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Genetic Approach for Traffic-Adaptive Reconfiguration of Programmable Filterless Optical Networks

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Abstract

In order to face the inexorable network traffic capacity growth, network operators have been challenged to find new solutions to upgrade their network capacity while minimizing the capital and operational costs. The Filterless Optical Network (FON) concept, based on broadcast-and-select nodes, has emerged as a promising cost-effective solution decreasing network costs by reducing the overall active switching elements such as the Reconfigurable Optical Add-Drop multiplexers (ROADMs) based on Wavelength Selective Switch (WSS), and replacing them with passive devices as optical splitters and combiners.

However, due to the broadcast-and-select nature itself, FONs require the establishment of fiber trees to prevent undesired laser-loop effects, constraining the routing possiblities between the nodes. Although it implies a reduction in expenditures, the elimination of active switching and filtering components means that reconfigurability of network connectivity in FONs will be achieved only exploiting the adaptability of modern coherent optical transmissions.

Moreover, FON enforces signal broadcast on all the outputs of the passive splitters, resulting in the transmission of optical signals over unintended links and in higher spectrum occupation with respect to an active photonic network.

To attenuate the spectrum waste of filterless solutions while keeping consinstent savings in terms of network costs, the concept of Programmable Filterless Optical Network (P-FON) has been proposed, which consist in equipping the network nodes with programmable optical switches that allow reconfiguration of fiber trees established in FON to accommodate demands. Indeed, P-FON is a flexible solution, which enhances many aspects of FON architectures by adapting them dynamically to the traffic and optimizing the tree establishment.

In this thesis, we propose a performance comparison among classical active switching solutions based on WSS, Filterless Optical Network (FON) and Programmable Filterless Optical Network (P-FON). We use both an ILP model and a Genetic Algorithm to evaluate the benefits and shortcomings of P-FONs. In particular, we focus on solutions which minimize two different objectives: 1) the total number of frequency slot units (FSUs) and 2) the maximum wavelength utilization across different fiber trees, which we label as "wavelength index" (WI) minimization. Numerical results shows that P-FONs allow to save great portions of spectrum with respect to passive FON solution, and also to minimize wavelength index (WI), especially in presence of varying but periodic traffic profiles.

Sommario

Per fronteggiare l'inesorabile crescita della capacità di traffico nelle reti, gli operatori sono stati costretti a trovare nuove soluzioni che aumentassero la capacità dei network riducendo però i costi monetari e operazionali. Il concetto di reti ottiche filterless (FON), basate su nodi broadcast-and-select, è emerso come una soluzione promettente, diminuendo i costi, riducendo il numero di elementi attivi di switching, come i Reconfigurable Optical Add-Drop multiplexers (ROADMs) basati sui Wavelength Selective Switch (WSS), e sostituendoli con dispositivi passivi come splitters e combiners ottici. Tuttavia, a causa della natura broadcast-and-select, i FON necessitano la costituzione di fiber trees per prevenire effetti laser-loop indesiderati, limitando i possibili instradamenti tra i diversi nodi. Sebbene risulti in una riduzione nelle spese, la rimozione di switching attivo e filtraggio ottico comporta che la riconfigurabilità di connessione nei FON potrà essere ottenuta soltanto sfruttando l'adattibilità delle trasmissioni ottiche coerenti moderne. Inoltre, l'architettura FON costringe il segnale ad essere mandato in broadcast verso tutte le uscite di uno splitter passivo, avendo come conseguenza sia la trasmissione indesiderata di segnali ottici su link terzi, sia un'occupazione di spettro più alta rispetto a un photonic network attivo. Per attenuare questo spreco di spettro delle soluzioni filterless mantendendo risparmi consistenti nei costi di rete, è stato proposto il concetto di reti ottiche filterless programmabili (P-FON), che consistono nell'equipaggiare i nodi di rete con switch ottici programmabili che permettono la riconfigurazione dei fiber tree costruiti nei FON per soddisfare le richichieste del traffico. Infatti le reti P-FON sono una soluzione flessibile, che migliora diversi aspetti delle architetture FON adattandole dinamicamente al traffico e ottimizzando la costruzione dei fiber trees. In questa tesi, proponiamo un confronto fra le performance delle classiche soluzioni active switching basate su WSS, delle reti ottiche senza filtri (FON) e delle reti ottiche filterless programmabili (P-FON). Useremo sia un

modello ILP che un algoritmo genetico per valutare i benefici e le carenze delle reti P-FON. In particolare, ci concentriamo su soluzioni che minimizzano due obbiettivi: 1) il numero totale di "frequeency solt units" (FSUs) e 2) l'utilizzo massimo di lunghezze d'onda tra i diversi fiber tree, che indichiamo come minimizzazione del "wavelength index" (WI). I risultati numerici mostrano che l'approccio P-FON permette di risparmiare grandi porzioni di spettro rispetto a quello FON, e anche di minimizzare il wavelength index (WI), specialmente in presenza di un profilo di traffico variabile ma periodico.

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Chapter 1

Introduction

1.1 Overview and Motivation

Networks nowadays must be designed to meet the unprecedented capacity required from new technologies as 5G and, due to the increase of internet services, that will lead to a growing number of users. Cisco's projections say that nearly two-thirds of the global population will have Internet access by 2023, so there will be 5.3 billion total Internet users (66 percent of global population) by 2023, up from 3.9 billion (51 percent of global population) in 2018. Moreover, the number of devices connected to IP networks will be more than three times the global population [7].
Optical networks represent the fundamental technology that network operators are exploiting to cope with the traffic increase. However, deploying network equipment in order to increase the network capacity leads to unfeasible economical scenarios.
The technological advances in digital signal processing, tunable transmitters and coherent detection allowed new solutions to be proposed. In order to keep costs under control, *Filterless Optical Networks* (FONs) are emerging as candidates to face this issue [8] and have already been deployed in Europe since 2012 [9].
In FONs, complex and expensive optical switching elements as Reconfigurable Optical Add-Drop multiplexers (ROADMs) based on Wavelength Selective Switch (WSS), are replaced by simpler and more cost-effective architectures, based on passive splitters and combiners which operate on the entire set of lightpaths using a *broadcast-and-select* switching approach.
Besides the reduction in capital expenditure (CapEx) [8], passive devices

provide further advantages in terms of operational expenditure (OpEx) due to easier maintenance and lower energy consumption [1].
However, these types of networks are characterized by the so called *broadcast-and-select* architecture, which leads to unavoidable wastage of spectrum and resources. Moreover, they also need the establishment of *fiber trees*, which must satisfy very strict constaints as laser loop avoidance and node connectivity. The result of these features is a fixed structure which cannot adapt to a dynamic traffic environment.
In order to face these issues, new approaches as *Programmable Filterless Optical Networks* (P-FONs) are proposed. The main concept of P-FONs consists in equipping nodes with programmable switches which can adapt to traffic demands, establishing fiber trees in an unidirectional manner and increasing the *flexibility* to solve the routing problems. At the slightly higher costs of physical equipments, P-FON seems to be able to reach consistent savings in terms of spectrum and wavelength utilization.
In this thesis, we focus on the problem of Routing and Spectrum Allocation (RSA) considering FON and P-FON architectures with fiber trees not established yet. Therefore, we will solve RSA problem considering the FON case only with fixed fiber trees already established, while we will do Tree Establishment (TE) before RSA calculation for the P-FON case.
For FON we actually find the pre-determined fiber trees by optimizing the spectrum consumption in the full-mesh case, in which every node in a considered topology try to reach all other nodes, and then we use this solution to accommodate different traffic situations. This is done because FON is not traffic-adaptive, as instead is P-FON, and then the best solution that can be achieved is obtained by optimizing the traffic scenario in the worst case.
Indeed, in P-FON simulations every time a traffic must be accommodated, the tree establishment changes, allowing a re-configuration of all the nodes every time it is required.
For this aim, we propose an ILP model and an heuristic approach based on the *Genetic Algorithm* logic, which was suitable for our work.
The Genetic Algorithm (GA) approach has been chosen because our case study can be reconnected to a binary minimization problem, allowing us to find and compare multiple solutions in reasonable amounts of time.
In the end, we also introduce a new objective called *wavelength index* minimization, to give a different point of view on RSA and tree establishment.

1.2 Thesis outline

The thesis is divided in 7 chapters, starting from the current one, and it is organized as follows:

- Chapter 2 gives an overview on the concepts of optical networks, focusing on the development of FONs and describing its characteristics and constraint of its tree establishment problem. It is concluded with a list of benefits and drawbacks.
- Chapter 3 introduces the concept and details of P-FON, starting from the "Architecture on Demand" paradigm used in the nodes and explaining the details through examples.
- Chapter 4 states the problem and presents the used ILP model.
- Chapter 5 shows in details the features of Genetic Algorithm and explains how it has been adapted in order to satisfy our problems.
- Chapter 6 presents the numerical results obtained evaluating the ILP and the genetic algorithms in different network scenarios.
- Chapter 7 concludes the thesis and discusses on possible future works.

Chapter 2

Background on Filterless Optical Networks

This chapter presents an overview on optical networks, introduces the concept of *filterless optical network* (FON) and shows a comparison between the network architectures of the traditional *active photonic networks* and *FONs*. In the end we highlight the advantages and disadvantages of a FON architecture also showing the structure of a filterless node and how the spectrum allocation can be improved in *elastic optical networks*.

2.1 Optical Networks overview

Optical networks are among the main technologies developed in order to meet the constantly growing capacity requirement of the Internet.
Light is the transmission medium of an optical network and is propagated through channels exploiting the usage of fiber-optic cables.
At the beginning, each fiber in an optical network was able to carry only one channel of light, resulting in a huge need for opto-electronic conversions, i.e the conversion of an optical signal into an electrical form, in order to regenerate and route the signals.
One of the first improvements has been the ability to carry multiple channels through a single optical fiber.
Each wavelength is carried at different frequencies and multiplexed (i.e. combined) in a single fiber through a process called *Wavelength Division Multiplexing* (WDM) [10].

Later, in a fixed configuration, all-optical devices called *Optical Add Drop Multiplexers* (OADM) allowed to mitigate the use of electronic devices and leave the propagation in the optical domain through the usage of switches that decides which wavelength needs to be added, dropped or passed.
The next step has been the addition of reconfigurability to switches, leading to *Reconfigurable Optical Add Drop Multiplexers* (ROADMs) based on *Wavelength Selective Switches* (WSSs), meaning that switches can be remotely controlled and any wavelengths can be added or dropped at any nodes. These kind of networks are the so called *Active Switching Networks*.

2.2 Filterless Optical Networks

Filterless optical networks (FONs) based on broadcast-and-select nodes can be considered as very attractive solutions for cost-effective and flexible capacity allocation in terrestrial and submarine applications, as stated in [1]. FONs are getting interest recently due to the constantly growing capacity required by the internet traffic which leads the network operators to keep capital expenditures (CapEx) and operational expenditures (OpEx) under control [11]. Active switched (the method currently deployed in most networks) and filterless photonic networks are showed in Fig. 2.1.

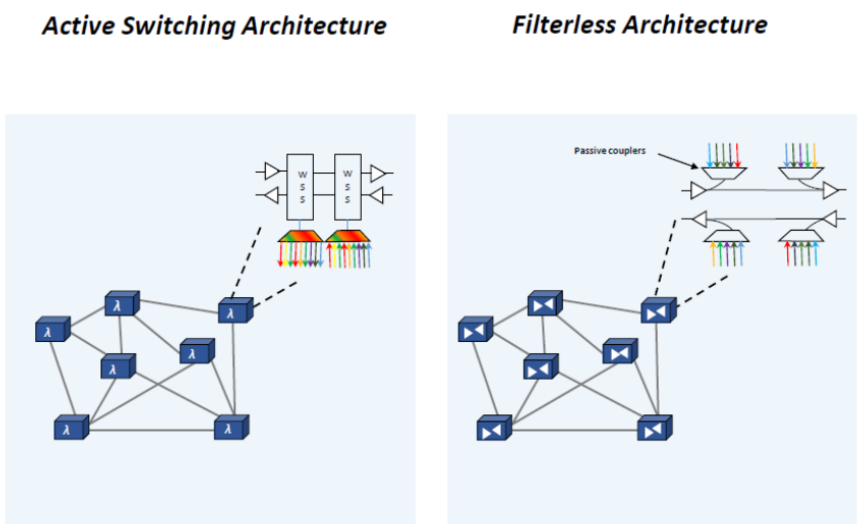


Figure 2.1: Active switching and Filterless Optical Networks architectures [1]

Instead of deploying reconfigurable optical add-drop multiplexers (ROADMs) based on wavelength selective switches (WSSs) at network nodes, as in conventional active photonic networks, filterless networks use simpler and less expensive passive components as *passive optical splitters and combiners* for fiber interconnections and agile edge nodes equipped with coherent transponders. The improvements in the technology of optical transmissions allow to meet flexibility and capacity requirements of modern networks even exploiting passive infrastructures as FONs, where nodes are equipped with tunable and coherent transceivers. In fact, wavelength tuning at the transmitter, wavelength selection at the receiver, and no configuration at intermediate nodes make filterless networks agility equal to the one of radio networks [2].

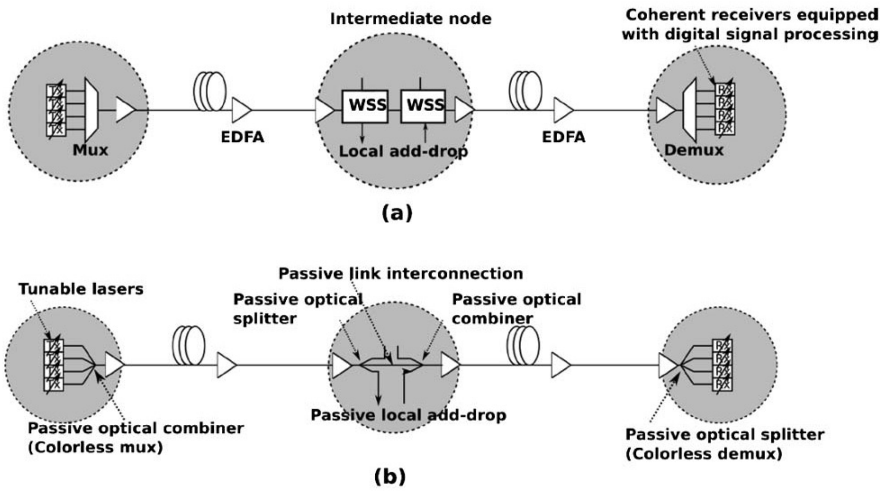


Figure 2.2: Active photonic switching (a) and filterless optical (b) transmission line architectures [2]

The differences between a filterless and a WSS-based active optical line are shown in Fig. 2.2. In (b), to combine or split the signals at the source and destination nodes there are passive optical combiners and splitters instead of multiplexers and de-multiplexers in (a). Intermediate node has no more expensive WSS-based elements, but is a passive link interconnection composed by both optical splitters and combiners. Therefore we can state that a filterless transmission line aims to the minimization of WSS elements and consist, then, of a sequence of optically amplified fiber links, equipped with Erbium Doped Fiber Amplifiers (EDFA), interconnected through passive optical splitters and combiners, ensuring the drop-and-continue and the passively add function [12] [2]. A new lightpath is provided by wavelength tuning at the source node, and then this lightpath is broadcasted, while exit nodes have an option for wavelength selection, which we have already called as *drop* [12]. Filterless networks are characterized by the *broadcast-and-select* nature, which is their main feature.

Coherent transmission systems provide tunable lasers and frequency selective coherent receivers. In this way, filterless networks are realized using passive optical splitters and combiners, instead of optical switches at the intermediate nodes such as optical WSSs and optical cross connects (OXCs).

The absence of filters and the use of only passive broadcasting devices might result in laser loop effects, i.e, WDM signal superposition and disruption due to the accumulated amplified spontaneous emission (ASE) noise of amplifiers. As a consequence, the establishment of a structure called *fiber trees*, which is is an evolution of the light-tree defined in [2], is needed to prevent the formation of laser loops. Within a single fiber tree, wavelengths are assigned to lightpaths to serve both the unicast and the multicast (or broadcast) traffic between network nodes.

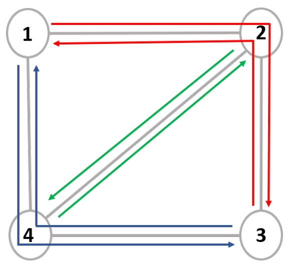


Figure 2.3: Example of three fiber trees on a simple network

Assuming bi-directionality of fiber trees, in Fig. 2.3 is shown a simple 4-nodes network, where every node is able to reach any other node using one of three bi-directional fixed connections, respectively coloured with red, green and blue. These different connections are fiber trees, and have been established satisfying some constraints which will be listed in Section 2.4 . The mono-directional case will be treated in the next chapter. Each physical link belongs to the fiber tree defined on it in both directions. Traffic

demands will be routed following a path defined by one of the connections and occupying a determined wavelength that cannot be used again in that specific direction due to the broadcasting issue.
The passive structure based on optical splitters and combiners of filterless node creates a broadcast-and-continue structure in which wavelength channels propagate beyond their designed path in all directions downward their source. We call these wavelength channels as *unfiltered* (or *wasted*) channels and they represent the main drawback of FONs as they lead to an increase in total spectrum consumption.
We can see an example of the broadcasting issue in Fig. 2.4. Being D1 the demand going from node 1 to node 4, using a lightpath on links (1,2) and (2,4), carried by the wavelength λ_x, it is propagated also in links (2,3) and (4,5), not allowing any other demands to re-use the wavelength λ_x and implying spectrum consumption.

