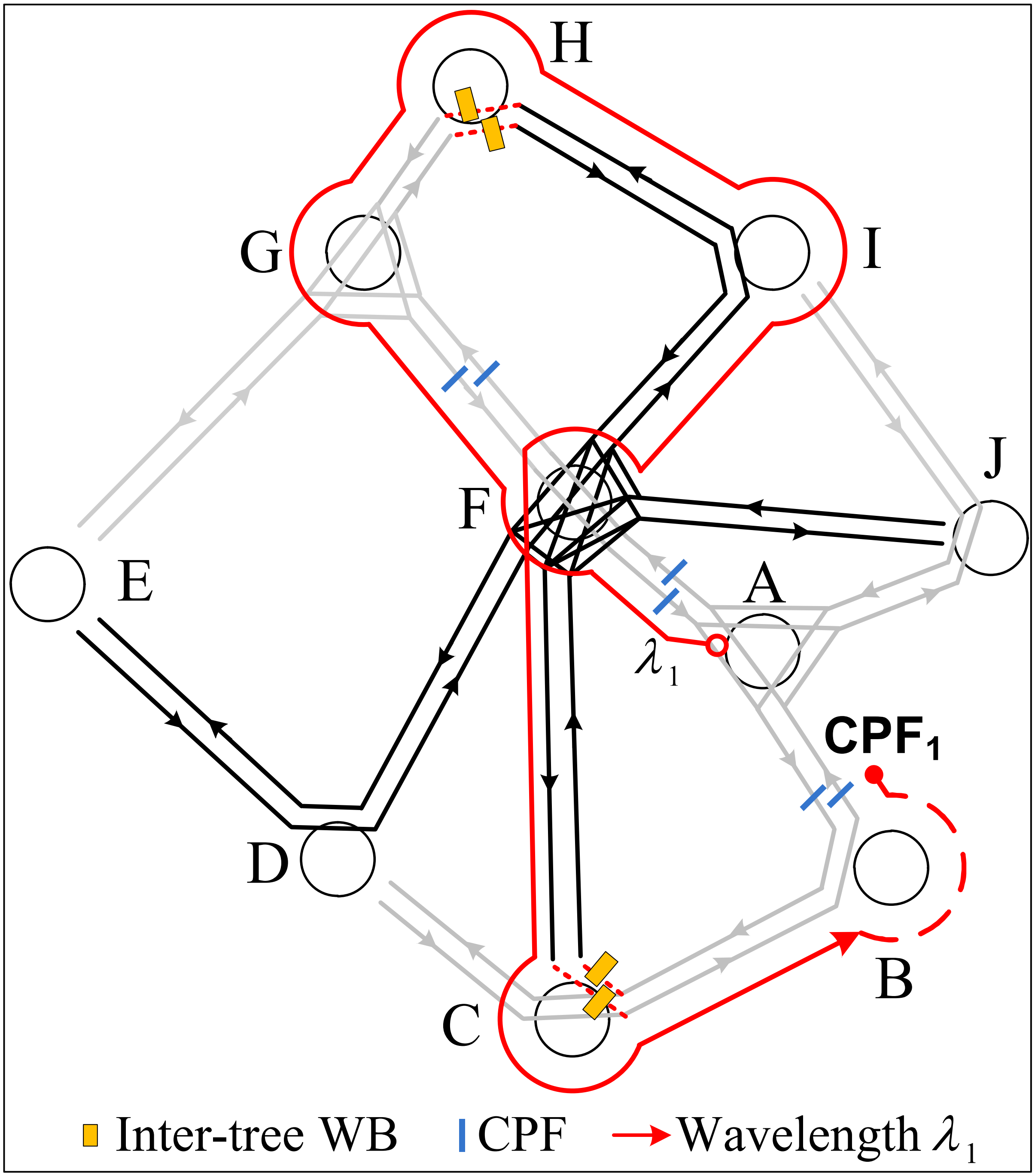


Figure 2.4 WB+CPF protection scheme on IT10. WB+CPF protection scheme applied on a filterless solution for the 10-node Italian network (IT10) (Archambault et al., 2010). Wavelength λ_1 (in red) added at node A is blocked by CPF_1 after reaching its destination at node B

In the final step, each traffic demand is routed through two link-disjoint paths (i.e., the primary and protection path, respectively). If more than two link-disjoint paths exist for one s-d node pair, the wavelengths, which are not used either in the primary or the protection paths, will be blocked by the first encountered inter- or intra-tree WB. Finally, the routing results are transformed into a conflict matrix, where nodes represent the networks traffic demands, and wavelength assignment is performed as a graph-coloring problem with the tabu search metaheuristic presented in (Archambault et al., 2010).

A WB+CPF protection method, in which intra-tree fixed CPFs are used (instead of WBs) for eliminating the laser loops, is also proposed. Figure 2.4 illustrates the hybrid WB+CPF approach with an example of a filterless solution for the 10-node Italian network (IT10) characterized by an intrinsic protection ratio of 47%. In this case, two pairs of inter-tree WBs are placed at nodes C and H in order to obtain a 100% protection ratio. As a result of inter-tree WB placement, one laser loop (represented in red) is created. An alternative to placing one pair of intra-tree WBs at nodes A (WB-only method) is to add 6 CPFs to drop wavelengths that have reached their destinations. To illustrate the blocking function of the CPF, we consider one wavelength λ_1 transmitted from node A to node B in Figure 2.4. The intra-tree CPF placed between nodes A and B prevents the laser loop of [A-F-G-H-I-F-C-B-A]. A CPF is a very simple fixed filter that can block only one wavelength, while WBs are more sophisticated reconfigurable devices that can block from one to all wavelengths. Thus, the WB+CPF approach can be considered as a more cost-effective solution while the WB-only approach is recommended in the cases where several wavelengths need to be blocked or reconfigurability is desired. A tradeoff between cost and reconfigurability can be realized with the WB+CPF method by implementing both intra-tree WBs and CPFs. Figure 2.5 illustrates this method with an example of a filterless solution for the 17-node German network (G17). In this case, 8 WBs and 14 CPFs are needed to achieve 100% protection, compared to 16 WBs by using the WB-only method.

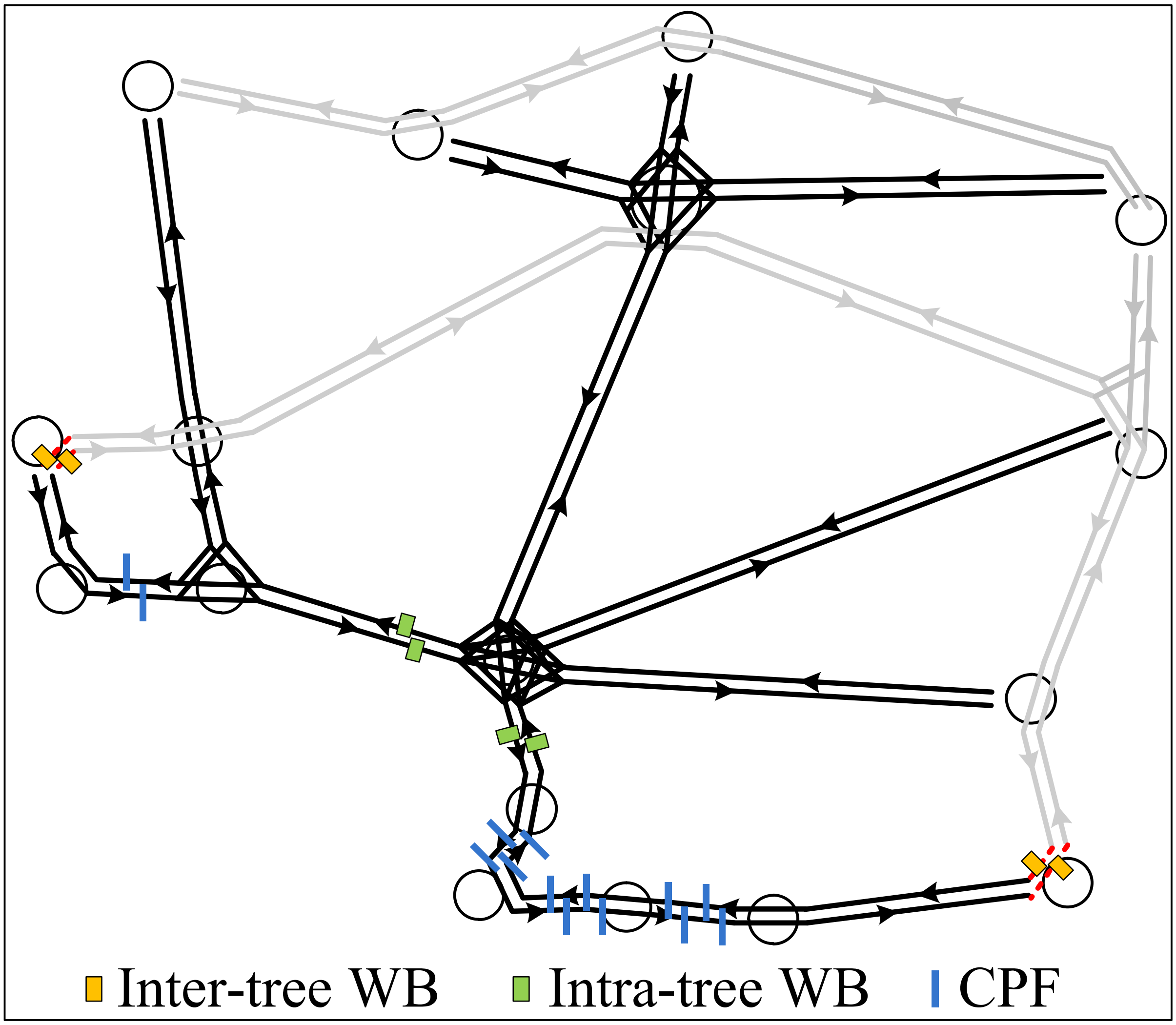
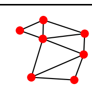
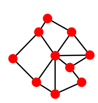
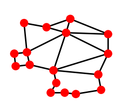


Figure 2.5 WB+CPF protection scheme on G17. WB+CPF protection approach, with both intra-tree WBs and CPFs, applied on a filterless solution for the 17-node German network (G17) (Archambault et al., 2010)

2.3 Performance Evaluation

A cost and performance comparison of the protected and unprotected filterless network solutions for three network topologies is summarized in Table 2.1. In this exercise, only the extra wavelength selective components used for optical-layer protection are considered in the cost calculation. The unit costs of the added components (indicated in arbitrary units) are normalized to the cost of an erbium-doped fiber amplifier (EDFA) (Ciena, 2014). As expected, 100% protection ratio is obtained at the cost of the additional WBs. However, the required amount of WBs is low, which makes the 1+1 protection very cost-effective, compared to active photonic switching solutions. Furthermore, some of the reconfigurable devices can be replaced by fixed CPFs to further reduce extra deployment costs. Performance results also show that the wavelength consumption for the proposed 1+1 protection is moderately higher than for the unprotected filterless solutions.

Table 2.1 Comparison of 1+1 protection methods

Network	**Topology**	**Protection method**	**Protection ratio**	**Wavelength consumption**	**Total cost [a] (a.u.)**
German 7-node		Intrinsic	71%	68	0.56
		WB-only	100%	89	18.6
Italian 10-node		Intrinsic	47%	42	0.56
		WB-only	100%	53	27.6
		WB+CPF	100%	65	18.7
German 17-node		Intrinsic	33%	126	1.16
		WB-only	100%	140	73.2
		WB+CPF	100%	143	37.4

a. Assumption of unit costs: WB = 4.5 (including two optical amplifiers with unit cost of 1.0); splitter, combiner, CPF = 0.02 (Ciena, 2014).

With the introduction of WBs and CPFs into a filterless network, the resulting network architecture, which can be referred to as a *semi-filterless* optical network (Chen et al., 2011), inherits the passive nature of the filterless network while providing 1+1 optical-layer protection. The use of wavelength selective components can provide 100% protection ratio without introducing extra fiber links but at the expense of higher wavelength consumption.

The cost and performance of proposed 1+1 protected solutions for filterless networks has also been compared with their active photonic switching counterparts, which inherently provide 1+1 dedicated protection. The results are shown in Table 2.2. In the analysis realized on the G7, IT10, and G17 networks, four different protected solutions are proposed, depending on the optimization criteria used for the protection path (to minimize the length of protection paths, or the number of inter-tree WBs) and the protection scheme (WB-only or

WB-CPF). For the G7 network, no laser loop was detected after the inter-tree WB placement, and so there is no need to place intra-tree WBs (or CPFs). The WSS-based solutions presented in Table 2.2 are simulated by using the commercial software NetCalc Optical Planner 3.1 and can be considered to be the best cases, in terms of average demand length and number of link segments per demand. Meanwhile, it should be noted that these two metrics are averaged on primary and protection paths, and that the total path length can be reduced by using the shortest protection path routing method. As we can see from Table 2.2, the wavelength consumption of filterless network solutions with dedicated protection, where the WBs and CPFs have been deployed, is in average 15% higher than that of active photonic networks. We observe that the filterless "solution 1/WB" for G17 exhibits a lower wavelength consumption than its active photonic counterpart, at the expense of the deployment of 20 WBs. For this network topology, the least node complexity protection path routing algorithm used in filterless solutions outperforms slightly the shortest path routing algorithm used in WSS-based solutions. The cost advantage of filterless solutions is clearly demonstrated in Table 2.2 as well. While maintaining a comparable level in wavelength usage, 1+1 protected solutions for filterless networks with a cost advantage greater than 50% compared to active photonic switching solutions can be obtained.

2.4 Conclusion

In this paper, we have proposed a 1+1 dedicated optical layer protection strategy for filterless networks based on the deployment of WBs and CPFs at some selected nodes, as well as an algorithm for their placement. Our proposed protection scheme is validated on a number of network topologies. Results of the cost and performance evaluation show that the resulting 1+1 protection solutions can achieve a significant cost saving with a comparable level of wavelength consumption to that of their active counterpart.

Table 2.2 Performance comparison of 1+1 protected solutions and active photonic switching solutions

Network topology	Solution	Number of wavelength selective devices	Average demand length (km)	Average number of link segments per demand	Number of wavelength [a]	Total added cost (a.u.)
German 7-node	Active photonic	18 WSS [b]	458	1.94	73	99
	Solution 1 [c]/WB	10 WB	493	1.94	85	45.8
	Solution 2/WB	4 WB	549	2.26	89	18.6
Italian 10-node	Active photonic	24 WSS	557	2.56	44	132
	Solution 1/WB	12 WB	604	2.97	48	54.7
	Solution 1/WB+CPF	8 WB+6 CPF	604	2.97	61	36.8
	Solution 2/WB	6 WB	663	3.20	53	27.6
	Solution 2/WB+CPF	4 WB+6 CPF	663	3.20	65	18.7
German 17-node	Active photonic	38 WSS	580	3.74	140	209
	Solution 1/WB	20 WB	688	4.39	133	91.2
	Solution 1/WB+CPF	14 WB+8 CPF	688	4.39	134	64.4
	Solution 2/WB	16 WB	742	4.82	140	73.2
	Solution 2/WB+CPF	8 WB+14 CPF	742	4.82	143	37.4

a. The unitary traffic matrix is applied for the IT10 and G17 networks. The traffic matrix for the G7 network was retrieved from (Betker, 2003).
b. Assumption of unit costs: WSS = 5.5 (including two optical amplifiers with a unit cost of 1.0) (Ciena, 2014)
c. Routing methods for the protection paths: solution 1 obtained by minimizing the length of protection paths; solution 2 obtained by minimizing the number of inter-tree WBs.

CHAPTER 3

ARTICLE II: FLEXIBLE BANDWIDTH ALLOCATION IN FILTERLESS OPTICAL NETWORKS

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Abstract

We introduce the new concept of an elastic filterless optical network and propose an efficient heuristic algorithm for solving the static routing and spectrum assignment problem. Our simulation results obtained for different network topologies under multi-period traffic show

increasing bandwidth savings with the growth of traffic load compared to a fixed-grid scenario. We also show the benefits of periodical spectrum defragmentation.

