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A novel adaptive restoration algorithm for cost minimization of translucent optical networks

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Abstract

One of the main cost in translucent optical networks is composed by the deployment of optoelectronic devices dedicated to signal regeneration and/or wavelength conversion. As a consequence, minimization of the total number of deployed 3Rs without increasing the overall blocking probability of the traffic set-up is one of the main objective of the network design.

In this work, we considered optical restorable networks where the computation and set-up of alternative paths after fibers failure (restoration) ensure the traffic survivability.

In an optical restorable networks there are two types of 3Rs: nominal 3Rs, which are associated to a specific nominal path, and restoration 3Rs, sharable among diverse restoration paths that are computed for diffferent failure scenarios. In order to minimize the overall cost of the network, it is fundamental to reduce as much as possible the number of restoration 3Rs.

For achieving this goal, we proposed an adaptive alternative routing algorithm which is aware of the already deployed restoration 3Rs and favor the computation of alternative paths able to reuse installed 3Rs. The 1830 PSS Engineering and Planning Tool (EPT) was the Nokia tool used and modified.

The proposed algorithm was compared to the fixed alternative approach already implemented in EPT, in order to eval-

uate the number of restoration 3Rs saved with our method. The evaluations were done by comparing diverse networks topologies, some created for this study by varying the connectivity degree of an initial network, others related to customers' ones. To complete the assessment of the advantages provided by our algorithm, we also varied the number of shortest paths calculated by the alternative algorithm.

The obtained results showed that the proposed adaptive routing algorithm allowed to reduce the whole network cost by requiring less restoration 3Rs than the ones calculated with the legacy algorithm today used in EPT, based on a fixed routing approach.

Sommario

Uno dei principali costi delle reti ottiche é rappresentato dall'installazione di dispositivi ottico/elettronici dedicati alla rigenerazione dei segnali e/o alla conversione delle lunghezze d'onda. Di conseguenza uno degli obiettivi principali nel dimensionamento delle reti ottiche é la minimizzazione del numero di rigeneratori (3R) installati senza incrementare la probabilitá di blocco del traffico.
In questo lavoro vengono considerate reti ottiche dove la protezione del traffico in seguito a guasti delle risorse di rete viene garantita tramite il calcolo di rotte alternative (restoration).
In queste reti sono presenti due tipi di 3R: 3R nominali, associati a una specifica rotta nominale, e 3R di restoration, condivisibili tra diverse rotte di restoration che vengono utilizzate in seguito a diversi scenari di guasto. Per minimizzare il costo totale della rete é fondamentale ridurre il piú possibile il numero di 3R di restoration.
A tal scopo abbiamo proposto un algoritmo che calcola rotte multiple per ogni richiesta di connessione e si adatta alle condizioni della rete basate sulla conoscenza dei 3R di restoration allocati precedentemente e momentaneamente liberi; in questo modo la scelta delle rotte multiple é guidata dai 3R liberi presenti nella rete.
Il tool Nokia usato e modificato in questo lavoro di tesi é il 1830 PSS Engineering and Planning Tool (EPT).

L'algoritmo proposto é stato confrontato con l'approccio giá implementato in EPT in modo da valutare il guadagno in termini di 3R allocati utilizzando il nostro metodo. Queste valutazioni sono state fatte confrontando diverse topologie di rete, alcune create per questo studio variando il grado di connettivitá di una rete iniziale, altre scelte tra le reti dei clienti.

Per completare le valutazioni sui vantaggi introdotti dal nostro algoritmo abbiamo anche analizzato le reti al variare del numero di rotte multiple calcolate per ciascuna richiesta di connessione.

I risultati ottenuti hanno mostrato che l'algoritmo proposto permette la riduzione del costo totale della rete richiedendo un minor numero di 3R di restoration rispetto a quelli richiesti dall'algoritmo ufficiale implementato in EPT, basato su un approccio che utilizza rotte multiple che non vengono peró scelte in maniera adattativa.

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Chapter 1

Introduction

1.1 Overview and Motivation

The increasing amount of services that network operators have to transport through their networks pushes operators to deploy high capacity devices able to cover long distances. Optical technology based on Wavelength Division Multiplexing (WDM) systems allows the transportation of high data rates through optical fibers for long distances guaranteeing an acceptable quality in the most efficient way, both in terms of energy and costs.
Due to their hierarchical structure, backbone networks collect traffic from periferic networks (metropolitan and provincial), carrying big amount of data (nowadays a single channel in an optical fiber can carry more than 200 Gbit/s and 500 Gbit/s forthcoming). But the optical reach, the distance that such high capacity devices can cover with a signal quality over a given quality threshold, decreases with the increase of the transmitted data rate, because the impact of physical layer impairments depends on the amount of information carried.
Optical transponders (OTs) are optoelectronic devices that allow the transport of such amount of traffic at a high rate into the optical fiber. At the same time, OTs can be used to regenerate the optical signal so as to permit the transmission over distances longer than the optical reach. Optical net-

works that use OTs for regeneration purposes are called translucent. Optical regenerators are obtained by coupling two OTs in a back to back configurations. The regeneration obtained by the OTs is three-fold: re-amplification, re-timing and re-shaping. For this reason such regenerations is called 3Rs in the following.
Beside signal regeneration, a 3R device allows to change wavelength. During a regeneration the optical signal is firstly converted in electronic domain, and then is optically re-transmitted in the network with any wavelength (independently of the input one). This chance contributes to reduce the blocking of the connections due to wavelengths unavailability. In some networks, 3Rs are not used for copying with physical impairment issues, but with wavelength continuity constraints.
Despite of the benefits 3Rs bring in the networks, their deployment represents an important part of the overall network cost. Network operators want to carry the traffic in the most cost-efficient way and one of the main challenge for them is the minimization of the number of 3Rs deployed in the network while keeping as low as possible the overall blocking probability (due both to physical impairments and to wavelength conversion).
The resources allocated into a network are outputs of a network dimensioning phase performed by a planning tool. Given as inputs the network topology (set of nodes, links and their features) and a traffic matrix (set of connections with transmission data rates, FEC, survivability requirements and so on), a planning tool calculates the paths that have to be followed by each connection and where to place optoelectronic devices, in particular 3Rs.
Routing and Wavelength Assignment (RWA) is the core process of dimensioning optical networks, as it decides how to route traffic connections and which wavelengths assign to each route.
Planning tools that are based on Integer Linear Programming (ILP) could provide optimal solutions, but they are computationally heavy and often are not usable. So heuristic algorithms providing a sub-optimal solution are used by planning tools for dimensioning networks.

Optical networks are subject of resource failures (OTs, fibers, amplifiers, ...). Due to the huge amount of transported traffic, it is mandatory for a network operator to guarantee the survivability of the traffic when a failure arises; i.e., operators want to guarantee the existence of an alternative path where to route the affected traffic. Survivability can be ensured either by the computation of a dedicated and precomputed path (protection process), or by the computation of the alternative path only once the failure arises (restoration). Extra resources are so required. While in the first case resources are dedicated to each path, in the second case they can be sharable if the computed paths are not related to the same failure scenario.
A good strategy for sharing restoration 3Rs is the better manner for an operator to improve the network cost efficiency.
In this work, we will focus on the reduction of 3Rs devices for restoration paths with the aim of proposing an enhanced RWA algorithm able to exploit as much as possible available restoration 3Rs and improve their sharing.
As greedy algorithms are used to dimension networks, adaptive algorithms aware of the current network state are the more attractive solutions. Then we proposed an adaptive alternative routing algorithm for restoration phase, that is aware of the presence of available restoration 3Rs in the network.
The 1830 PSS Engineering and Planning Tool (1830 PSS EPT) provided to Nokia customers has been used and modified for dimensioning diverse networks in order to validate the proposed algorithm.
The proposed approach is based on the actual RWA algorithm implemented for 1830 PSS EPT, but the adaptive approach allows a further reduction of restoration 3Rs allocated in the network.
A comparison between the proposed algorithm and the actual algorithm is taken in order to evaluate the improvement of the proposed algorithm.

1.2 Outline of the thesis

This thesis is divided in seven chapters, including the current one, and they are organized as follows:

- chapter 2 provides an overview about backbone networks and their evolution from opaque to translucent, then it describes some fundamental network components like Reconfigurable Optical Add Drop Multiplexer (ROADM) and Optical Transponders (OTs);
- chapter 3 provides a brief classification of RWA process taking into account physical layer impairments (PLI) and the Regenerator Placement Problem (RPP);
- chapter 4 describes the 1830 PSS EPT planning tool used in this work, giving a detailed explanation of its RWA process. It presents an overview on restoration techniques used in literature and the ones adopted by EPT, and it finally describes the simulator used to validate the algorithm proposed in this study;
- chapter 5 introduces the proposed routing algorithm named Adaptive Alternative RWA (AA-RWA), describing the adaptive mechanism and its difference with the Fixed Alternative RWA (FA-RWA) actually implemented in 1830 PSS EPT;
- chapter 6 compares the two algorithms AA-RWA and FA-RWA by dimensioning various study case and customers' networks, showing the results in terms of resources (deployed 3Rs and occupied optical wavelengths);
- chapter 7 presents the final conclusions about the advantages provided by the proposed algorithm and discusses about possible enhancements for future works.

Chapter 2

Translucent backbone networks

Optical backbone networks based on Wavelenght Division Multiplexing (WDM) evolved from traditional opaque networks to translucent networks able to carry the same traffic demands with a reduced cost of the network.
In this context, the placement of regenerators in translucent networks plays a fundamental role as the optical transponders used for 3R regeneration (Re-amplification, Re-shaping, Re-timing) represent the main part of the cost in backbone networks.
In this chapter we describe the evolution of backbone networks, and provide an overview on the fundamental network components like Reconfigurable Optical Add Drop Multiplexer (ROADM) and Optical Transponders (OTs), in order to have a good representation of the network environment discussed in our work.

2.1 The evolution of backbone networks

The whole architecture of telecom optical networks can be represented as in Fig. 2.1, where backbone network is the root that has the rest of the network segments attached to it. Backbone network (also called core network) represents the largest part of a telecommunication network and it is used to interconnect the lower subnetworks in the hierarchical structure, which provide then the final service to the clients through the access network.

The more we go up in the hierarchy (as shown in Fig. 2.1) the more the distances covered by the subnetworks and the traffic to be transported increase, as a consequence of the traffic grooming from a lower level to the higher. New optical technologies have been deployed in the metro part to support scalable aggregation of access traffic towards the backbone network [1]. Then it is evident that backbone network needs to provide a large transmission capacity (nowadays the data rate transported in a fiber can arrive even to 200 Gbit/s) to transport information through high distances (thousands of kilometers) guaranteeing high reliability.

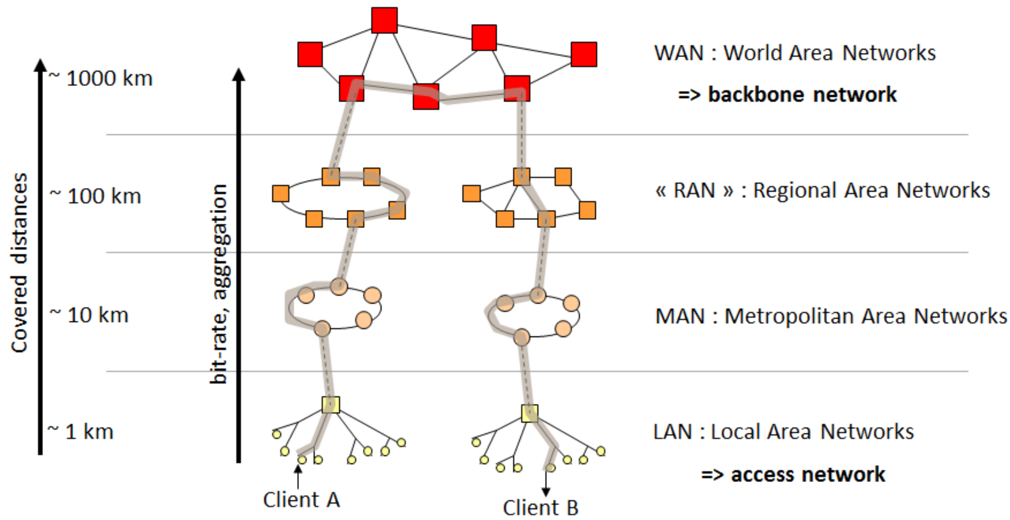


Figure 2.1: Architecture scheme of an optical transport network

2.1.1 WDM systems

Optical technology exploiting the wide spectrum of optical fibers is the fundamental key that allows the metro and backbone networks to carry large amount of information. WDM technology is the best approach to take advantage of the large available bandwidth in an optical fiber, as it divides the bandwidth of a single fiber into different wavelength channels that do not interfere with each other and can carry information simultaneously [2].

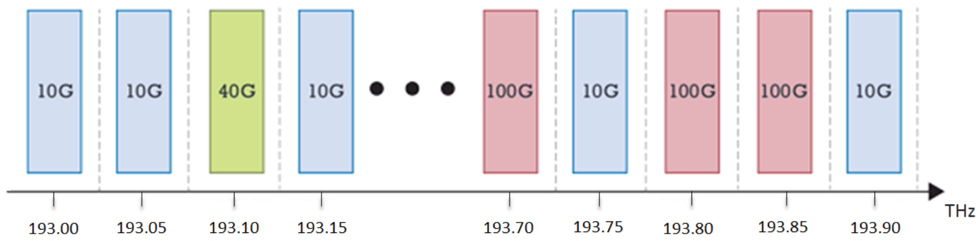


Figure 2.2: *Dense DWDM systems*

WDM systems are divided into different wavelength patterns according to the spacing between adjacent channels. Modern WDM networks typically support 88 channels using a fixed 50 GHz grid pattern within the C-band according to the Dense WDM system defined by industry standard ITU G.694.
The optical rates actually supported in WDM networks are 10G, 40G, 100G, as they all fit into the 50 GHz channels (Fig. 2.2). But while 40G and 100G signals use almost all the bandwidth of the 50 GHz channels, a 10G signal easily fits into the channel and it wastes about half spectrum of it. This waste of bandwidth reduces the spectral efficiency of the system, defined as the number of bit transmitted per Hz of optical spectrum.
Furthermore, the growth of traffic requires higher data rates, then carriers are already thinking about 400G and 1T channels in their future networks while keeping the same spectral efficiency [3]. In order to support these high transmission rates, new techniques of allocating bandwidth are needed together with a wide use of ROADM based nodes with colorless, directionless and contentionless (CDC) properties (an overview in section 2.2) and the development of distance-adaptive optical transponders capable to dynamically adjust the modulation format, coding rate and spectrum width according to the transmission link characteristics [1].
A new flexible grid pattern is already defined by ITU G.694.1, partitioned in much finer frequency slices having a spectral width of 12,5 GHz or 6,25 instead of 50 GHz (fixed D-WDM) [4]. The new standard supports mixed channel sizes thanks to the concept of superchannels. A high rate signal

can be transmitted over a group of multiple subcarrier channels, commonly referred to as a superchannel. Even if composed of single subcarriers, each superchannel is provisioned, transmited and switched across the network as a single entity [3]. For example using a flexible grid WDM system a service of 400G can be transmitted through a superchannel of 12 subcarriers (12x12,5 GHz).
One of the advantages of the flexible grid is the improvement in spectral efficiency, due to a closer matching of signals transported with the channel size.