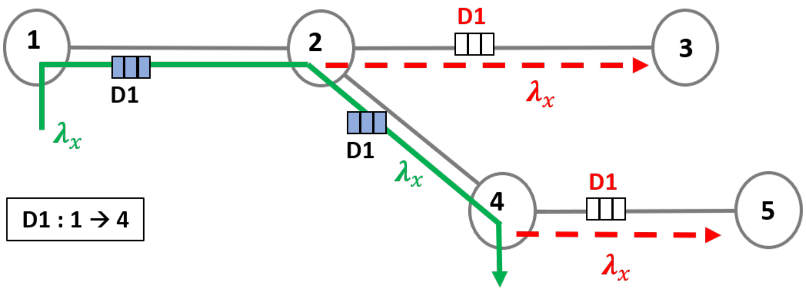


Figure 2.4: Example of FON broadcast-and-select architecture

2.3 Filterless Node Architecture

As we mentioned earlier, in FONs passive splitters and combiners replace ROADM-based WSSs, and their configuration at network nodes form the fiber trees.
The configuration of splitters and combiners at nodes depends on the traffic requirements and will determine as consequence the number of established trees in a given topology. In FONs the interconnections between nodes are static and passive, since it is impossible to change them once that passive splitter/combiner configuration has been designed, differently from active switching networks where a wavelength's path can be reconfigured thanks to functionalities of WSSs.

Any change in fibers interconnection at nodes lead to a change of the filterless architecture of that network since every node must be able to reach any other node belonging to the same network.
Another main difference is that in ROADM nodes only one add/drop port is needed (still exploiting the WSS module's functionalities), while in FONs, due to signal broadcasting, add/drop ports are required at each direction of every node. Fig. 2.5 shows the main differences between an active switching node and filterless node.

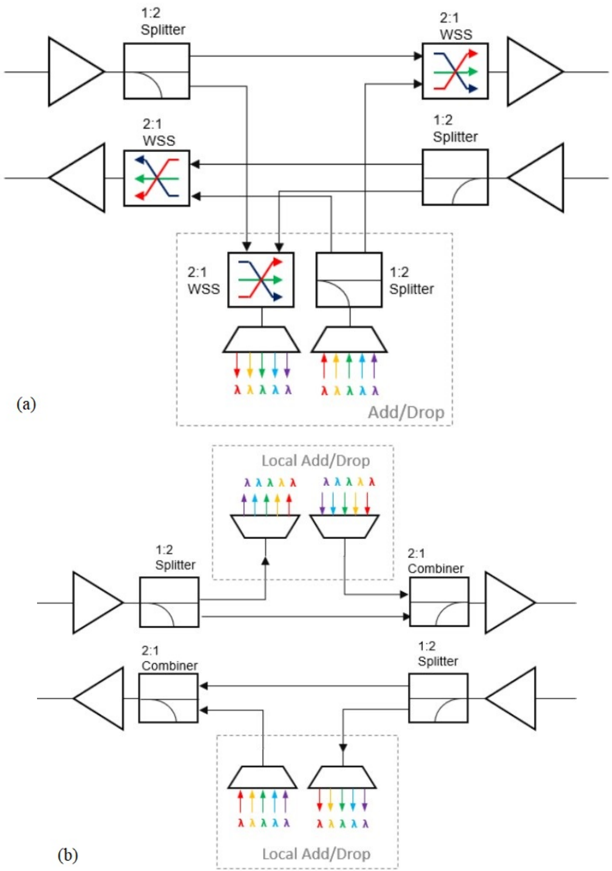


Figure 2.5: Nodal architecture of a 2-degree node in active switching (a) and filterless optical network (b)

The active switching node (a) is composed by WSS's, necessary for the wavelengths selection, and couplers in each direction while in the FON node (b) passive splitters and combiners connects the different directions.

It is important to note that in active switching networks the possibility to reconfigure nodes allows to obtain any possible wavelength path while in FON network each configuration inside nodes is fixed and not reconfigurable, meaning that any required modification needs a manual intervention on the physical node, resulting in a complete change in the structure of fiber trees.

2.4 Design of FON: Fiber Tree Establishment

The establishment of filterless fiber trees is achieved configuring the splitters and combiners in network nodes and obtaining a network connectivity which highly depends on this configuration. An example of the fiber trees establishment in a FON is shown in Fig. 2.6.
In the topology two fiber trees have been established, one in dotted green line and the other in continuous red line.
In the figure there can also be seen the details of node 5, to illustrate how fibers are interconnected. Remember once again that any addition or removal of the fiber interconnections at nodes implies a change in the network architecture and connectivity [2].

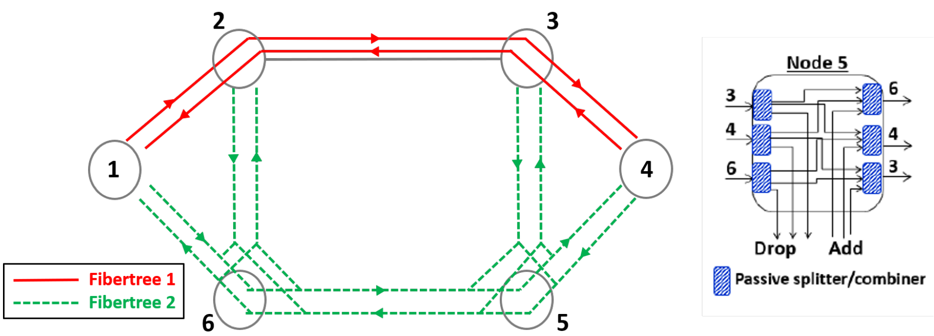


Figure 2.6: Example of FON fiber trees

2.4.1 Physical and Architectural Constraints

Tree establishment (TE) is fundamental in solving the Routing Wavelength Assignment (RWA)/Routing Spectrum Assignment (RSA) problem. Establishing fiber trees that satisfy all traffic demands and ensure that all the nodes are physically connected is the FON design problem presented in [3].

Filterless network solutions must satisfy a number of physical and architectural constraints, which are illustrated in Fig. 2.7.

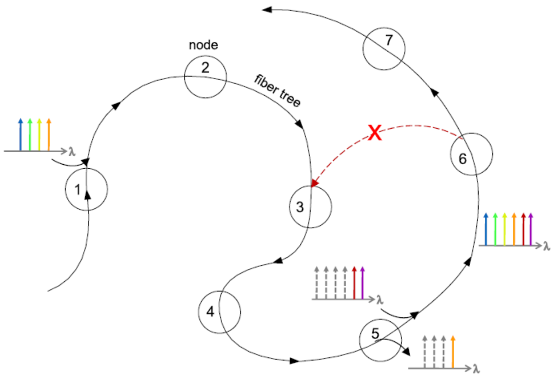


Figure 2.7: Filterless optical network's constraints [3]

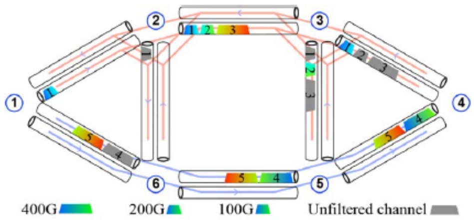
1. *Laser loop constraint*: No closed loop is allowed inside a filterless optical network in interconnecting the nodes, in order to avoid superposition of wavelengths and laser effects. These laser effects are due to amplified spontaneous emission (ASE) noise coming by erbium-doped fiber amplifiers (EDFAs) in optical links. In fact, when a channel is broadcasted, even the noise will be, and the presence of a closed loop would lead to an endless accumulation of disturbance. In Fig. 2.7, a laser loop (nodes 3-4-5-6-3) would be created by connecting node 6 to node 3.

2. *Fiber tree length*: For any source-destination combination in a fiber tree, a maximum distance is set. The losses due to the passive splitters/combiners must also be taken into account, as well as the optical signal-to-noise ratio (OSNR) degradation due to accumulated ASE noise in the optically amplified links.

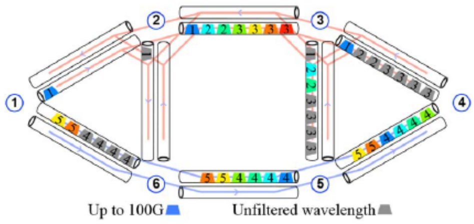
3. *Wavelength re-utilization*: The drop-and-continue architecture of the filterless nodes constraint the wavelength re-usage. As illustrated in Fig. 2.7, even after having reached its destination and being dropped (orange channel), in a channel the signal continues to be broadcasted, bringing with it the accumulated ASE noise. This means that, for wavelength assignment, *filterless solutions that minimize the number of wavelengths used must be chosen.*

2.4.2 Elastic Filterless Optical Networks

Until now, we have discussed about FONs having fixed configurations and starting to show their limits. In order to enhance their performance and flexibility, researchers it have started to look for solutions focusing on improving the of the bandwidth usage.
Elastic optical networking [4] [13], [14], also known as flexible, gridless, and flex-grid networking, is a method that improves spectral efficiency and flexibility, as channel spacing is no longer restricted to a fixed frequency grid where each channel occupies 50GHz and specific channel bandwidths can be assigned to the traffic demands depending on the capacity and distance requirements.
The problem constituted by the bandwidth assignment is still the RSA. Multicarrier-based bandwidth variable transponders and flexible spectrum selective switches [13], [14] are the main technologies which have permitted to reach this FON's approach.
The passive gridless architecture of filterless networks makes possible to implement elastic optical networking, avoiding replacement of the switching and filtering devices at nodes, in contrast to the current active photonic networks [4].
Furthermore, the gridless operation can be achieved at almost zero costs avoiding the necessity to deploy gridless wavelength selective switches, which are consistently more expensive than fixed-grid ones.
The concept of an *elastic* FON combines the benefits of FON architectures based on passive broadcast-and-select nodes with the spectral efficiency and flexibility of elastic networking [4].
Consider the example in Fig. 2.8 comparing elastic and fixed-grid filterless solutions in a six node network topology [4].
A set of passive broadcast-and-select nodes interconnected by edge-disjoint fiber trees form the physical layer architecture of elastic filterless networks. Each node is equipped with coherent transponders, permitting the selection of the modulation format and the corresponding channel capacity between two cases: quadrature phase shift keying (QPSK) and 16 quadrature amplitude modulation (QAM). In this example, we have considered 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. On the other hand,



(a)



(b)

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)

Figure 2.8: Illustration of elastic (a) and fixed-grid (b) filterless solutions in a six-node network topology for a given traffic matrix (c) [4]

50-GHz channels at 100 Gb/s are used in the fixed-grid case.
In Fig. 2.8, it can be seen the FON solution with 2 fiber trees, respectively blue and red.
Elastic filterless solution is in (a), *fixed-grid filterless solution* is in (b) and the considered *traffic matrix* is in (c).
The spectrum requirement of the elastic solution can be reduced to a single frequency slot unit (FSU) [e.g., 12.5 GHz, used in Fig.2.8(c)].
One of the main advantages is that filterless optical networks do not have any limitation on the FSU size, meanwhile the active switching optical networks are restricted to a minimum FSU size (for example 6.25 or 12.5 GHz).
Before beginning the analysis of the proposed example, take notice that spectrum assignment in elastic optical networks must respect four fundamental constraints [4]:

1. *Spectrum Contiguity constraint*: Each traffic demand must be carried by the necessary number of consecutive FSUs throughout its physical route.

2. *Spectrum Continuity constraint*: Each traffic demand must be assigned the same slots on all links it traverses.

3. *Guard Band constraint*: A guard band of 1 FSU is needed between any two neighboring channels to mitigate the interference and crosstalk effects.

4. There must be *no spectrum overlapping* between different connections.

Thus, in the example from Fig. 2.8, in the elastic filterless solution the bandwidth on the fiber link from node 2 to 3 required to carry demands 1–3 on is 175 GHz (14 FSUs including two FSU guard bands between the three neighbouring channels) , meanwhile in the fixed-grid filterless solution the highest value required is 350 GHz (seven 50-GHz channels). A major issue regarding resource consumption in filterless optical networks is the existence of unfiltered channels (shown colored in gray in Fig. 2.8(a) and 2.8(b)), which propagate all over the network from the source to destination nodes within a filterless fiber tree because of the drop-and-continue characteristic of filterless nodes [12].
These results, as expected, show an increase in the spectrum consumption due to the absence of filters and the consequent broadcasting, since the spectral resources occupied cannot be reused for other connections (unfiltered channels).

2.5 Advantages and Disadvantages of FONs

In the following. we summarize advantages and disadvantages of FONs with respect to conventional photonic active networks [11].

Starting from the benefits, we can list the following benefits:

- *Cost-effectiveness*: The main feature of FON is that, eliminating active photonic switching elements, we reduce capital and operational costs (CapEx and OpEx) interconnecting fiber links with passive optical splitters/combiners.

- *Robustness and efficiency*: The passive nature of filterless optical networks guarantees higher reliability and it also reduces energy consumption.

- *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.

- *Enabled flex-grid*: The passive gridless architecture of filterless networks allows elastic optical networking, as gridless operation is an inherent attribute of the filterless networks.

- *Colorless ability*: The filterless design enables colorless node operation, as optical terminals are able to access all DWDM channels and send/receive the wavelength per request.

- *Multicast capability*: The fiber tree formed by a set of interconnected fibers in filterless optical networks could be a suitable feature for accommodating multicast traffic exploiting its broadcasting attitude.

- *Multilayer networking*: The passive bypass and add-drop functionality at intermediate nodes allows the traffic from the Internet Protocol (IP) layer to be dynamically served in the optical layer without reconfiguring the intermediate nodes.

On the other hand, there is also a list of drawbacks:

- Filterless optical networks suffer from the drop-and-continue nature of filterless nodes [12], where wavelength channels propagate beyond their destination nodes.

- Due to the broadcasting nature of transmission where a signal is distributed along all branches in the fiber tree associated to the source node, there may be great privacy problems since the signal arrives also at nodes that are not supposed to receive it.

- The presence of unfiltered signals aggravates wavelength consumption, as the spectral resources occupied by these channels *cannot be reused* by any other lightpath.

- Since every node in a network must be able to reach every other node belonging to the same topology, FON is not a flexible solution because a little change in the infrastructure implies the complete recalculation of the solution.

Chapter 3

Programmable Filterless Optical Networks

In this chapter we will first introduce the concept of *Architecture on Demand* (AoD), a building block of *Programmable Filterless Optical Networks* (PFONs), and then, we will discuss PFONs, their structure, how they improve and exploit FONs and their advantages and drawbacks.

3.1 Architecture on Demand

3.1.1 Background

Active optical networks in the actual state of the art exploit the benefits of Wavelength Division Multiplexing (WDM). Breakthroughs in optical networking are pushing towards flexible spectrum resource allocation, as already discussed in section 2.4.2. In particular, optical networks are now able to manage channel bandwidth in a gridless (or flexible) manner to achieve higher spectral efficiency.
As in [5], the three main examples of technologies that require high flexible spectrum allocation are:

- The SLICE concept, which adjusts channel bandwidths by varying the number of sub-carriers in the transmitted OFDM (Orthogonal Frequency Division Multiplexed) signal [15];
- Optical packet switching systems, that use several parallel wavelengths for packet transmission [16];

- Elastic networks based on single carrier, which adapt the transmission modulation format to transmit at higher data-rates by exploiting extra OSNR (Optical Signal-to-Noise-Ratio) margins [17].

Nevertheless, these approaches have two major drawbacks:

1. They often consist of a hard-wired arrangement of devices restricting the upgradeability, limiting the support for new functionalities and reducing the capability of adapting the whole architecture to the network requirements.
   Hence, these architectures lack on a desirable capability required for future optical networks: *flexibility*.

2. The *scalability* of these architectures is hard limited by the number of devices required and the port-count of such devices.

3.1.2 Concept

In Architecture on Demand (AoD), optical cross-connects (OXC), instead of being fully equipped since their installation, they dynamically adapt their architectures in real time in order to fulfill the switching and processing requirements of a given network traffic.
AoD is implemented using an optical backplane that dynamically interconnects architecture-building modules that enable specific functions, such as spectrum selective switch (SSS), Arrayed Waveguide Grating (AWG) (de)-multiplexer, Erbium Doped Frequency Amplifiers (EDFAs), optical power couplers / splitters. The major advantage is the degree of *flexibility* that AoD guarantees. Since it is a highly modular technology, it facilitates dimensioning and provisioning, simplifies the introduction of enhanced or new functionality, and supports multiple services and arbitrary switching granularity [18]. Moreover, AoD eases dimensioning, provisioning and upgrading the optical cross-connect with enhanced or new functionalities. An instance of *flexibility*: if a new signal processing function is required (e.g., amplification, regeneration, wavelength conversion, etc.), a module providing such functionality is plugged into the optical backplane and, immediately, the system can start using it when and where required.
Lastly, AoD nodes are characterized with self-healing/self-restoration capabilities due to their flexibility and the ability to employ idle components as

redundancy for failure recovery [19].

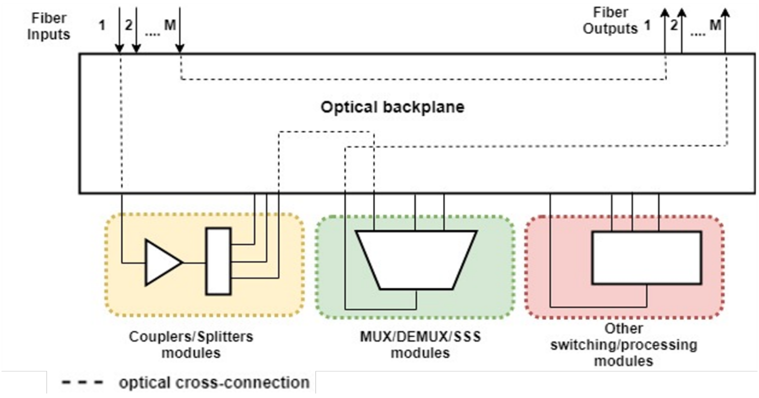


Figure 3.1: Filterless Architecture on Demand

3.1.3 AoD node

The AoD node is an OXC that dynamically provides ad hoc architectures according to switching and processing requirements of network traffic. Fig. 3.1 shows a possible implementation of AoD consisting on an optical backplane that interconnects input ports, architecture building module and output ports.
The building modules can be either single devices for optical processing such as MUX, DEMUX, spectrum selective switches (SSS), amplifiers (or even subsystems composed of several devices) and the optical backplane can be implemented with a large port-count optical switch.