3.1 Introduction

Elastic optical networking (Gerstel et al., 2012; Roberts et al., 2010), also referred to as flexible, gridless, and flex-grid networking, has the ability to improve spectral efficiency and flexibility, as channel spacing is no longer restricted to a fixed International Telecommunication Union (ITU) defined frequency grid, and specific channel bandwidths can be assigned to the traffic demands depending on the capacity and distance requirements. The corresponding bandwidth assignment problem is referred to as routing and spectrum assignment (RSA). Key technology enablers of elastic optical networks include multicarrier-based bandwidth variable transponders and flexible spectrum selective switches (Gerstel et al., 2012; Roberts et al., 2010).

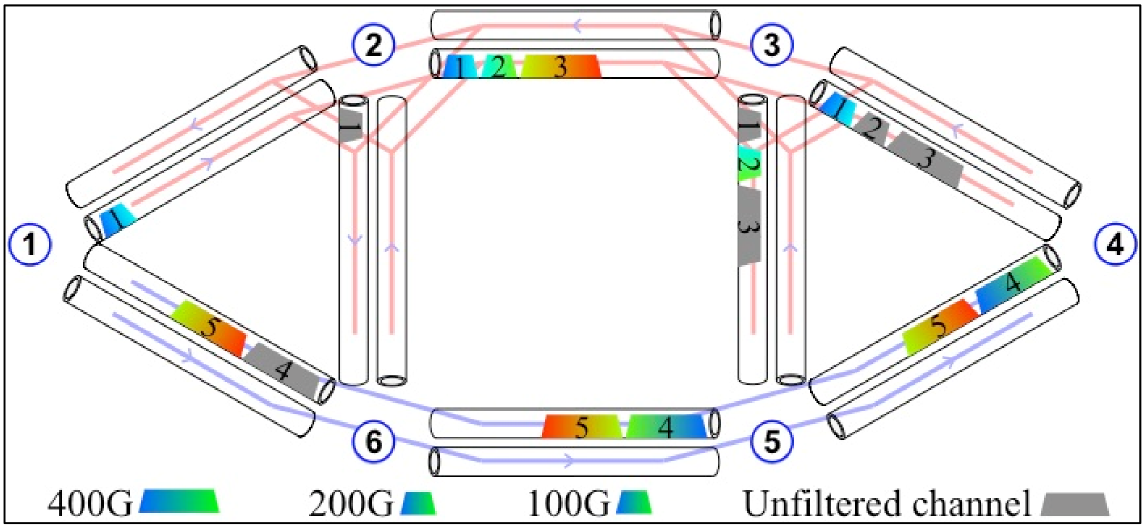
The filterless optical network concept has been proposed as a simple and cost-effective architecture to deliver network agility (Christine Tremblay et al., 2013; C. Tremblay et al., 2007). This concept is based on providing the network agility and reconfigurability by using tunable transmitters and coherent receivers at the terminals, as in radio networks. Consequently, in filterless optical networks, the active switching and colored components used at intermediate nodes and ingress/egress nodes, respectively, are replaced by passive optical splitters and combiners, leading to a significant cost reduction (C. Tremblay et al., 2007). Additionally, the passive gridless architecture of filterless networks makes them suitable for elastic optical networking, thus avoiding replacement of the switching and filtering devices at nodes (in contrast to the current active photonic networks). Therefore, the gridless operation can be achieved at almost no cost without having to deploy gridless wavelength selective switches, which are at present significantly more expensive than fixed-grid ones.

The existing studies of filterless network architecture have been considering fixed-grid scenarios, i.e., the standard ITU grid with 50/100 GHz channels spacing. In (Archambault et al., 2010), a design tool based on genetic and Tabu search algorithms was proposed to solve the physical link interconnection and static routing and wavelength assignment (RWA) problem in filterless networks. The analysis therein shows that filterless networks are cost effective and that resource optimization allows for keeping wavelength utilization within reasonable limits. The dynamic RWA problem in filterless networks was solved in (Mantelet, Cassidy, et al., 2013). A control plane for such networks was proposed in (Mantelet, Tremblay, et al., 2013), while the resilience against link and node failures was studied in (Xu Zhenyu et al., 2014).

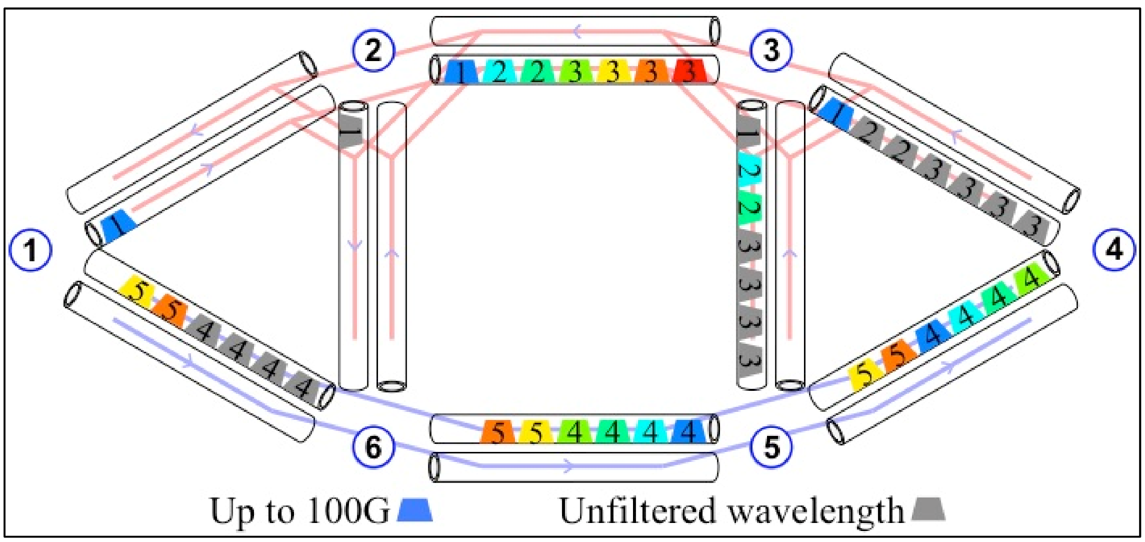
In this paper, we introduce the new concept of an elastic filterless optical network, which combines the benefits of filterless architectures based on passive broadcast-and-select nodes with the spectral efficiency and flexibility of elastic networking. An efficient heuristic algorithm is proposed for static RSA in elastic filterless networks under a multi-period traffic scenario. A comparison with fixed-grid filterless solutions indicates superior performance of the elastic filterless approach in terms of spectrum utilization. Moreover, simulation results show that additional bandwidth savings can be achieved by periodical spectrum defragmentation.

3.2 Elastic Filterless Optical Networks Concept

The physical layer architecture of elastic filterless networks is composed of a set of passive broadcast-and-select nodes interconnected by edge-disjoint fiber trees. The fiber trees, each denoting a set of interconnected optical fiber links, represent a solution to the fiber link interconnection problem obtained by a genetic algorithm based design tool from (Archambault et al., 2010), combined with the optical-layer protection scheme from (Xu Zhenyu et al., 2014) to provide 1+1 dedicated protection. The resulting physical topology and network connectivity are established by configuring the splitters and combiners at the nodes.



(a) Elastic filterless solution



(b) Fixed-grid filterless solution

Demand	Source	Destination	Traffic	Distance	Line rate	Modulation	BW (Flex)	BW (Fixed)
1	1	4	80 Gb/s	1200 km	1×100G	DP-QPSK	3×12.5 GHz	1×50 GHz
2	2	5	150 Gb/s	700km	1×200G	DP-16QAM	3×12.5 GHz	2×50 GHz
3	2	3	380 Gb/s	300 km	1×400G	DP-16QAM	6×12.5 GHz	4×50 GHz
4	4	6	400 Gb/s	700km	2×200G	DP-16QAM	6×12.5 GHz	4×50 GHz
5	4	1	200 Gb/s	1200 km	2×100G	DP-QPSK	6×12.5 GHz	2×50 GHz

(c) Traffic matrix

Figure 3.1 Illustration of elastic (a) and fixed-grid (b) filterless solutions in a six-node network topology for a given traffic matrix (c). The filterless solution with 2 fiber trees (blue and red, respectively) is shown in the background

Each node in the proposed elastic filterless network is equipped with coherent transponders (Gringeri et al., 2013), in which the modulation format and the corresponding channel capacity can be selected between quadrature phase shift keying (QPSK) and 16 quadrature amplitude modulation (QAM) through software control. In this work, we consider dual-polarization (DP) coherent transponders that can operate at channel capacities of 100 and 200 Gb/s (single-carrier) and 400 (dual-carrier) Gb/s, with a corresponding channel bandwidth of 37.5/37.5/75 GHz and reach of 2000/700/500 km, respectively (Gerstel et al., 2012; Roberts & Laperle, 2012). Soft-decision forward error correction (SD-FEC) with overhead close to 20% is assumed in order to achieve the maximum reach at the considered line rates. On the other hand, 50-GHz channels at 100 Gb/s are used in the fixed-grid case.

An illustration of the elastic filterless optical network concept is depicted in Figure 3.1a. Unlike the conventional 50-GHz fixed-grid filterless solution shown in Figure 3.1b, the spectrum granularity of the elastic solution can be decreased to a single frequency slot unit (FSU) (Gerstel et al., 2012) (e.g., 12.5 GHz, used in Figure 3.1c). In principle, filterless optical networks do not have any limitation on the minimum FSU size, while the active switching based optical networks are typically restricted to a minimum FSU size (for example 6.25 or 12.5 GHz) due to the cumulative filtering at intermediate nodes.

The advantage of spectral efficiency in the elastic filterless network, compared to the fixed-grid case, is illustrated in Figure 3.1 through a spectrum allocation example. In general, spectrum assignment in elastic optical networks is subject to four constraints. Firstly, each traffic demand must be carried by the necessary number of consecutive FSUs throughout its physical route, which is referred to as the spectrum contiguity constraint. Secondly, each traffic demand must be assigned the same slots on all links it traverses, which is referred to as the spectrum continuity constraint. Thirdly, a guard band of 1 FSU is needed between any two neighboring channels to mitigate the interference and crosstalk effects, referred to as the guard band constraint. Finally, there must be no spectrum overlapping between different connections. Thus, in the example from Figure 3.1, the bandwidth (BW) required to carry demands 1-3 on the fiber link from node 2 to 3 is 175 GHz (14 FSUs including two FSU guard bands between the three neighbouring channels) in the elastic filterless solution, while it requires 350 GHz (seven 50-GHz channels) in the fixed-grid filterless solution.

A major concern regarding resource consumption in filterless optical networks is the existence of unfiltered channels (shown in gray color in Figure 3.1a and Figure 3.1b), which propagate all the way from the source to terminal nodes within a filterless fiber tree due to the drop-and-continue feature of filterless nodes (Mantelet, Tremblay, et al., 2013). The unfiltered channels increase the spectrum consumption, as the spectral resources occupied by them cannot be reused for other connections. Therefore, developing an efficient RSA algorithm is crucial to reduce the impact of unfiltered channels on the spectrum consumption.

3.3 Problem Definition and Proposed RSA Algorithm for Elastic Filterless Networks (RSA-EF)

The RSA problem in elastic filterless networks can be defined as follows. Given a traffic matrix for a certain time period and a physical network topology, where each node is equipped with coherent transponders supporting a set of line rates *L* with specific spectrum width *B*, modulation format *M*, and reach *R*. The nodes are interconnected with a set of fiber trees ensuring 1+1 dedicated path protection, generated using the methods from (Archambault et al., 2010) and (Xu Zhenyu et al., 2014), as described above. To solve the RSA problem, we must decide on the working and the backup path for each connection request, select the most spectrally-efficient line rate whose reach is greater or equal to the path length, and assign spectral resources, i.e., FSUs. The objective is to optimize the overall spectrum utilization by minimizing the maximum number of FSUs used in each fiber link, while taking into account the constraints on the spectrum continuity, contiguity, overlapping and guard bands.

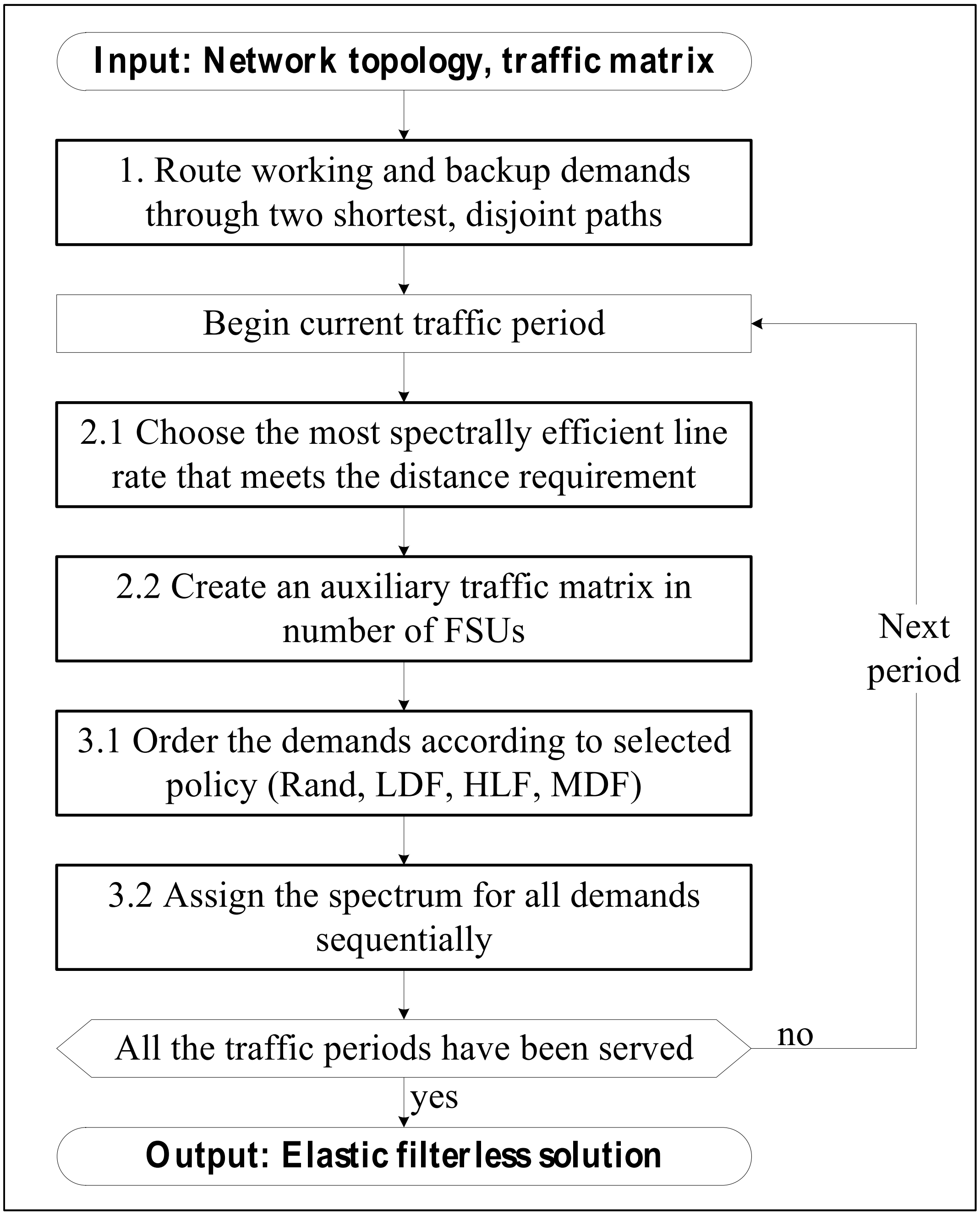


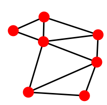
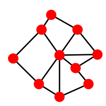
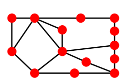
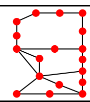
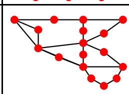
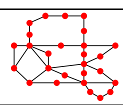
Figure 3.2 Flowchart of the proposed RSA-EF algorithm

The flowchart of the proposed static RSA algorithm for elastic filterless networks, denoted as RSA-EF, is shown in Figure 3.2. Due to the NP-completeness of the RSA problem (Christodoulopoulos et al., 2011), it is solved in two sequential steps, i.e., routing (R) and spectrum assignment (SA). The routing sub-problem is solved by selecting a shortest pair of disjoint paths in the fiber tree topology for the working and the backup path of each traffic demand. When solving the SA sub-problem, we consider a multi-period traffic scenario modeling the long-term traffic growth. The SA sub-problem is solved for the incremental traffic in each period without re-assignment of the previously assigned spectrum. In the beginning of each traffic period, an auxiliary traffic matrix containing the extra requested FSUs per demand is generated to accommodate the incremental traffic. In order to minimize spectrum consumption, the most spectrally efficient line rate whose reach meets the demand path length is selected for each demand. The spectral efficiency is defined as $L/(B+G)$, where G is the bandwidth of guard bands.