2.1.2 Translucent networks

In WDM networks a lightpath is defined as an end-to-end circuit switched optical connection that traverses one or more links using the same WDM channel for all the links belonging to the path. So a lightpath is completely optical for all its length and it does not regenerate the signal at any intermediate node.
Physical Layer Impairments (PLI) [5] such as optical noise, polarization mode dispersion, amplifier spontaneous emission, polarization dependent loss, chromatic dispersion and crosstalk can gradually degrade the quality of the lightpath until reaching an unacceptable quality threshold that blocks the connection. Defining the optical reach like the maximum distance an optical signal can travel before 3R regeneration is needed [5], a connection is blocked when a lightpath traverses a distance longer than the optical reach without any regeneration. We define request (or overall) blocking the percentage of connections blocked with respect to the total number of connections required.
In order to go beyond these transparent reach limits, signal regeneration is necessary to re-amplify, re-shape and re-time the optical signals.
Optical networks can be divided in three categories:

- opaque optical networks, where every node is capable of optoelectronic (O/E/O) conversion. Request blocking is negligible here as the optical path has the possibility to regenerate the signal at each hop. On the other hand, opaque networks are very expensive as each node has to be provisioned with optoelectronic conversion equipment;

- transparent optical networks, where traffic is carried end-to-end in the optical domain without any intermediate O/E/O conversion. This solution is the cheapest one as all the networks components are optical devices and there is no need of optoelectronic equipment in the nodes, but it presents more constraints, like wavelength continuity;
- translucent optical network provides only some sparse nodes with regeneration capabilities: a set of sparsely placed regenerators is used to mantain the acceptable level of signal quality for all the traffic connections [6]. It represents a trade-off between the previous two solutions as it reduces networt cost considerably with respect to opaque network while giving signals the possibility to regenerate and change wavelength in their path [7].

Of course transparent optical network would be the ideal solution in terms of network cost, but due to PLI many demands may be blocked, hence translucent optical network is considered the best solution to address such a concern by allowing for sparse regenerators in the network. An indirect advantage of allocating regenerators in the network consists in their wavelength conversion capability, that can be used to reduce wavelength collision when routing lightpaths [8].
In a translucent network a lightpath between a source and destination couple that does not require regeneration is called transparent lightpath. If the length of the lightpath is longer than the optical reach and then at least one regeneration is needed, the lightpath is called translucent. So a translucent lightpath may be divided in more components, where each component is a transparent lightpath [5]. Fig. 2.3 shows an example of a translucent lightpath composed by two transparent lightpaths.
The translucent optical networks bridges the gap between opaque and trans-

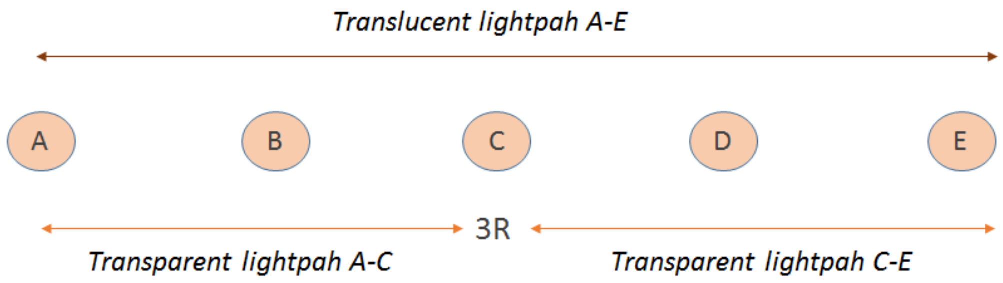


Figure 2.3: *Example of translucent and transparent lightpaths*

parent networks. Research work reveals that the performance of translucent optical network is very close to the one provided by the fully opaque network in terms of the overall blocking but at the same time it drastically reduces the costs, that can be compared to the costs of transparent optical networks.[2]

Due to these reasons translucent optical networks are the solution more deployed by network operator at the moment.

2.2 Node architecture

In the last decades operators have been focused on driving more functionalities from the electrical layer to the optical layer when possible because optical transport is less costly due to its high transmission capacity over very long distances. So the network nodes in backbone networks must have the capability to selectively drop traffic at a node, while allowing the remaining traffic to transit the node in the optical domain and switch it towards other directions. This capability is accomplished through the deployment of nodes like ROADM, that allows wavelengths carrying WDM channels to be added and/or dropped from a transport fiber without the need of an optoelectronic conversion.

The ROADM-based node architecture is one of the most used for translucent backbone networks thanks to an extensive range of features including colorless, directionless and contentionless features, and the capability to

support flexible grid and higher modulation formats.
Many possible configurations of ROADM nodes are available depending on the devices used to build the node. In figures 2.4 and 2.5 we describe some of these node architectures.
With node degree we indicate the number of external lines of the node. Each degree is an output line and is indicated with its direction (North, East, South and West). The figures divide each degree in two parts: drop on the left and add on the right.
The Wavelength Selective Switch (WSS) is a fundamental device in ROADM node architecture, as it can be used in Add/Drop blocks to select which wavelength channels are to pass through it while optically blocking the others. This can be realized with the Planar Lightwave Circuit (PLC), a device cheaper than the WSS but with less functionalities.
Depending on what the blocks called A and B in figures 2.4 and 2.5 represent, we have two main architectures:

- broadcast-and-select if A is a splitter and B a WSS;
- route-and-select if both A and B are WSS.

In a broadcast-and-select architecture, a broadcasting power splitter distributes the channels of the input signal to all the output ports of the splitter. While in route-and-select architecture, replacing the splitter with a WSS provides the ability to limit the channels directed to the other degrees to only those channels intended to be detected by the other degrees [9].
Fig. 2.4 shows a simplified scheme of a four-degree directional ROADM node architecture. It is directional because each degree is connected to his local add/drop block (represented with the block C in Fig. 2.4). The add/drop blocks for each degree can be implemented:

- through Arrayed Waveguide Grating (AWG) multiplexers and demultiplexers. This configuration is defined colored as we can add/drop a channel only from/to a specific port of the AWG;

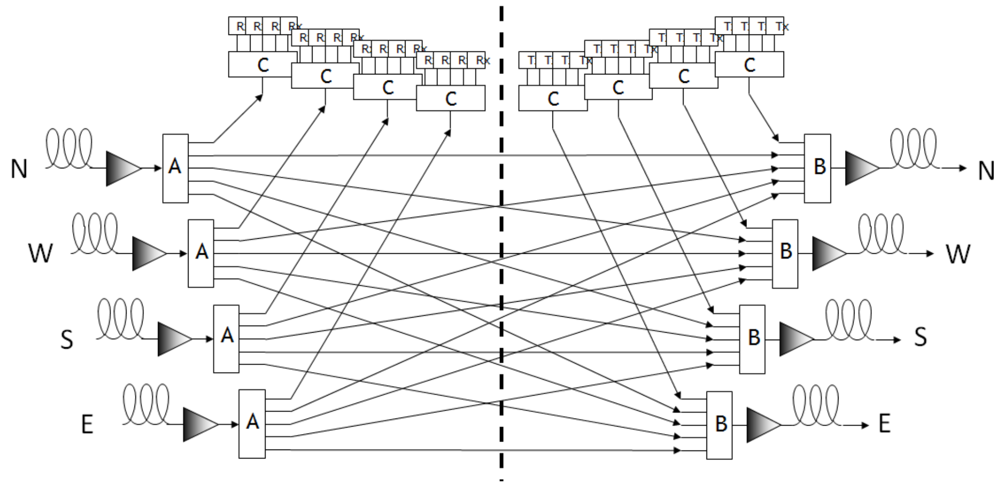


Figure 2.4: *Scheme of a four-degree colored and directional ROADM node*

- through a PLC capable to add/drop each channel in the desired port (colorless configuration).

Fig. 2.5 presents a scheme of a three-degree Colorless Directionless (CD) ROADM node architecture. In this architecture the Add/Drop blocks are not referred to a single degree like in Fig. 2.4 , but they manage channels coming from all the node degrees. To include the directionless feature, the Add/Drop block is composed by a WSS which combine the respective wavelengths coming from each degree to a single fiber. After a small optical amplification, these wavelengths are split to a multitude of coherent receivers [9]. The same operations in the opposite direction are performed in the add section.

In the discussed node architecture two or more signals with the same wavelength going to the same Add/Drop block would be in conflict, so this model is not contentionless. The best solution for contentionless is the quite recent model of node Colorless Directionless Contentionless (CDC) ROADM. The contentionless property of the CDC node architecture is given by the presence of MCS (Multicast Switch) blocks in the Add/Drop section. The MCS allows any signal to reach any Add/Drop port for any color preventing any interference between channels operating at the same wavelength, then

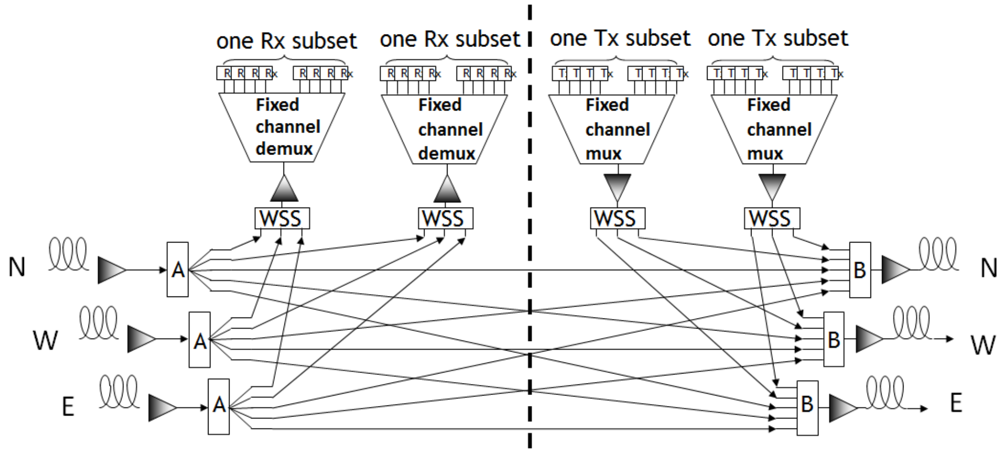


Figure 2.5: Scheme of a three-degree colorless and directionless ROADM node

the same color can be managed N times by the Add/Drop block, with the factor N depending on the type of MCS.

The CDC node architecture is the best node architecture that can be deployed as it allows wavelength add/drop to any port, any wavelength to add/drop to/from any direction (directionless), and to enable on the same Add/Drop block multiple copies of the same wavelength coming from different degrees (contentionless) [10]. Nevertheless, the CDC solution is not widely used until now due to its complexity and high cost.

2.3 OT and 3R process

This section is an overview about the regeneration process and Optical Transponders (OT); these are fundamental blocks in translucent backbone networks as they allow the set-up of lightpaths and provide the capability to regenerate an optical signal. The OT is the most expensive component of a backbone network, due to its complex based on the optoelectronic conversions it performs.

An OT is a device provided by a short reach interface on the client side and a WDM-compatible signal on the network side. It collects a black-and-white optical signal from the client interface and it performs a O/E/O conversion

in order to: add additional bits for FEC, map the information to be transmitted in OTN frames, modulate the signal in a given modulation scheme and send it on a specific frequency corresponding to a WDM channel and finally transmit in the network the optical signal with the correct power through the line interface.
Traffic matrices are always bidirectional, then for each link of the network we deploy two fibers (one for each direction) in order to transmit optical signals in both directions.
The operations previously described are inverted when the other direction is considered, when the OT receives a signal from the line interface and has to deliver it to the client. Each client and line interface is bidirectional as it has to receive and transmit signals, so it is equipped with both receiver and transceiver. In this way each OT can be used for both transmitting and receiving optical signals.
The OTs are used as endpoints of lightpaths in backbone networks, so becoming source and destination of a demand. Furthermore they allow the regeneration and/or wavelength conversion of optical signals through O/E/O conversion. The O/E/O regeneration is the more reliable and economic regeneration into the optical domain [8]. Such operation converts the optical signal that needs regeneration into electronic format and then uses the electronic signal to modulate an optical laaser in order to re-transmit the regenerated optical signal in the network.
If required by network constraints it is possible to change the wavelength of the lightpath while regenerating, to choose an output WDM channel that can be different from the arriving one. Thanks to the wavelength conversion capability it is possible to overcome wavelength collisions in congested links and avoid signal blocking.
In the following we name 3R such type of O/E/O regeneration.
There are many possible configurations of regeneration that can be chosen according to the type of OT used. Parameters like the number of line interfaces combined with the data rate handled are important to decide the right configuration of regeneration. Fig. 2.6 shows a typical regeneration

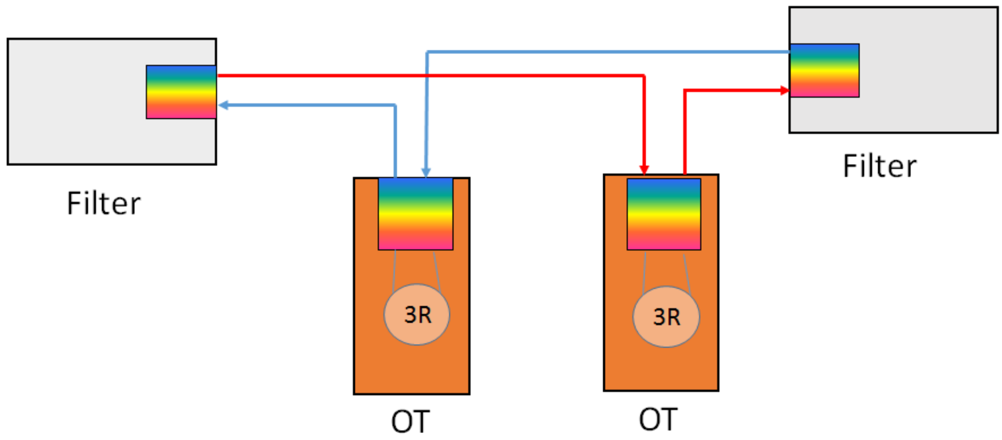


Figure 2.6: *Example of 3R process*

configuration where each OT is dedicated to O/E/O regeneration.
Unless the OT has more than one line interface, the 3R process needs two OTs, one for direction. Fig. 2.6 presents a simplified scheme in which we show the two OTs in the middle of the connection, but really the two OTs are placed inside a node passing through Add/Drop block.
The capability of dynamically change or not the input/output wavelength of the 3R operation depends on the type of Add/Drop block to which the 3R is connected 2.2.
An example of optical transponder scheme is shown in the Fig. 2.7, where we find a simplified scheme about the OT 130SNX10(LN). We chose to show this specific OT as an example because it is the OT used for the tests in section 6.3.
This OT is an optical muxponder because it has multiple clients interfaces, specifically 10 client interfaces each one of 10 Gbit/s, that are multiplexed on the line interface into only one WDM optical signal working at 130 Gbit/s (30 Gbit/s are used for the FEC overhead). The original signal is encoded with Soft Decision Forward Error Correction (SD-FEC) which add error detection and correction overhead information in order to lower the BER and extend the optical reach of the lightpaths.