The design of an AoD node is shown in Fig. 3.2. A set of N input ports are connected to a set of N output ports through a maximum of two AoD modules (one for the input, one for the output). For example, inputs may be connected either to a module or straight to an output, using an optical backplane crossconnection. With the term modules we are indicating elements as MUX, DEMUX, couplers, splitters and SSS.
In order to give a better idea, Fig. 3.3 shows an instance of an AoD possible configuration, as it is explained in [5]. Let us consider N as the number of input ports, equal to the number of output ports (for simplicity reasons), W the set of available spectral slots and M a traffic matrix of size NxW, where

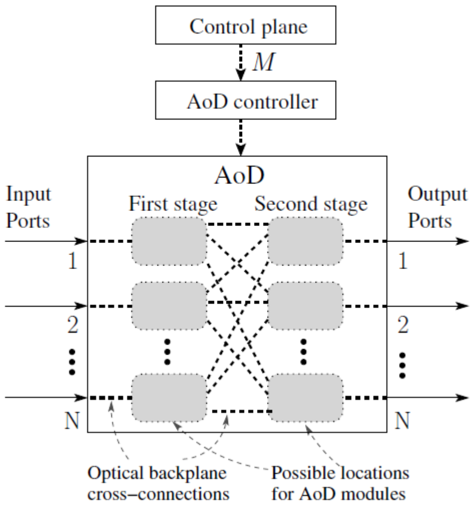


Figure 3.2: Architecture on Demand node model [5]

each element of the matrix *M(i,j)* is the required output port of wavelength j from input i.

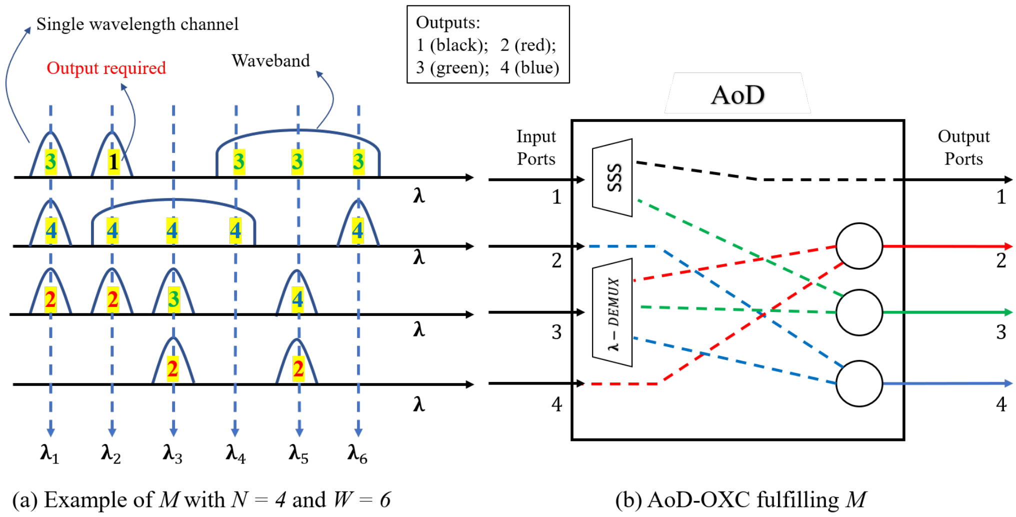


Figure 3.3: AoD configuration example [5]

Fig. 3.3 (a) shows an example of a traffic matrix M having $N = 4$ and $W = 6$, resulting in a traffic scenario with 10 single wavelength channels and two waveband channels, while Fig. 3.3 (b) shows one possible AoD-OXC satisfying the switching requirements of the considered channels. From this

example, it easy to understand that the configuration of an AoD node will depend by the traffic, and that it will change every time the traffic changes. This feature has allowed AoD nodes (also referred to as *Optical White Boxes*) [6] solutions and configurations to be considered as a promising technological option due to their remarkable functional and architectural flexibility.
In the end, AoD nodes with optical switching allow to connect input to output ports, bypassing unnecessary components.

3.2 Programmable Filterless Optical Networks

The natural evolution of FONs exploiting the flexibility of optical white boxes has given birth to the concept of *Programmable Filterless Optical Networks* (P-FON).
Programmability in FONs is obtained making an optical backplane composed by a single optical switch per node, exploiting only passive devices.
Ref. [6] proposed and evaluated this novel architecture enabling high-capacity, resource efficient and agile elastic optical networks.
There, white boxes have been shown to enable a reduction in the number of used optical backplane ports and their cost and power consumption.
This cost-efficient network planning approaches for white box based elastic networks comparing both fixed and dynamic traffic have been proposed in [20]. The objective of the proposed planning approaches is to dimension network nodes and perform routing and spectrum assignment to connection requests minimizing the number of needed components. The role of white boxes in the network's availability of connections is evaluated in [21].

In *Programmable Filterless white box networks* interconnections between nodes are formed with the help of programmable switches that serve as optical backplane. Connections are realized inside each node by fiber switching, connecting couples of input and output ports bypassing all components in the node, or by interconnecting the necessary ports via passive splitters and couplers. In other words, exploiting the AoD concept brings flexibility in routing reducing the broadcast of signals to unwanted ports. This decreases in spectrum waste and improves privacy issue respect to the passive filterless solution. Moreover, costs and power consumption will be decreased. The objective is to find an optimized way of routing the traffic demands between nodes in order to reduce the used components as much as possible, which in turn decreases further spectrum wastage compared to our previously proposed FONs solution.

Compared to active switching filtered solutions based on conventional ROADMs which deploy a number of SSSs per node, PFON can bring significant savings in cost and inherent support of flexible spectrum allocation operation.
Summarizing, in an optical white box, optical modules, such as splitters, amplifiers, or SSSs are interconnected through a programmable optical backplane in contrast to the conventional costly ROADMs.
Inside an optical white box, connections use only the components necessary to satisfy the processing requirements and bypass unneeded components, which improves cost, resource usage and reliability performance.

The possibility of re-configuring the fiber interconnections introduces flexibility in nodes, a feature that is absent in FON, and allows to reduce spectrum waste.
In any case, equipping all nodes in a FON with programmable switches does not guarantee eliminating spectrum waste. Indeed, there exist situations in which, even if a node is equipped with a programmable switch, avoiding spectrum waste remains impossible. This is due to the "*exclusiveness*" feature of the programmable switch, i.e., a programmable switch can either connect or dis-connect an input port to an output port, and cannot operate on specific wavelengths, such as a WSS [22].

In the end, it is important to note that the Tree Establishment (TE) in P-FON exploits uni-directional fiber trees allowing P-FON to associate two separated fiber trees to a given link in two different directions are possible, giving more flexibility to the routing of the demands and resulting in occupying (wasting) less wavelengths. P-FONs allows flexibility because TE is solved through "quasi ad-hoc" unidirectional fiber trees intended to satisfy a given traffic (as shown in section 3.2.1), instead of an "a priori calculation" in which bidirectional FONs fiber trees are established such that every node, through at least one of the trees, must be able to reach ideally every node in the topology. In other words, P-FONs allow to avoid those constraints that limits the freedom of tree establishment, as the *Node connectivity* one.
In chapter 4 we will be able to see more deeply the differences in the design of FONs and P-FONs.

3.2.1 P-FON Illustrative Example

In this section we illustrate a simple example of the P-FON architecture. Then, we show how to achieve an optimized tree establishment in P-FON.

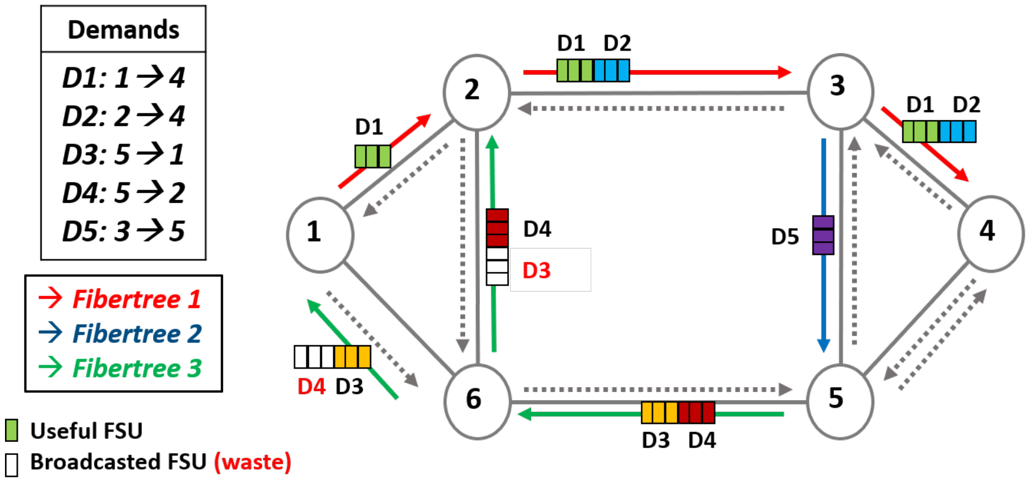


Figure 3.4: Solution deploying P-FON architecture in a 6-nodes network topology with five unidirectional demands

Fig. 3.4 shows a 6-nodes topology network with fiber trees establishment consisting in three uni-directional trees, drawn as fiber tree 1 (red arrows), fiber tree 2 (blue arrow) and fiber tree 3 (green arrows), unused links (dotted grey arrows) and an example of an RSA solution supporting 5 different demands, D1-D5, where D1 and D2 are accomodated by fiber tree 1, D5 by fiber tree 2, D3 and D4 by fiber tree 3.
In the image are highlighted with full-colored rectangles the *useful* (or *effective*) spectrum (considered as Frequency Spectrum Units, FSUs) and with empty blocks and red colored name the *broadcasted* (or *wasted*) spectrum, due to the broadcast-and-select architecture.
Equipping nodes with programmable switches help us to save more spectrum with respect to a FON architecture, as we have seen in section 3.2.2.
However, let us focus now on the routing and on the setup of the nodes belonging to this solution.

We can observe three different situations:

- Demand D1 needs to reach, starting from the node 1 (source node), the node 4 (destination node).
  Demand D2 has the same destination of D1 (i.e. node 4), but starts from node 2. Since node 2 is on the shortest path which allows D1 to be satisfied, and since the best paths for both D1 and D2 share the links 2-3 and 3-4, Fibetree 1 is established and satisfies both the demands. In this case, we have zero wasted wavelengths and we need a fiber tree composed by only three unidirectional links to satisfy two demands.

- D5 is "isolated" by the other demands, i.e. it needs a link that no other demand needs, so it requires the one-link length fiber tree 2.
  Even in this situation, we have no wastes, since D5 is added in node 3 and dropped in node 5, without being broadcasted anywhere.

- The two demands that allow us to observe a broadcasting behaviour here are D3 and D4.
  They both have the same source node (i.e. node 5) but different destinations. Their path share one link (5-6), and then they need to be splitted. In order to do it, fiber tree 3 is associated to links 5-6, 6-1 and 6-2. This will bring to a waste of spectrum received at node 6 from node 5. In detail, D3 occupies FSUs on link 6-2 that cannot be re-assigned to any other demands requiring that links, and D4 do the same on link 6-1.

3.2.1.1 Nodal Architecture of a P-FON solution

After seeing the overall RSA solution of the example in Fig 3.4, let us observe how the nodes are made. We will focus on nodes 3 and 6, which are shown in Fig. 3.5. Node 3 is configured to connect the input port 2 to only one output port 4, thus allowing the spectrum arriving from node 2, (from fiber 2-3) to reach only fiber 3-4 towards node 4. Note that, with such a configuration of the programmable switch in node 3, node 2 cannot connect to node 5 via node 3, however node 3 can still connect to node 5 through a simple "add" operation. As opposite, the spectrum wasted beyond node 6 (on fibers 6-1 and 6-2) shows an example in which a programmable switch cannot help avoid spectrum waste. This is because two demands, D3 and D4, passing through node 6 are destined to two different nodes, nodes 1 and 2 respectively, and the programmable switch at node 6 cannot cut any of the

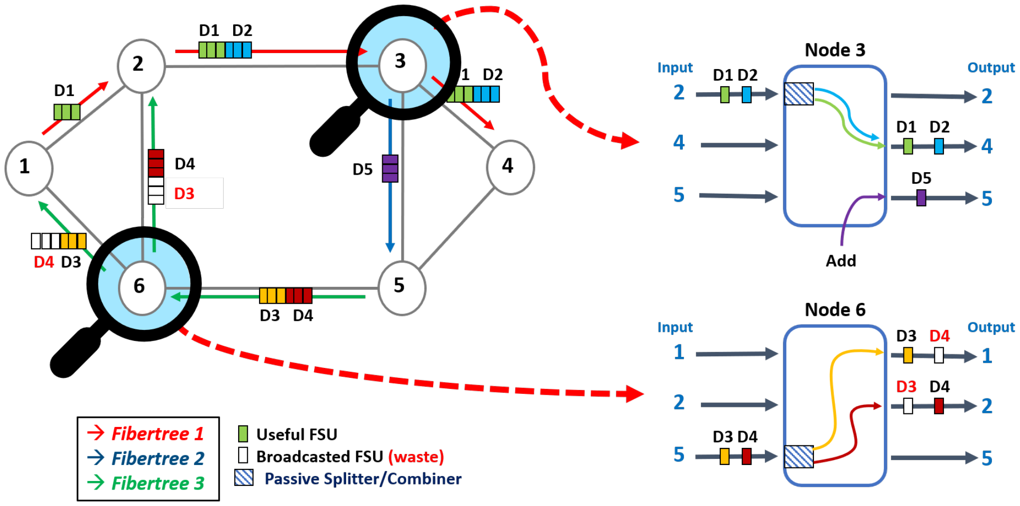


Figure 3.5: Node architecture of a P-FON solution

connections towards any of nodes 1 and 2. Therefore, the spectrum arriving to node 6 from node 5 needs to be propagated to both nodes 1 and 2 and the exclusiveness feature of the programmable switch cannot help to avoid spectrum waste on fibers 6-1 and 6-2 [22].

3.2.1.2 Optimized Tree establishment in P-FON

In the previous example in Fig. 3.4, we have demonstrated that, although P-FON is an easy and not expensive solution, the spectrum wasting avoidance cannot be always achieved.
Nevertheless, sometimes the optimization of uni-directional fiber trees establishment implying some improvements in the routing of demands can be adopted, such that the use of programmable switches is maximized, allowing in this way the reduction in spectrum waste.
Fig. 3.6 shows an example of how routing can be optimized to permit the use of programmable switches and to minimize spectrum consumption.
In the figure, D4 is routed on fiber tree 4, added ad hoc as advantages of PFONs, instead of fiber tree 3, exploiting unused links and making it possible to configure the programmable switch as node 6 (switch configuration shown in Fig.3.6) to avoid spectrum waste on fiber 6-1.
We also show in Fig. 3.6 how the configuration of the programmable switch in node 3 is modified with respect to that shown in Fig. 3.4 to adapt to the

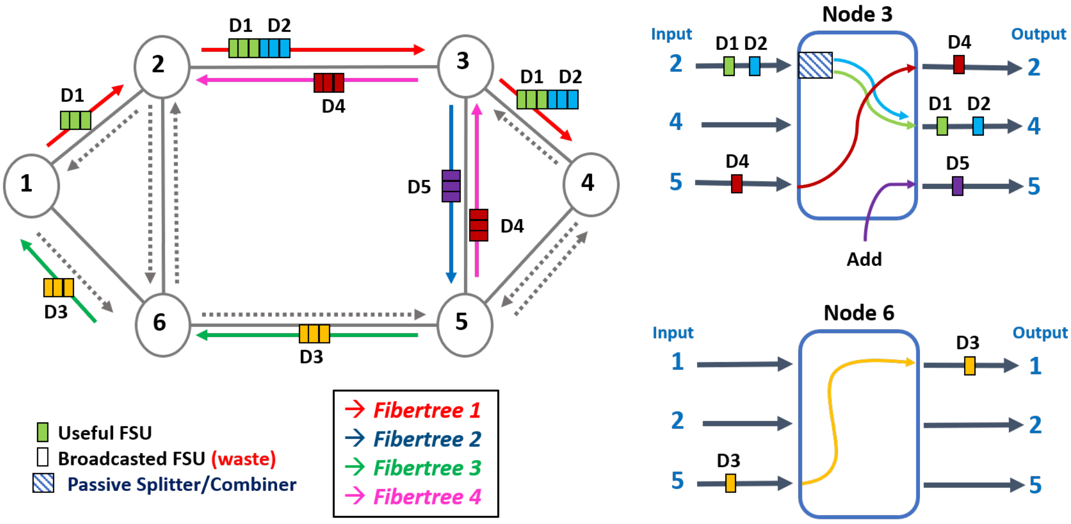


Figure 3.6: Optimized routing of demands with respect to the PFON solution in Fig. 3.4

new RSA of traffic demands. In this case in particular, we observe that the usage of an optical splitter/combiner can be avoided, resulting in even more savings in architectural costs, simply considering a different path resulting in the establishment of uni-directional fiber tree 4.
Here we also note that the re-configurability option of programmable switches can help to perform re-routing of lightpaths in case of a link failure.
Unfortunately, it can be intuitively acknowledge that an effective re-configuration of programmable switches in FONs becomes more difficult as the number of traffic demands to be accommodated increases, especially in more complex topologies [22].