The algorithm proceeds by ordering the traffic demands for the current period using an ordering policy, and sequentially assigning FSUs to each demand. Three policies have been considered for ordering the demands: the longest distance first (LDF) (i.e., serve first the demand with the longest distance), the highest line rate first (HLF), and the most demanding first (MDF) (i.e., the largest value of the product of the path length and requested line rate). The algorithm first checks if a part of the traffic can be accommodated by the already used FSUs and modulation format between the same source-destination node pair. If the previously assigned bandwidth is not sufficient, the algorithm assigns the first available continuous spectrum from the short wavelength side to the current demand. The RSA-EF process is complete when all the demands in all periods have been accommodated.

In RSA-EF, the routing of both working and backup paths is predetermined for each demand before performing the SA, and a greedy algorithm is used to decide the ordering policy. The computational complexity of RSA-EF, for a single demand in a given period, depends linearly on the size of the fiber tree accommodating the demand because the algorithm needs to check every branch of the fiber tree due to the filterless broadcast-and-select node architecture. Therefore, the worst-case computational complexity in a single period can be expressed as $O(D \cdot N)$, where D is the total number of demands and N is the number of nodes in the network.

Table 3.1 Results of the RSA algorithm for six elastic filterless optical network solutions

Network	Topology	Filterless network connectivity	Avg. dem. length (km)	Total traffic (Tb/s)	Spectrum utilization (in number of FSUs)					Spectrum utilization improvement	Percentage of unfiltered spectrum: Elastic (Fixed-grid)
					Fixed-grid	Elastic					
						Rand	LDF	HLF	MDF		
G7		1.33	597	5.4	192	167	167	164	**160**	17%	40% (46%)
				16.2	452	337	339	325	**319**	29%	
				32.8	856	607	600	601	**586**	32%	
				55.0	1408	977	963	**947**	956	33%	
				82.8	2088	1401	1371	1367	**1349**	35%	
IT10		0.8	717	5.3	196	195	**186**	194	192	5%	32% (39%)
				16.3	476	396	**373**	383	376	22%	
				32.7	840	632	613	616	**606**	28%	
				54.1	1312	956	**912**	949	923	30%	
				81.8	1904	1346	1313	1336	**1307**	31%	
RN1		0.48	836	7.8	192	222	220	215	**210**	-9%	25% (32%)
				19.7	504	423	391	398	**383**	24%	
				56.7	1288	975	912	914	**894**	31%	
RN2		0.34	869	8.3	216	260	**243**	**243**	254	-13%	18% (23%)
				21.4	540	472	**450**	454	454	17%	
				63	1440	1089	1032	**1017**	1023	29%	
RN3		0.37	785	6.8	160	198	197	200	**196**	-23%	19% (24%)
				18.2	420	376	365	**357**	359	15%	
				54.1	1092	849	809	800	**789**	28%	
RN4		0.24	809	13.2	320	426	402	420	**395**	-23%	23% (28%)
				35.8	872	811	770	782	**755**	13%	
				106.3	2324	1825	1757	1760	**1705**	27%	

3.4 Simulation Results

The RSA-EF was implemented and its performance in terms of spectrum utilization was validated through simulations on the 7-node German network (G7), 10-node Italian network (IT10) (Archambault et al., 2010), and 4 reference long haul network topologies (2000 km max. demand length), shown in Table 3.1. Traffic matrices with incremental number of 100 random connections were used for the G7 and IT10 networks, while non-uniform traffic matrices representing realistic evolution scenarios for a time period of 5-10 years were used for the 4 reference networks. We analyzed the benefits of elastic versus fixed-grid deployment, as well as the influence of periodical spectrum defragmentation on the spectrum consumption.

In the elastic scenario, channel bandwidths *B* equal to 37.5/37.5/75 GHz with modulation formats *M* of DP-QPSK/DP-16QAM/DP-16QAM were assumed for line rates *L* of 100/200/400 Gb/s, respectively, separated with guard bands *G* = 12.5 GHz added at the end of each channel. We also assumed that up to 400 FSUs (5 THz) are available on each fiber and that additional fibers can be deployed if the fiber capacity limit is reached. In addition to the three demand ordering policies considered in the SA sub-problem, a random ordering policy (Rand) has also been considered as a benchmark, and its results were averaged over 50 simulation instances for each network. The wavelength consumption for the fixed-grid scenario was obtained by applying the RWA algorithm from (Archambault et al., 2010), where demands are accommodated using fixed 50-GHz wavelength channels of 100 Gb/s capacity.

3.4.1 Elastic vs. Fixed-grid Filterless Solutions

The simulation results are summarized in Table 3.1. The spectrum utilization improvement of the elastic solutions increases with the traffic load, as a result of always using channels with the highest spectral efficiency for demands shorter than 700 km. The elastic solutions exhibit a significant reduction of spectrum utilization (from 27 to 35%, depending on the network topology) at high traffic load, compared to the fixed-grid cases. However, the spectrum consumption advantage of elastic over fixed-grid reduces and even vanishes at low traffic levels, as a consequence of always favoring the line rate with the most spectrally-efficient modulation format, leaving unused capacity for future usage.

Table 3.1 also shows the benefit of elastic spectrum assignment compared to the fixed-grid in filterless optical networks in terms of reduction of unfiltered spectrum, defined here as the ratio of the spectrum occupied by the unfiltered channels to the total utilized spectrum. As shown in the table, the percentage of unfiltered spectrum varies from 18 to 40%, depending on the network topology, in the elastic filterless solutions, compared to 23 to 46% in the fixed-grid filterless solutions. As can be expected, the percentage of unfiltered spectrum increases with the filterless network connectivity, defined in (Xu Zhenyu et al., 2014) as

$2k/(n(n-1))$, where k is equal to the number of fiber link interconnections and n to the number of nodes. On the other hand, the benefits of the proposed RSA-EF are particularly visible in the networks with relatively high connectivity. Additionally, the proposed demand ordering policies exhibit a moderate impact on spectrum utilization when compared to the random one.

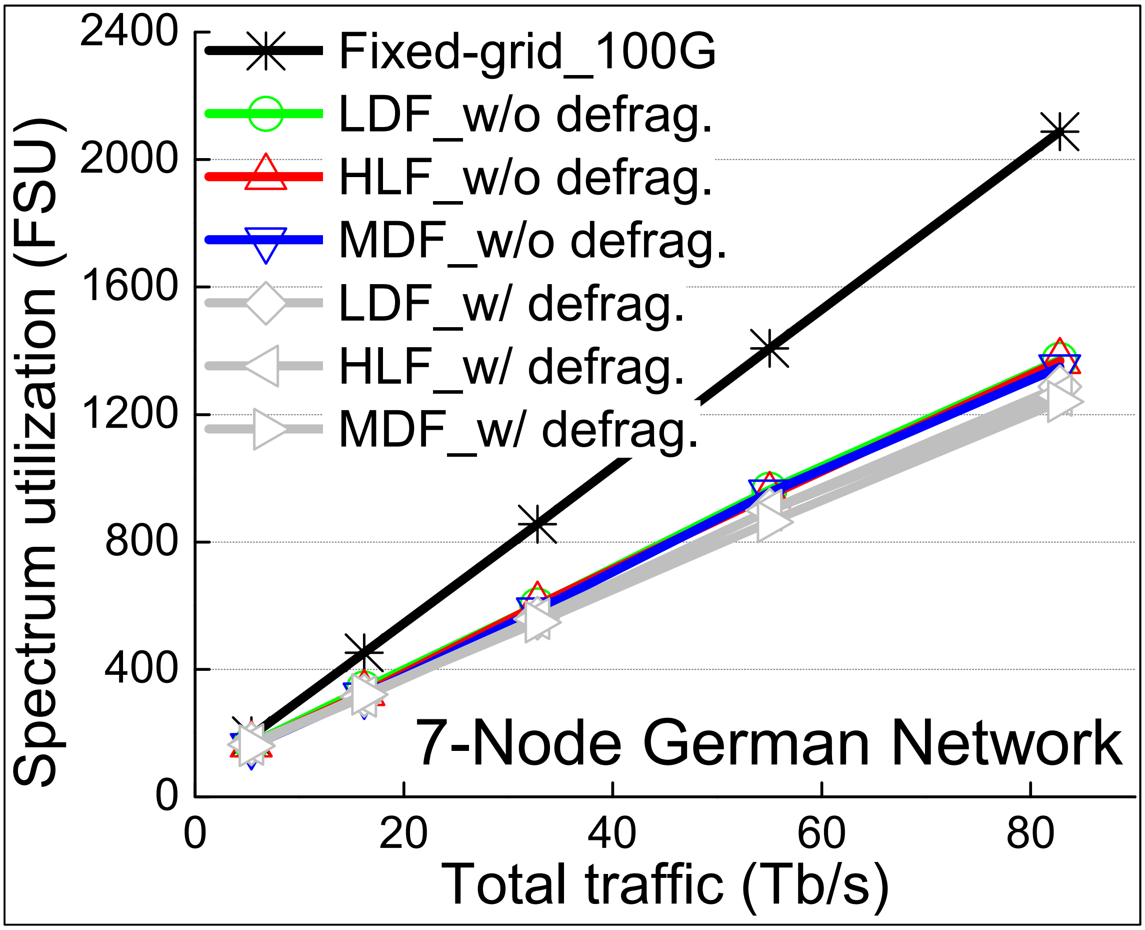


Figure 3.3 Spectrum utilization as a function of traffic load for two networks and two cases: “with defragmentation” vs. “without defragmentation” (a) 7-Node German network

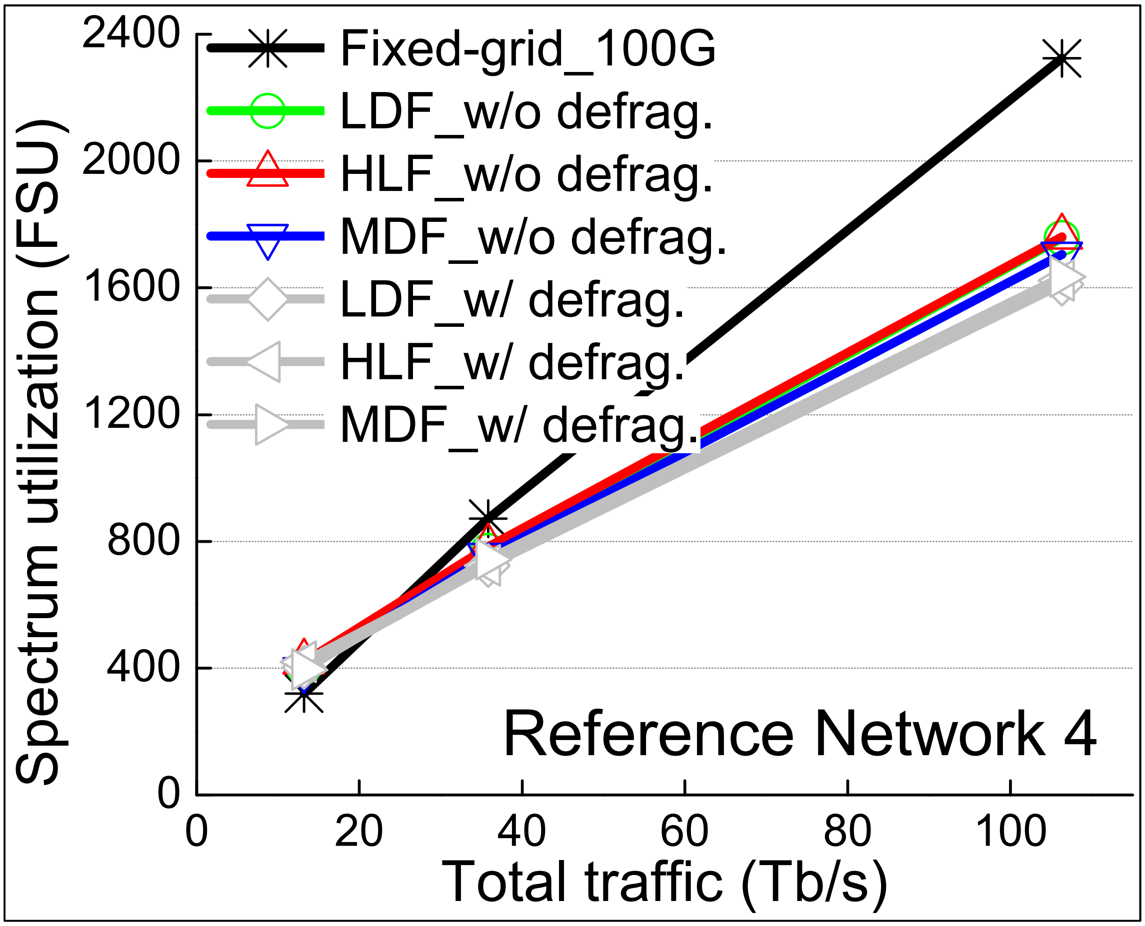


Figure 3.4 Spectrum utilization as a function of traffic load for two networks and two cases: "with defragmentation" vs. "without defragmentation" (b) Reference network 4

3.4.2 Impact of Periodical Spectrum Defragmentation

We also evaluated the impact of spectrum defragmentation on the spectrum utilization for the elastic case (i.e., the algorithm starts at step 2.1 instead of 1 in Figure 3.2) for the G7 and reference 4 networks. In the first scenario, referred to as the "without defragmentation" case, the spectrum assigned in a certain traffic period does not get re-assigned in the following periods. The second scenario, referred to as the "with defragmentation" case, depicts an ideal situation in which all spectral resources can be reassigned in each traffic period. As can be seen from the results presented in Figure 3.4, periodical spectrum defragmentation allows for additional improvements (from 6 to 10%) in spectrum utilization. The benefits of spectrum defragmentation are moderate in the studied cases because the optimization process in the "without defragmentation" case aims at minimizing the spectrum consumption over long-term traffic evolution. It does so by selecting the most spectrally efficient line rate for each demand already in the starting period, leaving sufficient capacity free to accommodate the traffic growth in the subsequent periods without occupying additional spectrum.

3.5 Conclusion

In this paper, we have introduced the new concept of an elastic filterless optical network and defined the static RSA problem in such networks. We have proposed a tailored efficient RSA-EF algorithm for minimizing the spectrum consumption and tested it on 6 different network topologies under a multi-period traffic evolution scenario. Simulation results show a reduction in spectrum utilization (of up to 35%) at high traffic load, as well as in the percentage of unfiltered spectrum (of up to 6%), compared with the fixed-grid case. The improvement in spectrum utilization is the most remarkable in the networks with higher connectivity, although the percentage of unfiltered spectrum therein is the most significant. Moreover, moderate improvements in spectrum consumption of elastic filterless optical networks have been obtained through periodical spectrum defragmentation. Although the cost factor is out of the scope of the study, the spectrum utilization improvement of elastic filterless solutions can also be expected to be delivered with a moderate cost impact, given that the difference between fixed-rate and flexible transponders resides mainly in the functionality integrated in the digital signal processing (DSP) modules.

The advantages and performance of elastic filterless networks can be further enhanced by formulating the RSA problem in elastic filterless networks using integer linear programming (ILP) to obtain optimal solutions with respect to different optimization criteria, or by designing more sophisticated heuristic RSA algorithms targeting the optimization of both cost and spectrum consumption in elastic filterless networks.