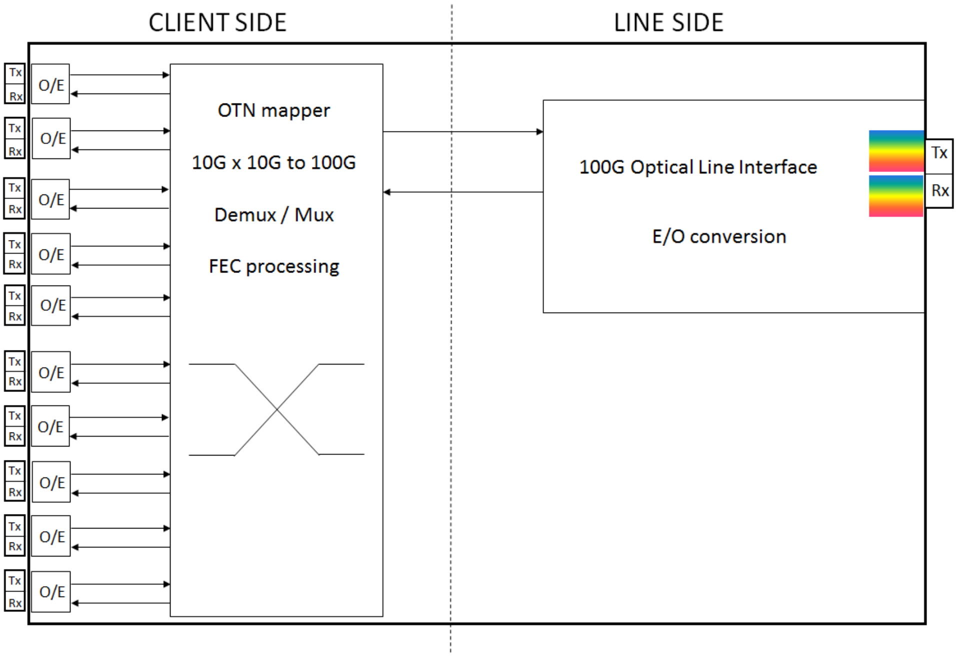


Figure 2.7: *Optical Muxponder 130SNX10(LN)*

The OTs electronics and optical components capable to manage high rate coherent signals have significative impact on the whole cost of the OT. Working with coherent signals gives operators the possibility to transmit over long distances signals with rate above 40 Gbit/s (up to 250 Gbit/s commercially available).

Chapter 3

RWA: state of art

3.1 Introduction

Routing and Wavelength Assignment (RWA) is one of the core problems to be solved in planning optical networks. Given a network topology and a traffic matrix (set of traffic connections, also called demands), RWA calculates lightpaths between the couple of nodes associated to each demand.
In transparent networks there is no node with optoelectronic devices dedicated to regenerator or wavelength conversion, the demands can be set-up only through transparent lightpaths (in 2.1.2 we provided the definitions of transparent and translucent lightpaths). In case the transparent lighptath is not feasible the connection is blocked.
In a transparent network RWA is known to be a NP-complete problem [11]. Its aim is to minimize the overall blocking probability (percentage of demands blocked because of the absence of feasible lightpaths among the selected paths). Many works in technical literature deal with RWA problem in transparent networks proposing both ILP formulations and heuristics (a survey is presented in [12]).
As stated in Chapter 2 , the optical backbone networks deployed by operators are translucent networks. For this type of networks the RWA problem is even more complicated, as the placement of regenerators/wavelength con-

verters (3Rs) in the network has to be solved jointly. The main challenge in translucent network becomes the minimization of allocated 3Rs so that all the traffic connections can be set-up.

3.2 Routing and wavelength assignment

An RWA problem has to find a path associated to the request (routing problem, R) and then associate a free wavelength along this path (wavelength allocation, WA). These two subproblems can be solved separately (R+WA) or jointly (RWA).

3.2.1 Routing phase

The routing problem is a fundamental subphase in RWA. In technical literature we can find three main approaches [13]:

- Fixed routing: any connection request between a given couple of nodes is always routed through a fixed path, usually the shortest path (calculated by Dijkstra-like algorithms). This solution is fast, but it presents many blocked connections due to resources unavailability;
- Fixed Alternative routing: a connection request between a given couple of nodes is routed among one of k fixed paths (they are called fixed because are pre-calculated and are not aware of the current state of the network). The alternative routing requires more computation time, but it decreases the previous blocking probability providing suboptimal solutions;
- Adaptive Alternative routing: the connection request is routed among one of K paths selected according to a network-status aware policy (they are called adaptive as the network resource weights change with the network state). The adaptive approach requires even more computation time, but it provides the best results.

The alternative approach is the most used as it provides the demand multiple feasible routes reducing the overall blocking probability. In Chapter 5 we will describe with more details the routing process explaining the routing phase of the planning tool used in this study together with the description of the proposed routing algorithm.

3.2.2 Wavelength assignment phase

Usually wavelength assignment problem comes after the routing of the demands. A suitable wavelength is assigned to the chosen path according to various policies, the most common of which are:

- First Fit: the first available wavelength among the path links is selected;
- Random: the wavelength is chosen randomly with uniform probability from the set of available wavelengths associated to the path.

The First Fit policy is usually preferred due to its low computational complexity and implementation simplicity. On the other hand, Random policy outperforms First Fit when transmission impairments are considered in RWA, because intra-channel and inter-channel crosstalk become high when First Fit is used [14].
Other possible policies for wavelength assignment are: Least Used, Most Used, Best Fit, Min Product, Least Loaded. We do not provide further details about these policies as they are not used in our work.

3.3 Offline vs Online

Network planning process can deal with two main types of traffic matrices [15]:

- Static: the set of demands is fixed and known in advance;

- Dynamic: the demands arrive while the network operates. In simulation studies, such events are emulated by creating new demands with a random process and each demand has a random pre-defined holding time.

According to this classification, RWA problem can be defined:

- Offline if the traffic matrix is static;
- Online if the traffic matrix is dynamic along time.

All optical backbone operators typically do a traffic forecast in order to know the bandwidth to allocate between two nodes. should be allocated between the clients. The set of traffic connections (also called demands) is usually at least partially known, enabling the network operator to perform resource allocation task offline [16].
The offline RWA is known to be an NP-hard optimization problem [15]. A common technique used to solve offline RWA problem is a heuristic approach where the demands of the static traffic matrix are considered sequentially [17].
Many heuristic algorithms proposed in technical literature (e.g. [18] and [19]) have used this technique by considering demands sequentially, converting an offline RWA into an online RWA.
Ideally, the offline RWA should be solved through ILP, but ILP formulations are not suitable for large scale problems due to their huge complexity. Then heuristic algorithms are the only practical technique, even if they do not guarantee the optimal solution for the problem.

3.4 Impairments Aware RWA

A lightpath is feasible if it can be correctly received at its destination node, that is the ratio of uncorrect decoded bits is lower than a given threshold. The incorporation of PLI (in section 2.1.2 more details about PLI) in the RWA problem is fundamental to drastically reduce the blocking probability.

The algorithm integrating PLI in RWA are called IA-RWA in the literature [20].

3.4.1 IA-RWA in transparent networks

To take into account the PLI, a further step has to be added into the RWA routine, where the cumulation of PLI along the path is computed. PLI verification should be added either at the end of RWA solution or between R and WA subproblems or can be considered during the routing phase (as some proposed ILP solutions do [16]).
A heuristic approach is described in [21], where a given number of permutations of the demand set is used in order to minimize the blocking probability. For each permutation of the demands, fixed alternative routing is performed. Then wavelengths are assigned to the routes chosen following a First-Fit policy and finally the paths feasibility is verified. Results in terms of blocking probability are saved for each permutation and the one with the lower blocking probability is saved as the final solution.
A related problem is considered in [19], where an enhanced Random Search RWA (RS-RWA) algorithm is proposed. For a certain number of different random demands ordering, the algorithm performs sequential processing of connection requests in order to find the lightpath assignment that achieves the lowest overall blocking probability.
If an ILP is used for RWA problem, all the demands are considered at the same time in order to find the solution. To include PLI, constraints related to the impairments can be added for the routing phase in order to choose only feasible paths among the possible ones. As stated in section 2.1.2, many physical layer impairments can be considered, as so it would be difficult to deal with all of them associating to each one a specific constraint. Then it is often used a qualitative parameter like the Q-factor (quality factor), which represent the PLI with just one parameter making much easier a modelization of the problem.

3.4.2 IA-RWA in translucent networks

In translucent optical networks the IA-RWA problem has to be solved taking into account the possibility of 3R processes in some nodes along the path. Then the selection of such nodes play a fundamental role in the network dimensioning.
The Regenerator Placement Problem (RPP) allows the choice of a restricted number of nodes provided with 3Rs, so that any couple of nodes in the network can set-up feasible connections.
RPP can be solved before or jointly with RWA. The best solution (implemented in the planning tool described in Chapter 4) is to solve the two problems jointly because the total number of resources should be a result of planning rather than being fixed a priori [22]. Section 3.5 provides an overview about RPP techniques.
If RPP is processed at the beginning of the problem, the Routing with Regenerator Problem (RRP) optimally routes a translucent lightpath using the minimum number of 3R regenerators [23]. In technical literature we can find several works facing this problem.
In [17], RRP is solved with few subphases:

- firstly, connections needing regenerators are organized into a sequence of transparent connections thanks to an ILP. In this way the initial traffic matrix is converted into a new one composed of all node-destination pairs that can be transparently connected;
- the second phase applies an IA-RWA algorithm for transparent networks with the transparent matrix previously calculated as input.

In [18], the authors study the problems of Regenerator Site Selection (RSS) and Regenerator Placement for Mixed Line Rate optical networks (MLR-RSSRP). They propose an ILP for small scale problems and heuristic algorithms in order to solve large scale problems. The optical reach expressed with the maximum covered distance by an optical signal is used to measure the effect of impairments. Different line rates correspond to different reach values, so a set of reaches A is associated to each line rate. The proposed heuristic divides the problem in two subphases:

- demands ordering: deciding the demand sequence to be processed according to the number of hops of the shortest paths or the line rates (i.e. routing first the demands with more number of hops in the shortest path and higher line rates);
- routing of the demands through the shortest path jointly with regenerator placement (if the path length is longer than the reachability associated to the demand rate).

3.5 Regenerator Placement Problem (RPP)

In this section we describe the main techniques used in technical literature to solve RPP:

- Transparent Islands (TI);
- Sparsely placed 3Rs.

As we are in a translucent network environment, both approaches need to choose a set of nodes to equip with 3Rs. They differ each other on how they choose these strategic nodes [2].

3.5.1 Transparent islands

A transparent island (TI) is a set of nodes able to estabilish connection among nodes belonging to the same island using transparent lightpath, so without needing regenerations. TI-based translucent optical networks are optical networks composed by adjacent TIs. Only boundary nodes are equipped with regenerators so that interconnection between different TI are allowed.

3.5.1.1 Connectivity graph

One of the most promising single-layer translucent design technique is the connectivity graph [24], which is associated to the idea of transparent islands. Given a graph *G(N,A)*, its connectivity graph *G'(N,A')* is obtained adding in the set *A'* all the feasible logical links between any couple of nodes beloging to the same TI. In other words, the logical links in *A'* represent the couple of nodes that can be connected through a transparent lightpath. Applying an alternative routing over a connectivity graph, we obtain a *k*-path (*k-p*) connectivity graph, where each logical link *(i,j)* ∈ *A'* represents at most k physical routes [22]. In Fig. 3.1 the logical edge 1-3 in graph *G'(N,A')* is mapped into k=3 paths in the physical graph *G(N,A)*.

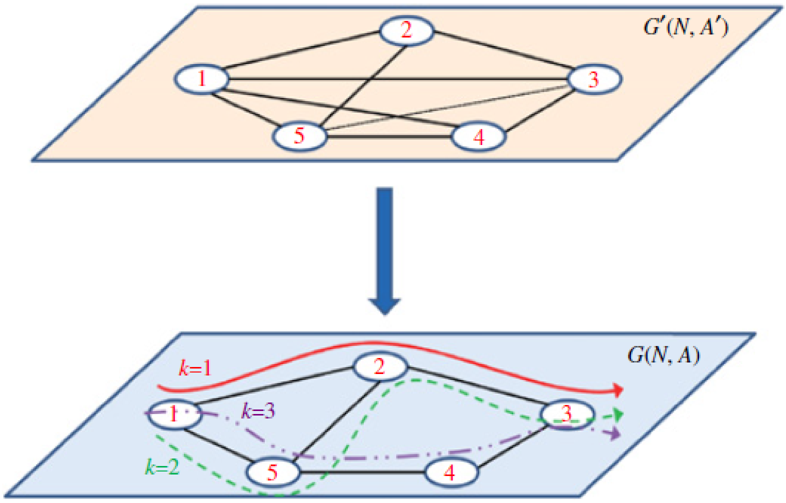


Figure 3.1: *Mapping of the logical edge 1-3 over k=3 physical routes*

In [25] the concept of "wavelength class" is introduced; wavelength classes divide the DWDM channels into three main groups according to the range of optical reach. Then the *k-p* connectivity graph is extended to a "wavelength-aware" *k-p* connectivity graph, where each wavelength class has its own connectivity graph according to their different optical reach.

Based on the concept of connectivity graph, in [22] an hybrid method combining a simplified IA-ILP and heuristic algorithms has been proposed.

3.5.2 Sparsely placed 3Rs

In sparse 3R placement approach any node can potentially host regenerators. The sparse placement strategy usually allocates less 3Rs than what TI-based translucent networks do [2]. In the following we describe some of the several regenerators placement strategies proposed in technical literature.
In [26] two main approaches about the selection of regeneration nodes using sparsely placed 3Rs are proposed:

- Nodal Degree First (NDF) algorithm iteratively chooses the regeneration nodes according to their nodal degree: at each step it adds to the regeneration node list the node mostly connected and decreases by one the nodal degree of the neighbor nodes. This routine is repeated until a given number of regenerator nodes has been selected;
- Centered Node First (CNF) algorithm order all the nodes according to their decreasing order of topological centrality, which takes into account how many time a node is crossed by the shortest path of each couple of nodes in the network. The nodes with higher rank are equipped with regenerators.

In [27] regenerator placement and wavelength assignment problems are solved jointly thanks to the introduction of a new auxiliary graph model. For each demand the shortest path is calculated and proper weights are updated on every edge of the auxiliary graph, this mechanism help the RWA phase of future requests. In this way, the total number of regenerators required due to wavelength continuity constraint is minimized.