3.2.2 P-FON vs FON vs Active

In this section we compare the routing and spectrum allocation and resource consumption obtained using a P-FON architecture concept with the ones from FON and Active Switching approaches [6], in order to list the major benefits and drawbacks of the proposed concept.
Fig. 3.7 shows a simple illustrative example of the programmable filterless network architecture.
Before making further considerations, is due to note once again that in the figure the filled blocks represent the useful signals, while the empty ones

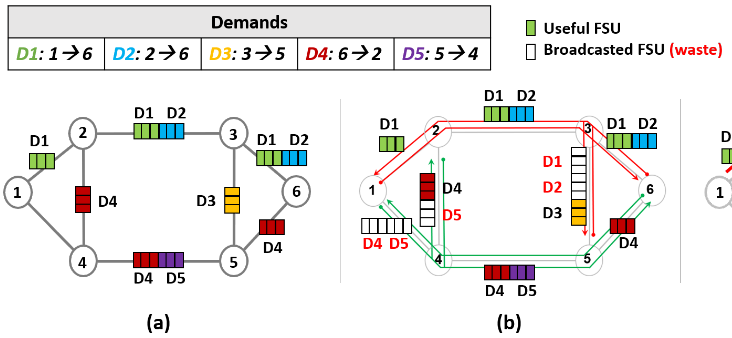


Figure 3.7: A solution for 5 demands routed on a 6-node network topology in case of different architectures: (a) Active switching - conventional ROADMs, (b) passive Filterless Network, (c) Programmable Filterless Network

denote the unfiltered signals present due to the signal broadcast and drop-and-waste transmissions.
Here, a 6-node physical topology and five demands (denoted as D1 - D5) are considered.
A solution based on conventional ROADMs is shown in Fig. 3.7 (a).
Considering a FON, one possibility of accommodating the demands is shown in Fig. 3.7 (b). This passive FON solution exploits two fiber trees, in red and green respectively. Demands D1 - D3 are routed over the red tree, while D4 and D5 use the green tree.
Fig. 3.7 (c) shows a possible solution deploying a P-FON architecture.
Compared to Fig. 3.7 (b), the white box-based network has a lower spectrum waste caused by unfiltered channels, implying a greater possibility of spectrum reuse (as it can be seen from the figure looking at D3 on link 3-5), and enhanced privacy (see how in the white box-based solution only D5 propagates to one unintended node (Node 2), whereas in the passive solution D5 is received by Nodes 1 and 2, while D1 and D2 propagate to Node 5).

Fig. 3.8 describes some details of the architecture of two nodes supporting the three solutions. Fig. 3.8 (a) shows a conventional ROADM with route-and-select configuration deployed in Node 3 of the example network.
We can observe that in Active Switching a node with degree d (i.e. with d links connected to it) will require $2d$ SSSs to support the express traffic in this configuration, plus a splitter and a coupler in the add/drop part.
Fig. 3.8 (b) depicts the architecture of Node 3 in the passive FON solution,

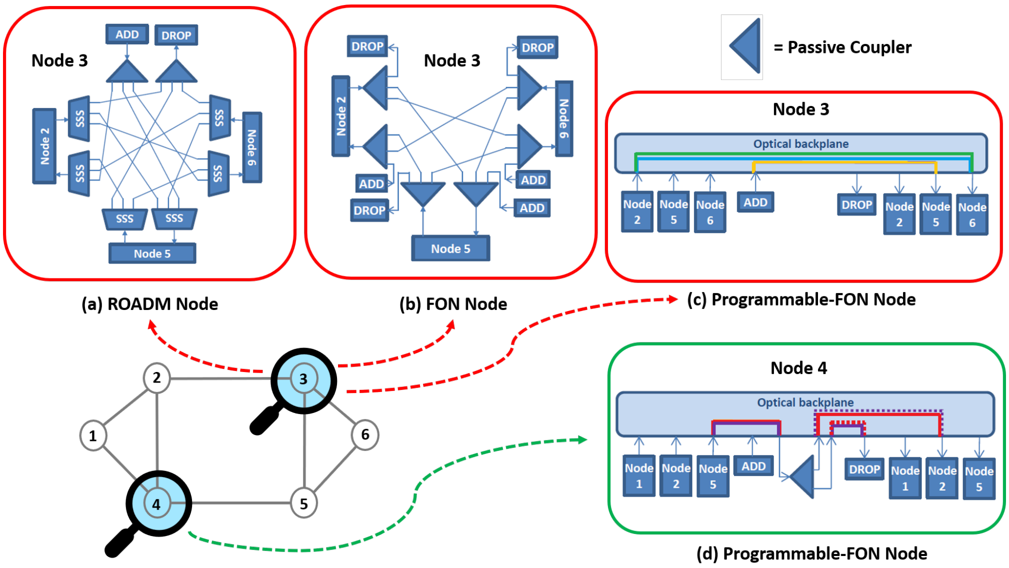


Figure 3.8: Detailed node setup supporting the example from Fig. 3.7: (a) Node 3 in the conventional ROADM network, (b) Node 3 in the passive filterless network, (c) Node 3 and (d) Node 4 in the white box-based programmable filterless network architecture. [6]

comprising 8 splitters 1:3.

In FONs, a node with degree *d* will require *2d* splitters allowing *1:d* connections to support this configuration.

For the white-box based solution, i.e. the P-FON one, the architecture of Nodes 3 and 4 is depicted in Fig. 3.8 (c) and (d). Notice that here the paths of each demands are coloured with the same color of the demand itself.

In general, in P-FON cases, each node uses a single optical NxN switch whose size depends on the degree of the node and on the number and degree of the necessary passive devices.

As shown for Node 3, the support of fiber switching allows for signals to be forwarded directly from an input to an output port, bypassing unnecessary components.

So, looking closer to 3.8 (c), D1 and D2 (respectively colored in green and light-blue) are sent from the incoming port from Node 2 to the outgoing port towards Node 6, while D3 (in yellow) is added towards Node 5.

A scenario where fiber switching is not possible is shown for Node 4 in Fig. 3.8 (d). There, signals on D4 and D5 (respectively colored in red and purple) must not reach the same output port so they must be split before being di-

rected to their corresponding outputs. Due to the absence of filtering, parts of each signal remain present on both split copies (represented by dotted lines) [6]. Anyway, sometimes this problem could be avoided through an optimization of fiber tree establishment, as we will see in the following section 3.2.1, which will be focused on P-FON only.
In the end, the P-FON advantages and drawbacks can be intuitively seen. Compared to the passive FON solution, a P-FON approaches exploits a lower number of splitters/couplers and their degree is lower. Combined with fiber switching, this translates to a *lower insertion loss and a lower number of used ports of the optical switching backplane*. Unluckily, as it is probably the major drawbacks of both the FON and P-FON concepts, despite resulting in big saves in terms of CapEx and OpEx, the routing solutions do not reach yet the ones obtained with an Active Switching ROADM-based network, which per definition doesn't waste any wavelegth and/or FSU.

3.3 Wavelength index minimization

Until now, our focus has been the minimization of total FSUs consumption, since this is the first and main advantage taken by the P-FON architectures. Anyway, this is not the only approach that an implementation of programmable switches can bring to a network operator. In fact, a situation that may happen is the one in which a big number of traffic demands choose the same shared fiber tree in order to satisfy the spectrum minimization problem and reduce at the minimum the wastes. This could lead to a traffic congestion in the eventuality that all wavelengths on a determined path has been already chosen, forcing the network to allocate other demands in a tree which will cause wastes in the same way.
Therefore, we are going to illustrate now an alternative approach to the problem solving of routing allocation considering the minimization of the *wavelength index* (WI, as we called it) instead of the total FSUs.
The *wavelength index* minimization consist in an equal distribution of wavelengths allocations aiming to reduce the maximum amount of wavelengths used in a certain fiber tree.
To make an example, consider to have 45 traffic demands to be accommodated in a network and a variable number of trees, N.
If N=3, then the optimal solution would be that each tree has $45/3 = 15$ wavelengths occupied.

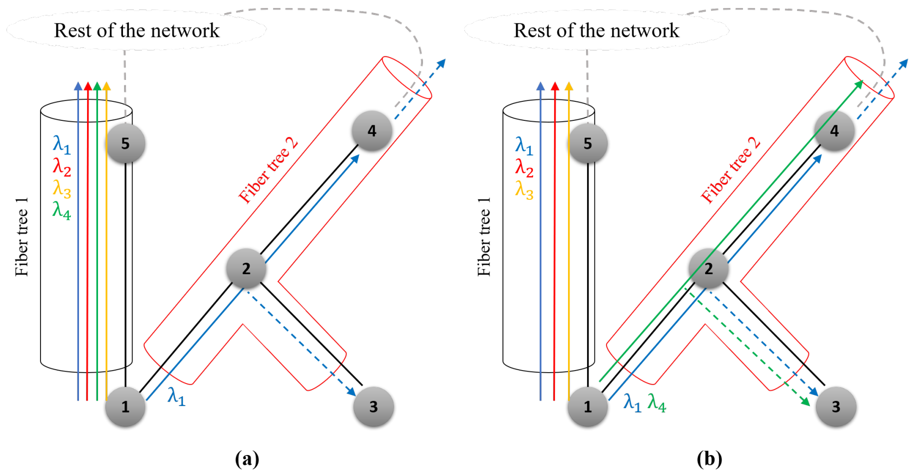


Figure 3.9: Examples of different wavelength usages without (a) and with (b) wavelength index considerations.

Considering again 45 demands, with N=4 we could have respectively 10, 10, 10 and 15 wavelengths in the trees. Then this 15 becomes our "wavelength index", and we want to minimize it as much as possible. So a better solution could be a distribution like 12, 12, 11 and 10, being 12 our new wavelength index, lower and better with respect to 15. The idea of WI starts from the assumption that even the RSA solving through the minimization of total FSUs could be not enough to face traffic congestion in some cases. In fact, when a wavelength is assigned, it will not be used again for more than one demand in the full tree. So, even if it is true that we save spectrum, some solutions could be unsatisfying for an operator.
Therefore, a different solution could be found changing the point of view, trying to minimize the amount of wavelengths used in every single tree, obtaining a more fair distribution of this fiber trees' resource.
Making another example, in Fig. 3.9 we can see an illustration of the concept discussed in this section.
Consider a subsection of a network, composed by those 5 nodes and interconnected as shown. Wavelengths are represented by λs. Assume that each fiber cannot use more than 4 wavelengths (so 4 λs). Moreover, two fiber trees have been established: Fiber tree 1 (black cylinder) and Fiber tree 2 (red cylinder) and the only way of reaching the rest of the network is passing by node 4 or node 5. In the first case, Fig. 3.9(a), the TE is done in order to reach the rest of the network starting from node 1, so it will occupy immediately all

the available λ, and then will be be forced to choose anyway the Fiber tree 2 for more connection requests.
On the other hand, in Fig. 3.9(b), we do not consider anymore spectrum wastes as a factor in wavelength allocation, since even before the wavelength (for example) on link 2-3 would have been used anyway. So a network operator could prefer to use the fiber tree 2 before, and in a near future, if requested, there could be still place to use another wavelength on the fiber tree 1. This could be very useful in the case that there would be a node that can be reached by a congested tree only, and then the only way to find a path through it would be do a complete recalculation of network's resources. Distributing equally the wavelengths in different fiber trees, this problem will emerge later with respect of more classical approaches.
Moreover, it could leads to benefits in amplifiers (and so costs) considerations, since allowing to establish more fiber trees, reducing the path lengths walked by a demand.

3.4 Related Work

In this section we are going to list first the related work on FONs, and then those on PFON and also some works on related topics.

The filterless optical network architecture, first introduced in [23], has been proposed as a reliable and cost-effective solution to offer network agility. The passive filterless physical layer characteristics are validated in [24] while a path computation element PCE-based control plane for filterless optical networks is proposed in [12]. The filterless optical network has been tried for the first time in a network in Croatia and then Germany in 2012 and 2014 [25]. The feasibility of filterless optical networks in metropolitan and aggregation networks is studied in [26]. Therein, a comparative cost analysis of a filterless and a conventional network solution for the metro optical network is performed. Resilience of elastic filterless networks under link and/or node failures is explored in [27] by constructing the optical fiber trees so as to guarantee for at least two link-disjoint paths between each pair of nodes in the network. The concept of semi-filterless networks, where some network nodes are filterless and others are filter-equipped, has been proposed in [28]

In [29] are evaluated the performance of fully-filterless and semi-filterless (i.e., hybrid solutions between fully-filterless and active photonic architectures) optical-network architectures in terms of cost of network elements and spectrum utilization, in a metro-network scenario.

The feasibility of AoD has been experimentally demonstrated in [30] [31], while the supported types of flexibility are investigated in [32]. In [33], the resiliency of filtered AoD-based optical networks is studied by incorporating node-level survivability with network-level protection from link failures. In [34], the routing, modulation format and spectrum assignment (RMSA) problem in AoD-based networks is solved modeling the configuration of AoD in the networks by introducing the concept of internal node configuration (INC) matrix. In [35], space division multiplexing (SDM) has been identified as one of the key technological developments to support the capacity of scaling needs for future optical networks. In [36], the RMSCA problem in elastic SDM network based on filtered hard-wired nodes is solved by an ILP in an effort to minimize the total number of used spectrum slot indexes from all the available spectrum slots. In addition, a heuristic algorithm named stepwise greedy algorithm (SGA) is proposed to solve the RMSCA problem in realistic scenarios. The work in [37] solves the planning problem of programmable SDM networks implemented through filtered AoD nodes with the aim to reduce the network switching resources. An hardware-aware strategy based on the two-objective binary particle swarm optimization (BPSO) to solve the routing, modulation format, spectrum and core allocation (RMSCA) problem in programmable filterless SDM networks is proposed in [38]

Chapter 4

Problems Statement and ILP models

In this chapter we state the problem of Routing and Spectrum Allocation (RSA) and Tree Establishment (TE) in case of Programmable FONs. Then we will present the ILP model proposed to solve it.

4.1 Problem Definition

As we have seen in chapter 3, P-FON could lead to great savings in term of spectrum usage with respect to a classical FON case. Moreover, it introduces TE flexibility, while still reducing the huge CapEx and OpEx required by the Active Switching networks.
Anyway, it is still impossible to achieve zero wastes due to the broadcast-and-select nature of these architectures. A non-optimized RSA solution may lead to notable losses, making both FON and P-FON not eligible solutions. It is fundamental therefore to minimize the total spectrum consumption to accommodate traffic demands in a network topology.

We propose in this chapter the ILP model of the P-FON case. To do further considerations and comparisons in the progress of this work, we considered two different situations:

- Fiber trees not given: a network operator has to build a Programmable Filterless Optical Network on a given topology. It has to decide how to interconnect fibers in the nodes exploiting AoD such that the total wavelengths utilization will be minimize. This is our main case study.

- Fiber trees given: a network operator has already deployed a FON and fixed the fiber trees, and it needs to route given sets of traffic demands minimizing the total spectrum and wavelength assignments. This scenario has been used only to do benchmark considerations and its ILP model has been illustrated in [39].

In a Programmable Filterless Optical Network, The problem of RSA and TE (RSA+TE) is defined as follows:

- *Given*:
  - A physical network topology consisting of filterless nodes equipped with programmable switches and single-fiber bidirectional links.
  - A set of traffic demands each characterized with a source and a destination
  - A set of available wavelengths.
- *Decide*:
  - The routing and spectrum assignment of traffic demands (and as consequence the internal configuration of programmable optical switches).
  - How to establish P-FON unidirectional fiber trees.
- *Objective*: minimize overall spectrum consumption, i.e. minimize the sum of utilized and wasted wavelengths.
- *Subject to*:
  - *fiber tree constraints*: i.e. each fiber link belongs to exactly one fiber tree and a fiber tree cannot contain closed loops.
  - *Wavelength continuity and contiguity constraints*: each virtual link need to be assigned to only one wavelength that is not assigned in the path and keeps it in every step of his path.
  - *Maximum links capacity*: each link has a maximum capacity in terms of wavelength channels.

- *Laser Loop avoidance*: place splitters and combiners in order to avoid this invalidant condition.
- *Traffic demands satisfaction*: every request must be able to reach its destination.

4.2 Assumptions

In *P-FONs* the problem takes as input only a physical topology and a set of traffic demands. The TE is a part of the problem.
A fundamental point is given by the uni-directionality of fiber trees, forcing that links should not be assigned to only one fiber tree for both directions. So if link (i,j) belongs to fiber tree_x, link (j,i) could not belong to fiber tree_x, but must be assigned to fiber tree_y. This is different from the pure FON case in which bi-directionality was a constraint.

4.3 ILP model: P-FON RSA+TE

4.3.1 Sets and parameters

- $G = (N, A)$ represents the graph used to model the physical network topology, where:
  - N is the set of nodes.
  - na: cardinality of N (i.e. $na = |N|$).
  - A is the set of *bidirectional* links which elements (i,j) are such that i∈N, j∈N
- L represents the set of possible wavelengths [elements: l∈L]
- D represents the set of possible demands which elements are (s,t) are such that s∈N, t∈N (s: source, t: destination)
- F represents the set of possible *uni-directional* fiber trees [elements: f∈F].
- M is a big number at least greater than maximum possible wavelength consumption that could be the maximum wavelength index or the total wavelength consumption

– S represents a subset of nodes such that S $\subseteq$ N and $|S| > 2$.