CHAPTER 4

ARTICLE III: ROUTING AND SPECTRUM ASSIGNMENT IN ELASTIC FILTERLESS OPTICAL NETWORKS

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Abstract

Elastic optical networking is considered a promising candidate to improve the spectral efficiency of optical networks. One of the most important planning challenges of elastic optical networks is the NP-hard routing and spectrum assignment (RSA) problem. In this paper, we investigate offline RSA in elastic filterless optical networks, which use a passive

broadcast-and-select architecture to offer network agility. Here elastic optical network is referred to as the optical network that can adapt the channel bandwidth, data rate, and transmission format for each traffic demand in order to offer maximum throughput. In elastic filterless networks, the presence of unfiltered signals resulting from the drop-and-continue node architecture must be considered as an additional constraint in the RSA problem. In this paper, first the RSA problem in elastic filterless networks is formulated by using integer linear program (ILP) to obtain optimal solutions for small networks. Due to the problem complexity, two efficient RSA heuristics are also proposed to achieve suboptimal solutions for larger networks in reasonable time. Simulation results show that significant bandwidth savings in elastic filterless networks can be achieved compared to the fixed-grid filterless solutions. The proposed approach is further tested in multi-period traffic scenarios and combined with periodical spectrum defragmentation, leading to additional improvement in spectrum utilization of elastic filterless optical networks.

4.1 Introduction

As a consequence of the wide deployment of broadband access networks and the increasing volume of cloud-based services, global network traffic is continuously growing at a high pace (Ericsson). However, the revenues of the network operators remain moderately flat. Consequently, the optical transport systems have to be upgraded to meet this imbalance by augmenting transmission capacity and efficiency, while minimizing both capital expenditures (CAPEX) and operational expenditures (OPEX).

Under these challenging conditions, elastic optical networking (also referred to in the literature as flexible, flex-grid, or gridless networking, e.g., in (Gerstel et al., 2012; Jinno et al., 2009; Patel et al., 2012; Roberts et al., 2010)) shows the potential to improve spectrum efficiency. The migration from fixed-grid to flex-grid paradigm has opened a gate to bring new architectural options in optical network design. According to the International Telecommunication Union (ITU) dense wavelength division multiplexing (DWDM) frequency grid definition (ITU-T, 2012), channel bandwidth in elastic optical networks will be tailored for traffic demands with different data rates to optimize spectrum efficiency of individual channels. In the resulting architecture, different channel bandwidths can be assigned to the traffic demands depending on the capacity and distance requirements and the network conditions. The corresponding bandwidth allocation problem is generally referred to as the routing and spectrum assignment (RSA) problem. Key enabling technologies for realizing elastic optical networks include multicarrier-based flexible transponders (Roberts et al., 2010) and flexible spectrum/wavelength selective switches (Gerstel et al., 2012).

To address the CAPEX and OPEX concern, the filterless optical network concept (C. Tremblay et al., 2007) has been proposed as a reliable and cost-effective solution to offer network agility. The demonstration has been made on national and regional networks (Christine Tremblay et al., 2013). This concept is based on the premise that the need for agility and reconfigurability can be provided by using tunable transmitters and coherent receivers at the network edge terminals, similar to radio networks. In the resulting network, all active switches and colored components used for local signal add-drop are replaced by passive splitters/combiners. This broadcast-and-select network architecture is also considered as a promising approach for software defined networking (SDN) (Gringeri et al., 2013). Furthermore, the inherently passive gridless architecture of filterless networks makes them suitable for elastic optical networking, as the current fixed-grid DWDM line systems can be upgraded to elastic ones without the need to replace the switching and filtering devices at intermediate nodes. Therefore, elastic filterless optical networks, which combine the advantages of both filterless network architectures and flex-grid scheme, have been introduced in (Xu Zhenyu et al., 2015). In this network architecture, each node is equipped with coherent transponders capable of adapting the line rate according to the capacity and distance requirements of the traffic (Gringeri et al., 2013). The modulation format, and the corresponding channel capacity and spectral width, can be selected between quadrature phase shift keying (QPSK) and 16-quadrature amplitude modulation (16QAM) through software control (Xu Zhenyu et al., 2015).

In this paper, we are solving the offline RSA problem in elastic filterless optical networks and quantifying the improvement in spectrum utilization that can be achieved by using a flex-grid approach instead of a conventional fixed-grid approach in these networks. An integer linear programming (ILP) formulation and two heuristic methods, based on a greedy approach and genetic algorithm, are devised to solve the offline RSA problem in elastic filterless optical networks considering realistic traffic scenarios. Two line rate selection methods are proposed. The first method's objective is to optimize the spectral efficiency while the second method aims to reduce the transponder cost in the spectrum assignment process. Furthermore, the benefits of periodical spectrum defragmentation are also quantified through simulations.

The remainder of this paper is organized as follows. Section 4.2 gives the background of filterless optical networking and an overview of the related work. Section 4.3 provides a formal definition of the offline RSA problem in elastic filterless optical networks. Section 4.4 presents the ILP formulation for solving the RSA problem in a single traffic period and analyzes the size of the proposed formulation along the derivation of lower and upper bounds on spectrum usage. Due to the computational complexity of ILPs, in Section 4.5 we propose two heuristic algorithms for the RSA in large networks with long-term traffic growth. Section 4.6 presents the numerical results and quantifies the improvement in spectrum utilization for different network topologies and traffic scenarios. Finally, Section 4.7 provides concluding remarks.

4.2 Background and Related Work

4.2.1 Filterless Optical Networks: Concept and Advantages

The concept of filterless optical networks, first introduced in (C. Tremblay et al., 2007), leverages the breakthroughs of coherent transmission and electronic dispersion compensation technologies to offer network agility and cost-efficiency. Instead of deploying reconfigurable optical add-drop multiplexers (ROADMs) based on wavelength selective switches (WSSs) as in conventional active photonic networks, link interconnections between network nodes and local add-drop are realized by passive splitters/combiners at intermediate nodes. Consequently, the filterless architecture relies on the wavelength tuning of tunable transmitters at the source nodes and the wavelength selection capability of the coherent receivers to achieve the selection function at the destination nodes.

A two-step approach has been proposed for solving the filterless network design problem in a fixed-grid scenario (Archambault et al., 2010). In the first step, the physical interconnection problem, defined in (Christine Tremblay et al., 2013), had to be solved to ensure the network's physical connectivity. Given the problem complexity, a genetic algorithm has been used to solve the fiber link interconnection problem by constructing sets of interconnected optical fibers referred to as *fiber trees* (Archambault et al., 2010). The problem was subject to the constraints of network connectivity, laser effect (Christine Tremblay et al., 2013) (i.e., accumulated amplified spontaneous (ASE) noise), and fiber tree length. An example filterless solution of an Italian 10-node (IT10) network topology with two fiber trees (i.e., black and gray) is illustrated in Fig. 1. The generated fiber trees must be edge-disjoint and span all nodes to ensure maximal physical topology connectivity. The resulting broadcast-and-select filterless architecture (as shown in Figure 4.1), and therefore the filterless network connectivity, is created by configuring splitters/combiners at each node.

Based on the obtained fiber link interconnection solution, in the second step, static routing was performed by selecting the shortest path for each connection. Finally, the wavelength assignment (WA) problem was solved as a graph-coloring problem with a tabu search metaheuristic (O'Brien et al., 2008) with the objective of minimizing the total number of used wavelengths. Each wavelength channel in an actual fixed-grid solution (i.e., 50-GHz spectral granularity) was assumed to carry up to 100 Gb/s of traffic.

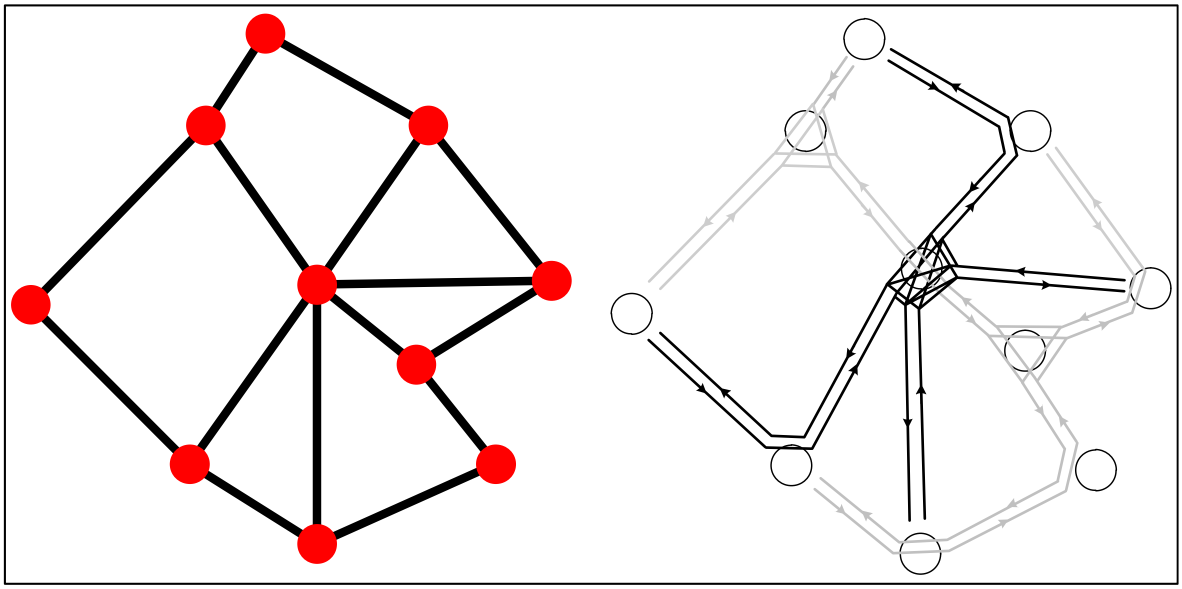


Figure 4.1 The Italian 10-node network topology (Archambault et al., 2010) (left) and a filterless solution (right) with two edge-disjoint fiber trees (in black and gray color respectively) obtained by solving the fiber link interconnection problem

Filterless optical networks have the following advantages compared to the conventional photonic WDM networks based on active switching.

1) *Cost-effectiveness*: Filterless optical networks reduce CAPEX and OPEX by eliminating active photonic switching elements in the optical line system and interconnecting fiber links with passive optical splitters/combiners.

2) *Robustness and energy efficiency*: The passive nature of filterless optical networks does not only provide better network reliability, but also reduces energy consumption.

3) *Agility*: Network agility is improved. Connection establishment in a filterless network is much simpler and faster than in active photonic networks, since only terminal nodes need to be configured.

4) *Enabled flex-grid, colorless ability*: The passive gridless architecture of filterless networks makes them naturally suitable for elastic optical networking, as gridless

operation is an inherent attribute of the filterless networks. Moreover, the filterless design enables colorless node operation, as optical terminals are able to access all DWDM channels and send/receive the wavelength per request.

5) *Multicast capability*: The fiber tree formed by a set of interconnected fibers in filterless optical networks inherently supports the light-tree concept proposed in (Sahasrabuddhe & Mukherjee, 1999) and is a particularly suitable feature for accommodating multicast traffic.

6) *Multilayer networking*: The passive bypass and add-drop functionality at intermediate nodes are key enablers for multilayer networking (Gerstel et al., 2014), allowing the traffic from the Internet Protocol (IP) layer to be dynamically served in the optical layer without reconfiguring the intermediate nodes.

However, filterless optical networks suffer from the drop-and-continue nature of filterless nodes (Mantelet, Tremblay, et al., 2013), where wavelength channels propagate beyond their destination nodes. The presence of unfiltered signals aggravates wavelength consumption, as the spectral resources occupied by these channels cannot be reused by any other lightpath.

4.2.2 Related Work

The architecture of filterless optical networks has been explored in recent years. In (C. Tremblay et al., 2007) and (Christine Tremblay et al., 2013), the authors presented an introduction of the concept. In (Archambault et al., 2010), a filterless network design and simulation (FNDS) tool for solving the physical link interconnection and a static routing and wavelength assignment (RWA) problem was presented, and cost-effective filterless solutions were compared to active photonic networks. In (Savoie et al., 2010), the authors validated the filterless physical layer by simulating the transmission performance of one fiber tree with the commercial software VPItransmissionMaker^{TM}. In recent works (Mantelet, Cassidy, et al., 2013; Mantelet, Tremblay, et al., 2013), the authors proposed path computation element

(PCE)-based control plane for filterless optical networks and studied the dynamic RWA problem. Resilience of filterless networks under link and/or node failures was studied in (Xu Zhenyu et al., 2014), where the authors proposed a 1+1 dedicated optical layer protection strategy and solved the static RWA problem for survivable filterless networks.

However, all previous work on the filterless network remains in the context of standard fixed ITU frequency grid (i.e., 50-GHz channel spacing (ITU-T, 2012)). Facing the increasing interest in superchannels (Bosco et al., 2011), as well as the variations in capacity required by different applications, it is unlikely that long-haul transmission will keep using the conventional WDM systems with fixed channel spacing.

An extensive survey of elastic core optical networking can be found in (Guoying et al., 2013) The RSA problem in elastic optical network has been widely studied by formulating the problem as ILP and solving it by heuristic algorithms, e.g., in (Jinno et al., 2009), (Patel et al., 2012), and (Christodoulopoulos et al., 2011). However, most of the related works study the problem in networks based on active switching, where flex-grid switching components (e.g., gridless WSS) are required at the intermediate nodes. In this paper, we focus on the RSA problem in elastic filterless optical networks and consider the following two traffic scenarios. The first one is referred to as a "*with defragmentation*" scenario, where all spectral resources can be reassigned in a traffic period under consideration or there is no previously existing traffic in optical networks. The second one is referred to as a "*without defragmentation*" scenario, which assumes that the spectrum assigned in a certain traffic period stays unchanged in the following periods. The second scenario is more realistic for operators scheduling multi-period traffic.

The concept of elastic filterless optical networks has been first presented in (Xu Zhenyu et al., 2015), where the physical layer structure of filterless network consisting of sets of edge-disjoint fiber trees has been inherited to leverage the advantages of flex-grid enabled broadcast-and-select filterless architecture. Each node in the proposed elastic network is equipped with software-controlled tunable transceivers (Gringeri et al., 2013) capable of selecting modulation format and channel capacity depending on the required bandwidth. A heuristic algorithm has been proposed for solving the RSA problem in elastic filterless optical networks with a spectral granularity of 12.5-GHz frequency slot units (FSUs). The preliminary study demonstrated improvement of spectrum utilization in elastic filterless networks compared to a fixed-grid case. To extend upon our previous work, in this paper we present a formal definition of RSA problem in elastic filterless networks, we formulate it as an integer linear program to find optimal solutions for smaller networks, and propose advanced RSA heuristics to improve the spectrum utilization in larger network instances.

4.3 RSA Problem Definition in Elastic Filterless Optical Networks

Given a physical network topology and a set of traffic demands for a certain time period, the objective of the RSA problem is to firstly decide proper routes in a fiber tree based filterless topology; secondly choose the most spectral-efficient or cost-efficient line rate (depending on the selection method) while always guaranteeing its maximum reach is not exceeded by the demand length; and finally allocate appropriate spectral resources (in terms of the number of FSUs) to each connection request, while minimizing the overall spectrum consumption, i.e., minimizing the maximum number of FSUs used in any fiber link. In this work we consider two RSA strategies. In the first approach, applied in the proposed ILP and genetic algorithm based RSA heuristic, the routing and the spectrum assignment subproblems in the RSA process are solved jointly. This can offer better insight into resource utilization and leads to lower resource consumption. However, solving the RSA problem in a compound manner might result in higher problem complexity in terms of the number of constraints/variables resulting in potentially excessive computation times. Therefore, the RSA problem is often decomposed into routing and spectrum assignment subproblems, solved sequentially, which is the approach used in our second scheme, applied in the greedy RSA heuristic. In this case, traffic demands are routed on shortest physical paths and a low-complexity greedy algorithm is employed for spectrum assignment.

In both RSA strategies, the following four constraints must be satisfied. Firstly, each traffic demand must be carried by an optical channel (also referred to as a “superchannel” (Bosco et al., 2011)) consisting of a set of consecutive FSUs on each link included in its physical route, referred to as the spectrum contiguity constraint. Secondly, the same part of the spectrum must be assigned to the demand throughout its physical path and there should be no spectrum overlapping between optical channels on any link, referred to as the spectrum continuity constraint, as we assume no spectrum converters are available. Thirdly, each traffic demand must be accommodated with sufficient spectrum resources including a guard band at the end of each optical channel to mitigate interference and crosstalk effects, referred to as the traffic accommodation constraint. Fourthly, only one optical channel can be selected among all candidate physical routes for each traffic demand, referred to as the optical channel routing constraint, assuming that the physical transmission distance of the optical channel is within the optical reach limit of desired date rate.