3.6 Conclusions

This overview on RWA is useful to introduce the RWA of the planning tool used in this work. The RWA in Nokia planning tool is an offline RWA problem performed with a greedy algorithm that incrementally solves the RWA of each demand jointly with RPP. A focus on the RWA phase of the Nokia planning tool will be provided in section 4.4.
In Chapter 5 we will see how the RWA algorithm proposed in this work better solves RPP than the implemented algorithm in the Nokia planning tool, thanks to the utilization of an adaptive alternative routing.

Chapter 4

Planning tool for network dimensioning

4.1 Introduction

In this chapter we describe the Nokia planning tool for network dimensioning used and modified in our work. It is necessary to explain how RWA phase is performed by the planning tool in order to fully understand the routing algorithm proposed in this study (Chapter 5).
Then we provide a brief description of the Nokia simulator of the real GMPLS node behavior in optical networks (section 4.5), as the simulator is used in our work to validate the network dimensioning performed by the planning tool.

4.2 Nokia planning tool

The 1830 PSS EPT is a software tool for automated design and planning of optical networks. Given a network topology *G(N,A)*, a planning tool has to accommodate a traffic matrix composed by a given number of demands (traffic connections) required by users.
For each demand between a couple of source-destination nodes, the user has

to specify:

- The traffic rate, nowadays the most common demands rates in backbone networks are 10, 40, 100 and 200 Gbit/s;
- The FEC adding an overhead to the original signals (2.3);
- Any resiliency scheme.

The network planning tool has to:

- design the network elements like Optical amplifiers, In-Line Amplifiers (ILA), network nodes (the possible node architectures were presented in 2.2), optical filters, OTs;
- verify that the demands requirements are satisfied and check the physical feasibility of the chosen optical paths;
- verify that demands (with restoration resiliency scheme) impacted by the Failure Scenarios (FSs) specified in the failure scope can be restored and provide the restoration path associated to each demand for each FS;
- calculate the target power, gain and other information useful for the network elements;
- provide the Bill-of-Material (BOM) list specifying all the prices of the nerwork equipment to deploy into the network;
- provide the installation report to collect the relevant information to cable the network elements.

A planning tool is usually structured into three main phases, as represented in Fig. 4.1.
The line design provides everything that allows the correct dimensioning of the optical layer. For example it defines the amplifier types together with their input/output power according to the optical links they are associated.

Figure 4.1: Planning tool main phases

The equipment dimensioning phase provides the placement of the cards, decide the number of shelf into the racks and their power.
The only phase we deeply studied in this work was RWA. In the RWA phase the network planning tool has to firstly compute a path associated to a demand and then to reserve optical resources like WDM channels and nodes where to place 3Rs. Any alternative path calculated for resilience purpose is also computed in this routine.

4.3 Survivability

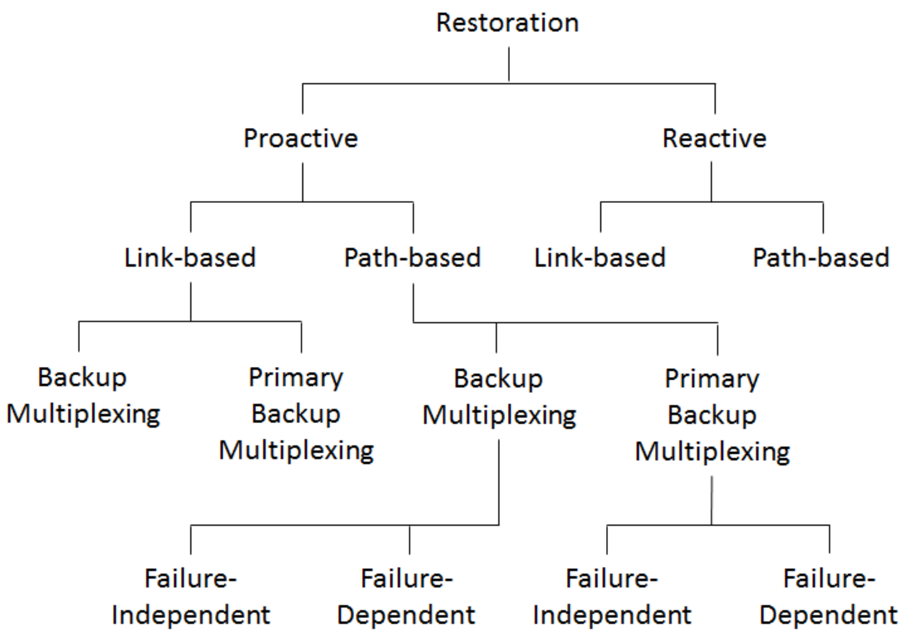
Optical networks are able to transport up to 16 Tb/s in an optical link. With this huge amount of traffic its survivability is an important concern for network operators and many strategies ensuring high quality and reliable services in a cost-efficient way are investigated. The approaches to ensure survivability can be generally classified as protection and restoration [28].
Pure protection schemes can be adopted in order to guarantee a fast recovery during link or node failures. An example of protection is the 1+1 protection, which pre-assigns a backup lightpath together with the nominal lightpath and guarantees instantaneous recovery from any failure on the main path by switching to the backup path when the failure occurs [29]. As a drawback, two lightpaths are assigned for a single demand, doubling the average wavelength occupation in the network links.
In GMPLS networks automatic reconfigurations are possible, hence other recovery schemes are possible.

Restoration schemes compute and establish new lightpaths for connections affected by a failure only once the failure arises. Resources allocated with restoration schemes are not dedicated to a specific demand, but shared between diverse demands when their failed paths do not belong to the same FS. The drawback of restoration technique is that it does not guarantee a sure recovery of the failed demand and the recovery times are longer than for protection.
As RWA is the module used for GMPLS-based networks, this study focuses on the restoration mechanism.

4.3.1 Restoration techniques classification

Many restoration techniques are possible in network dimensioning to ensure the recovery of traffic in a network. The authors of the study [30] classified the main restoration schemes as shown in Fig. 4.2.

Figure 4.2: *Restoration techniques classification*



A restoration scheme is defined as:

- Proactive if the restoration paths of all the demand impacted by all the possible FSs are pre-calculated during the network dimensioning. Then when a failure occurs, the demands affected by the FS are re-routed to the previously calculated routes;

- Reactive if the restoration paths are not pre-calculated during the network dimensioning, but are calculated after the failure occurs according to the network resources availability at the moment.

A restoration path can be calculated according to two policies:

- Link-based: the affected demand is re-routed around the failed resource. If the failed resource is a link, the restoration path will use all the available resources (nodes, links, 3Rs) of the nominal path, and it will bypass the failed link with a sub-path between its endpoint nodes;

- Path-based: an alternative path between the source and destination nodes of the impacted demand is calculated.

According to the sharing of restoration paths (also called backup paths), three main solutions are possible:

- Backup multiplexing: multiple demands can share backup resources under the assumption that only one of the demands sharing the same resources can fail at the same time;

- Primary backup multiplexing: multiple demands can share the same backup resources with a nominal path of another demand. In this way the resources are always used for the nominal path, except when the nominal path fails and then the resources can be used by the restoration paths of other demands.

A further classification is done considering how the restoration paths are related to a specific FS:

- Failure-Dependent scheme calculates different restoration paths for all the FSs that affect each demand. Every time a FS occures, the restoration path is calculated according to the failed resources of the FS;
- Failure-Independent scheme calculates a unique restoration path for each demand. The restoration path needs to be as much as possible disjoint from the nominal path in order to guarantee the restoration of the demand for all the FS impacting it.

4.3.2 Restoration in 1830 PSS EPT

The Nokia planning tool guarantees restoration through a reactive path-based scheme, hence it calculates the restoration paths of failed demands after the failure occurs.
Two main configuration of restoration are available in 1830 PSS EPT:

- *Upon Failure*: when a failure arises the newly computed restoration path tries to exploit as much as possible the active resources of the nominal path. This configuration follows the Failure-Dependent scheme, with the calculated restoration path which is likely close to a path obtained applying a link-based restoration scheme;
- *Guaranteed Restoration*: the restoration path is computed before any failure, for this reason it has to be as much as possible disjoint from the nominal path. This configuration follows the Failure-Independent scheme.

Both protection and restoration schemes can be applied together in networks planning; some demands can be only protected and others only restored, in some cases demands can require both protection and restoration schemes. For jointly protected and restored demands the restoration is not only computed for the nominal but also for the protection paths.
In our work we are focusing on nominal and restoration phases only, so in

the rest of this chapter we do not refer anymore to protection.
In section 4.5 the restoration configuration we decided to use (for both planning tool and simulator) for the final tests is presented.

4.4 RWA

The RWA performed by 1830 PSS EPT takes into account all the network constraints in order to provide as output feasible connections with respect to the deployed devices. The aim of a vendor planning tool is to:

- Satisfy all the demands of the traffic matrix given as input, being able to route their nominal paths, but also their protection and restoration paths, if protection and restoration schemes are required by the customers' demands;
- Minimize the total cost of the nework. Then minimize the allocated resources, especially 3Rs as OTs required for 3R process are among the most expensive devices in an optical network;
- Maximize the optical performances of the network, exploiting the optical reach of transparent links.

In this section we describe the main steps performed by the network planning tool during RWA phase, which is split in two main subphases: nominal and restoration.
The inputs of the planning tool for the network dimensioning are:

- The network topology *G(N,A)*;
- The traffic matrix with the set of demands required by the customers;
- The failure scope if restoration is required. The failure scope defines the FS specifying the resources that can fail and how many of these resources can fail at the same time;

- The value of parameter k, defining the number of the shortest paths to compute; this number of paths is used for both nominal and restoration phases.

The implemented RWA is classified as an offline RWA because we know a priori the fixed traffix matrix requested by the customers.
We already stated in section 3.3 that offline RWA is a NP-hard problem, and that a common approach is to consider the demands in a sequential order. Considering the demands one after the other, we convert the offline RWA into a kind of online RWA that can be solved with a heuristic algorithm.
This planning tool has been created to deal with optical translucent networks dimensioning, so it has to place the minimum number of regenerators in the network in order to route all the customers' demands, according to their resiliency needs.
While several heuristic algorithms present in technical literature (3.5) solve RPP before the RWA phase, in RWA developed for EPT the RPP is solved jointly with the routing phase, as regenerators are allocated while demands are computed. Then the concepts of TI and connectivity graph are not applied by the used planning tool, and the final output of the dimensioned network is more similar to the sparsely placed 3Rs approach, because this solution allows the minimization of allocated 3Rs.

Figure 4.3: *Planning tool overall workflow for RWA phase*

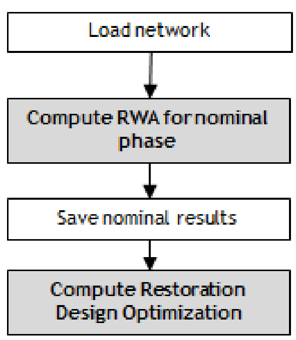


Fig. 4.3 shows the main steps followed by the planning tool for RWA

phase. After having loaded the network topology, the nominal and restoration phases are performed one after the other.
The nominal phase has to be performed firstly, as restoration takes into account the impact of a given FS on each nominal path.
In the following subsections we describe the RWA process for nominal and restoration phases.

4.4.1 Nominal phase

First of all, we collect all the demands of the input traffic matrix in a set D without using any priority order among all the demands.
All the demands in D are considered sequentially. For each demand we compute its RWA together with the check of physical impairments and the allocation of nominal 3Rs, if needed.
The whole process for associating a nominal path to a demand can be divide into the following steps (Fig. 4.4):

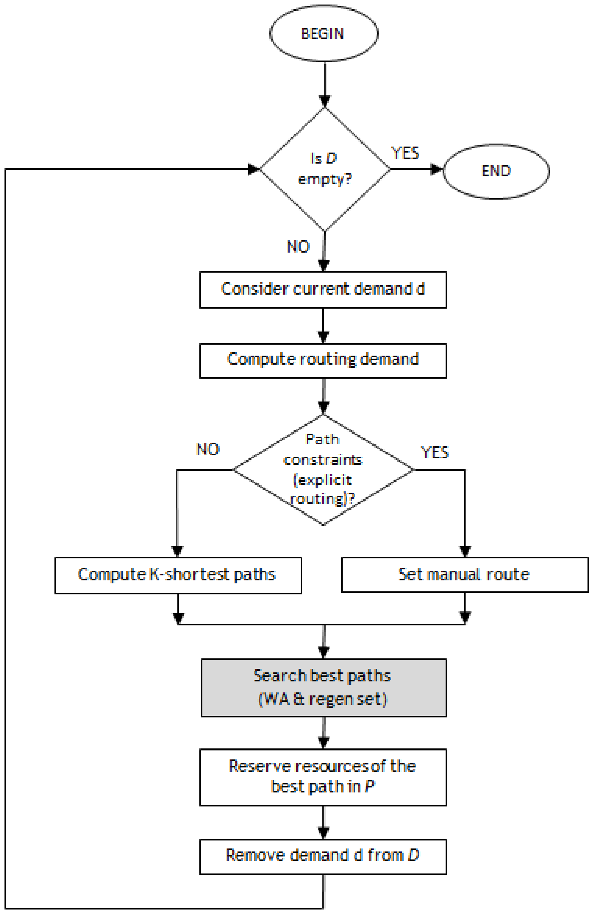
- Routing computation;
- Search of the best paths jointly with wavelength assignment and regenerator placement, if necessary;
- Reserve resources associated to the best path (the selected nominal path for the current demand).

In the routing phase (first step) the nominal path can be:

- manually routed if the user expressly asks the nominal path to pass through specific resources;
- computed by the tool, the path is chosen among a list of K-shortest paths computed through Yen's algorithm (more details are provided in 5.2).