4.3.2 Decision Variables

– $q_{ij,st}$ (binary) takes the value of 1 if logical link (s,t) is mapped on physical link (i,j)

– $w_{ij,st,l,f}$ (binary) takes the value of 1 if wavelength l is assigned to logical link (s,t) mapped on link (i,j) belonging to tree f

– $h_{ij,l,f}$ (binary) takes the value of 1 if wavelength l is used on link (i,j) belonging to fiber tree f

– $e_{ij,jk,st,l,f}$ (binary) takes the value of 1 if link (i,j) and (j,k) belong to logical link (s,t) with wavelength l on fiber tree f

– $x_{ij,f}$ (binary) takes the value of 1 if physical link (i,j) belongs to fiber tree f

– $z_{ij,st,f}$ (binary) takes the value of 1 if logical link (s,t) mapped on physical link (i,j) is on fiber tree f

– y_f (binary) takes the value of 1 if fiber tree f is used

– $g_{i,f}$(binary) takes the value of 1 if node i belongs to fiber tree f

– $p_{ij,l,f}$ (binary) takes the value of 1 if on link (i,j) belonging to tree f is used wavelength l

– $c_{st,f}$ (binary) takes the value of 1 if the logical link (s,t) is mapped on the tree f

– $ya_{st,l}$ (binary) takes the value of 1 if the logical link (s,t) is used wavelength l

– xa_l (binary) takes the value of 1 if the wavelength l is used, 0 otherwise

4.3.3 Objective function

$$min \sum_{(i,j)\in A} \sum_{(s,t)\in D} \sum_{l\in L} w_{ij,st}^{l,f} + \sum_{(i,j)\in A} \sum_{f\in F} \sum_{l\in L} p_{ij}^{l,f} \quad (4.1)$$

The first term of the objective function refers to the *wavelength* used properly (*effective*), while the second term refers to the *channel waste*. The objective of the optimization is to minimize both, and this is obtained as consequence of minimization of their sum, i.e. the *total wavelength channel waste*.

4.3.4 Constraints

$$\sum_{(i,j)\in A} q_{ij}^{st} - \sum_{(j,i)\in A} q_{ji}^{st} = \begin{cases} 1 & if \;\; s = i \\ -1 & if \;\; t = i \\ 0 & otherwise \end{cases} \qquad \forall i \in N, \; (s,t) \in D \quad (4.2)$$

Eqn. 4.2 is the *Flow constraint.* It guarantees the mapping over the physical topology for each virtual connection (s,t) of the logical topology. In particular, this equation will be: equal to 1 if we are considering a source node (s=i), representing exit flow only; equal to -1 if we are considering a destination node (t=i), representing entering flow; equal to 0 if we are in a middle node, meaning that the flow which comes in is equal to the one which goes out.

$$z_{ij}^{st,f} \leq x_{ij}^{f} \qquad \forall (i,j) \in A, (s,t) \in D, f \in F \quad (4.3)$$

$$z_{ij}^{st,f} \leq q_{ij}^{st} \qquad \forall (i,j) \in A, (s,t) \in D, f \in F \quad (4.4)$$

$$z_{ij}^{st,f} \geq x_{ij}^{f} + q_{ij}^{st} - 1 \qquad \forall (i,j) \in A, (s,t) \in D, f \in F \quad (4.5)$$

Eqn. 4.3, 4.4, 4.5 assure the mapping of paths on the fiber trees. They connect the physical to the virtual links in order to have knowledge of which fiber tree (connection) is used by each link. In other words, a logical connection (s,t) will be accommodated in a fiber tree (f), associated in turn with a physical link (i,j). This triplets avoid unfeasible situations, like an (s,t) passing on a (i,j)is but associated to a (f) in another link.

$$c_{st,f} \cdot M \geq \sum_{(i,j) \in A} z_{ij}^{st,f} \qquad \forall (s,t) \in D, f \in F \quad (4.6)$$

$$c_{st,f} \leq \sum_{(i,j) \in A} z_{ij}^{st,f} \qquad \forall (s,t) \in D, f \in F \quad (4.7)$$

$$\sum_{f \in F} c_{st,f} = 1 \qquad \forall (s,t) \in D \quad (4.8)$$

Eqn. 4.6, 4.7, 4.8 are needed to avoid that there are some logical connections (s,t) not accommodated on any fiber tree (f) (4.6) and also that they don't exceed the capability of the network (4.7). Meanwhile equation 4.7 assure that each demand (s,t) belongs to one *fiber tree* only.

$$q_{ij}^{st} + q_{ji}^{st} \leq 1 \qquad \forall (s,t) \in D, (i,j) \in A \quad (4.9)$$

Eqn. 4.9 guarantees that the same demand cannot pass in both directions on the same link, in order to satisfy also the *loop avoidance constraint.*

$$w_{ij,st}^{l,f} \leq ya_{st}^{l} \qquad \forall (i,j) \in A, (s,t) \in D, l \in L, f \in F \quad (4.10)$$

$$w_{ij,st}^{l,f} \leq z_{ij,st}^{f} \qquad \forall (i,j) \in A, (s,t) \in D, l \in L, f \in F \quad (4.11)$$

$$w_{ij,st}^{l,f} \geq ya_{st}^{l} + z_{ij,st}^{f} - 1 \qquad \forall (i,j) \in A, (s,t) \in D, l \in L, f \in F \quad (4.12)$$

$$\sum_{l \in L} ya_{st}^{l} = 1 \qquad \forall (s,t) \in D \quad (4.13)$$

Eqn. 4.10, 4.11, 4.12, 4.13 assure that the *wavelength assignment constraints* are satisfied. In particular, the inequalities from 4.10 to 4.12 guarantee that a certain wavelength (l) is associated to only one logical demand (s,t), on a physical link (i,j) in that direction, belonging to the determined fiber tree (f). Meanwhile, equation 4.13 guarantees that only one wavelength must be used to go from s to t.

$$w^{l,f}_{ij,st} + w^{l,f}_{ij,ur} \leq 1 \tag{4.14}$$

$$\forall (i,j) \in A, (s,t) \in D, (u,r) \in D, l \in L, r \neq t, u \neq s$$

Eqn. 4.14 guarantees the *wavelength collision avoidance*, i.e. two different logical links, pointed as demands (s,t) and (u,r), cannot use the same wavelength on the same link.

$$w^{l,f}_{ij,st} + w^{l,f}_{jn,st} - 2 \cdot e^{l,f}_{ij,jn,st} \geq 0 \tag{4.15}$$

$$\forall f \in F, l \in L, (s,t) \in D, (i,j) \in A, (j,n) \in A, n \neq i, j \neq s, j \neq t$$

$$w^{l,f}_{ij,st} + w^{l,f}_{jn,st} - 2 \cdot e^{l,f}_{ij,jn,st} \leq 1 \tag{4.16}$$

$$\forall f \in F, l \in L, (s,t) \in D, (i,j) \in A, (j,n) \in A, n \neq i, j \neq s, j \neq t$$

Eqn. 4.15, 4.16 are used to identify the transit nodes. They are constraints needed to identify if node j is a transit node between node i and node n, keeping informations on direction from where the connection comes and where it is addressed.

$$p^{l,f}_{ju} \geq e^{l,f}_{ij,jn,st} \tag{4.17}$$

$$\forall f \in F, l \in L, (i,j) \in A, (j,u) \in A, (j,n) \in A, (s,t) \in D, u \neq i, u \neq n,$$
$$n \neq i, j \neq s, j \neq t$$

Eqn. 4.17 is used to identify utilization wastes of wavelength (l) on fiber tree (f) due to the broadcasting property of filterless networks, considering again the node j as a transit node.

$$p^{l,f}_{ju} \geq w^{l,f}_{ij,st} \tag{4.18}$$

$$\forall f \in F, l \in L, (i,j) \in A, (j,u) \in A, (s,t) \in D, u \neq i, j = t$$

$$p^{l,f}_{ju} \geq p^{l,f}_{ij} \qquad \forall (i,j) \in A, (j,u) \in A, f \in F, l \in L, u \neq i \tag{4.19}$$

Eqn. 4.18, 4.19 are broadcasting conditions.
Eqn. 4.18 assures that the wavelengths exiting due to the broadcasting from a destination node (j=t) cannot be less than the actual wavelength utilization addressed to that destination.
Eqn. 4.19 is a constraint regarding the propagation of wavelengths due to the broadcasting. In particular,

$$w_{ij,st}^{l,f} + p_{ij}^{l,f} \leq 1 \qquad \forall (i,j) \in A, (s,t) \in D, f \in F, l \in L \quad (4.20)$$

Eqn. 4.20 assures that a wavelength occupied due to propagation cannot be used by the working path of logical link on a physical path. In fact, a link *(i,j)* associated to a certain tree (f), a certain demand *(s,t)* and a certain wavelength (l), cannot be at the same time *useful* and *wasted*.

$$\sum_{(i,j)\in A} \sum_{(s,t)\in D} \sum_{f\in F} w_{ij,st}^{l,f}/M + \sum_{(i,j)\in A} \sum_{f\in F} p_{ij}^{l,f}/M \leq xa_l \qquad \forall l \in L \quad (4.21)$$

Eqn. 4.21 assures that the same wavelength cannot be used more than one time. It's a wavelength usage constraint.

$$\sum_{f\in F} x_{ij}^f = 1 \qquad \forall (i,j) \in A \quad (4.22)$$

Eqn. 4.22 guarantees that each couple (i,j) must be associated only to one fiber tree *f*.

$$\sum_{j\in N|:(i,j)\in A} x_{ij}^f + \sum_{j\in N|:(j,i)\in A} x_{ji}^f \leq g_i^f \cdot M \qquad \forall f \in F, i \in N \quad (4.23)$$

$$\sum_{j\in N|:(i,j)\in A} x_{ij}^f + \sum_{j\in N|:(j,i)\in A} x_{ji}^f \geq g_i^f \qquad \forall f \in F, i \in N \quad (4.24)$$

$$\sum_{(i,j)\in A} x_{ij}^f = \sum_{i\in N} g_i^f - 1 \cdot y_f \qquad \forall f \in F \quad (4.25)$$

Eqn. 4.23, 4.24, 4.25 guarantee that the number of links must be equal to (number of nodes - 1) in order to don't have *isolated links* (i.e. links which are not connected to the rest of the tree but still considered as a part of it).

$$\sum_{(i,j)\in A} x_{ij}^{f} \leq y_f \cdot M \qquad \forall f \in F \quad (4.26)$$

Eqn. 4.26 is used to check how many trees have been selected in the pool of possible number of trees, and which trees are indeed used.

$$\sum_{i\in S, j\in S| :(i,j)\in A} x_{ij}^{f} \leq |S| - 1 \qquad \forall f \in F, |S| > 2 \quad (4.27)$$

Eqn. 4.27 it's the *no loop constraint*, assuring that there won't be any loop inside any fiber tree.

The P-FON ILP problem has many variables and an order of magnitude that increases the computational time. In this scenario, programmable unidirectional fiber trees must be established, generating in this way exponentially many constraints that are related to the increasing size of the physical network topology. The high complexity of the P-FON model is given by the fact that all the possible combinations of unidirectional fiber trees establishment (note that in P-FON scenario these possibilities grows exponentially with respect of FON TE), wavelength assignment and the consequent propagation (broadcasting) of them must be accounted, which makes it intractable also with very small networks. Indeed, in our tests, calculation time became very huge even for the 6-node network, lasting from 1 day to even more than a week in the worst case (i.e. the full mesh one). This has led us to not use ILP approach for big networks.

Chapter 5

Genetic Algorithm for RSA/RWA and TE in P-FONs

In this chapter we present the Genetic Algorithm (GA) developed to solve the programmable switch configuration and RSA/RWA problem in P-FON architectures. First, we will introduce the concept of genetic algorithm and its elements, and then we will show how the RSA and TE problem can be solved with it.

5.1 Background on Genetic Algorithms

The Genetic Algorithm (GA) concept takes inspiration from the natural evolution of life, i.e. a random process driven by competition among members of a population which will reproduce and create new generations. Considering as members of a *population* the *possible solutions* of a certain *problem*, this idea can be exploited to solve challenges that can be reformulated as binary problems. Exploiting the utilization of bits, we can consider every bit as a *gene*, every group of genes as a *cluster*, and a group of clusters as a *solution*. The direction that the algorithm will follow searching for a solution is indicated by the *feasibility* and *fitness* values, which represent the solution's quality and depend by the nature of the considered problem. GA aims to find a global optimum by performing *selection* and other *genetic operations* in order to obtain a solution which satisfies all the constraints depending by a chosen objective. These operations allow to create new populations starting from the previous ones, i.e. start new *generations* propagating or modifying the best old solutions. We will discuss the methods of *selection* and the *genetic operations* that we applied in Sections 5.2.1 and 5.2.2, since there is not a general way to implement them but they could change for each different problem to which the GA is applied. Through this process, it is possible to reach a satisfying solution in a computationally reasonable amount of time.

5.2 GA for RSA and TE in P-FON

In our GA, a solution is encoded in a string of bits where every option is modelled as each single bit. This bit is called *gene* and, since we are going to consider a binary decision problem, it can assume only values 0 and 1.
To describe multiple options without ambiguity issues, the genes are grouped in *gene clusters*, which are groups of bits where only one of them can be equal to 1. This is called 1-of-N encoding. Genes in a cluster can also be all equal to zero, meaning that the cluster is *inactive*. A *solution* is formed by a sequence of clusters in arbitrary positions. Fig. 5.1 shows an example of genes, clusters composed by 2 bits and solution.

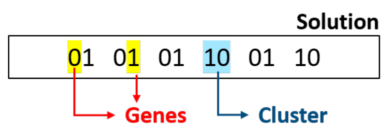


Figure 5.1: Examples of genes, cluster and solution

Initial population is created randomly. The *feasibility* value will tell if all constraints of a solution (as loop avoidance, routing of demands etc.) are satisfied and assumes the value of a real number belonging to the interval [0,1], where 1 tells that the considered solution is feasible. The reason feasibility is not equal just to 0 or 1 is that the heuristic needs to reach a feasible solution before starting to optimize it, refining feasibility value which will assume decimal values and lead the GA moving towards the best result in the solution space. The *optimization* process will also need to specify for each solution an objective function, referred as *fitness function*. In this algorithm, we assume that the fitness function has to be minimized, since our goal is to obtain the minimum total spectrum usage (RSA) or the minimum wavelength distribution (WI) in a network.

At each generation, selection and some other genetic operations (section

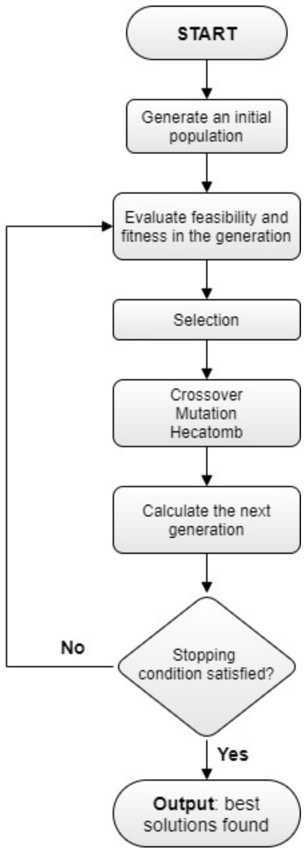


Figure 5.2: Flowchart of Genetic Algorithm

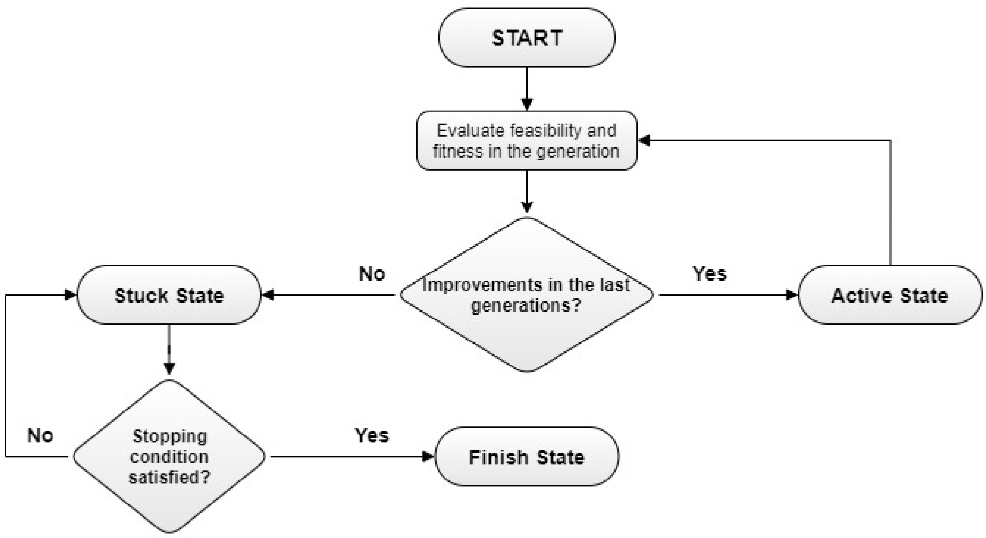


Figure 5.3: States of the Genetic Algorithm

5.2.2) are performed and the best solutions are given back as output. We call *best solution* the result which is feasible and with the best fitness value.

The steps and operations of the GA are shown in Fig. 5.2 and will be explained in the next sections. After reaching a feasible solution, the GA doesn't stop, but do further actions that will depend on three different *states* of the algorithm: *Active, Stuck* and *Finish state* (Fig. 5.3).

The steps are the following:

- The algorithm tries to reach the best available solution during the *active state*.
- If it does not find a better output after many generations, GA enters in the *stuck state*, in which genetic operations are applied and new solutions can be found.
- The *finish state* is triggered by seeing no improvements after reaching a number of generations created equal to twice the number of genes.

5.2.1 Preselection and Selection

Best solutions needs to propagate their genes increasing the probabilities of reaching better solutions in next generations. Thus, GA operates *Preselection* and *Selection* operations.
In ***Preselection*** the population in the current generation is divided in three classes: *first class* contains best solutions only, *second class* contains feasible solutions but with a fitness value slightly worse than the ones in the first class and *third class* contains solutions with feasibility not equal to 0.
In ***Selection*** two operations can be applied on members of a population:

1. *Elitism*: some of the best solutions of the current generation might proceed to the next one without any changes.
2. *Tournament*: Solution are randomly chosen from the classes defined in the preselection with different percentage.
   70% of them comes from the first class, 20% from the second one and 10% from the third one. Then, they "fight" by pairs with the following win conditions:

- feasible solutions wins over unfeasible ones.
- if both unfeasible, the one with higher feasibility wins.
- if both feasible, the one with higher fitness wins.