As mentioned earlier, the existence of unfiltered channels represents a major concern in the filterless architecture. Different from the conventional RSA for the optical networks based on active switching, in filterless networks the spectrum continuity constraint must differentiate between the spectrum occupied by optical channels carrying useful traffic towards their destination from the spectrum occupied by the unfiltered channels propagating downstream beyond their destination nodes. There must be no spectrum overlapping among unfiltered channels and the useful channels.

4.4 ILP Formulation of the RSA Problem in Elastic Filterless Optical Networks

In this section, we mathematically formulate the RSA problem in elastic filterless networks as an ILP model, denoted as RSA-EF-ILP, with the objective of minimizing the overall spectrum consumption. Only one traffic period is treated in the model due to ILP's computational complexity. In the proposed formulation, we assume that each physical link within the network consists of multiple bidirectional pairs of fibers. Given a set of pre-calculated candidate physical routes for each source-destination (s-d) node pair in a pre-determined fiber tree topology, only one route per node pair is selected by the RSA-EF-ILP to accommodate the traffic demand. The RSA-EF-ILP uses the following notation and variables.

Notation

$G(V, E)$:	Physical network topology.
V:	Set of nodes $[v_1, v_2, \dots, v_n]$.
N_V:	Number of nodes.
E:	Set of fiber links $[e_1, e_2, \dots, e_m]$.
N_E:	Number of fiber links.
N_T:	Number of filterless fiber trees.
U:	Set of available FSUs $[u_1, u_2, \dots, u_s]$, where the size of each FSU is set to 12.5 GHz.
N_U:	Number of available FSUs in each fiber link.
L:	Set of available line rates L with specific spectrum width B, modulation format M, reach R, and cost C, respectively.
D:	Set of traffic demands. According to the line rate selection method, each element $d_{ij} \in D$ defines the number of requested FSUs T_d from v_i to v_j in the topology and carries the traffic specified in the traffic matrix.
N_D:	Number of demands.
P:	Set of physical routes. Each element P_d defines a set of available candidate physical routes for demand d, $P_d \subset P$.
E_d:	Set of links traversed by demand d, $E_d \subset E$.
$\bar{E}_d$:	Set of links passed by unfiltered channels accommodating demand d due to the drop-and-continue feature of filterless nodes, $\bar{E}_d \subset E$.
D_e:	Set of traffic demands which are routed through link $e \in E$, $D_e \subset D$.
GB:	The number of FSUs placed at the end of each optical channel acting as a guard band.

Variables

x_{de}^{u}:	= 1, if FSU $u \in U$ on link e is occupied by demand d; 0, otherwise.
z_{de}^{u}:	= 1, if FSU u on link e occupied by demand d is the starting FSU of the channel; 0, otherwise.

y^u:	= 1, if FSU *u* is assigned to at least one demand on any link in the network; 0 otherwise.
k_{pd}:	= 1, if physical route $p \in P_d$ is selected for demand *d*; 0, otherwise.

Objective

Minimize $\sum_u y^u$

The objective function minimizes the spectrum consumption over all links in the network, i.e., the maximum number of occupied FSUs in any fiber link.

Constraints

The objective function is subject to the following constraints:

1) FSU contiguity constraints

$$z_{de}^{u} \leq \sum_{u' \in [u, u+T_d+\mathrm{GB}-1]} x_{de}^{u'} / \left(T_d + \mathrm{GB}\right)$$
$$d \in D,\ e \in E_d \cup \bar{E}_d,\ u \in [1, N_U - T_d - \mathrm{GB}] \tag{4.1}$$

$$z_{de}^{u} + T_d + \mathrm{GB} - 1 \geq \sum_{u' \in [u, u+T_d+\mathrm{GB}-1]} x_{de}^{u'}$$
$$d \in D,\ e \in E_d \cup \bar{E}_d,\ u \in [1, N_U - T_d - \mathrm{GB}] \tag{4.2}$$

Constraints (4.1) and (4.2) are the FSU contiguity constraints. They ensure consecutiveness of FSUs (including the guard band) assigned to traffic demand *d* on each fiber link *e* included in its physical route. In constraint (4.1), when *u* is the starting FSU of the bandwidth assigned to demand *d* on link *e*, then T_d+GB-1 FSUs following *u* on *e* must also be assigned to *d* in order to keep the right-hand side of (4.1) greater than or equal to the value of variable, z_{de}^{u} which is set to 1. If *u* is not the starting FSU, the left-hand side of (4.1) equals zero, and the inequality always holds. Constraint (4.2) is used to make the sum of variables x_{de}^{u} exactly equal to T_d+GB in the case when z_{de}^{u} is set to one.

2) Spectrum continuity constraints

$$\sum_{d\in D_e} x_{de}^u \le 1 \quad e\in E,\ u\in U \tag{4.3}$$

$$x_{de}^u + \sum_{d'\in D_e} x_{d'e}^u \le 1 \quad d\in D,\ e\in \bar{E}_d,\ u\in U \tag{4.4}$$

$$z_{de}^u = \sum_{e'\in E_d\cup \bar{E}_d} z_{de'}^u / \left(\left|E_d\right| + \left|\bar{E}_d\right|\right) \quad d\in D,\ e\in E,\ u\in U \tag{4.5}$$

$$\sum_{u\in[1,N_U-T_d-\mathrm{GB}]} z_{de}^u = k_{pd} \quad d\in D,\ e\in E_d\cup \bar{E}_d,\ p\in P_d \tag{4.6}$$

Constraints (4.3)–(4.6) are referred to as spectrum continuity constraints. Constraint (4.3) ensures that each FSU u on link e is assigned to at most one demand d. Constraint (4.4) ensures that each FSU u on link e occupied by an unfiltered channel accommodating demand d cannot be assigned to any other demand d' passing through the same link. Constraint (4.5) ensures that each FSU u in link e' included in the physical route accommodating demand d is the starting FSU of the channel only in the case when z_{de}^u in the left-hand side of (4.5) is set to one, i.e., when u in link e is the starting FSU of the channel assigned to the demand d, otherwise the sum of the right-hand side of (4.5) must equal to zero. Constraint (4.6) ensures that only one starting FSU belonging to a continuous bandwidth block is assigned to the traffic demand d in each link e along the selected physical route p, when k_{pd} is set to 1, and no presence of the signal when k_{pd} is set to zero.

3) Traffic accommodation

$$\sum_{u} x_{de}^u = \left(T_d + \mathrm{GB}\right) k_{pd} \quad d\in D,\ e\in E_d\cup \bar{E}_d,\ p\in P_d \tag{4.7}$$

Constraint (4.7) ensures the assignment of a sufficient number of FSUs containing the requested bandwidth T_d and the guard band GB along physical route p assigned to demand d, in which case k_{pd} is set to 1; and no assignment of bandwidth along the remaining candidate routes for demand d, in which case k_{pd} is set to 0.

4) Optical channel routing

$$\sum_{p} k_{pd} = 1 \quad d \in D \tag{4.8}$$

Constraint (4.8) ensures that only one physical route p among the pre-computed candidates P_d is assigned to each demand d.

5) Spectrum utilization

$$y^u \geq \sum_{d} \sum_{e \in E_d \cup \bar{E}_d} x_{de}^u / \left(N_D N_E\right) \quad u \in U \tag{4.9}$$

Constraint (4.9) verifies the maximal number of FSUs assigned to all demands, which is being minimized by the objective function and ensures that y^u is set to 1 if the FSU u has been assigned to at least one demand d on any link e.

4.4.1 Line Rate Selection

For each demand d, the requested bandwidth in number of FSUs T_d is the total bandwidth occupied by selected line rates. Two line rate selection schemes, for maximizing the spectrum efficiency (MaxSE) and minimizing the transponder cost (MinCS), respectively, are utilized to decide the T_d prior to the ILP formulation.

In the MaxSE scheme, the most spectrally efficient line rate whose reach meets the demand path length is selected for each demand with the purpose of minimizing the spectrum consumption. The spectral efficiency is defined as $L/(B+\text{GB})$.

On the other hand, in the MinCS scheme, for each demand we select the most cost-efficient line rate whose reach is greater or equal to the path length. The minimum cost of line rate provisioning demand d, can be obtained by solving the problem defined as follows.

$$\text{minimize} \sum_i c_i q_i \tag{4.10}$$

$$\text{subject to} \sum_i l_i q_i \geq \lambda_d \qquad q_i \in \mathrm{Z}^*, \forall i : r_i \geq \Lambda_d \tag{4.11}$$

where q_i is the number of selected line rates l_i, each with reach r_i and transponder cost c_i. The total requested bandwidth for the given traffic and the length of demand d are λ_d and Λ_d, respectively.

4.4.2 Size of the Proposed Formulation

To quantify the size of the proposed RSA-EF-ILP formulation, we consider the number of variables $N_{\text{var\_ILP}}$ and constraints $N_{\text{cnstr\_ILP}}$ as a function of the number of filterless fiber trees N_T, number of nodes N_V, number of fiber links N_E and number of available FSUs N_U, which can be calculated as follows.

$$N_{\text{var\_ILP}} = \left(2N_U N_E + N_T\right)\left(N_V^2 - N_V\right) + N_U \tag{4.12}$$

$$N_{\text{cnstr\_ILP}} = \left(4N_T N_E N_U + 2N_T N_E + 1\right)\left(N_V^2 - N_V\right) + N_E N_U + N_U \tag{4.13}$$

Expressions (4.12) and (4.13) refer to the worst case scenario in which the virtual network topology is a full mesh so the number of demands is equals to $N_D = N_V^2 - N_V$, and each demand has N_T available optical channels in a filterless network with N_T fiber trees. Since N_T

is a relatively small constant in a given filterless solution, it follows that $N_{\text{var\_ILP}} \approx N_V^2 N_U N_E$ and $N_{\text{cnstr\_ILP}} \approx N_V^2 N_U N_E$.

4.4.3 Lower and Upper Bounds on the Number of FSUs

In this section, we derive lower and upper bounds on the maximum number of required FSUs in an elastic filterless network. We assume that there are N_D traffic demands which need to be accommodated in a physical topology with N_V nodes and N_E links, and the optimal physical route p for each demand d within N_T fiber trees has been determined.

4.4.3.1 Lower bound

A lower bound (LB) of the maximum number of used FSUs with known routing solution can be determined by the number of assigned FSUs on the most congested fiber link without considering the unfiltered channels in the filterless architecture, and can be calculated by (4.14). This expression also includes the guard band consisting of GB FSUs, which has to be added at the end of each spectrum allocated to optical channels.

$$\mathrm{LB} = \max_{\forall e \in E} \left(\sum_{d \in D_e} T_d + \mathrm{GB} \times \left(\left| D_e \right| - 1 \right) \right) \tag{4.14}$$

4.4.3.2 Upper bound

An upper bound (UB) on the maximum number of used FSUs with known routing solution can be obtained by using the existing sequential graph-coloring algorithm presented in (Mukherjee, 2006) for determining the minimum number of required wavelengths under the wavelength continuity constraint in conventional wavelength-routed networks. We apply this algorithm to filterless networks by taking unfiltered channels into consideration. To do so, we first need to create an auxiliary graph $G(N, F)$, where each traffic demand d is represented by a node $n \in N$ in graph G. Two nodes in the graph are connected by an undirected link $f \in F$ if their corresponding optical channels including unfiltered channels share a common physical fiber link. Graph G is then colored by assigning colors to nodes from N in descending order of their node degree such that no two adjacent nodes share the same color. Let $N(G) = n_1, n_2, \ldots, n_k$, where $\deg(n_i) \geq \deg(n_{i+1})$ for $i = 1, 2, \ldots, k-1$, and $\omega = \max_{1 \leq i \leq k} \min\left[i, 1 + \deg(n_i)\right]$. The following formula calculates the upper bound of the spectrum consumption in terms of the number of FSUs.

$$\mathrm{UB} = \omega \times \left(\max_{\forall d \in D} T_d + \mathrm{GB} \right) - \mathrm{GB} \tag{4.15}$$

4.5 Heuristics for the RSA Problem in Elastic Filterless Optical Networks

Due to the computational intensity of the ILP formulation, obtaining optimal RSA solutions for high traffic loads in large network topologies may be intractable. Therefore, we propose two computationally efficient heuristic algorithms, i.e., Greedy and genetic algorithm (GA), for solving the RSA problem with larger input instances to find suboptimal solutions in an acceptable computation time. Both algorithms are designed with the objective of minimizing the maximum number of used FSUs and devised to solve the problem in a multi-period scenario modeling long-term traffic growth.

4.5.1 Multi-Period Greedy RSA Heuristic (MP-GR-RSA)

The proposed Multi-period Greedy RSA algorithm, referred to as MP-GR-RSA, is a two-step RSA heuristic, in which the RSA problem is divided into routing (R) and spectrum assignment (SA) subproblems, solved sequentially. Algorithm 4.1 illustrates the procedures of the proposed MP-GR-RSA.

The first step implies solving the routing subproblem in a filterless optical network. Given a physical network topology $G(V, E)$ and a set of multi-period traffic demands D, a filterless solution with N_T sets of edge-disjoint fiber trees spanning all network nodes is obtained by using the genetic algorithm presented in (Archambault et al., 2010). The traffic demands are then routed over the resulting filterless topology using the shortest path algorithm.

Algorithm 4.1 Heuristic MP-GR-RSA in Elastic Filterless Optical Networks

```
Input:    G(V, E) and D in P traffic periods
Output:   RSA result for all periods
Routing (R)
          generate a filterless topology with N_T fiber trees by solving the fiber link
          interconnection problem
          route D in the N_T fiber trees on shortest paths
Spectrum Assignment (SA)
          let SP be a list of spare capacity in previously assigned FSUs
          SP = Ø
          for each traffic period p = 1 to P do
            if p > 1 then
              compute the incremental traffic for current period
              if SP ≠ Ø then
                accommodate current traffic with SP
              end if
              update SP list
            end if
            choose a line rate selection method and construct an auxiliary traffic matrix
            containing the extra requested FSUs per demand based on the incremental
            traffic, update SP list
            select the ordering policy among Rand, LDF, HLF and MDF
            sort D in descending order with selected ordering policy
            for each demand d in D do
              assign first available continuous block of FSUs to d
            end for
          end for
```

The second step is to perform the spectrum assignment. To model the expected traffic growth, we consider a multi-period "without defragmentation" scenario where the SA subproblem is solved for the incremental traffic in each period without re-assignment of the previously assigned spectrum. In the beginning of each traffic period, an auxiliary traffic matrix containing the extra requested FSUs per demand is generated to accommodate the incremental traffic. The line rate selection method MaxSE or MinCS defined in Section IV.A is applied for each demand.

The algorithm proceeds by ordering the traffic demands for the current period using an ordering policy, and sequentially assigning FSUs to each demand. Four policies have been considered for ordering the demands: random (Rand), the longest distance first (LDF), the highest line rate first (HLF), and the most demanding first (MDF) (Xu Zhenyu et al., 2015). These ordering policies are described respectively as follows.

Random (Rand): The order of demands in Rand policy is determined as a return of the random permutation from 1 to N_D inclusively.

Longest Distance First (LDF): In the LDF ordering policy, priority in spectrum assignment is given to demands routed over longer paths, as it is more difficult to find a set of continuously available FSUs along longer paths.

Highest Line Rate First (HLF): In the HLF ordering policy, demands with higher traffic volume are prioritized, since such demands require a greater number of continuously available FSUs.

Most Demanding First (MDF): MDF ordering policy is a hybrid choice of the LDF and HLF, in which the priority criteria is calculated as a product of the path length and requested line rate of each demand.

The MP-GR-RSA algorithm first checks if part of the traffic can be accommodated by the already used FSUs and modulation format between the same s-d node pair (line 9 in Algorithm 4.1). If the previously assigned bandwidth is not sufficient, MP-GR-RSA assigns the first available continuous spectrum from the short wavelength side to the current demand. The MP-GR-RSA process is complete when all the demands in all periods have been accommodated.

Computational Complexity: In MP-GR-RSA, the routing of traffic demands is predetermined for each s-d node pair before performing the spectrum assignment phase, and a greedy algorithm is used to decide the ordering policy. This results in a low computational complexity of MP-GR-RSA, as its complexity for a single demand in a given period depends linearly on the size of the fiber tree accommodating the demand because the algorithm needs to check every branch of the fiber tree due to broadcast-and-select nature of filterless optical networks. Therefore, the worst-case computational complexity in a single period can be expressed as $O(N_D N_V)$.