In both cases, the paths are saved into a set K containing all the paths defined in the routing phase (the only manually routed path or the K-shortest

Figure 4.4: Nominal phase RWA



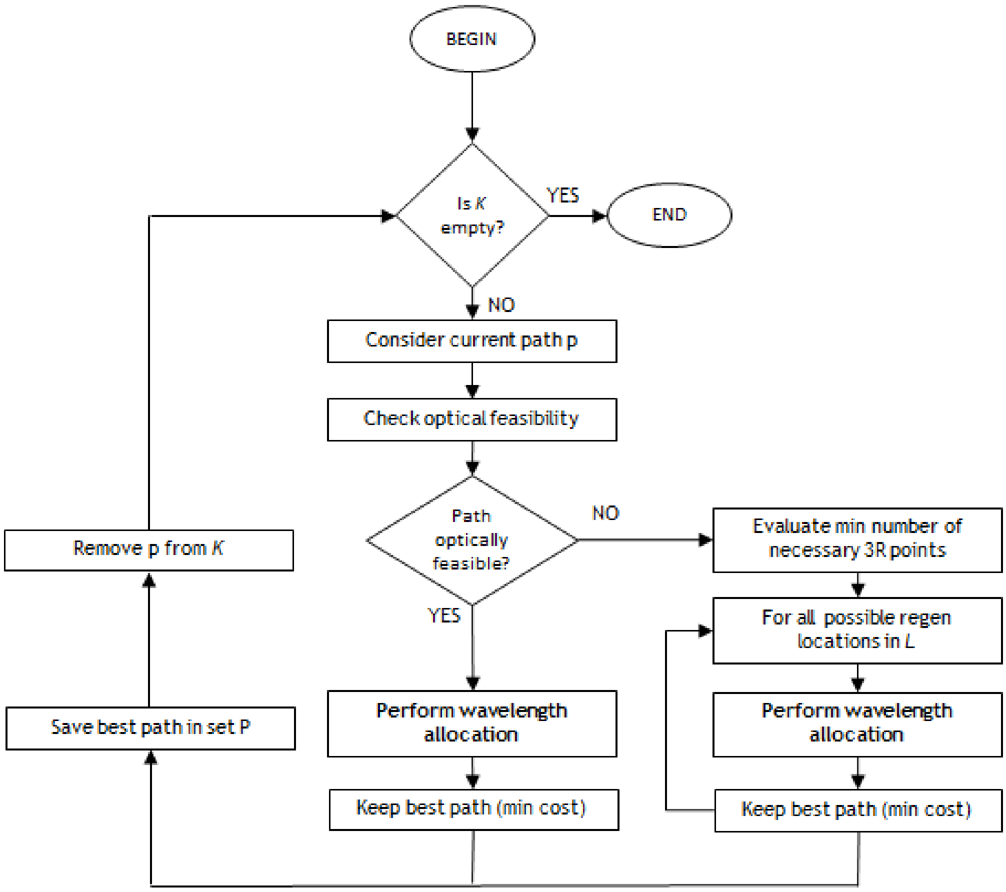
paths).

This set K is used as input for the second step: the research of the best paths performed together with wavelength assignment and regenerator placement. Fig. 4.5 shows a simplified scheme of this subroutine (used also in the restoration phase).

This step performs the same operations sequence for each one of the paths in K.

At the beginning, the optical feasibility of the current path of K is verified. If the path is feasible, the demand can be routed through a transparent lightpath without the need of regenerating the optical signal in any 3R. If it exists a contiguous wavelength along the path, it is chosen for the

Figure 4.5: *Search best paths (WA and 3R placement)*



wavelength allocation, otherwise 3Rs are placed to solve the wavelength constraints. Then the overall cost of the path is computed. The cheapest lightpath among all the lightpaths found among the set of K is kept and stored into the set P, storing all the selected paths.
If from the optical feasibility verification comes out that the path is unfeasible, the problem becomes more complex as RPP is added to the WA. As the wavelength has no impact on the calculation of the path feasibility, an evaluation of the number of necessary 3R points for the path is performed

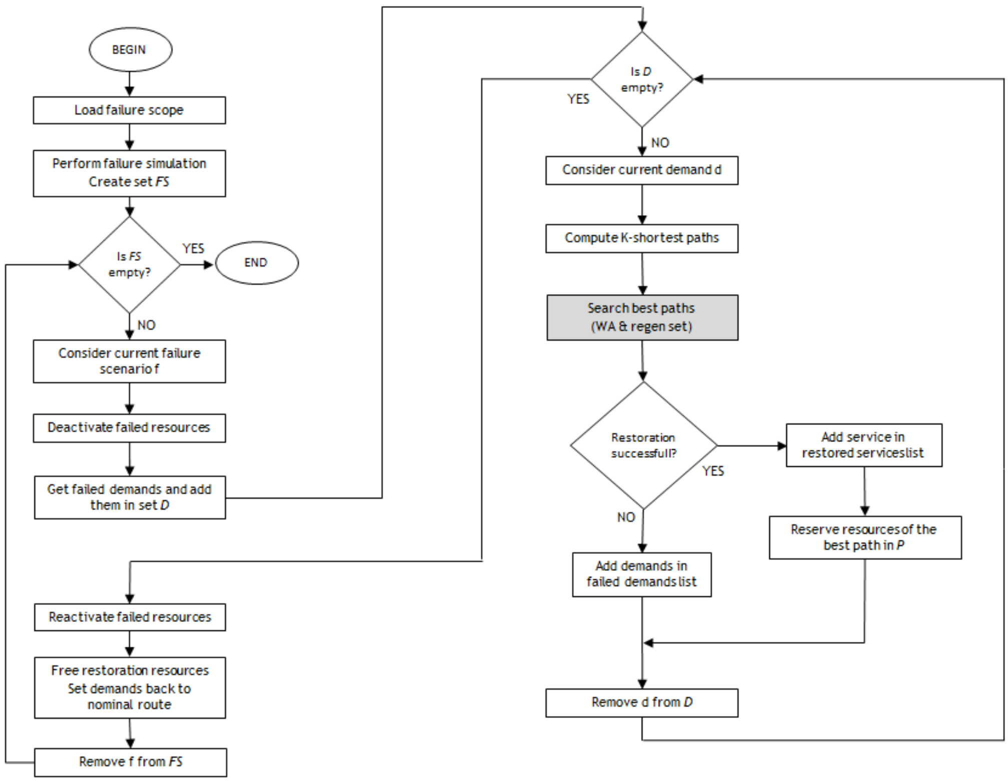
independently of the wavelength in the WA phase.
The next problem to solve is the selection of these points of regeneration along the path. To achieve it, all the possible combinations of 3Rs placement are calculated. All the calculated combinations of 3R placement along the path are stored in the set L.
For each element of L, the WA phase is performed. Because of the presence of 3Rs along the path, we have the possibility to route a translucent lightpath that can change the wavelengths in 3R points (we described in section 2.3 the possibility of changing wavelength during a 3R process).
Taking into account this opportunity, the WA for the path is performed associating all the available wavelengths to every transparent lightpath composing the translucent lightpath. The solutions where the same wavelength is used along the whole translucent lightpath is usually preferred by customers, because wavelength conversion implies an extra cost from an operator point of view.
In this way all the possible combinations of translucent lightpaths are calculated together with their cost. The cheapest translucent lightpath with its 3R placement combination saved in L is then stored into set P.
When all these operations are computed for all the paths in K, the set P contains the best translucent lightpaths associated to the current demand.
The final step of RWA for the nominal phase consists in choosing the cheapest translucent lightpath from the set P and reserve its related network resources.
After that, RWA for the current demand is computed and we can skip to the next demand in set D.

4.4.2 Restoration phase

The restoration phase comes once the nominal phase has been completed. According to the failure scope set as input, all the possible FSs are calculated. A FS can include the failing of single or multiple resources (links and/or nodes) at the same time.

A simplified scheme of RWA for the restoration phase is shown in Fig. 4.6.

Figure 4.6: *Restoration phase RWA*



The planning tool simulates the occurrence of every FS, then all the FS are applied in order to provide a restoration path for each impacted demand. For each FS, the failed network resources are deactivated changing consequently the network topology for the current FS environment.
All the demands whose nominal trails have been affected by the current FS are stored in a specific order into a set D.
For each demand in D, the routing phase is performed through the computation of K-shortest paths with Yen's algorithm. Of course the calculated K paths do not pass through the failed resources, as they have been deleted previously from the network topology associated to the considered FS.

Given the K-shortest paths as input, the subroutine represented in Fig. 4.5 and described in 4.4.1 for searching the best paths jointly with WA and regenerator placement is performed.
The only difference with the equivalent operation in nominal phase consists in the computation of the cost associated to the paths. While in nominal phase the resources can not be shared, in restoration phase the resources (channels and 3Rs) can be shared with different FSs, as a consequence the associated cost is multiplied for a weight according to the following scenarios.
For the links their weight is modified as follows::

- $w_l = 1$ if the link is not used by the nominal trail of the considered demand. In this case, the weight does not produce any change on the cost of the link (as in nominal phase);
- $0 < w_l < 1$ if the link is used by the nominal trail of the considered demand. In this way the cost of the link is lower and it could be included in the minimum cost solution and likely chosen for restoration.

For the 3Rs their weight is modified as follows:

- $w_n = 1$ if the considered 3R does not exist yet and has to be deployed in the network. Hence the 3R cost is equal to the real cost for deploying a 3R;
- $0{,}8 < w_n < 1$ if the considered 3R is an available restoration 3R already allocated for previous FSs and then sharable by the current restoration path;
- $0{,}5 < w_n < 0{,}8$ if the considered 3R is a nominal 3R dedicated to the nominal path of the current demand.

This mechanism, based on the new weights, is used to favor the restoration path to reuse the available resources of its nominal path and of other restoration paths not belonging to this FS. This reuse allows the minimization of the overall cost of the network..

After this subroutine the set P is filled with the best feasible restoration paths calculated for the current demand. If the set P is not empty, the current demand can be restored and the resources associated to the cheapest restoration path in P are installed if not present and reserved.
Then the next failed demand for the current FS is considered. After all the failed demands by the current FS have been considered:

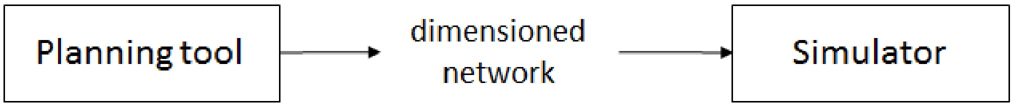
- the failed resources of the current FS are reactivated;
- the resources used for the restoration paths of the current FS are set free;
- the failed demands in the current FS are set back to their nominal paths;
- the process will analyse the next FS.

The restoration phase is completed when all the FS have been simulated.
The network dimensioning terminates when the whole RWA phase is complete.

4.5 Simulator

The Generalized Multi-Protocol Label Switching (GMPLS) network simulator, provided to Nokia customers, is based on the GMPLS node software that runs in a virtual environment. The real GMPLS node behavior is reproduced and collected in the GMPLS network simulator. The outputs are related to the routing of traffic connections for nominal/protection paths and the routing of restoration paths for each FS, in addition to the used resources, in terms of wavelengths and 3Rs.
While the planning tool allocates network resources like OTs in regeneration capable nodes, the simulator goal is to select the involved resources of given traffic connections. It does not allocate new resources, it just uses the allocated resources by the planning tool in the network dimensioning

Figure 4.7: *Planning tool/simulator relation*



phase(Fig. 4.7).
We used it to validate the network design made by the planning tool. A reliable network design is a network dimensioning able to satisfy in the field all the traffic connections of a given traffic matrix and to cover all the FSs specified in the failure scope.
In order to achieve a good network design, the planning tool needs to follow the GMPLS node behavior in the RWA process. For example, when a FS occurs, the simulator is inclined to restorate the failed connections with restoration paths using as much as possible the nominal path resources, trying to bypass the fault resources in a "Fast Re-Route" approach (bypass with a short subpath the unavailable subpath). As a consequence RWA restoration phase should favor the restoration paths to re-use nominal resources too, activating the restoration configuration *Upon Failure* described in section 4.3.
There are some differences between the planning tool and the simulator. For example the simulator allows paths to pass through the same link back and forth (creating a kind of loop in the path) in order to take some available resources like a 3R, while the RWA software of the planning tool forbids this behavior because it is not optimal for minimizing the overall network cost.
Due to these behavior differences, the same demand may be routed through different paths using different resources by the planning tool and the simulator. It is possible that the simulator finds congested links which were not congested using the planning tool, or that a demand needing regeneration can not find any 3R avalable because of 3R contention.

The latter example is the main reason of blocked connection for the tests made in this chapter. It is not so unusual that a 3R allocated by the planning tool for a specific demand is used in the simulation from another demand. It is like a "stealing" mechanism where demands can take available 3Rs assigned by the planning tool to other demands.
We describe the 3R contention by the following simple example using both network design and network simulator tools.

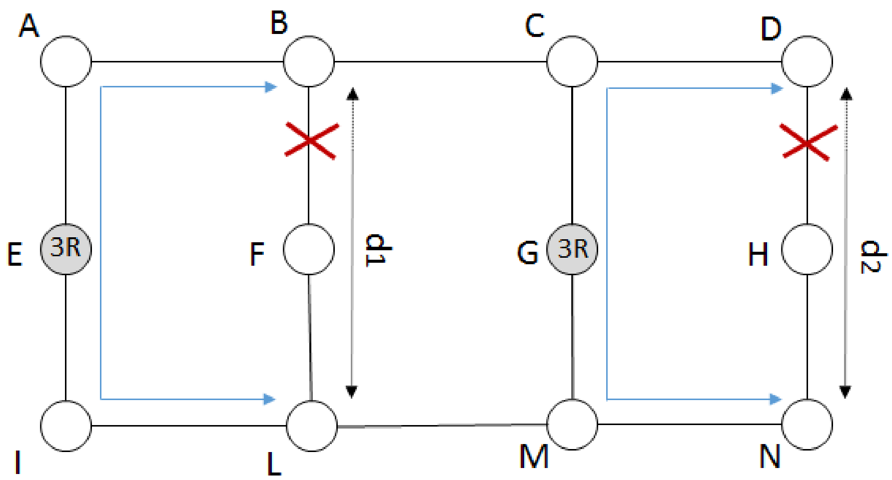


Figure 4.8: *Example: planning tool network dimensioning*

Fig. 4.8 shows a network with two traffic demands (d_1 and d_2). Let us suppose all the links and nodes have the same properties, and that the maximum optical reach in this network is 2-link hop. The nominal paths of the two demands are:

- B-F-L for demand d_1;
- D-H-N for demand d_2.

Let us consider a FS involving the fault of the two links B-F and D-H at the same time. Both nominal paths are impacted, so they need a restoration path each.
Fig. 4.8 shows a possible planning tool dimensioning, where a 3R is needed

to restore each demand in order to have a feasible restoration path. In the example, the planning tool selects for restoring d_1 the restoration path B-A-E-I-L allocating a 3R in node E, instead of using the path B-C-G-M-L which is equivalent in terms of PLI.

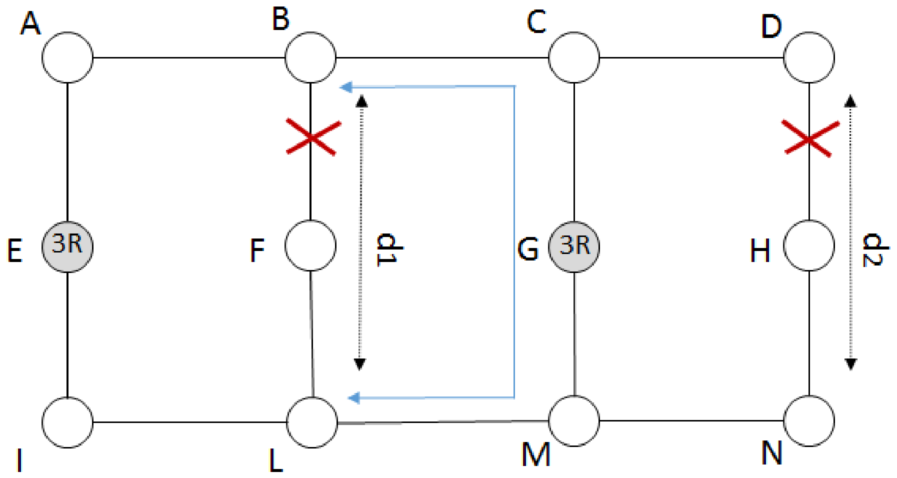


Figure 4.9: *Example: simulation phase*

Fig. 4.9 shows the simulator results for this FS. If the fault of link B-F occurs before the other one, in order to restore demand d_1 the simulator can choose the path B-C-G-M-L using the 3R in node G. But when the fault of link D-H occurs, the restoration path D-C-G-M-N can not be used because the 3R in G is already in use. As assumption, a transparent lightpath can not be longer than two links, then every other restoration path for demand d_2 is not feasible, and therefore d_2 can not be restored.
The simulator highlights the potential 3R contention (or "conflict") by indicating a not restorable demand that is restorable by the design tool.