Note that *feasibility* and *fitness* values calculations are based on the nature of the considered problem. There is only one fitness value associated to each solution and it is used to do comparisons and assignations in the *preselection* and *tournament*.
Consider now the assignation problem, i.e. having solution and decide which class it belongs to. Assume to have a current best solution.
We define F as feasibility value, *fit* as fitness value (the bigger it is, the worst it gets) and M as a margin. There are two possible cases:

1. If a feasible solution solution *has not been discovered yet*, the assignation to classes is the following:

   - First class: solutions with $F >$ (current best F - M) $\wedge$ *fit* not greater more than 20% w.r.t. the current best *fit*.
   - Second class: solutions with $F >$ (current best F - M) $\wedge$ *fit* greater more than 20% w.r.t. the current best *fit*.
   - Third class: solutions with $F \neq 0$.

   The value of *Margin* is:

$$M = \begin{cases} 0.2 & if\ current\ best\ F\ < 0.5 \\ 0.1 & if\ 0.5 \leq\ current\ best\ F \leq 0.7 \\ 0.05 & if\ 0.7 \leq\ current\ best\ F\ < 0.9 \\ 0.01 & if\ current\ best\ F\ \geq 0.5 \end{cases} \tag{5.1}$$

2. If a feasible solution solution *has been discovered*, i.e. solutions with $F = 1$, the assignation to classes is the following:

   - First class: solutions with $F = 1 \wedge$ *fit* not greater more than 5% w.r.t. the current best *fit*.
   - Second class: solutions with $F = 1 \wedge$ *fit* greater more than 5% w.r.t. the current best *fit*.

- Third class: solutions with $F > 0{,}95$
  $\wedge$ *fit* not greater more than 25% w.r.t. the current best *fit*.

To increase probability of succeeding to the current best solutions but without excluding the worse ones, 70% of the solutions involved in the tournament are chosen randomly from Class 1, 20% from Class 2 and 10% from Class 3.

5.2.2 Genetic Operations

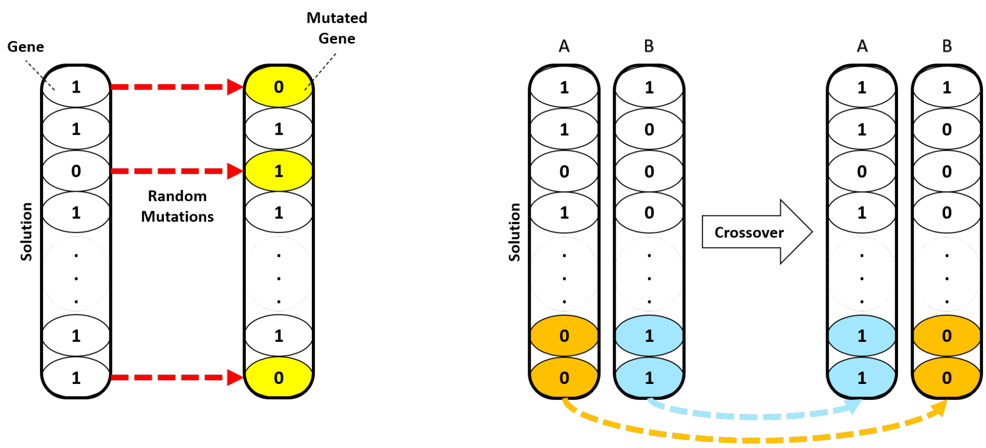


Figure 5.4: Examples of Mutation and Crossover

Sometimes just selecting the best solutions generations after generations doesn't lead to obtain the best result. Random changes can redirect the path to a better solution. This is why the GA needs three genetic operations: *Mutation*, *Crossover* and *Hecatomb*.

Mutation (Fig. 5.4) inverts random genes in a solution, setting them equal to 1 if they are 0 or vice versa. To increase efficiency of the mutations, instead of choosing a random bit, we can circularly shift active genes in the cluster, avoiding to create invalid elements with respect to our definition of *solution, genes and cluster*. The probability of having a mutation depends on the number of clusters in a solutions and the actual state. In *active state*, it is between 0% and 25% of the size of the solution (1/4 of the genes). Then, it decreases till a minimum of 2% . In *stuck state* the probabilities are set equal to the initial settings. If a better solution is found, the algorithm comes back to the *active state*. This is done until *final state* conditions are satisfied.

Crossover (Fig. 5.4) consist in switching two entire parts of two different solutions. After the *tournament*, two solutions are selected, splitted at a random gene and mixed. Probability of crossover in the *active state* is 50% while in the *stuck state* is decreased progressively until 30% .
Research on crossover operations are studied in [40].

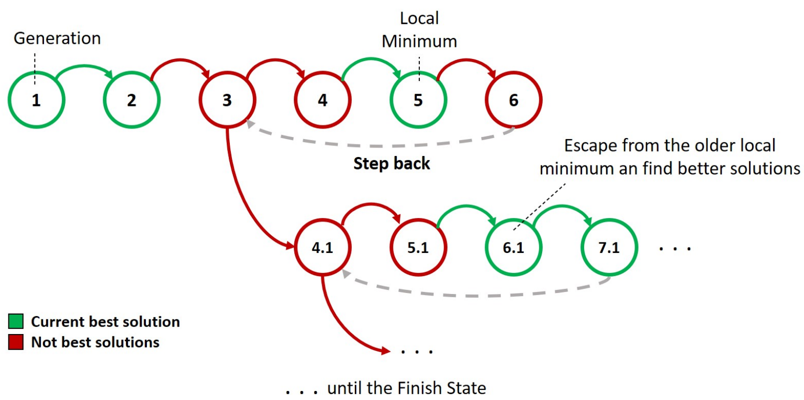


Figure 5.5: Concept of Hecatomb in the GA

Hecatomb is activated in the *stuck state* and consists in a *stepback* trying to escaping a local minimum and looking for better solutions.
The local minimum is compared with future solutions that could be found after the hecatomb. Once the stepback has been done, the GA applies again the genetic operations, which may lead to to different outcomes.
In Fig. 5.5 we see an example of the hecatomb concept.
Every circle represents a generation. If the circle is green, one best solution has been found. At first iteration hecatomb does not happen. In the example, generation 6 does not find a better solution than 5, which is the local minimum. Thus, a stepback in generation 3 is done, and genetic operations are applied again creating generations 4.1, 5.1 and so on. Every new solution found are compared to generation 5, which is still our current best solution. At generation 6.1 a better solution is found, meaning that the hecatomb procedure has been useful. The procedure is repeated till the reaching of the Finish state condition. In order to let the Hecatomb work properly, we kept the GA in the *stuck state* for a number of generations equal to 10 times the number of clusters in a solution. Concluding, note that the hecatomb

procedure *may* lead to better solutions, but does not always happen.

5.2.3 RSA+TE

We have seen the concepts of *solution*, *gene* and *cluster* previously. In the Tree Establishment (TE) problem, we considered:

- an integer L equal to the number of bi-directional links
- a complete *solution* composed by $2L$ clusters
  (considering uni-directional trees, so two directions for each link)
- each uni-directional link as a cluster
- every cluster composed by N genes
- value of N equal to the number of fiber trees

In other words, each link in a specific direction is associated to a *cluster* of size N where N is an integer number of considered number of trees belonging to the interval $\{2,M\}$. 2 trees is the minimum possible case, while M is the maximum number of trees that we pass as input.

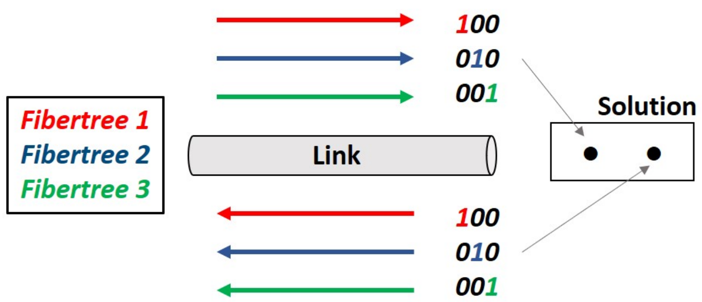
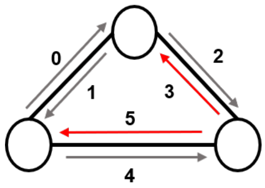


Figure 5.6: Example of possible solutions corresponding to a single link with M=3

Consider the example in Fig. 5.6. In this example, we suppose that three (N=M=3) different fiber trees could be allocated on one bi-directional link (L=1) in both directions ($2L$=2). So each cluster will be composed by 3 genes and all their possible values are shown in the figure. They will assume only one of those values. Depending on the position of the gene equal to 1 (in the image the one with the same colour of the corresponding fiber tree), one of the fiber tree will be allocated on the link in a certain direction. The solution of this simple case will be composed by two clusters (represented by the two black point) that will be equal to two of the possible "group of genes", one per each direction.



Link	Tree 0	Tree 1
0	0	1
1	0	1
2	0	1
3	1	0
4	0	1
5	1	0

Solution

01 01 01 10 01 10

Figure 5.7: Example of a solution converted in binary form

To see an example on an entire topology, consider now Fig. 5.7. A simple network is composed by 3 nodes, connected by 3 physical links, i.e. 6 unidirectional logical links. Each link has been labelled with an integer index, from 0 to 5. We are in the case N=2, i.e. two fiber trees has been established in this solution: Tree 0 (red) and Tree 1 (gray). As consequence, a cluster will be composed by two genes: the first one corresponding to Tree 0, the second to Tree 1. Every unidirectional link is associated to a cluster, as can be seen looking at the rows of the table. Thus, for instance, link 2 belongs to Tree 1, so its correspondent gene cluster will be 01, where the 0 in the first position indicates that Tree 0 on that link is deactivated, while the 1 in the second position means that our link 2 belongs to Tree 1. Ordering and grouping all the clusters, we obtain a solution.
Fig. 5.8 shows a flowchart for increasing values of N and restart operation This logic allow us to achieve better solutions.
Increasing the value of N, also the size of each cluster will grow. Anyway, after a certain value, it will be impossible to satisfy the establishment of every desired fiber tree. In order to find this "breaking point", M is set as a reasonable high number and the GA, once finished evaluation with N fiber trees, will start again increasing N by one, till reaching M.
Every evaluation is done R times, where R is the number of "restarts" passed as input. After that a solution has been created, the next step is calculate its *feasibility*, which is given as the number of successfully routed demands in the trees divided by the total number of traffic demands, being a value between 0 and 1. The traffic is passed as input.

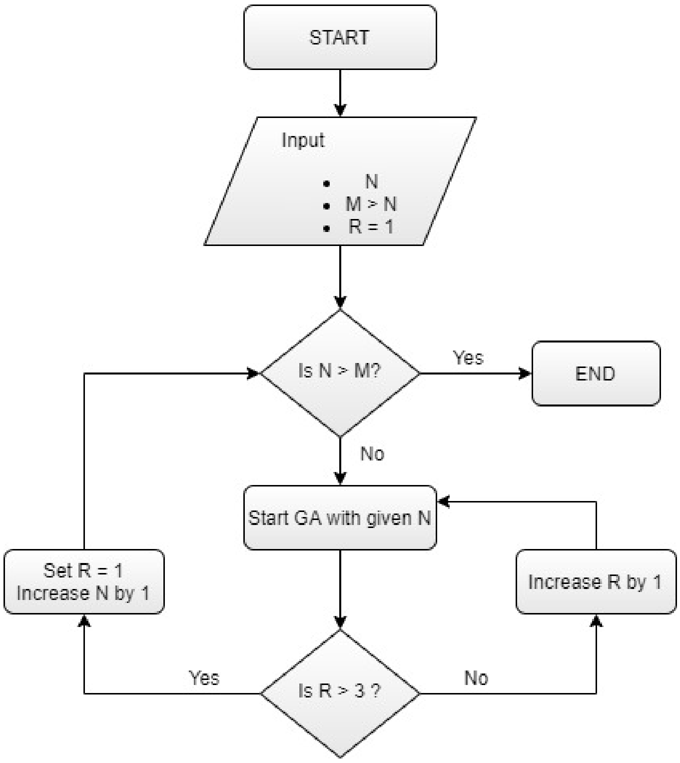


Figure 5.8: Flowchart for increasing number of trees and restart operation

The objective function, consisting in the minimization of total FSUs usage, will lead the rest of the GA. In case of multiple connections satisfy a certain demand, the one which minimize the objective function is always chosen. In this way, we obtain multiple binary solutions and these are the ones on which the GA will make *Selection* and *Genetic Operations*. The passages will follow exactly the ones described in Section 5.2.
So considering:

- S : set of solutions [elements: s ∈ S]
- A : set of links [elements: (i,j) ∈ A]

The fitness value (*fit*) will be calculated as:

$$fit = min(s \in S) \qquad (5.2)$$

where

$$s = \sum_{(i,j)\in A} FSU_{ij} \qquad \forall (i,j) \in A \quad (5.3)$$

meaning that the fitness value will be equal to the minimum total FSU consumption between every solution (s ∈ S), calculated separately for every solution as the sum of each single FSU on each link of a topology.

5.2.4 Wavelength Index

In the end, we used the GA also to cope with the wavelength index minimization problem. As anticipated in section 3.3, the WI concept changes the point of view of a network operator, focusing on optimizing the wavelengths distribution in different fiber trees and allowing the re-usage of wavelengths. As consequence, the objective function has been modified too.
Now the aim is to reduce as much as possible the maximum number of wavelength assigned in a single fiber tree, guaranteeing the distribution of demands in different fiber trees causing also a decrease of utilized wavelengths. The fitness value will now depend by the maximum wavelength index used in a fiber tree, following the logic in which a lower value corresponds to a better solution. So considering:

- S : set of solutions [elements: s ∈ S]
- W : Number of used wavelengths in one fiber tree
- F : set of fiber trees [elements: f ∈ F]

The fitness value (*fit*) will be calculated as:

$$fit = min(s \in S) \quad (5.4)$$

where

$$s = max(W_f) \qquad \forall f \in F \quad (5.5)$$

meaning that the fitness value will be equal to the minimum solution corresponding to the maximum number of wavelengths used in one fiber tree in that particular case.

The feasibility remains the indicator of constraints satisfaction and traffic demands accommodation.

5.2.5 GA for RSA in FON

The GA can be used also in the FON scenario with fixed given trees, and is a modification of the P-FON case just explained. Link are set from unidirectional to bidirectional, and there will be no need to calculate tree establishment since the fiber trees are passed as input. The objective remains the minimization of total FSUs consumption, meaning in this case to choose the fiber tree which waste less for each demand. Thus the RSA is solved routing the traffic in this fixed fiber trees, evaluating feasibility and fitness and choosing the best results. GA in this case has proven to behave exactly like his ILP counterpart illustrated in [39], as we expected.

5.2.6 Traffic demands

In order to create the traffic, we developed a program which takes as input the number of demands in each sets, the number of sets and the list of nodes in a topology. All the possible demands are created through a permutation process and saved in a matrix. If the *full mesh* case is requested, only one set is possible and the ordered list of demands is printed.
Otherwise, the elements in the matrix are shuffled and it's returned the desired number of demands. This process is repeated a number of times equal to the number of sets passed as input. Moreover, it is checked every time that the new set created is different from all the previous ones, in order to guarantee diversity in results.

5.3 Summary of Genetic Algorithm

In the end, we used the GA in:

- **FON**: all trees have been already calculated and passed as input. This is needed to simulate a given trees FON scenario and route all demands in the best way possible. The objective is the minimization of FSUs total consumption.
- **P-FON**: the GA solves tree establishment and RSA following the Programmable-FON constraints, with the objective of minimizing the

total overall spectrum (FSUs) used in the network or the wavelength index (WI) in the fiber trees.

Chapter 6

Numerical Results

This chapter focuses on the numerical results obtained evaluating the ILP and the Genetic Algorithm in different network scenarios. First, we present performance metrics, and then we discuss the case studies and the numerical results.

6.1 Performance Metrics

As performance metrics, we calculated:

- **Total number of FSUs**: number of FSUs utilized, given by the sum of Effective FSUs and Wasted FSUs.
- **Number of effective FSUs**: number of FSUs utilized to satisfy the traffic demands without considering wasted/broadcasted FSUs.
- **Wasted FSUs**: number of FSUs broadcasted due to the unavoidable broadcast-and-select architecture.
- **Average Path length**: this value has been calculated in kilometers (km). Consider d as a demand, we calculated:

$$\textit{Path length per } d = \sum \textit{Length of links used by } d \tag{6.1}$$

$$\textit{Avg. Path Length} = \frac{\sum_d \textit{ Path Length per } d}{\textit{Number of demands}} \tag{6.2}$$

- **Longest Path**: considered only in the Italian 10 topology, we collected the longest path length of a demand. This allows to quantify the impact of P-FON on demand's length. It is measured in km.

- **Execution time**: amount of time needed by the ILP or the GA to provide a solution. Time is calculated in minutes (min).

- **Wavelength index**: WI has been calculated as the objective of the minimization only in the Italian 10-nodes topology. It indicates the maximum index of wavelengths utilized in the network.

6.2 Heuristic validation

6.2.1 Case Study

In this thesis we evaluated the benefits and improvements of the P-FON approach by doing simulations with different sets of traffic demands. In this section we consider a 6-node topology, shown in Fig. 6.1 (a), where link lengths are specified.