4.5.2 Multi-Period Genetic Algorithm Based RSA Heuristic (MP-GA-RSA)

To further improve the performance of RSA heuristic in elastic filterless optical networks, we propose a multi-period RSA heuristic based on a genetic algorithm, referred to as MP-GA-RSA, which solves the RSA problem in a combined manner in order to provide a more global view on the overall spectrum consumption.

As an evolutionary optimization algorithm inspired by natural selection and genetics, GA starts with an initial set of individual solutions called population, where each individual is represented by a chromosome. In our case, each chromosome represents a routing solution. Each element in the chromosome is called a gene. The chromosomes evolve through sequential iterations called generations. In each generation, new chromosomes called offspring are created from two randomly selected parent chromosomes through a crossover or mutation operator to create diverse solutions. The fitness value of the chromosomes is then evaluated to select top-quality individuals who will be selected for the next generation, mimicking the process of natural selection. The process is run until a termination criterion is satisfied, such as reaching a certain number of generations.

In MP-GA-RSA, a gene represents the selected physical route for one demand and the fitness value of individual solutions corresponds to the maximum number of required FSUs for the selected routing combined with the spectrum assignment for a random demand sorting policy. The chromosomes with lower fitness values have higher probability to be selected to form the new generation. As a termination criterion, we use the maximum number of iterations without improvement of the objective function, i.e., the maximum number of occupied FSUs. Algorithm 4.2 illustrates the procedures of our proposed MP-GA-RSA.

Routing Paths Computation: Given the physical network topology $G(V, E)$, a set of traffic demands D in different time periods, and the GA parameter settings (i.e., the population size N_{pop}, number of iterations N_{ite} and mutation probability P_{mut}), we first generate the filterless topology containing N_T fiber trees by the FNDS tool (Archambault et al., 2010) and search for all physical candidate routes for every traffic request from D in each filterless fiber tree using the shortest path algorithm.

Initialization: For each traffic period, the heuristic accommodates the incremental traffic by first checking if a part of the traffic can be supported by the already used FSUs and modulation format between the same s-d node pair. If the previously assigned bandwidth is not sufficient, then the algorithm assigns the first available continuous spectrum from the short wavelength side for the remaining traffic in the current period during the GA process.

Figure 4.2 illustrates the structure of the population used in the GA process. We initialize every chromosome in the population by randomly selecting one candidate physical route (represented with different colors as shown in Figure 4.2) for each demand d, which represents one gene in the chromosome. One chromosome represents exactly one possible routing solution for D. The number of chromosomes in the population can be tuned by the input parameter N_{pop}. Larger population size augments the searching space allowing exploration of more diverse solutions, but also increases the computational time.

After initializing the population, we evaluate the fitness value of every chromosome in the population using the fitness evaluation function (line 38 in Algorithm 4.2), which is a two-step RSA heuristic with random demand ordering policy. The objective of this function is to assign the spectrum to the demands D with input routing solution (i.e., one chromosome), and sequentially assign the first available continuous spectrum to each d in D according to the given order. One of two line rate selection methods (i.e., MaxSE or MinCS) is applied to decide the amount of the requested spectral resources (i.e., FSUs). The fitness value returned from the fitness evaluation function is evaluated as the maximum number of assigned FSUs.

Algorithm 4.2 Heuristic MP-GA-RSA in Elastic Filterless Optical Networks

Input: $G(V, E)$
D in P traffic periods
GA parameters:
N_{pop} //maximum number of chromosome in the population
N_{ite} //number of iterations (generations)
P_{mut} //mutation probability
Output: RSA result for all periods

Routing Paths Computation

generate a filterless topology with N_T fiber trees by solving the fiber link interconnection problem
compute all candidate physical routes for each d of D using k-Shortest Path algorithm in the N_T fiber trees

Genetic Algorithm (GA)

let SP be a list of spare capacity in previously assigned FSUs
$SP = Ø$
for each traffic period $p = 1$ to P **do**
  if p > 1 **then**
    compute the incremental traffic for current period
    if $SP \neq Ø$ **then**
      accommodate current traffic with SP
      update SP list
    end if
  end if
let Pop be a population with N_{pop} chromosome x
Initialize each x in Pop by randomly selecting one available physical route for each demand
  for $i = 1$ to N_{pop} **do**
    Evaluate the fitness $F(i)$ for Pop using the *Fitness Evaluation Function*
    //the fitness value is the maximum number of assigned FSUs for given routing instance
  end for
  while $i \leq N_{ite}$ **do**
    Replace Pop with a new population generated by the binary tournament selection

```
        for j = 1:2: N_pop do
          Select a pair of parent chromosomes from Pop randomly
          Crossover the parents and generate two offspring, c1 and c2
          Mutate the two offspring with the probability P_mut
          Evaluate the fitness of c1 and c2
          if F(c1) < F(j) then
            Replace chromosome j with c1
          end if
          if F(c2) < F(j+1) then
            Replace chromosome j+1 with c2
          end if
          if minimum F is decreased then
            reset i to 0
          end if
        end for
        i++
      end while
    end for
```

***Fitness Evaluation Function* (*FitFnc*)**

```
    function FitFnc(x, D)
    output: maxF //maximum number of assigned FSUs
      route all traffic demands with input routing solution
      choose a line rate selection method and construct an auxiliary traffic matrix containing requested FSUs per demand
      sort D in descending order with random ordering policy
      for each demand d in D do
        assign first available continuous FSUs for d
      end for
      maxF = maximum index of FSU in all links
    end function
```

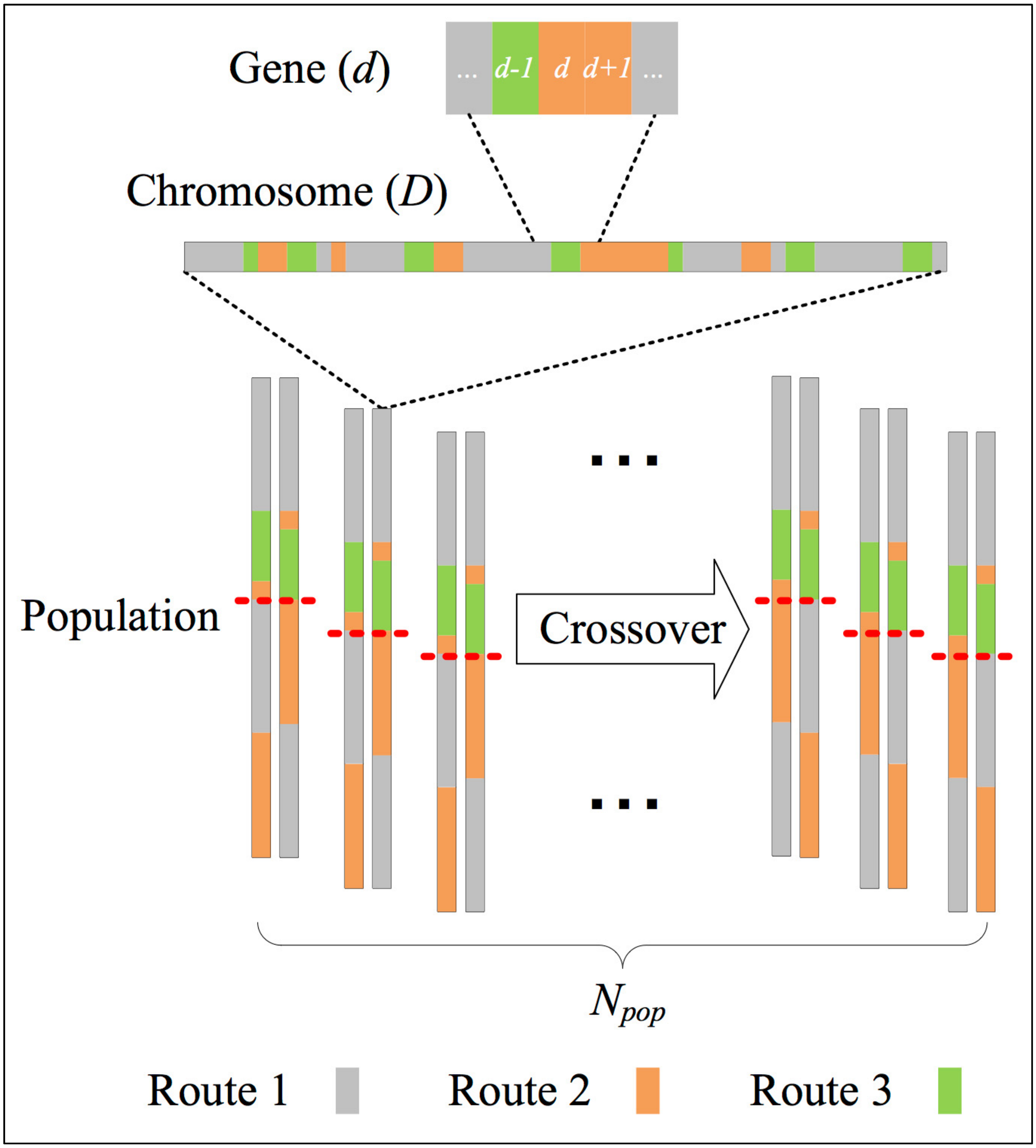


Figure 4.2 An illustration of the structure of the population used in the GA process with maximum three different physical candidate routes (represented by three different colors) per demand *d*

Selection, Crossover and Mutation: Another factor that largely influences the practical execution time of the GA process is the number of iterations N_{ite}, which determines the number of reproductions of the population in a run. For each iteration, we first use the binary tournament selection method, in which two randomly selected individuals are compared to identify the one with better (i.e., lower) fitness value and this fittest one replaces an individual in the population. We then randomly select a pair of parent chromosomes from the resulting population of tournament winners, and perform 1-point crossover at a random location between them to produce two offspring (see the illustration in Figure 4.2). Each offspring undergoes a mutation by randomly altering the physical route of a single demand with mutation probability equal to P_{mut}. Finally, the best N_{pop} individuals among the current population and newly created offspring are selected as survivors for the next generation. The crossover and mutation operations are repeated $N_{pop}/2$ times in each iteration. If the value of the objective function is improved, the counter of iterations is reset to zero, allowing the algorithm to run for N_{ite} more iterations.

The MP-GA-RSA heuristic terminates and outputs the RSA multi-period solution when no further improvement of the fitness function, i.e., spectrum consumption, can be achieved after a given number of iterations N_{ite} for all traffic periods.

Computational Complexity: In MP-GA-RSA, the candidate physical routes for all s-d node pairs are computed by the *k*-shortest path algorithm in the filterless topology before the GA process, so the complexity of the heuristic is dominated by the GA process, where at least N_{ite} generations of population have to be evaluated. The total number of generations of population in the GA process is bounded by the product of the number of iterations N_{ite} and the number of available FSUs N_U. In each generation, the value of the fitness function has to be computed for N_{pop} chromosomes. The computational complexity of the fitness evaluation function is identical to MP-GR-RSA algorithm. Therefore, the worst-case computational complexity in a single period can be expressed as $O(N_{ite} N_U N_{pop} N_D N_V)$.

4.6 Simulation Results

To evaluate the performance of the RSA-EF-ILP and proposed RSA heuristics in terms of spectrum utilization, we first validated the Greedy and GA RSA heuristics by comparing their simulation results of first traffic period to those obtained by the RSA-EF-ILP on a relatively small topology, i.e., 6-node network. As the ILP is not scalable for larger networks, we implemented the proposed multi-period RSA heuristics, namely MP-GR-RSA and MP-GA-RSA, and compared the performance of elastic filterless solutions and their fixed-grid counterparts in terms of the spectrum utilization on a German 7-node (G7), IT10 and four reference networks. Furthermore, we analyzed the benefits of periodical spectrum defragmentation by comparing the results in the case "with defragmentation" to the "without defragmentation" scenario on the G7 and reference network 4.

The heuristic algorithms were implemented in MATLAB and tested on an HP workstation equipped with eight Intel Xeon 2.67 gigahertz processors and 16 gigabyte RAM. The ILP was solved using IBM ILOG CPLEX solver v12.4 (IBM, 2014).

In the simulation results of elastic filterless optical networks, we considered dual-polarization (DP) coherent transponders that operate at line rates L of 100, 200, and 400 Gb/s. Their main characteristics are described in Table 4.1. Soft-decision forward error correction (SD-FEC) with an overhead close to 20% was assumed in order to extend the maximum reach at the considered line rates. The guard band of 1 FSU was added between the optical channels. We also assumed that up to 400 FSUs (5 THz) are available on each fiber and that additional fibers are deployed if the bandwidth capacity limit is reached.

4.6.1 ILP vs. Heuristic

Table 4.2 shows the spectrum consumption results obtained by the RSA-EF-ILP, Greedy and GA RSA heuristics for two different line rate selection approaches, with the best results highlighted for each case. The parameters of the GA heuristic are tuned experimentally to 20, 50, 0.2 for the population size N_{pop}, number of iterations N_{ite}, and mutation probability P_{mut}, respectively. The best results in terms of spectrum consumption, obtained by the Greedy and GA RSA heuristics, are used as an initial value of N_U (i.e., the maximum number of available FSUs in each fiber link) for RSA-EF-ILP. Such an approach is for the purpose of reducing ILP's complexity, since the results obtained by the ILP should be at least as good as those obtained by the heuristics. All approaches were tested using uniform and random traffic matrices generated for the 6-node network. Lower (LB) and upper bounds (UB) on spectrum consumption were computed using (4.14) and (4.15) after obtaining the optimal routing by RSA-EF-ILP. The results show that, for small networks, different ordering policies of the Greedy heuristics have similar performances in terms of spectrum consumption for uniform and random traffic scenarios. Among these policies employed by the Greedy RSA algorithm, the Rand policy consumes slightly more spectrum than the other three policies. For both traffic scenarios, the results indicate that the GA-based RSA heuristic outperforms the Greedy RSA heuristic and can achieve optimal solutions, i.e., for small networks the results are equal to the ones obtained by RSA-EF-ILP. This can be explained by the fact that the GA approach optimizes jointly the routing and the spectrum assignment.

Table 4.1 Characteristics of Transponders

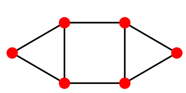
	Line rate (Gb/s)	Modulation format	Channel bandwidth (GHz)	Reach (km)[a]	Cost (a.u.)[a]
Conventional	100	DP-QPSK	50	2000	1.5
Coherent transponder	100	DP-QPSK (Single-carrier)	37.5	2000	1.5
	200	DP-16QAM (Single-carrier)	37.5	700	2
	400	DP-16QAM (Dual-carrier)	75	500	3.7

a. Ciena, private communication.

In the 6-node topology we notice that the theoretical lower bound of RSA-EF-ILP, calculated by the method presented in Section 4.4.3, cannot be achieved. This can be explained by the increase of spectrum consumption due to the presence of unfiltered channels and the spectrum continuity constraint within the elastic filterless networks.

In Table 4.2, the total cost of deployed transponders is calculated. According to the results for single traffic period, the MinCS approach effectively reduces both the cost and the spectrum consumption when compared to the MaxSE case. However, the objective of the MaxSE approach is to improve the performance for long-term traffic growth. Hence, the most spectrally efficient line rates are used, leaving unused capacity reserved for future usage.

Table 4.2 Comparison of Spectrum Consumption Performance of ILP Formulation to Heuristics in Elastic Filterless Optical Networks

Network topology	Traffic	Spectrum consumption (FSU)				Cost[d]
		LB/UB	ILP	Greedy Rand[c]/LDF/HLF/MDF	GA	
	*MaxSE*					
	uniform[a]	19/42	**33**	38/37/37/37	**33**	43.1
	random[b]	22/64	**36**	46/45/45/45	**36**	50.2
	MinCS					
	uniform	16/28	**24**	28/28/28/28	**24**	22.5
	random	21/61	**34**	44/43/43/43	**34**	39.8

a) Uniform traffic with entry of one 10 Gb/s per s-d node pair
b) Randomly generated traffic of maximum 400-Gb/s per s-d node pair, the results are averaged over 15 simulation instances
c) The results of Rand are averaged over 50 simulation instances
d) The cost of deployed transponders is calculated based on the optimal ILP solution

4.6.2 Flex- vs. Fixed-grid Filterless Solutions

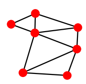
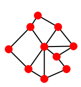
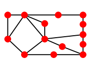
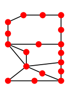
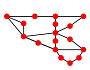
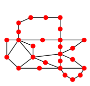
Table 4.3 shows the comparative results of the flex- and fixed-grid filterless solutions on larger network topologies applying the MaxSE and MinCS line rate selection methods. Non-uniform traffic demands representing realistic evolution scenarios for a time period of 5-10 years have been used for four long-haul reference networks (2000 km max. demand length), while for the G7 and IT10 networks, we applied a randomly generated traffic matrix with incremental traffic load to simulate the multi-traffic-period scenario. The parameters of the GA heuristic are tuned accordingly to 60, 150, 0.1 for N_{pop}, N_{ite}, and P_{mut}, respectively.