Chapter 5

Adaptive Alternative RWA

5.1 Introduction

Restoration paths are usually longer than their nominal ones. In national-wide core networks this creates the need for optoelectronic regenerations. Analyzing the network dimensioning of several customer's networks, we noticed that often the required 3Rs associated to a restoration path are set up without taking into account available 3R resources that have been deployed for other restoration paths that failed in previously emulated failure scenarios.

The allocated 3Rs in restoration phase are sharable resources allocated for traffic requests whose nominal path failed in a given FS. Hence restoration paths calculated for different FSs can share a restoration resource like a 3R or spectral channel as these restoration paths are not active at the same time.

For this reason we decided to exploit at the best restoration 3Rs already deployed in the network, as devices like OT (necessary for 3R process 2.3) are among the most expensive devices in an optical network.

In our study, the only reason for a restoration path of deploying new 3Rs instead of reusing an available restoration 3R is that none of the K-shortest paths calculated during the restoration phase passes through the available

3Rs. During this internship we focused on the routing search associated to the restoration phase to achieve our goal: the minimization of the overall restoration 3Rs.
In section 3.2 we showed how routing algorithms are classified in technical literature: fixed routing, fixed alternative routing and adaptive alternative routing.
Adaptive routing is a very attractive topic as it allows to improve the routing performances according to the current state of the network. As a consequence, we can find in literature some examples of adaptive routing technique. [20] dynamically collects links wavelength occupancy information in order to adaptive update the links weights. In this way links with more wavelengths already allocated have a higher weight, so the algorithm is able to better balance the load in the network (increasing the average channel utilization) and then reducing the blocking rate.
The approach adopted by 1830 PSS EPT is alternative as each traffic connection can choose its route among K-shortest paths calculated by the Yen's algorithm (section 5.2 provides overview of the Yen's algorithm).
We call:

- Fixed Alternative RWA (FA-RWA) the RWA routine used by the legacy planning tool;
- Adaptative Alternative RWA (AA-RWA) the RWA routine proposed in this work for restoration phase.

The legacy planning tool uses a fixed alternative approach for the routing of RWA phase. By changing the fixed feature into an adaptive one, we can improve the planning tool dimensioning in terms of allocated resources.
During the adaptive phase, the information to take into account in the K-shortest paths phase is the availability of 3Rs in nodes.
The K shortest paths chosen with AA-RWA include more paths exploiting available restoration 3Rs than the K shortest paths obtained by using FA-RWA.

5.2 Yen's algorithm

Both analysed algorithms (FA-RWA and AA-RWA) use Yen's algorithm for the research of the K-shortest paths, but while FA-RWA research on a fixed graph, AA-RWA changes dynamically the graph edges and nodes weight for each K-shortest paths research in restoration phase. In the following we describe the algorithm before analysing the differences between the two approaches.

Yen's algorithm is the most used algorithm searching the K-shortest paths problem: given a graph with non negative edge cost, it provides the K shortest paths without loops between a couple of nodes source-destination [31].

We define:

- the set A containing the K shortest paths between source and destination;
- the set B containing the possible paths calculated during the algorithm that can be included in set A;
- A^k as the k-th shortest path;
- the nodes sequence of A^k: 1^k, 2^k, ..., $(Q\text{-}1)^k$, Q^k, where Q is the number of nodes in path A^k;
- A_i^k as the deviation path from A^{k-1} at node i, where i ranges from 1 to Q^k-1;
- R_i^k as the root path of A_i^k, the subpath of A^k from node 1 to i (equal to the subpath of A^{k-1} for the first i nodes);
- S_i^k as the spur path of A_i^k, the subpath of A^k from node i to Q^k.

Yen's algorithm uses a Dijkstra-like algorithm for the calculation of the shortest path between a couple of nodes as a subroutine.

At the beginning, the two sets A and B are empty. As first step, the

shortest path A^1 between source and destination is computed with Dijkstra's algorithm and added to A.
Then the algorithm incrementally calculates the shortest path A^k from the previous shortest path A^{k-1}, for k-values from 2 to K. This routine can be divided in two main parts:

- find all the deviation paths A_i^k for i-values from 1 to $(Q-1)^{k-1}$ and add them to B;
- choose the cheapest path in B, add it to A and remove it from B.

The algorithm stops when the size of the set A is equal to K or before calculating all the K paths if there is no other route between source and destination.
More details about these routines are showed in the pseudocode shown in Listing (5.1), where the complete scheme of Yen's algorithm is shown.

Listing 5.1: *Implementation of Yen's algorithm for K-shortest path research*

```
BEGIN YEN K-Shortest Paths{
 determine the shortest path A^1 from source to
 destination;
 add A^1 to set A;
 for(k from 2 to K){
   for(i from 1 to (Q-1)^{k-1}){
     select the rooth path R_i^k;
     for(path p in A){
       if(root path of P == R_i^k)
       remove edge (i,i+1) of p from the graph;
     }
     spur path S_i^k = shortest path from i to
     destination;
     A_i^k = R_i^k + S_i^k;
     add A_i^k to B;
     add the edges previously removed to the graph;
```

```
    }
    sort set B;
    A^k = B[0];
  }
  return set A;
} END YEN K–Shortest Paths
```

5.3 Implementation of AA-RWA

As stated in section 5.1 , AA-RWA's aim is to better exploit the available restoration 3Rs in the network during the restoration phase. As the network awareness only concerns the restoration phase, FA-RWA and AA-RWA do not differ for the K-shortest paths search in the nominal phase.

In the dimensioning of backbone translucent networks performed by Nokia planning tool, we observed that restoration 3Rs are usually distributed in the network as it is preferable to have sparse 3Rs instead of concentrating them in specific areas. This means that usually a node with regeneration resources can be sorrounded by nodes without 3R capability.

In the K-shortest path research using FA-RWA we do not have any information about the actual state of the network (3R resources or link congestion). Then all the edges have the same weight w_e and all the nodes have the same weight w_n.

To improve the behavior of the K-shortest paths search, we want to introduce the capability to recognize the presence of an available 3R in neighbor nodes during the discovery of each shortest path.

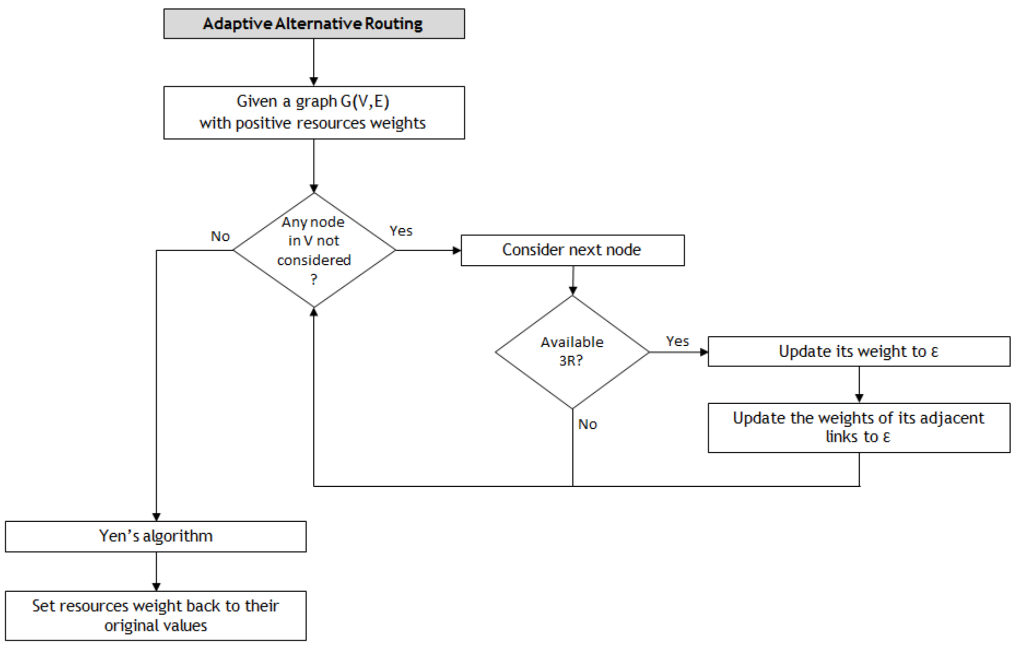
At the beginning of the routing of any restoration path, we lower the weight w_n of nodes with available 3Rs and also the weight w_e of their adjacent links to a very low value $\varepsilon = 10^{-5}$. After the restoration path phase, we set back the resources weights to their original values. We can have two types of available 3Rs:

- nominal 3Rs belonging to the nominal path, which is failed by the current FS. These 3Rs are mainly re-usable by its restoration path;

- restoration 3Rs allocated in previous FS and then sharable between restoration paths of different FS.

With the proposed AA-RWA we are aware of the presence of all the available 3Rs in the network (adaptive routing) and we favor the K-shortest paths research to exploit these available resources through dynamic edges and nodes weights updates. Other works in technical literature propose dynamic updates of the resources weights during the computation of the shortest path. In [32] a dynamic algorithm applied to directed graphs is used in real-time environment, where the edges weights change dynamically between the routing of consecutive demands.

Figure 5.1: *Conceptual scheme of Adaptative Alternative routing*



In Fig. 5.1 and related pseudocode 5.2 we present a conceptual representation of the AA-RWA main steps for the K-shortest paths search of every restoration path. To improve the computation time performance, many optimizations hidden in this scheme have been done. Basically, in the real implementation the updates of the nodes weights are computed in many steps during the whole RWA process, while the scheme simplifies the operations reducing all the mechanism in an update of all the nodes weight performed at the beginning of each restoration path phase.

Listing 5.2: Adaptative alternative routing

```
BEGIN AA-RWA {
Given a graph G(V,E) with positive resources weights:
  for (nodes in V) {
    if (available 3R){
      update its weight to ε;
      update the weight of its adjacent links to ε;
    }
  }
  Yen algorithm modified;
  set resources weight back to their original values;
} END AA-RWA
```

5.3.1 Path weight calculation

In this section we focus on the routine used inside the Yen's algorithm to find A^1 and, as a subroutine, to find the spur paths S_i^k.
We define the following sets related to a generic path P:

- L(P) is the set of edges composing the path P;
- N(P) is the set of nodes related to the edges in set L(P), without considering in the set the source and destination nodes of P.

The most used algorithm for the calculation of the shortest path in a graph with non negative edge cost is the Dijkstra's algorithm. Dijkstra-like algorithms calculate the weight w_p of a path P like the sum of the edges weight

w_e associated to the path:

$$w_p = \sum_{e \in L(P)} w_e \tag{5.1}$$

The FA-RWA legacy approach calculates the weight of a path using the Dijkstra approach.
While in AA-RWA we decided to calculate the total weight of a path taking into account not only the weight w_e of the edges but also the one nodes weight w_n. Excluding source and destination nodes because they are present in all the possible paths and are not discriminatory for finding the shortest path, the path weight using AA-RWA is calculated as following:

$$w_p^{'} = \sum_{e \in L(P)} w_e + \sum_{n \in N(P)} w_n \tag{5.2}$$

5.3.2 Observations about nodes weights

The choice of associating a weight even to the nodes avoid random choices between subpaths that would have the same weight without considering nodes weights. In this section we provide some examples explaining the reason behind the needs of the nodes weight during the K-shortest paths calculation. We compare two versions of AA-RWA:

- AA-RWA$_1$ does not consider nodes weight, so the path weight is calculated as in the equation 5.1;
- AA-RWA$_2$ considers nodes weight, so the path weight is calculated as in the equation 5.2 (AA-RWA$_2$ is equivalent to the AA-RWA proposed in this work).

In the example in Fig. 5.2 there are two competitor subpaths, P$_1$ (A-E) and P$_2$ (A-C-D-E), respectively composed by one and three links. The subpath P$_2$ includes a node that present an available 3R, so Tab. 5.1 shows the weights of the two subpaths using AA-RWA$_1$ and AA-RWA$_2$ (assuming negligible the contribute of ε).

Figure 5.2: Example 1 about nodes weight

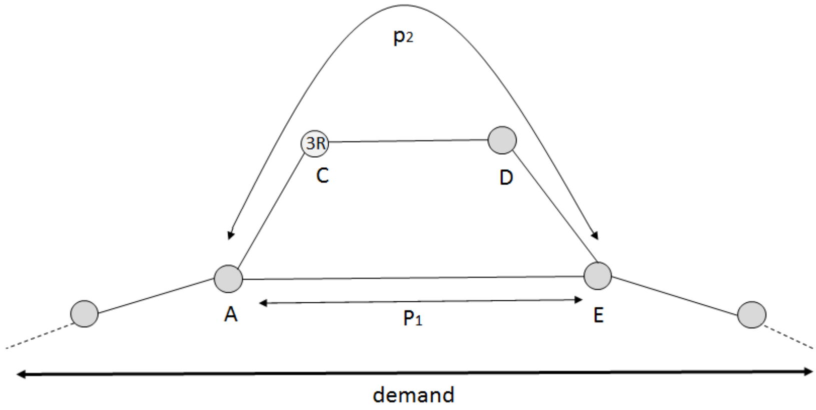


Table 5.1: Example 1: weights of the subpaths using AA-RWA$_1$ and AA-RWA$_2$

	AA-RWA$_1$	**AA-RWA$_2$**
P$_1$	w_e	w_e
P$_2$	w_e	$w_e + w_n$

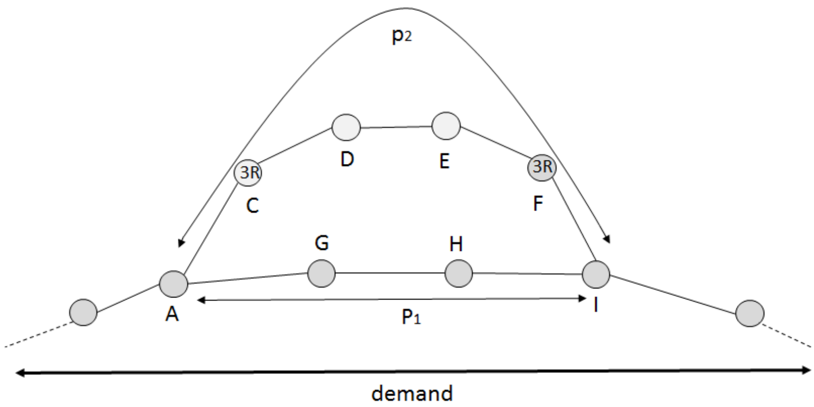
The subpaths P_1 and P_2 would have the same weight if we do not consider the weights of the nodes (AA-RWA$_1$), and then the choice of the best subpath would be random, on the other hand using AA-RWA$_2$ the two subpaths have different weights and the shortest subpath P_1 would be chosen.