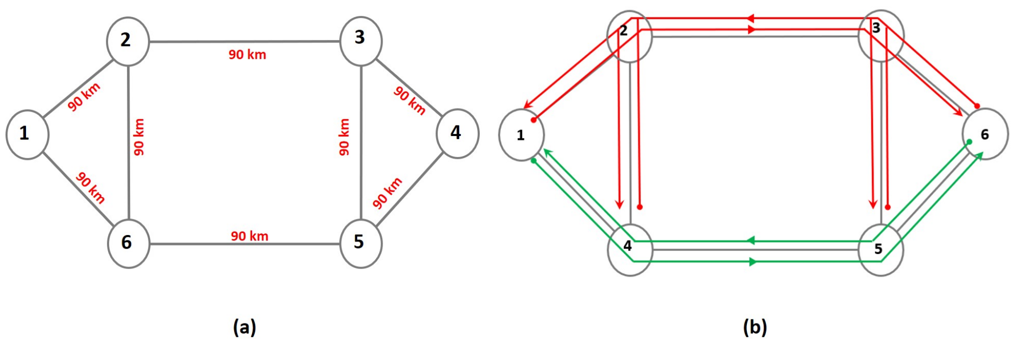


Figure 6.1: 6-node topology (a) and with given trees FON (b)

We defined a variable called *demand index* as:

$$\beta = \frac{\textit{number of demands in the considered case study}}{\textit{number of demands in the Full Mesh case}} \tag{6.3}$$

The values of β corresponding to different numbers of demands in the this network are listed in Table 6.1.

Table 6.1: Sets of demands and corresponding β values in the 6-node network

Number of Demands	β
8	0.27
15	0.5
23	0.77
30	1

To validate our heuristic we considered the ILP utilization in three different cases:

1. **Active Switching**: simulate nodes equipped with active switching elements, which are assumed to be too expensive but don't have wastes. These is the spectrum usage that a P-FON should aim for.

2. **FON**: applied with fixed bidirectional given fiber trees shown in Fig 6.1 (b). This is our main meter of comparison, allowing us to show the benefits of P-FON approach.

3. **P-FON**: ILP applied only for $\beta \leq 0.77$, since if β equal to 1 (or in bigger networks) is meaningless due to the huge time wastes. We discussed about the inadequacy of ILP approach for P-FON in chapter 4.

Then, we run the Genetic Algorithm in two of these network scenarios: FON and P-FON, for all the values of β.

6.2.2 Assumptions

Before comparing directly the GA results with the ones of the ILP, we have to analyze them and explain what has led to chose and to average determined solutions rather than others.

In the GA we implemented a function which allow to set as initial value the Maximum Number of fiber trees that we want to use while establishing connections minimizing the total FSUs required in the network.
For example, if we set this parameter equal to 5, the algorithm will try to

find a solution using 2 (our minimum staring point), 3, 4 and 5 fiber trees. The solution could also not exist, giving as result a fitness value of 10^6.
To make another instance, trying to put 20 unidirectional fiber trees in a network equipped with a smaller number of unidirectional links is unfeasible by definition or, considering a more pertinent case, even if the number of fiber trees is reasonable, often it could be possible that there is no solution which satisfies all the constraints allocating correctly at the same time all the demands of a given traffic.
For these reasons, it has been introduced the *Restart* operation. In our simulations we have set 3 restart for every tree considered.
So, recalling the previous example with maximum number of trees equal to 5, the algorithm does 3 simulations for the 2 trees case, 3 simulations for the 3 trees case, 3 simulations for the 4 trees case and finally 3 simulations for the 5 trees case, for an overall of 12 simulations.
This happens for each value of β, for every set of demands. For simplicity reasons and avoiding to show redundant data, we are not going to list now all the results obtained, but only the best solutions, which will be first averaged and then compared with other cases.

6.2.3 Results

Fig. 6.2 shows the total FSUs consumption of all approaches considered with different values of β. The "missing bar" in the graph for $\beta = 1$ is due to the time required by the ILP in that P-FON scenario. In fact, that particular simulation (full-mesh case) lasted more than a week and thus has been considered inappropriate to be used even with bigger networks. It can be seen in the figure that for low values of β the P-FON achieve results almost equal to the Active scenario, while for higher values of β P-FON waste more FSUs but behaves better with respect to the FON case, wasting less spectrum.

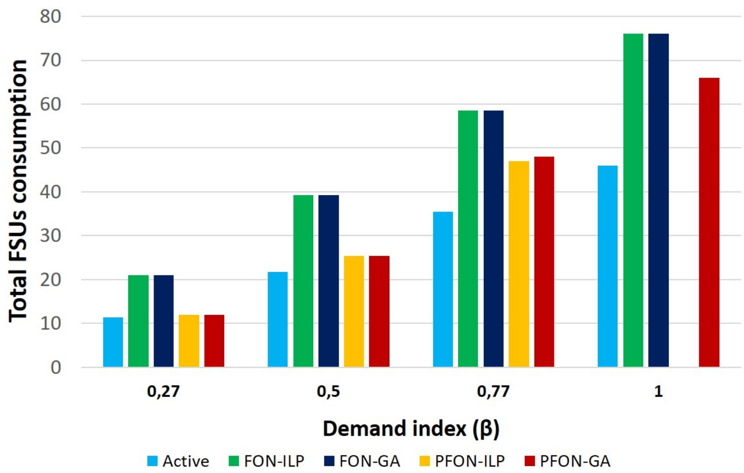


Figure 6.2: Total FSUs consumption comparison in a 6-node network.

Table 6.2: Percentage of difference in optimality gap between ILP and GA.

β	*FON ILP*	*FON GA*	% err	*PFON ILP*	*PFON GA*	% err
0.27	21	21	0	12	12	0
0.5	39.33	39.33	0	25.33	25.33	0
0.77	58.5	58.5	0	47	48	2
1	76	76	0	-	66	-

Moreover, in Table 6.2 we calculated the percentage of difference in optimality gap between ILP and GA. Results show that the percentage of error (% err) between the GA and the ILP model is almost always equal to 0, except for $\beta = 0.77$ in the P-FON scenario, where is equal only to 2 %. Analyzing the FSUs consumption of this scenario, we immediately notice that FON with given trees waste more than other approaches.

Table 6.3: Percentage of FSU savings between P-FON and FON considering both ILP and GA for the 6-node network.

% of savings	β=0.27	β=0.5	β=0.77	β=1
P-FON ILP vs FON	42.9	35.6	19.66	-
P-FON GA vs FON	42.9	35.6	17.95	13.16

Table 6.3 shows the percentages of P-FON's savings with respect to FON. In the best case, for the lower value of β, P-FON allows to save till almost 43% of FSUs with respect to FON approach. For bigger values of β, this percentage decreases but is still consistent.

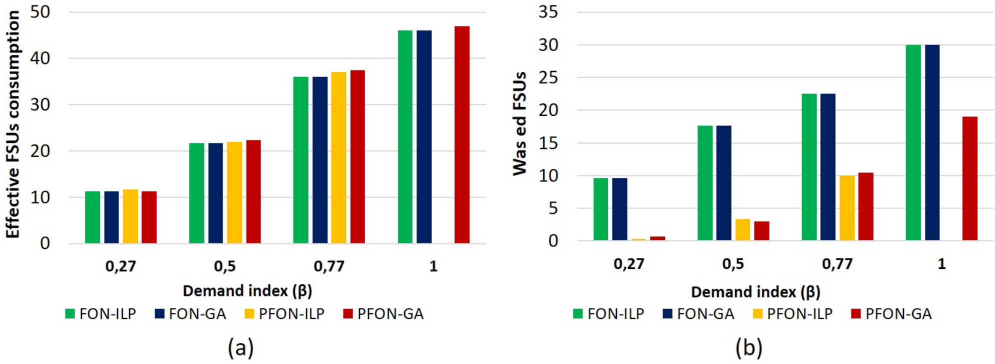


Figure 6.3: Effective (a) and Wasted (b) FSUs consumption comparisons in a 6-node network.

Fig. 6.3 shows the effective FSUs and the wastes in PFON and FON scenarios. We can observe in (a) that the effective utilization of FSUs in both cases are almost equal, meanwhile in (b) P-FON minimize the wastes, limiting the drawbacks of the broadcast-and-select architecture.

The ILP in the P-FON case calculated every time directly the best number of fiber trees necessary to satisfy our objective. The GA cannot do it, but simulates till a given maximum number of fiber trees to be established and then we have to pick the best results.

Table 6.4 lists the number of unidirectional fiber trees in the best results cases for each value of β.

Table 6.4: Chosen numbers of fiber trees used by the GA and ILP model giving back the best solution for each value of β in the P-FON scenario.

P-FON	β=0.27	β=0.5	β=0.77	β=1
ILP	5	6	6	-
GA	4	4	4	6

The degree of freedom and *flexibility* depends directly from the number of fiber trees. These are the main advantage of using Programmable optical nodes. However, choosing the best value is not an assured statement and can be deduced only after some tries. As anticipated in previous chapters, choosing both a value too high or too low will return bad and not optimized results, since low values will not give flexibility and too high values will congested the network. These behaviours could be seen in Fig. 6.4, where we compare different performance metrics for each number of trees calculated.
For instance, consider that the 6-node topology consists in only 9 bidirectional links, translated in 18 unidirectional links. So, for the first two values of β it is unnecessary to try in the network more than four fiber trees. Anyway, the calculation of 5 trees in the cases with higher traffic has shown that trying to allocate more trees was a bad idea since results get worst. This is the reason of the missing bars in the graphs.
In Fig. 6.4 (a) we see that the total FSU utilization is coherent for all the cases, in (c) the effective FSU consumption behaves in a similar way, while in (d) we see that the amount of trees influences the wastes, showing that too many trees could congest the network bringing unavoidable wastes. In the end, Table 6.5 shows the computational time for each of the ILP and the GA. We can observe that the GA has a significantly lower computational time with respect to the ILP. This means that the ILP model cannot be used for further calculations in bigger networks scenarios since these would need unfeasible times. Note that, increasing the number of fiber trees increases also the time requested to evaluate a solution, adding these to reasons to avoid choosing too many trees.

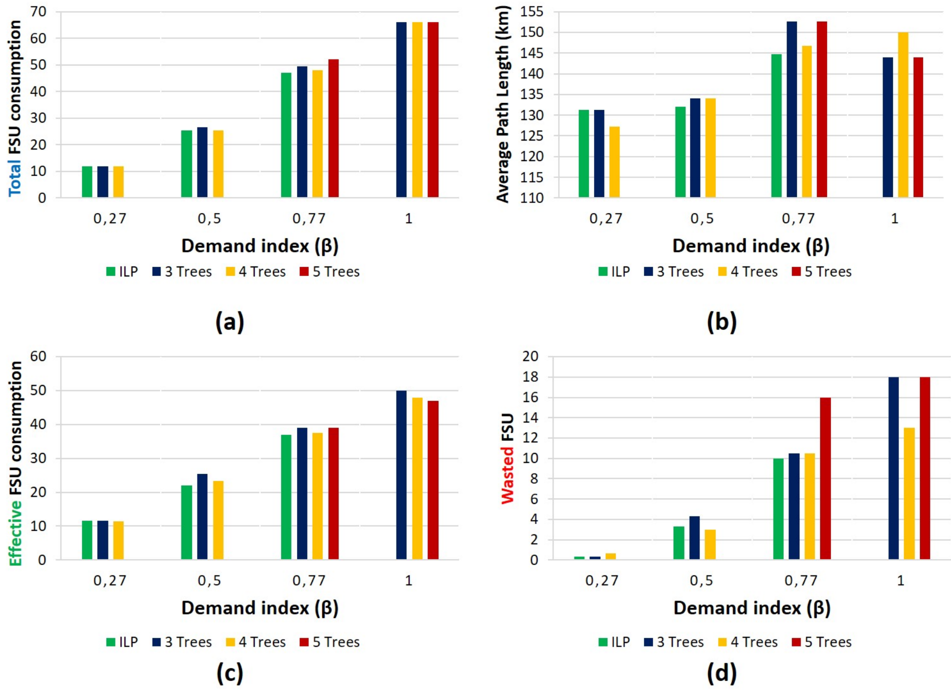


Figure 6.4: Results from allocating different trees in P-FON GA compared to P-FON ILP doing TE. Bar-graphs of Total (a), Effective (c) and Wasted (d) FSU consumptions and Average Path Lengths (b).

Table 6.5: Execution time of GA and ILP in simulations for different values of β

	Trees	β=0.27	β=0.5	β=0.77	β=1
ILP	-	5 min	1.5 days	4 days	$>$ 1 week
P-FON GA	2	5 min	6.33 min	10 min	11 min
	3	5 min	6.33 min	12 min	11 min
	4	-	-	13 min	11 min

6.3 Numerical results on larger network instances

We consider now a larger network instance evaluating only the performances of the GA since the ILP model makes it unfeasible to obtain results for this network in a reasonable amount of time and computational power. The considered network is the Italian 10-node topology shown in Fig. 6.5.

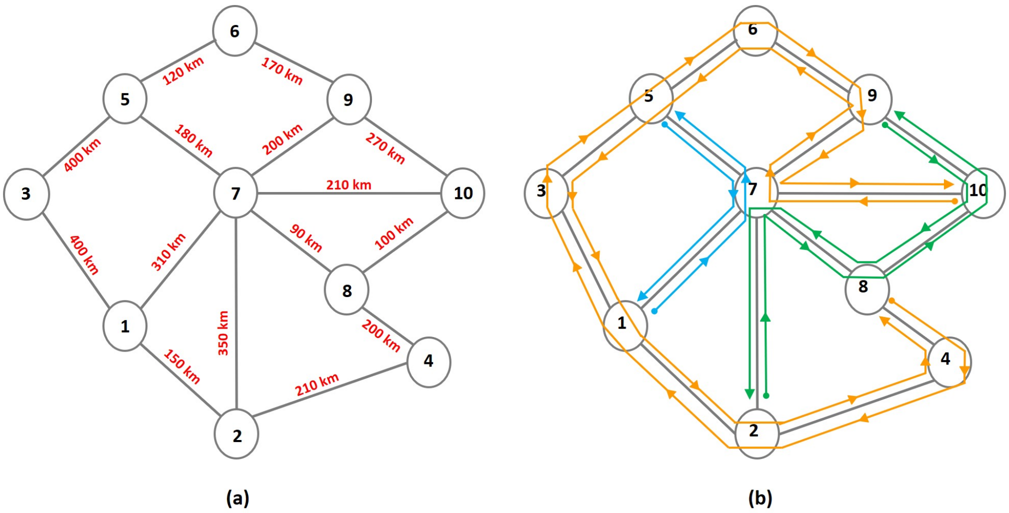


Figure 6.5: Italian-10 node topology (a) and given trees FON (b)

Table 6.6: Sets of demands and corresponding β values in the 10-node network

Number of Demands	β
15	0.17
30	0.33
45	0.5
60	0.67
75	0.83
90	1

The values of β used in the following considerations are listed in Table 6.6. We compare best performances of P-FON and FON scenarios and evaluate the usage of different trees, starting from 2 to 6 trees. Fig. **??** shows the given trees considered in the FON case. Note that the implementation of hecatomb and restart operations in the GA has been fundamental in this network with respect to the 6-node topology, in particular increasing the numbers of demands. Without these genetic operations results were worse than the one we are going to analyze. So the following values are the achievements of many repeated simulations and restarts, from which we extracted the averages and plotted the data of best results following the list in section 6.1.

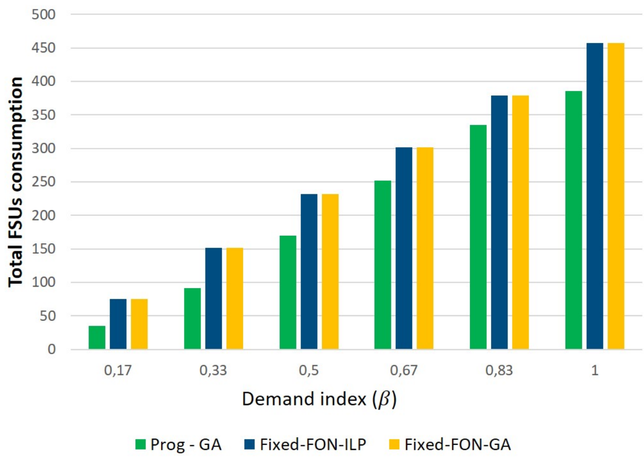


Figure 6.6: Comparison of the Total FSUs consumptions for the Italian 10 nodes topology between P-FON and FON.

Fig. 6.6 illustrates the total number of FSUs obtained by the P-FON approach with respect to the FON one with given fiber trees. Results shows that given trees FON scenarios consume always more FSUs than PFON one. In particular is possible to save on average 54.43 FSUs, involving a lot of savings in spectrum consumption.

Table 6.7: FSUs total consumption and gain % of P-FON with respect to FON for different values of β.

	β=0.17	β=0.33	β=0.5	β=0.67	β=0.83	β=1
FON	75	151.8	231.4	301.1	378.5	457
P-FON	34.9	91.5	169.3	251.7	334.8	386
Gain %	53.46	39.72	26.84	16.4	11.56	15.54

Table 6.7 shows the amount of total FSUs required by both P-FON and FON cases, expressing the gain's percentage of the programmable approach. Increasing the value of β, i.e. the number of traffic demands in the network, the percentage become smaller, but still consistent. Fig. 6.7 shows the

comparison between P-FON and FON of Effective used and Wasted FSUs in the network. In this case, there is not only a reduction in wastes, but also an improvement of effective FSUs utilization, which was not observable in the 6-node topology study. These benefits of the P-FON approach is a consequence of the *flexibility* which characterize them. It is more relevant in larger networks with more links, allowing to choose better/shorter paths, established ad hoc for traffic demands.