Wavelength consumption for the fixed-grid cases was obtained by using the routing and wavelength assignment algorithm presented in (Archambault et al., 2010). In order to make a fair comparison, we assume that one 50-GHz wavelength channel in a fixed grid can support a traffic demand of up to 100 Gb/s, and that additional wavelength channels are required to accommodate higher line rates. The characteristics of conventional transponder are described in Table 4.1.

4.6.2.1 Spectrum Utilization Improvement

The spectrum utilization improvement shown in Table 4.3 is defined as the ratio of the difference in spectrum utilization between the elastic and fixed-grid cases over the spectrum consumed in the fixed-grid case. The spectrum utilization improvement increases with the traffic load as a result of using the most spectrally efficient line rate (400G) for demands shorter than 700 km. The results show that elastic filterless solutions exhibit a significant reduction in terms of spectrum utilization (from 35 to 56%, depending on the network topology) at high traffic load, compared to the fixed-grid filterless solutions. In larger networks the proposed MP-GA-RSA heuristic exhibits an obvious advantage on spectrum utilization (from 6 to 32% on average, depending on the topology) compared to the MP-GR-RSA. This result also reveals inherent benefits of the combined RSA algorithm over the two-step R+SA algorithm.

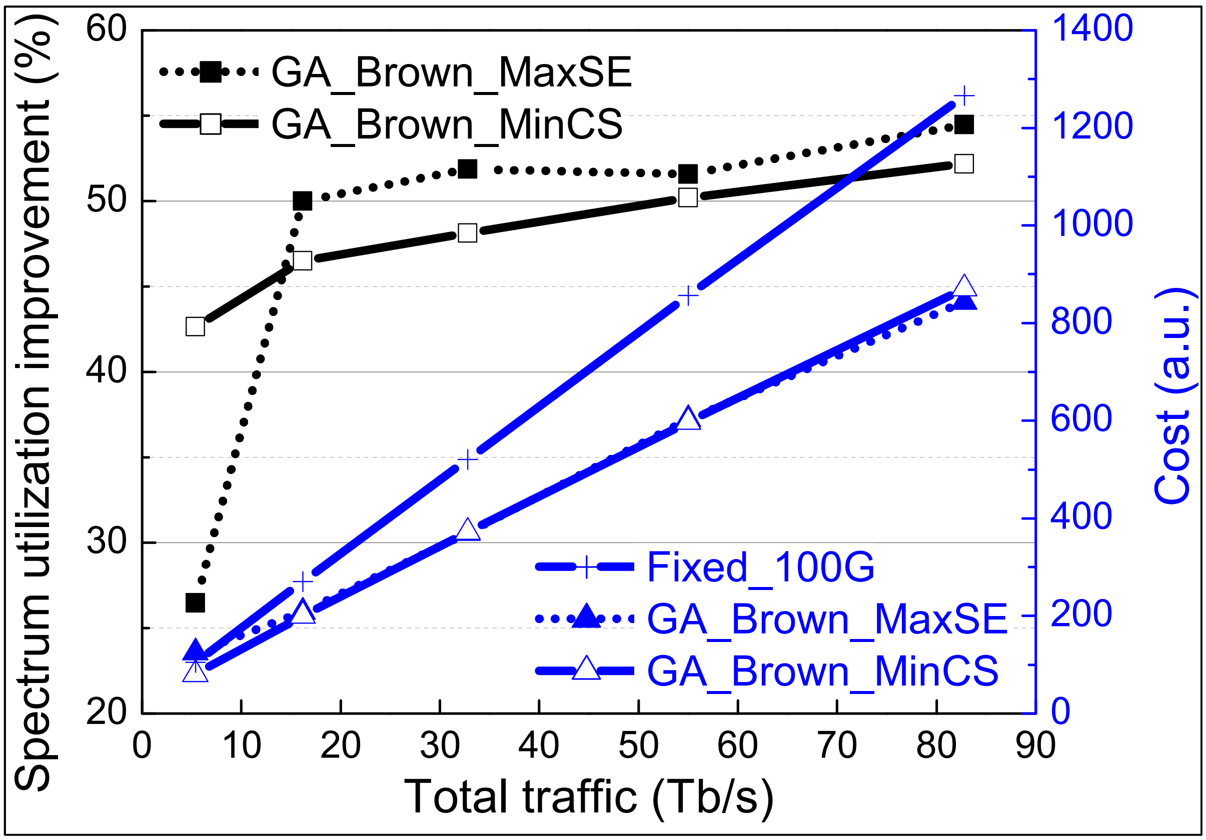
Table 4.3 Results of the Heuristic MP-GR-RSA and MP-GA-RSA Algorithms for Six Elastic Filterless Optical Networks

Network	Topology	Avg. demand length (km)	Total traffic (Tb/s)	Spectrum utilization (FSUs)						Spectrum utilization improvement (%)	Percentage of unfiltered spectrum (%): Elastic/Fixed
				Fixed 100G	Elastic						
					MP-GR-RSA				MP-GA-RSA		
					Rand	LDF	HLF	MDF			
G7		371	5.4	68	63[a] (48)[b]	60 (44)	67 (49)	60 (45)	50 (**38**)	26 (**43**)	**45**/51
			16.2	172	107 (110)	102 (104)	103 (105)	106 (105)	**86** (92)	**50** (47)	
			32.8	320	172 (188)	171 (187)	179 (176)	168 (187)	**154** (166)	**52** (48)	
			55.0	504	274 (292)	273 (283)	268 (282)	268 (284)	**244** (251)	**52** (50)	
			82.8	736	379 (410)	372 (402)	371 (407)	382 (389)	**335** (352)	**54** (52)	
IT10		506	5.3	104	110 (80)	104 (73)	131 (81)	104 (77)	90 (**69**)	13 (**34**)	**47**/56
			16.3	260	186 (180)	178 (174)	199 (186)	178 (173)	160 (**153**)	38 (**41**)	
			32.7	432	268 (296)	271 (289)	282 (301)	261 (282)	**235** (257)	**46** (41)	
			54.1	716	403 (464)	400 (452)	415 (460)	394 (449)	**343** (388)	**52** (46)	
			81.8	1024	573 (645)	569 (630)	584 (633)	565 (626)	**494** (540)	**52** (47)	
CRN1		546	7.8	112	157 (103)	159 (104)	155 (104)	159 (108)	141 (**96**)	-26 (**14**)	**53**/63
			19.7	284	243 (253)	238 (251)	234 (255)	238 (255)	**220** (235)	**23** (17)	
			56.7	728	509 (547)	501 (545)	497 (548)	501 (556)	**458** (503)	**37** (31)	
CRN2		604	8.3	140	217 (144)	199 (136)	223 (140)	199 (**132**)	195 (**132**)	-39 (**6**)	**55**/64
			21.4	360	329 (350)	**300** (332)	320 (344)	314 (329)	**300** (326)	**17** (9)	
			63	940	670 (749)	620 (708)	668 (733)	627 (713)	**604** (694)	**36** (26)	
CRN3		468	6.8	112	169 (105)	164 (104)	167 (104)	164 (104)	150 (**96**)	-34 (**14**)	**56**/67
			18.2	300	269 (268)	262 (265)	265 (262)	262 (265)	244 (**242**)	19 (**19**)	
			54.1	812	507 (575)	496 (569)	496 (559)	500 (565)	**468** (526)	**42** (35)	
CRN4		356	13.2	216	335 (199)	325 (196)	332 (200)	325 (196)	254 (**152**)	-18 (**30**)	**62**/72
			35.8	596	551 (523)	538 (518)	548 (522)	545 (518)	429 (**401**)	28 (**33**)	
			106.3	1612	985 (1130)	963 (1101)	973 (1123)	970 (1115)	**706** (823)	**56** (49)	

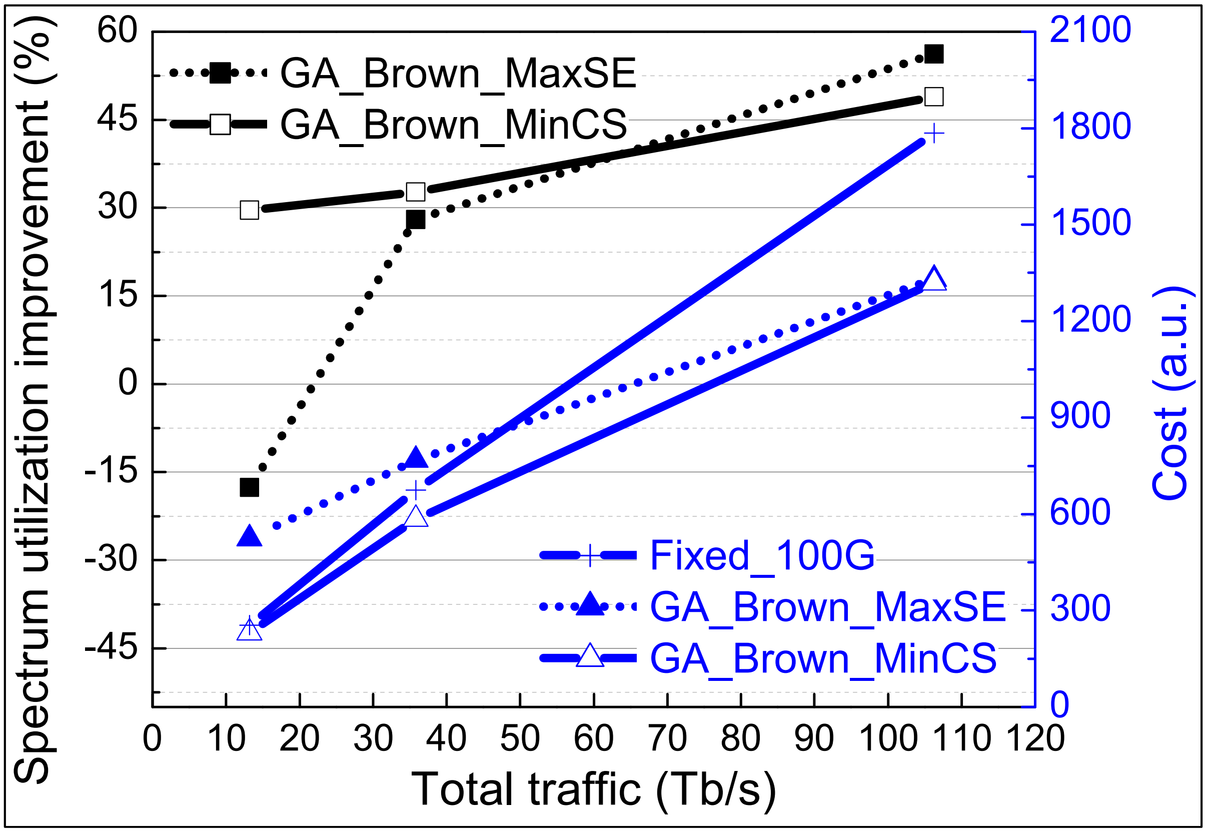
a) The results on the outside of parentheses are obtained based on the MaxSE line rate selection method.
b) The results within parentheses are obtained based on the MinCS line rate selection method.

4.6.2.2 Unfiltered Channels

Table 4.3 also shows the benefit of elastic spectrum assignment compared to the fixed-grid in filterless optical networks in terms of reduction of unfiltered spectrum. It is defined here as the ratio of the spectrum occupied by the unfiltered channels to the total utilized spectrum. The percentage of unfiltered spectrum shown in Table 4.2 has been averaged over all traffic periods. As shown in Table 4.2, the percentage of unfiltered spectrum varies from 45 to 56%, depending on the network topology, in the elastic filterless solutions, compared to 51 to 67% in the fixed-grid filterless solutions.



(a) 7-node German network



(b) Ciena reference network 4

Figure 4.3 Comparison of line rate selection method in terms of spectrum utilization improvement and cost as a function of traffic for (a) the German 7-node and (b) the Ciena reference network 4

4.6.2.3 3) Impact of Line Rate Selection Method

The impact of the line rate selection method on the spectrum utilization improvement and the cost is illustrated in Figure 4.3. In the MaxSE case, we observe that the spectrum consumption advantage of elastic over fixed-grid reduces and even vanishes for the reference network 4 topology at low traffic level. It is a consequence of always favoring the line rate with the most spectrally-efficient modulation format and leaving a significant amount of unused capacity for future usage. However, as the total traffic increases, the MaxSE scheme outperforms the MinCS in terms of the spectrum utilization.

The same tendency has been observed for the cost of deployed transponders. The MaxSE scheme tends to achieve lower cost in long-term traffic growth compared to the MinCS method, although the MinCS scheme can effectively reduce the short-term cost. Furthermore, Figure 4.3 shows that in contrast to the fixed one, the elastic filterless solution can achieve up to 33% and 26% cost saving in high traffic level for the G7 and Reference network 4 respectively.

4.6.2.4 Computational Complexity

There is an obvious trade-off between computational complexity and the resulting spectrum efficiency. Table 4.4 evaluates the computational time of the MP-GR-RSA and MP-GA-RSA heuristic algorithms. As expected, the results clearly indicate that MP-GA-RSA is more time-consuming than MP-GR-RSA because of its long evolutionary process to solve the routing and spectrum assignment subproblems jointly. On the other hand, MP-GA-RSA can achieve much better results on spectrum usage.

Table 4.4 Comparison of Computational Time of MP-GR-RSA to MP-GA-RSA Heuristic in Elastic Filterless Optical Networks

Network	Computational time (in elapsed minutes)[a]	
	MP-GR-RSA	MP-GA-RSA
7-node German	0.02	222
10-node Italian	0.04	281
Ciena reference network 1	0.03	288
Ciena reference network 2	0.04	454
Ciena reference network 3	0.03	197
Ciena reference network 4	0.09	577

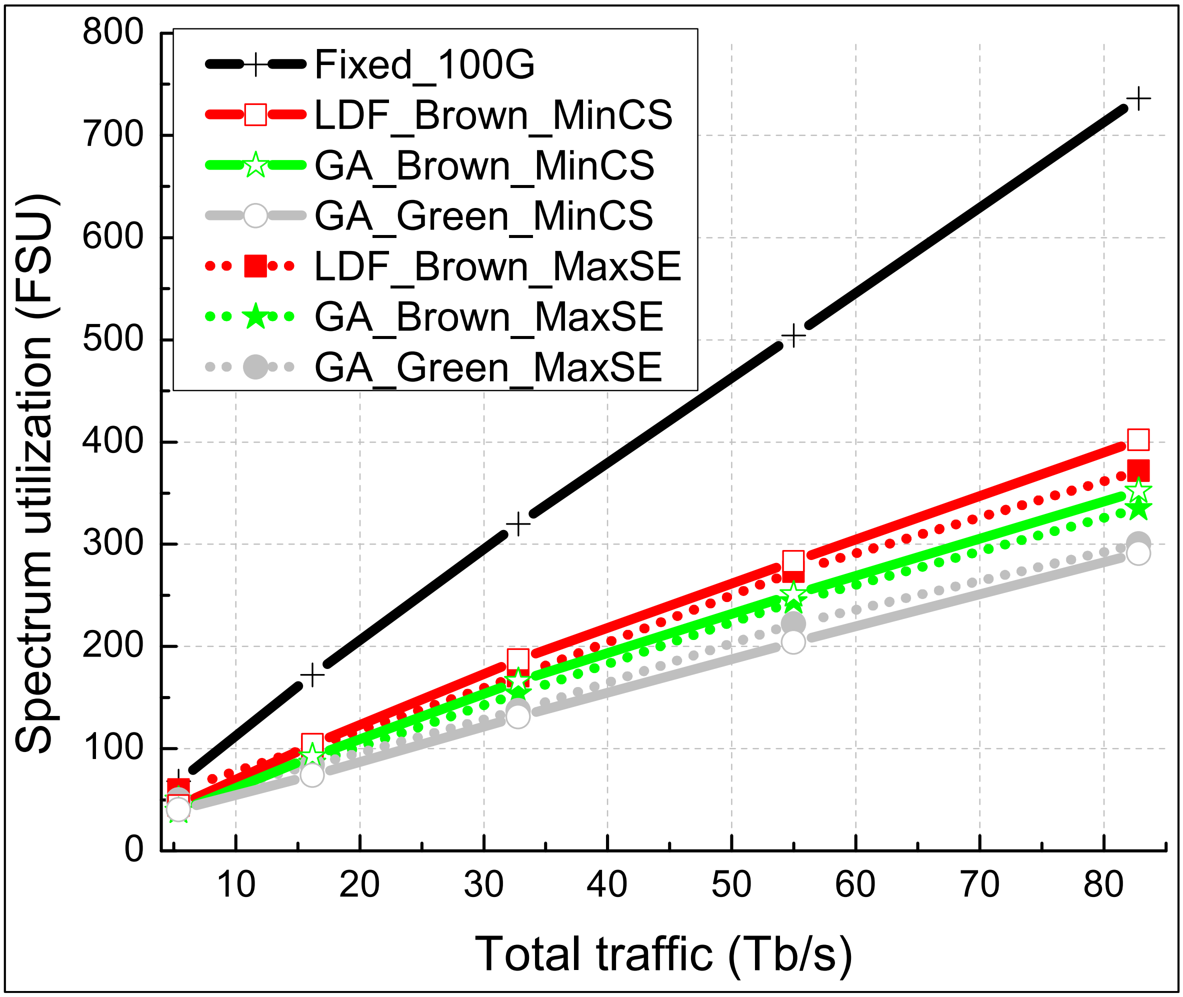
a) The computational time is calculated based on the MaxSE line rate selection method for all traffic periods.