We can generalize the example to all the situations involving two paths that differ for two links with only the longest having an available 3R. In these cases, AA-RWA$_2$ always choose the shortest path even if it does not have available 3Rs.

The situation of the example is not the only one in which subpaths with different lengths have the same weights using AA-RWA$_1$. For example a path with two available 3Rs placed in not adjacent nodes(nodes not connected by a link) would have the same weight of a path four links shorter but with no 3Rs.

Another common situation is when a subpath with two available 3Rs is three links longer than a subpath without 3R. The example in Fig. 5.3 represent this situation, with two subpaths (P_1 and P_2) composed respectively by two and five links, where P_2 has two availables 3Rs situated in not adjacent nodes.

Figure 5.3: Example 2 about nodes weight



Tab. 5.2 shows the weights of the two paths using AA-RWA$_1$ and AA-RWA$_2$.

Table 5.2: Example 2: weights of the subpaths using AA-RWA$_1$ and AA-RWA$_2$

	AA-RWA$_1$	**AA-RWA$_2$**
P_1	$2 * w_e$	$2 * w_e + w_n$
P_2	w_e	$w_e + 2 * w_n$

This example justifies the introduction of a weight for the node. The node weight has to be greater than the edge weight to avoid the selection of subpaths longer than two links in situations similar to the presented one.

$$w_n > w_e \tag{5.3}$$

According to this rule, AA-RWA$_2$ would choose the shorter subpath P_1, while AA-RWA$_1$ chooses the longer subpaths P_2.
The rational behind this choice is discourage the selection of long subpaths (even if they have available 3Rs) for not occupying too many links and keep the network less congested. In order to minimize the modification of the planning tool behavior for the routing phase, our aim is just to favor kind

of "triangulations" with available 3Rs close to the subpaths calculated by FA-RWA, like the examples in section 5.3.3. This means that the permitted deviations from the shortest path are done in the following cases:

- 1-link longer than FA-RWA subpath, if they have one available 3R;
- 2-link longer than FA-RWA subpath, if they have two available 3Rs situated in adjacent nodes.

Of course, we favor even longer subpaths if they include more than two available 3Rs, but it is not a common case.

5.3.3 Comparison between FA-RWA and AA-RWA

In the following subsection we describe how the two aproaches FA-RWA and AA-RWA work in presence of an available 3R showing two examples of the most common situations occuring during the search of a path to be included in the K shortest paths list.

Figure 5.4: *Triangulation with a 3R*

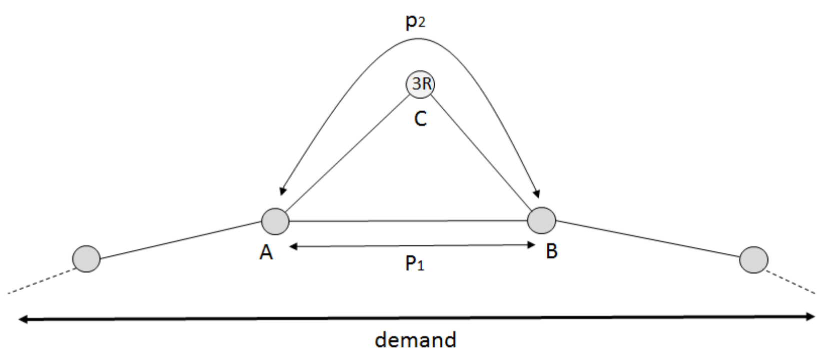


Fig. 5.4 shows an example of a "triangulation" with an available 3R, where we only represented a part of a bigger network. In this example a restoration path has to be found for recovering a demand.
During the K-shortest path research, consider a possible path passing from the subset of nodes A and B as in Fig. 5.4. With FA-RWA the chosen path

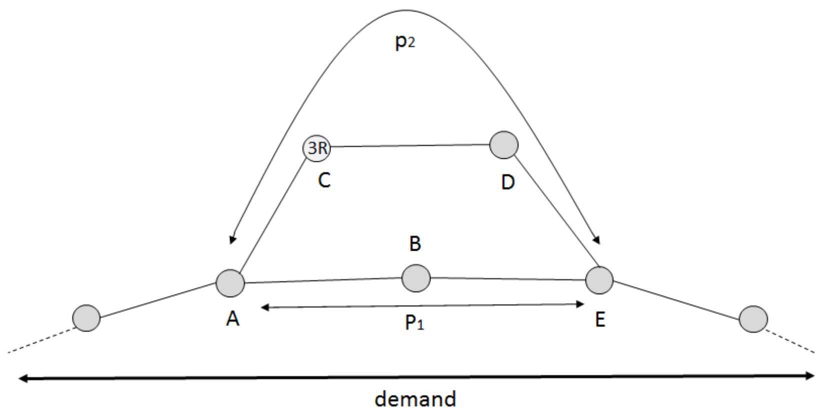
would pass from the subpath P_1 (A-B), without considering the available 3R present in C, that could be very useful if the physical impairments degrades the path over a tollerate threshold making it unfeasible.
On the contrary, the AA-RWA algorithm would add a subpath to "triangulate" with node C and choose the subpath P_2 (A-C-B) in order to include the available 3R in the seleceted path. The weights associated to the two subpaths P_1 and P_2 for FA-RWA and AA-RWA are shown in 5.3.

Table 5.3: *Triangulation: weights of the subpaths P_1 and P_2*

	FA-RWA	**AA-RWA**
$\mathbf{P}_1$	w_e	w_e
$\mathbf{P}_2$	$2 * w_e$	$3 * \varepsilon$

Another common example is a sort of "extended" triangulation (Fig. 5.5).

Figure 5.5: *"Extended" triangulation with a 3R*



Like in the previous example an available 3R is present in node C. The output of the resources weights is updated at the beginning of the routing discovery as shown in Tab. 5.4 for FA-RWA and AA-RWA.
Again, for FA-RWA the shortest path will include the subpath P_1 (A-B-E), while for AA-RWA the selected subpath is P_2 (A-C-D-E) as passing through the node C with at least an available 3R.

Table 5.4: "Extended" triangulation: weights of the subpaths P_1 and P_2

	FA-RWA	AA-RWA
$\mathbf{P}_1$	$2 * \mathrm{w}_e$	$2 * \mathrm{w}_e + \mathrm{w}_n$
$\mathbf{P}_2$	$3 * \mathrm{w}_e$	$\mathrm{w}_e + \mathrm{w}_n + 3 * \varepsilon$

As a drawback, the selection of longer routes in the K-shortest paths list involves the occupation of more links increasing the probability of congestion when further demands for the same FS have to be routed.

Chapter 6

Results Evaluation

6.1 Introduction

The aim of this chapter is to validate the advantages introduced by the proposed AA-RWA algorithm described in Chapter 5 by comparing the dimensioning results obtained with the ones obtained with the FA-RWA used by the legacy tool (1830 PSS EPT) on some case studies.
As the purpose of our work is to reduce the monetary cost of the network (reducing the resources allocated) with respect to the cost obtained with FA-RWA in the restoration phase, we focus on the statistics about the sharable resources allocated in the restoration phase: 3R and optical channels. So we are mainly interested in the parameters regarding the number of allocated 3R and the related gain AA-RWA takes with respect to FA-RWA. We also checked how many channels the proposed routine uses in order to give a more detailed analysis of the network design by the two approaches.
The simulator described in section 4.5 was used to validate the network design obtained with the two approaches and check how reliable they are facing the "real behavior" in the field.
We define:

- a restoration path as a successful attempt of provisioning restoration to a demand affected by a FS;

- the number of allocated 3R for restoration in the network dimensioning using the two approaches ($3R_{FA-RWA}$ for the legacy algorithm and $3R_{AA-RWA}$ for the proposed algorithm), where a 3R represents a pair of OTs needed for a 3R regeneration process (as stated in section 2.3);
- the number of restoration paths calculated by the tool in the dimensioning of the network ($rest_{tool}$);
- the number of restoration paths calculated by the tool but blocked by the simulator ($blocked_{sim}$).

The comparison of the two approaches is mainly based on the following parameters:

- $3R_{FA-RWA}$;
- $3R_{AA-RWA}$;
- the number of 3R saved using AA-RWA with respect to FA-RWA:

$$\Delta 3R_{saved} = 3R_{FA-RWA} - 3R_{AA-RWA} \tag{6.1}$$

- the percentage of 3R saving, defined as:

$$S_{3R\%} = \frac{\Delta 3R_{saved}}{3R_{FA-RWA}} * 100 \tag{6.2}$$

- the average number of channels allocated per link;
- the percentage of restorations blocked calculated by the simulator, defined as:

$$P_{blocked_Rest} = \frac{blocked_{sim}}{rest_{tool}} \tag{6.3}$$

6.2 Case studies and general assumptions

In this section we present the network topologies used for the comparisons, we describe the assumptions taken into account to create the networks and the traffic matrices, and we eventually describe the main assumptions used for the planning tool and the simulator.

6.2.1 Case studies

In order to see the impact of the adaptive alternative routing under different conditions, we used various network topologies and diverse traffic matrices. We define the connectivity degree of a network as:

$$\delta = \frac{2 * L}{N} \tag{6.4}$$

where L is the number of bidirectional links and N is the number of nodes of the network.
We expected that the modified tool would have better performances and a higher impact on more connected topologies, where there are more possible paths that can be included in the k shortest paths. So we used different topologies with different connectivity degree to evaluate the differences between the two routines as a function of network connectivity.
Three network topologies (Fig. 6.1, Fig. 6.2, Fig. 6.3) were used for the simulations. All the three networks have the same number of nodes but a different connectivity degree, as shown in Tab. 6.1.

Table 6.1: *Networks topologies*

Network	**n. nodes**	**n. links**	δ
Network A	30	41	2,7
Network B	30	48	3,2
Network C	30	56	3,7

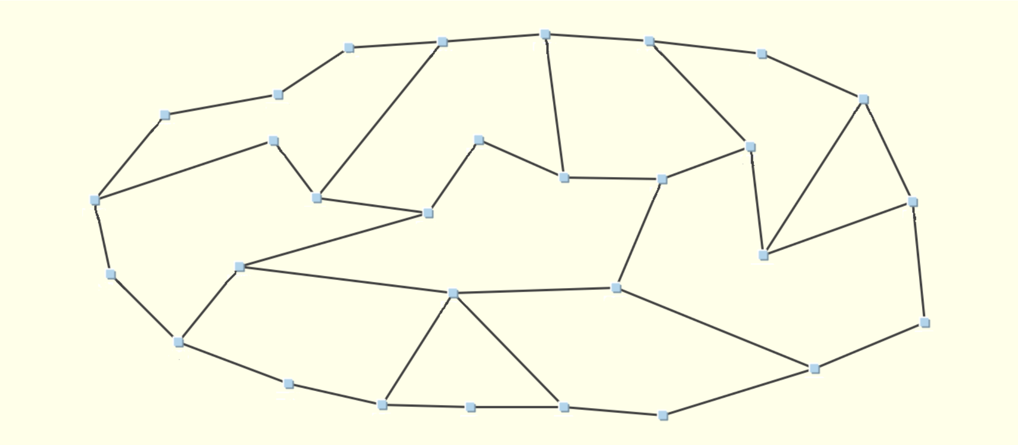


Figure 6.1: Network A

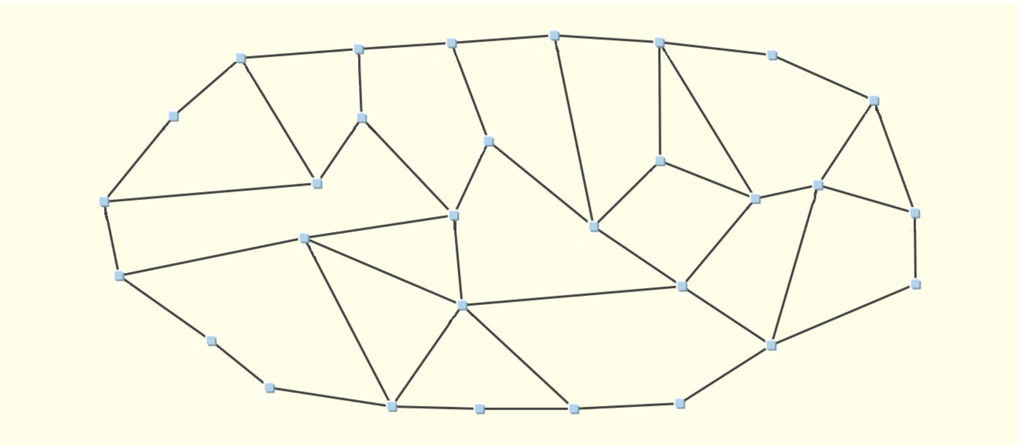


Figure 6.2: Network B

As the design of a network depends on the offered traffic matrix, testing the three network topologies for only one traffic matrix would not allow us to make an accurate comparison between the two approaches. What we want to obtain is the average behavior of the tool, and this can be obtained averaging a certain number of simulations.
Hence we used 30 different traffic matrices where the demands are randomly chosen between all the couple of nodes of the networks. The only constraint we set to these traffic matrices is that the sum of the demands of each traffic matrix has to be the same, so we decided the total number of demands for

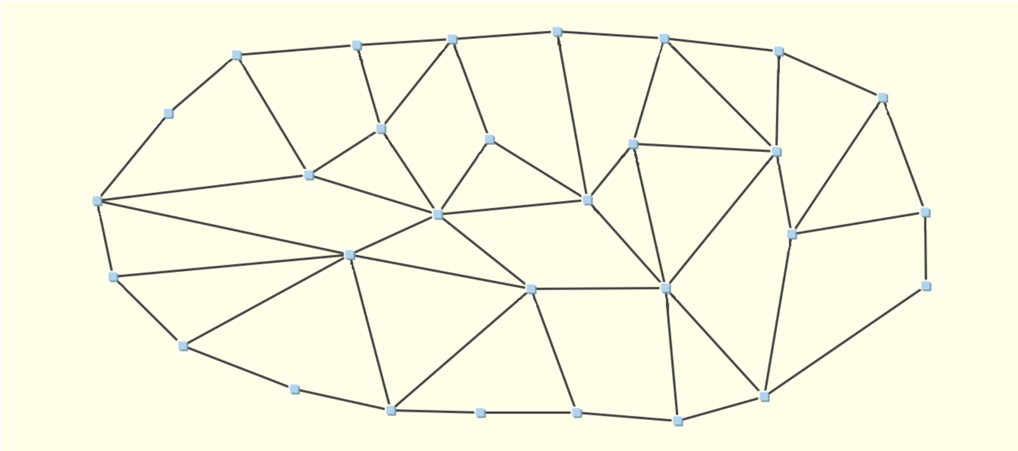


Figure 6.3: *Network C*

each traffic matrix is 60.
To give more practical value to our work we also compared the two approaches testing two real customers' networks (Fig. 6.4, Fig. 6.5) with their actual traffic matrices. Tab. 6.2 reports some details about these case studies. We chose these two customers' networks because they have a different connectivity degree (2,38 and 3,87) and different number of nodes, so as to study the behavior of the two approaches under different conditions.