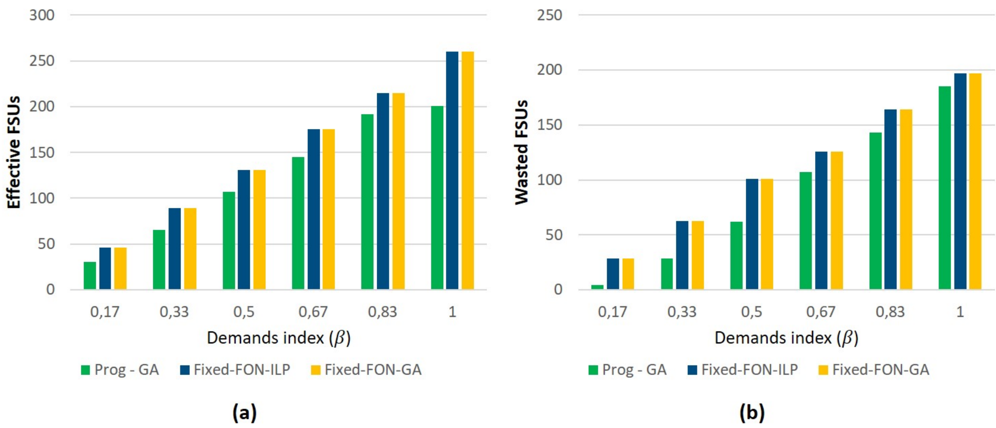


Figure 6.7: Comparison of Effective (a) and Wasted (b) FSUs consumptions for the Italian 10 nodes topology between TE P-FON and Given Trees FON

We can observe that, as already happened for the smaller 6-nodes topology, the minimization of Total FSUs influence the distribution of Effective and Wasted FSUs. However, as we claimed in chapter 3, it is impossible to avoid wastes even in P-FON and with the increasing of β.

Fig. 6.8 shows the average path lengths calculated in different scenarios. With respect to FON, also in this case the P-FON has proved to be more efficient, saving til 35 % of kilometers from the paths of effective demands thanks to its flexibility.
The outgoing depends on the value of β, it's not a fixed value. Shorter paths means that the demands will need on average less resources and optical elements to arrive from their source to their destination, so lower costs and gaining. Projecting this concept to bigger networks could be very important in CapEx and OpEx considerations.

Figure 6.8: Comparison of Average Path Lengths in the Italian 10 nodes topology between P-FON and FON solutions.

Let us consider now the P-FON scenario only. As we already claimed, the GA doesn't know the best number of fiber trees to establish in a network before actually calculating different cases. This allowed us to do further observations on the behaviour of PFON solutions. Fig. 6.9 shows the averages of every best solution in base of the number of trees utilized. So, for each value of β, every simulation of every set has calculated 3 times (due to restart) each case starting from 2 trees to 6 trees. Between one of the 3 results for each set, it has been selected the best solution and later averaged with all the other best solutions utilising the same number of trees but for a different set.

We state that too many or too few number of unidirectional fiber trees exploited to accommodate a certain traffic will led to solutions worst than the one which fits better being more balanced. However, this is not a global value, as we can see from Fig. 6.9 (a) for different values of β the most suitable results are returned by different indexes.
The fittest numbers of trees used in each case are showed in Table 6.8.

	β=0.17	β=0.33	β=0.5	β=0.67	β=0.83	β=1
Numtrees	6	5	5	4	4	5

Table 6.8: Best number of trees used by GA P-FON for each value of β

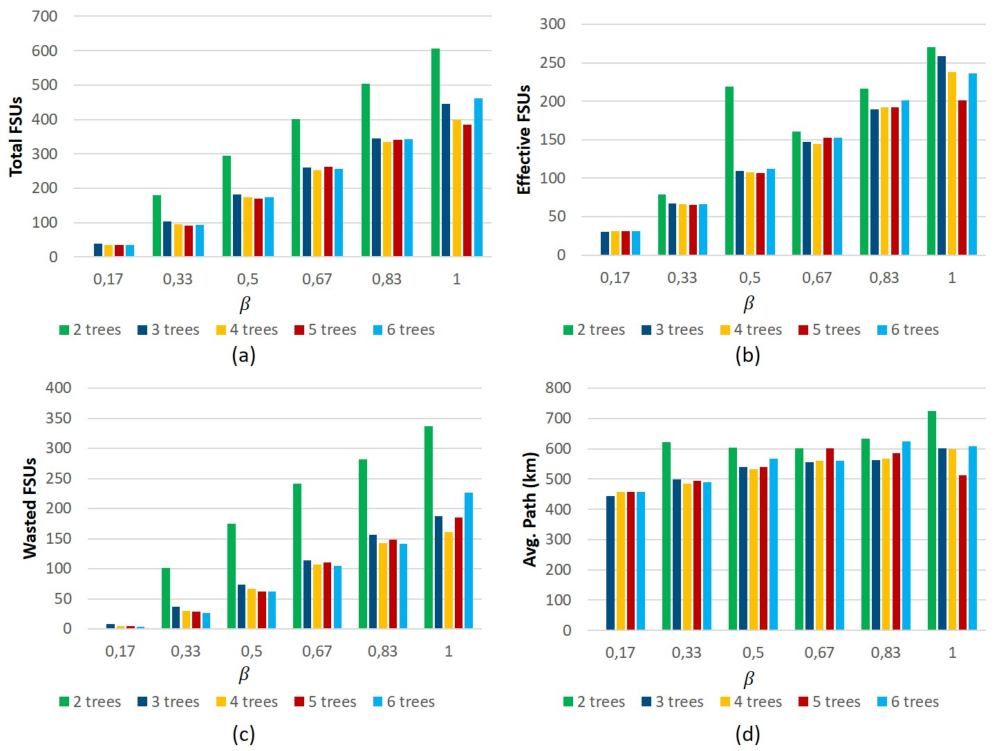


Figure 6.9: Averages results for P-FON obtained by all simulations divided per number of used trees, illustrating Total (a), Effective (b), Wasted (c) FSUs and the Average Path Length (d) for each value of β

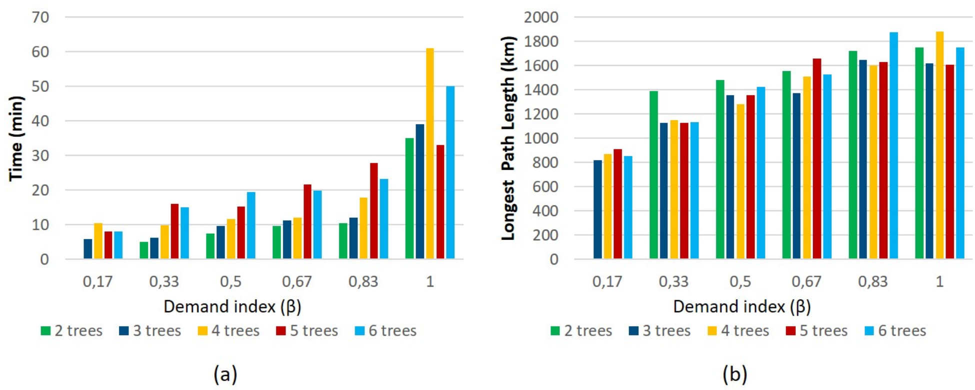


Figure 6.10: Time in minutes (a) and Longest path length (b) for each number of trees and for each value of β

Fig 6.10 (b) shows the Longest Path lengths. This could be useful for further network costs considerations as the amplifier allocation in the network. We see that the longest path increases almost as directly proportional to the values of β. This happens because of the congestion of the network in presence of traffic close to the full mesh and the consequent decreased flexibility of the P-FON scenario. For example, with lower β values, the algorithm can assign unidirectional fiber trees to different demands, being able to reduce the total FSUs by choosing a different path and without constraining two demands to travel on the same road. After a certain threshold, all the demands will not have choices because the fiber trees will be allocated to satisfy, between the others, also the more distant demands, having less choice in routing since their limited choice could be occupied by a more fittest connection. So, accumulating even the demands coming from the nodes intercepted by these fiber trees, an increasing amount of traffic is obliged to choose longer paths in absence of freedom.
As last consideration, we see that increasing the size of traffic demands and the number of trees has an important impact on the computational time required by the GA. In fact, as shown in Fig. 6.10 (a), the time required from a full mesh case ($\beta = 1$) in the worst calculation case (with 4 trees) can take till more than 6 times the faster simulation. The anomaly in the longer case is explained soon: the GA doesn't know if or when it will ever reach a better solution than its current one, and this is why we did all the *active, stuck* and *finish state* considerations. It could happen, as in this set of data, that a better solution has been found almost at the Finish state, having kept the algorithm in the *stuck state* for the maximum allowed number of generations. So, the process will enter again in the *active state*, and restart with his new current best solution. If this happen twice or more, the full mesh case (i.e. the most computationally heavy) results in that peak of time. Anyway, adopting a GA still allows to reach satisfying solutions in reasonable times.

6.3.0.1 Wavelength Index minimization

We now move to a different set of simulations, considering the minimization of wavelength index (WI) as an objective function. We considered a different approach to the spectrum minimization problem trying to distribute equally the assigned wavelengths between different fiber trees instead of min-

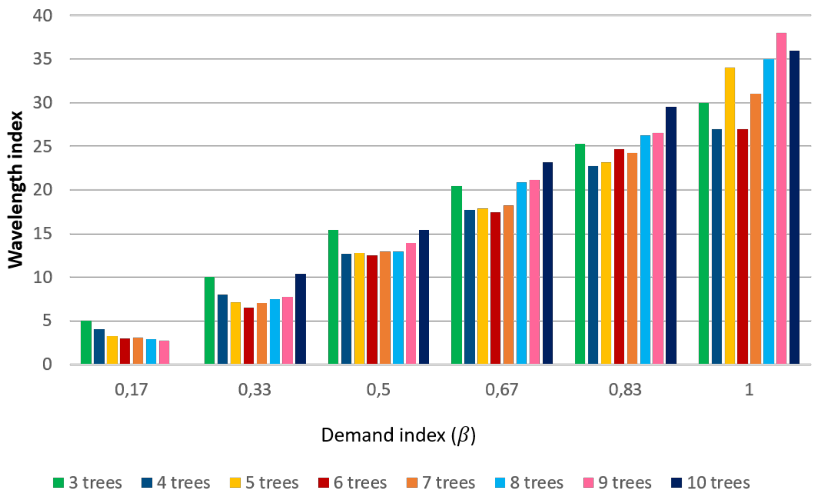


Figure 6.11: Maximum Wavelength index used by a tree, calculated for each number of trees established and for each value of β

imizing the spectrum only. This could be interesting basing on the network operator necessities, allowing him to avoid eventual trees congestions.
We studied the WI minimization problem in an Italian 10-nodes topology with the same sets of demands and values of β used before. Simulations have been done only in a P-FON environment, considering every node equipped with programmable switches.
In this section we are going to compare the results between each tree establishments, i.e. the ones obtained trying to allocate different numbers of trees in the network. In order to do this, we considered a range of values starting from 3 to 10 trees. We can see from Fig. 6.11 that, for the majority of β values, the best wavelengths distribution in this topology happens when using 4 or 6 trees. This is a good compromise between the dimensions of the network, the number of fiber trees and the traffic demands.

We see that for β=0,17 the best solution is obtained using 9 trees, while for higher values the graphs tend to assume the lowest peak in 4 or 6 trees. Moreover, even changing the objective function from FSU to WI minimization, a too high number of trees leads to unfeasible solutions, as pointed out by the absence of 10 trees case (dark blue column) for β=0,17. In fact, for this case all results have returned invalid solutions, not succeeding in the establishment of all the 10 trees. This behavior is highlighted in Table 6.9, where all results are listed for each tree and for each value of β. Following the row with trees equal to 4 or 6, it's easy to note that their WI values are the best available almost always.

Table 6.9: Best values of wavelength index for each value of β, averaged on all sets and for each number of fiber trees used in different cases.

Trees	β=0.17	β=0.33	β=0.5	β=0.67	β=0.83	β=1
3	5	10	15.4	20.4	25.3	30
4	4	8	12.7	17.7	22.7	27
5	3.2	7.1	12.8	17.9	23.2	34
6	3	6.5	12.5	17.4	24.7	27
7	3.1	7	12.9	18.22	24.2	31
8	2.88	7.5	13.9	20.9	26.3	35
9	2.67	7.7	15.4	21.1	26.5	38
10	-	10.4	16.1	23.2	29.5	36

Anyway, other factors can influence the choice of a network operator to adopt this approach. For this reason, in Fig. 6.12 we illustrate the comparisons between different average (a) and longest (b) path lengths depending once again by the β value and the number of trees established.

We can see a very particular behaviour, especially looking at Fig. 6.12 (a), were average path length seems to keep growing with the increasing of β, as expected, but the full mesh case shows that better roads can be obtained even with higher number of trees and demands. Fig. 6.12 (b) shows simply a constant increase of the maximum lengths.

Thirdly, one of the main advantages of this approach is the low computational time requested. Fig. 6.13 shows the average time consumption. We have been able to obtain the results in a span between 2 and 10 minutes each one, considering a determined set of one value of β for a given number of trees, meaning 1 or 2 hours for a complete calculation for that set with tree number going from 3 to 10.

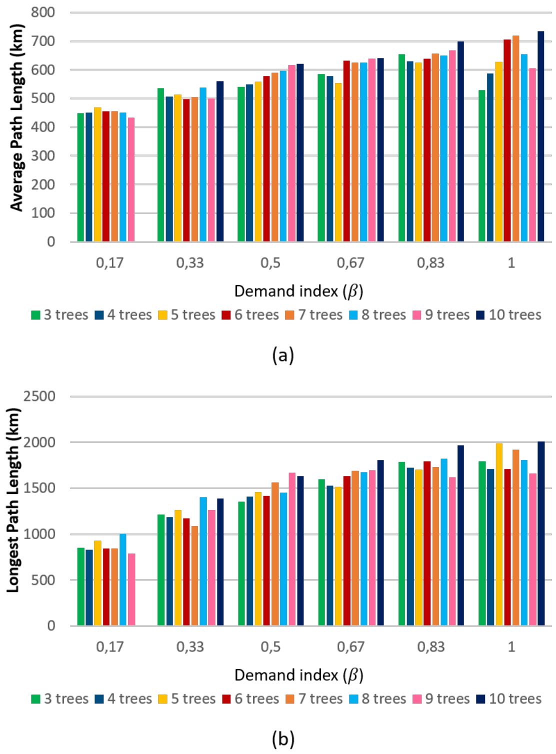


Figure 6.12: Average (a) and Maximum (b) path lengths in kilometers calculated for each number of trees and for each value of β

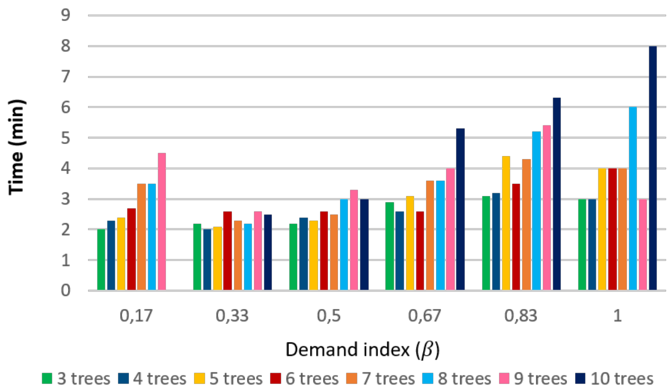


Figure 6.13: Average time requested (in minutes) by a single set calculated for each number of trees and for each value of β

Chapter 7

Conclusions

Filterless Optical Networks (FONs), based on broadcast-and-select architecture, are emerging as promising cost effective solution to face the increasing network costs but still improving the network's capacity. Due to their broadcast nature FON incur in great wastage of spectrum due to its absence of flexibility in the routing of demands once that bi-direcctional *fiber trees* has been established, since these need to satisfy a series of constraints as *laser-loop avoidance* and *node connectivity* which prevent a re-calculation.
As consequence, a more dynamic solution has been identified by considering Programmable Filterless Optical Networks (P-FONs). In this case, each filterless node is equipped with all optical switching elements which establish unidirectional fiber trees calculated ad-hoc after the traffic demands. At the cost of slightly higher expenses, P-FONs have a big impact on the reduction of the spectrum waste with respect to FONs. Thanks to this *flexibility* in tree establishment, P-FONs has become very interesting.
In this thesis we have investigated the major benefits and drawbacks of this approach, comparing it with the already cited FON. Then, we proposed an ILP model and exploit an heuristic approach based on a Genetic Algorithm in order to prove the benefits of P-FONs. We considered two main objective functions solving the Routing and Spectrum Allocation (RSA) problem while minimizing the total Frequency Spectrum Units (FSUs) or the Wavelength Index (WI). The network scenarios considered have been; 1) FON with fiber tree establishment already deployed and therefore assumed as given by the problem and 2) P-FON with tree establishment to be deployed and therefore to be determined by the problem.
To present a satisfactory analysis of comparisons, we solved the ILP model

and the heuristic for the RSA considering two topologies: 1) a 6-nodes network with all links 90 km long and 2) the Italian 10-node network.
Results validate the genetic algorithm showing a similar behaviour to the ILP model. However, the ILP application has not been always possible due to the unsuitable time requirements of this approach. GA results has proven to be very encouraging, showing that, for different traffic demands situations, a P-FON architecture behaves better than a FON one under the following evaluated points: 1) Total FSUs required to satisfy the traffic, 2) Effective FSUs associated to the demands (i.e. unavoidable), 3) Wasted FSUs due to the broadcast and select nature of both FON and P-FON, 4) Average Path Length walked by each demands and also 5) Longest Path Length. All results has been taken and averaged after many simulations to guarantee the best possible efficiency and accuracy in the analysis.
For the WI we considered results obtained using the GA in the Italian 10-nodes network. Comparisons have been done between different cases of tree establishments, depending on the number of trees. Unluckily, since it's a new approach, the choice of adopt this approach stands by the network operator in base of his necessity.

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