4.6.3 Benefits of Periodical Spectrum Defragmentation

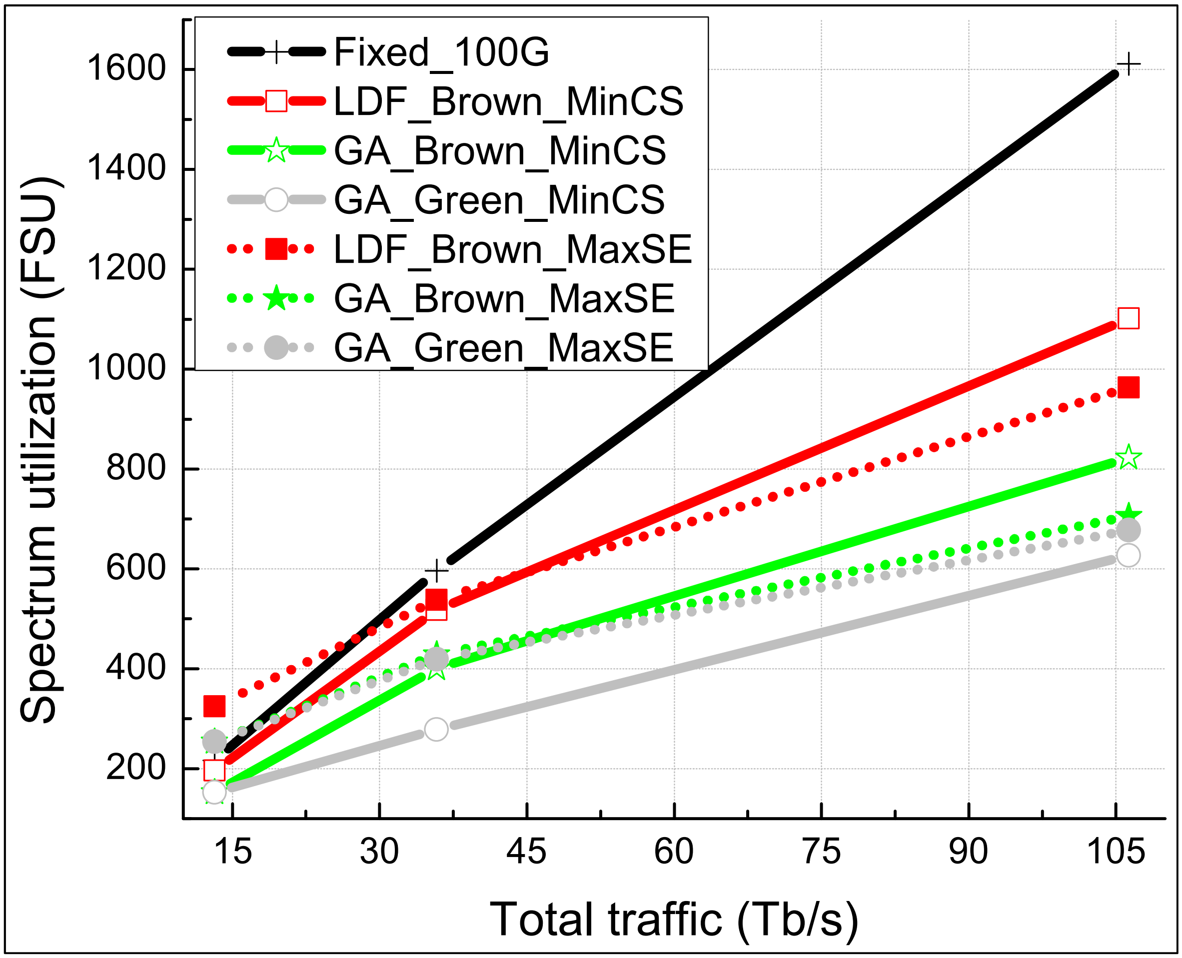
We also evaluated the impact of spectrum defragmentation on the spectrum utilization for both the fixed- and elastic filterless solutions. Herein, we compare two scenarios. In the first one, referred to as "without defragmentation" case, the spectrum assigned in previous traffic periods does not get re-assigned during any of the following periods. The second scenario, referred to as "with defragmentation" case, depicts an ideal situation in which all spectral resources can be reassigned in each traffic period, according to the optimal design for the total traffic demand in the considered period. In Figure 4.4, it can be seen that performing periodical spectral defragmentation more effectively improves spectrum utilization in the MinCS scenario (up to 21% and 31% for the G7 and reference network 4, respectively) compared to the MaxSE scenario (up to 11% and 4% for two aforementioned topologies, respectively). Therefore, it seems highly beneficial to perform defragmentation periodically, particularly if employing the MinCS scenario for the case with a large traffic load.

4.7 Conclusion

In this paper, we have investigated the offline RSA problem in elastic filterless optical networks. Two line rate selection methods (i.e., MaxSE and MinCS) have been proposed to take the transmission distance into consideration when solving the RSA problem. The problem was formulated as an ILP to obtain optimal solutions for smaller-sized networks. Due to the intractability of the ILPs, two efficient heuristic approaches were developed to obtain sub-optimal RSA solutions for larger networks in reasonable time. First, a greedy version of the heuristics performed routing and spectrum assignment in subsequent phases, and found feasible RSA solutions in short computational time. The second version of heuristics, based on a genetic algorithm, solved the routing and spectrum assignment problems jointly, and obtained solutions of superior quality at the expense of a longer computational time. Both heuristics were applied to realistic multi-period traffic scenarios modeling long-term growth of the network traffic. Different variants of multi-period network planning were investigated, encompassing scenarios with and without traffic defragmentation.



(a) 7-node German network



(b) Ciena reference network 4

Figure 4.4 Spectrum utilization as a function of traffic for (a) the German 7-node and (b) the Ciena reference network 4 and two cases: "with defragmentation" vs. "without defragmentation" (between two traffic periods)

Simulation results show that for large size networks significant bandwidth savings can be achieved in flex-grid filterless solutions due to increased spectrum efficiency compared to the fixed-grid filterless networks studied in the prior work (Archambault et al., 2010). In the MaxSE case, the spectrum savings can reach up to 56% under high traffic loads. The results further demonstrate that more significant improvement in terms of spectrum utilization in elastic filterless optical networks can be achieved in the MinCS case when periodical spectrum defragmentation is performed. Compared to the "without defragmentation" scenario, the improvement can reach up to 31% for certain network scenarios.

GENERAL CONCLUSION

In summary, the work in this thesis addressed the resilience and survivability issue in filterless optical networks, which are passive optical core networks based on the dense wavelength-division multiplexing (DWDM) and coherent optical transmission technologies. A dedicated protection strategy was proposed for the filterless networks and validated on a number of network topologies. The resulting 1+1 protection solutions showed significant cost advantage when compared to active photonic switching networks while using a comparable number of wavelengths. Moreover, we introduced the concept of an elastic filterless optical network for next generation long-haul optical networks and investigated the offline routing and spectrum assignment (RSA) problem in the resulting networks. Two line rate selection methods (i.e., MaxSE and MinCS) were proposed to take the transmission distance into account when solving the RSA problem. The RSA problem was formulated as an Integer Linear Programming (ILP) to obtain optimal solutions for small networks. Due to the complexity of ILPs, two efficient heuristic methods (i.e., greedy and genetic algorithms) were developed to obtain sub-optimal solutions for larger networks in reasonable time. Both heuristics were applied to realistic multi-period traffic scenarios modeling long-term growth of the network traffic. Simulation results showed that for large size networks huge bandwidth saving could be achieved in flex-grid filterless solutions owing to increased spectral efficiency compared to fixed-grid filterless networks studied previously. The results also demonstrated that further improvement in terms of spectrum utilization in elastic filterless optical networks could be achieved when periodical spectrum defragmentation is performed.

1. Resilience reinforcement in filterless optical networks

As regards the work related to the resilience reinforcement in filterless optical networks against network failures, **Article I** proposed a dedicated optical-layer protection strategy with the objective to enable the 1+1 link-disjoint protection for each end-to-end connection in a given filterless topology. Therefore, the protection ratio is guaranteed to be 100%, whereas it was not the case in previous work, where each filterless solution has solely an intrinsic protection ratio due to limited connectivity of network topology. In a fully protected filterless solution, protection paths are set up by using the wavelength selective components (i.e., wavelength blocker (WB), colored passive filter (CPF)) placed at selected nodes for interconnecting fiber trees. The principle behind this protection strategy is as follows. By enabling the placement of WBs, referred to as inter-tree WBs, at some intersecting nodes between edge-disjoint fiber trees, it is possible to create extra protection paths passing through different fiber trees. Additionally, it is allowed to employ WBs, referred to as intra-tree WBs, and CPFs within the fiber trees, thus enabling the elimination of the laser effect (i.e., accumulative amplified spontaneous emission (ASE) noise) as well as reducing the number of unfiltered channels resulting in improved performance in terms of the wavelength consumption. To reduce the wavelength consumption with minimum number of employed wavelength selective components, a heuristic algorithm was developed to efficiently solve the inter-tree WB placement and well-known routing and wavelength assignment (RWA) problems. Two novel protection schemes, i.e., WB-only and WB+CPF, were also proposed offering good wavelength consumption and lower cost when compared to the WSS-based solutions. Proposed protection solutions have been validated on German 7-node (G7), Italian 10-node (IT10), and German 17-node (G17) networks. Solutions can always be found for a network topology by using the appropriate number of WBs in the proposed protection algorithm. Simulation results illustrated that significant cost advantage can be achieved by the proposed 1+1 protection solutions compared to active photonic switching solutions. The wavelength consumption of filterless network solutions with dedicated protection, where WBs and CPFs have been deployed, was in average slightly higher than that of their active counterpart.

2. Introduction of elastic filterless optical networks

All previous work on the filterless network remains in the context of standard ITU grid with fixed 50-GHz channel spacing. The adoption of the paradigm of flexible bandwidth allocation (also referred to as flex-grid/gridless) addressed the spectral efficiency and flexibility issues in filterless optical networks. **Article II** of this thesis introduced a novel concept, namely Elastic Filterless Optical Networks, where each node is equipped with coherent transponders that can adapt the channel bandwidth, data rate, and transmission format for each traffic demand in order to offer maximum throughput. The proposed scheme leverages both the benefits of filterless architecture based on passive broadcast-and-select nodes and the spectral efficiency and flexibility of elastic networking, enabling an efficient usage of the spectrum resources. We have proposed a tailored efficient routing and spectrum assignment algorithm (RSA-EF) for minimizing the spectrum consumption and tested it on six different network topologies (i.e., G7, IT10, and Reference network 1-4) under a multi-period traffic evolution scenario. Simulation results showed a reduction in spectrum utilization at high traffic load, as well as in the percentage of unfiltered spectrum, compared with fixed-grid filterless solutions. Moreover, the improvement in spectrum utilization is the most remarkable in the networks with higher connectivity, although the percentage of unfiltered spectrum therein is the most significant.

3. Investigation of routing and spectrum assignment problem in elastic filterless optical networks

In **Article III**, we investigated offline RSA in elastic filterless optical networks. An ILP model was developed to optimally solve the RSA problem on a 6-node network in a static traffic scenario. Due to the intractability of the ILPs, two efficient heuristic approaches, based on Greedy (MP-GR-RSA) and Genetic Algorithm (MP-GA-RSA), were devised for six larger network topologies (i.e., G7, IT10, and Reference network 1-4) in a long-term traffic scenario providing good performance in terms of spectrum utilization and computational time when compared to the ILP solution. First, a greedy version of the heuristics performed routing and spectrum assignment in subsequent phases, and found feasible RSA solutions in short computational time. The second version of heuristics, based on a genetic algorithm, solved the routing and spectrum assignment problems jointly, and obtained solutions of superior quality at the expense of a longer computational time. In both heuristics, the line-rate selection method can be controlled in the spectrum assignment process aiming to optimize particular performance objectives (i.e., maximize the spectral efficiency (MaxSE) and minimize the transponder cost (MinCS)). The simulation results showed that the GA-based RSA heuristic outperforms the Greedy RSA heuristic and can achieve optimal solutions for small networks, i.e., equal to the ones obtained by the ILP approach. The results also indicated that elastic filterless solutions exhibit a significant reduction in terms of spectrum utilization at high traffic load, compared to the fixed-grid filterless solutions. In addition, elastic filterless solutions showed the benefit of reduction of unfiltered spectrum compared to the fixed-grid filterless solutions. Besides, the MaxSE scheme tended to achieve lower spectrum utilization and cost in long-term traffic growth compared to the MinCS scheme, although the MinCS scheme can effectively achieve the short-term advantages. Furthermore, the impact of spectrum defragmentation on the spectrum utilization for both the fixed- and elastic filterless solutions has been evaluated. The results showed that performing periodical spectral defragmentation more effectively improves spectrum utilization in the MinCS scenario compared to the MaxSE scenario, since the later scenario focuses on the long-term spectrum efficient. Therefore, it is highly beneficial to perform defragmentation periodically, especially for the case with a large traffic load.

Future Work

With respect to future work, we would like to point out some research topics that might be interesting to be considered to extend our work as follows.

- **Optimization of the placement of wavelength selective components**

  Regarding the network survivability issue in the filterless optical networks, there are some studies that focus on solving the inter-tree WB placement problem. It might be beneficial to obtain the minimum wavelength consumption by placing a number of wavelength selective components at optimum network nodes for survivable filterless networks. It is also worth to explore the advantages of advanced algorithms when implemented to solve the resulting RWA problem, where a joint optimization of the wavelength consumption and the number of deployed wavelength selective components might result in improved performance.

- **Shared protection schemes**

  In this thesis we proposed a dedicated protection strategy for the filterless optical networks. However, it might be beneficial to extend our work to support shared protection approaches resulting in much lower redundant resource occupation and improved wavelength consumption performance.

- **Dynamic provisioning and spectrum assignment**

In the context of resource scheduling issue in elastic filterless optical network, it might be interesting to extend the proposed RSA algorithms to support dynamic traffic scenarios.

- **Management and control for elastic filterless optical networks**

An interesting future work for the elastic filterless optical networks is to design an efficient management and control mechanism based on the emerging SDN paradigm to optimize network resource usage and automate certain network reconfigurations under a specific network scenario.

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