Table 6.2: *Customers' case studies*

Network	**n. nodes**	**n. links**	δ	**n. demands**
Customer A	57	68	2,38	38
Customer B	31	60	3,87	53

In Fig. 6.5 we observe there are many ILA (In-Line Amplifier) and GT (Glass Through) respectively represented with triangles and circles. These entities are not considered nodes as their only role is respectively to amplificate the signal and connect fibers, so they do not have any switching or regeneration capabilites.

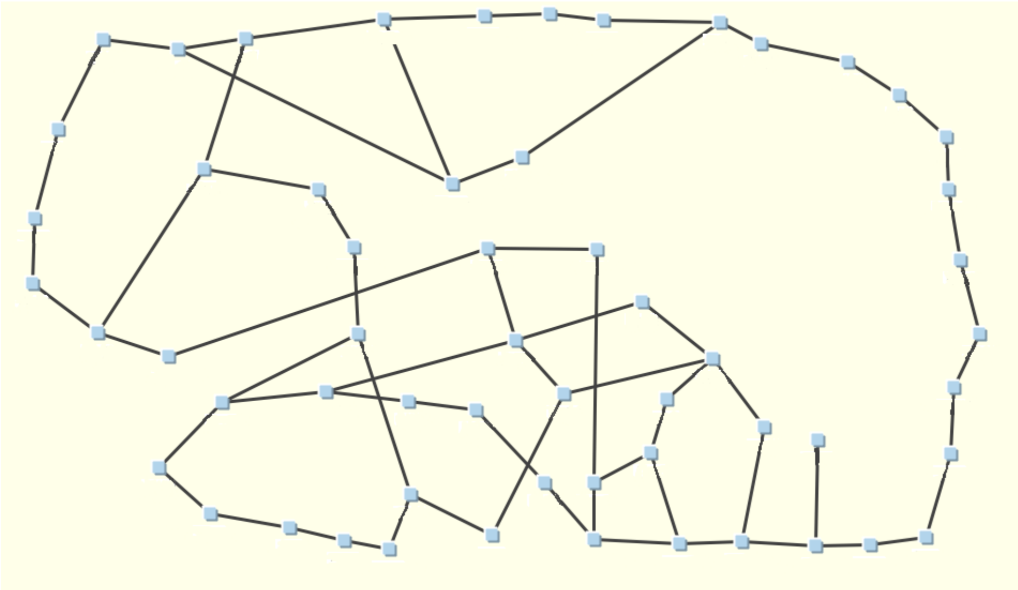


Figure 6.4: Customer A

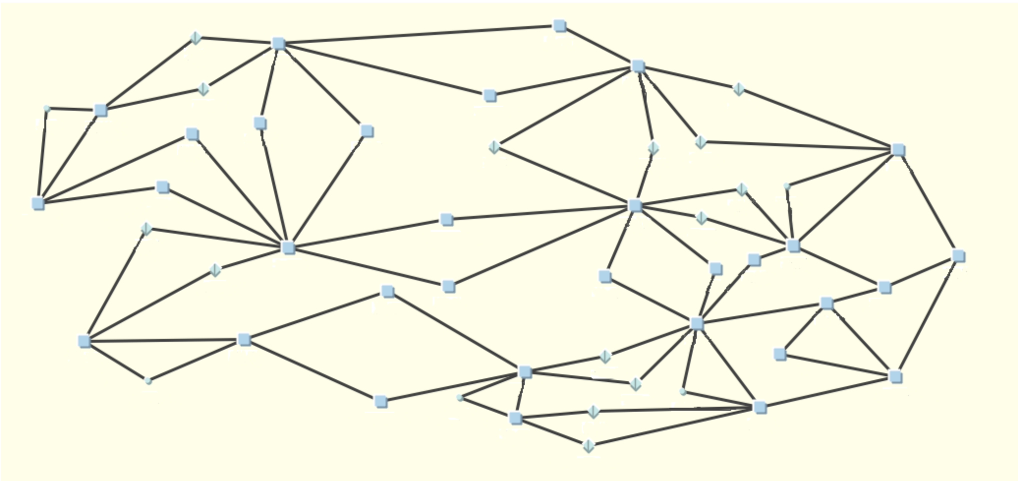


Figure 6.5: Customer B

6.2.2 Assumptions

6.2.2.1 Node architecture and traffic matrices

The node architecture used for all the network topologies used for this study is the CD ROADM equipped with at least two Add/Drop blocks. The other possible node architecture was the CDC ROADM, but we already explored

in section 2.2 it has less node constraints than the CD ROADM because it is also contentionless, so we chose the more constrained node architecture because results obtained with CD ROADM are also valid with the use of CDC ROADM, while conversely is not the case.
About traffic matrices, the adaptive mechanism of the proposed algorithm has an impact if all the demands use the same type of OT. Then we decided to use the OT 130SNX10(LN) already described in 2.7, for carrying 100 Gbit/s for the payload and 30 Gbit/s for the channel coding SD-FEC.

6.2.2.2 Configurations of the planning tool and the simulator

As mentioned in the first section of this chapter, the simulator has been used to validate the solutions obtained from the planning tool.
In order to obtain a solution as close as possible to the one obtained from the simulator we set the configuration of restoration to the node *Fast reroute* of the planning tool. This configuration favors the restoration paths to re-use the available resources of their nominal path, trying to find where it is possible to bypass the fault using the shortest feasible path.
The simulator has many possible configurations, we choose the configuration closer to the real behavior of networks in the field:

- the trails failed by each FS are restored in a completely random order; there is no priority for restoration between the demands and there is no constraint about restoring one after the other all the demands failed between a couple of nodes;
- for FSs that involve more than one resource, we assume that all such resources fail at the same time.

6.2.2.3 Parameter k for k-shortest paths

The parameter k is key in this work because it heavily affects the output of the planning tool. For a high value of k the restorations can be chosen

between more available paths, so we expect a higher reuse of already deployed resources, meaning an increase of the resource sharing and reduction of the whole network cost. While for lower values of k we have fewer choice of paths and the planning tool allocates more resources than needed.
Ideally, we should choose a very high value of k able to discover all the possible paths in the network, but the computation time required is proportional to k so a good trade-off between time complexity and completeness of the solution is necessary.
Because of the size of customers' networks, the maximum value of k that can be chosen in the planning tool is $k = 30$. This upper bound is able to exploit the most significant paths for the nominal trails and restorations. For a large number of networks studied we achieve the best dimensioning of the network in terms of minimization of resources allocated from lower values of k, and then with less computation time spent.
For all these reasons it is clear why the value of k plays a decisive role in the planning tool results, so it would be interesting to study how the restoration resources depend on the parameter k.
Other works present in literature use various values of k, for example:

- [33] and [34] use k=3;
- [35] varies the value of k from 2 to 10 with increment 2;
- [36] uses the following values of k 10, 20, 30, 40, 50, 100.

To have an idea of the trend of the restoration resources needed for the restoration phase, and because of the time greedy simulation, we decided to do simulations with the foloowing strategic values of k: 1, 5 , 10, 20, 30.
In order to show a complete analysis of a network, we tested the three networks topologies with only one traffic matrix for all the possible values of k, from 1 to 30. We did the same with the customers' networks, as the small number of customers' networks studied allowed us to do it.

6.2.2.4 Failure scope

The failure scope we used for all the tests includes the failure of all the links broken one per time. It would be interesting to study the output of the planning tool for a double failure (two links failed at the same time), but there would be too many FSs due to the high number of 2-links failure combinations and RWA process would take too much computation time.

6.2.2.5 Routing of the nominal trails

Another important assumption we have to make is about the routing of the nominal trails. Our work is focused mainly on the restoration phase, so we are not interested in the statistics about the 3R dedicated to the nominal paths because the planning tool routine for the nominal phase is the same for both the approaches, consequently the resources allocated for the nominal phase are the same.

As we explained in Chapter 4, the routing of the nominal trails follows the same procedure of the routing of the restorations, so it is affected in the same way by the value of the parameter k. As things stand, if we study the output of the tool for each network and traffic matrix, we would see a different number of nominal 3R as a function of k, but this would heavily influence the statistics about the 3Rs necessary for restoration (remind that nominal 3Rs can be used by a restoration trail if nominal trail it belongs to is broken by the FS).

In this study we are not interested in the nominal phase, so all the nominal trails were manually routed in order to have the same nominal routes for each demand regardless of k. Doing so the number of nominal 3Rs is k-invariant and the decrease of number of restoration 3R with the increase of k can be observed without biasing conditions.

6.3 Results

In this section we present how both algorithms, FA-RWA and AA-RWA, of the restoration phase of the planning tool design the previously described networks with respect to k and we compare them using the parameters listed in section 6.1.
First of all, we see a complete analysis of a single traffic matrix applied to the three network topologies using all the possible values of k, from 1 to 30. Then, as stated in section 2.1, we compare the outputs of the two planning tools in the design of the three network topologies by averaging the results obtained with the 30 traffic matrices chosen.
Finally, we see how both planning tools design the two customers' networks declared in section 6.2.1 using all the possible values of k.

6.3.1 Complete analysis of a case study

Before showing all the case studies we deeply analyze one among them for studying how restoration 3Rs depend on the amount of k-shortest paths available for computing the restoration path.
In this case study we used a single traffic matrix (called M1), composed by 60 demands, for the three network topologies described in section 6.2.1. In this way it is possible to observe the impact of the connectivity degree increasing from Network A to C on the results obtained with the use of the two approaches.
In this section we considered all the possible values of k, from 1 to 30, so as to have a contiguos and not discrete curve of results with respect to k.
Both planning tools provided a network design able to restore all the demands affected by each FS. The number of restorations needed for each case studies is showed in Tab. 6.3.

It can be surprising that a higher number of FS requires less restoration paths, but this is due to the fact that for more connected networks the k shortest paths are shorter than in less connected networks (remember that

Table 6.3: FS and number of restorations needed for case studies

Network	n. FS	n. restorations needed
Network A	41	398
Network B	48	317
Network C	56	296

all the networks have the same number of nodes). As a consequence, nominal trails are in average shorter in Network C and when a failure arises less nominal trails are impacted.
The proposed algorithm uses the adaptive alternative routing for restoration phase, so the choice of restored path can differ between the two approaches. As a consequence, they allocate a different amount of resources in the network, such as 3Rs and channels.
Fig. 6.6, Fig. 6.7 and Fig. 6.8 show the number of restoration 3Rs allocated by both planning tools with respect to k for each case study.

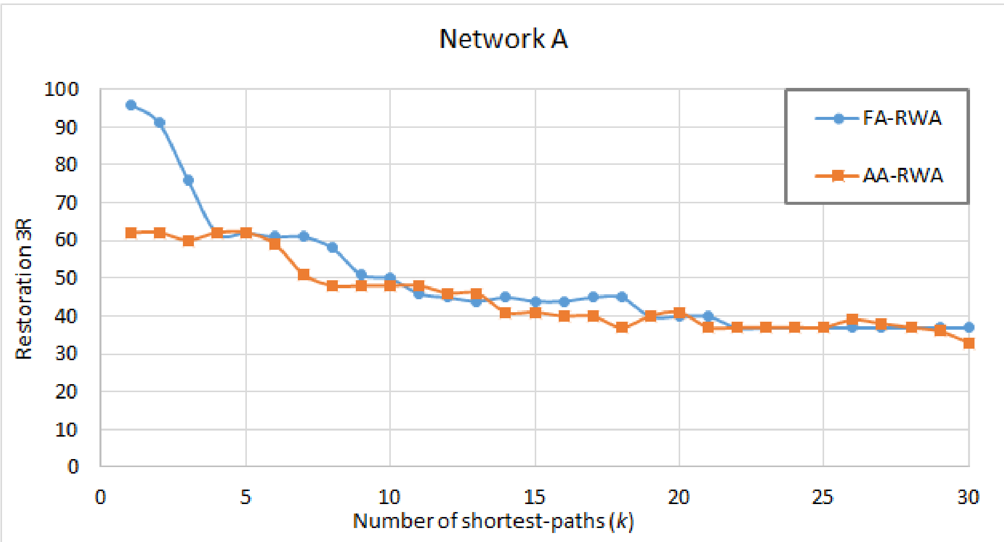


Figure 6.6: M_1: 3R of restoration allocated for Network A

The initial observations are that:

- the number of restoration 3Rs allocated by both algorithms decreases

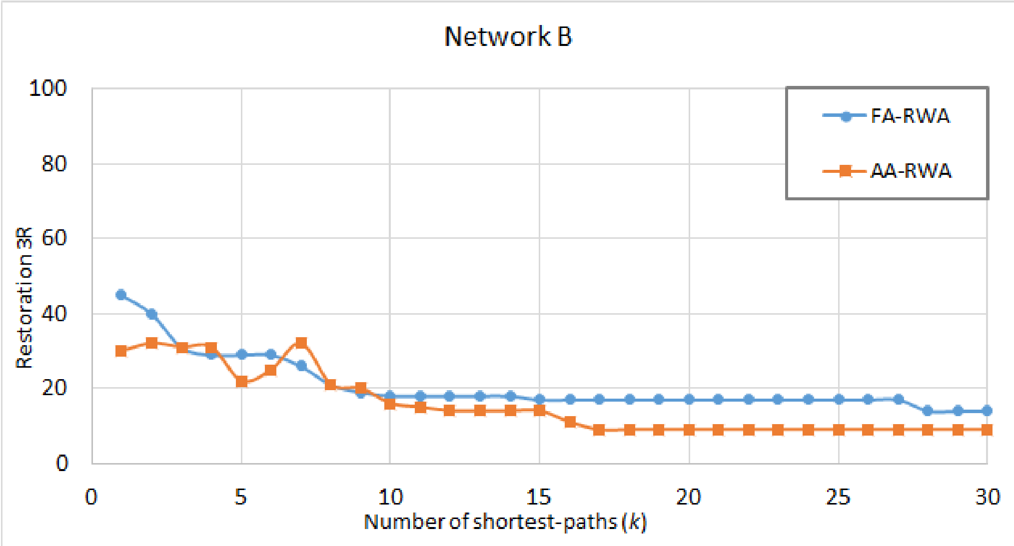


Figure 6.7: *M_1: 3R of restoration allocated for Network B*

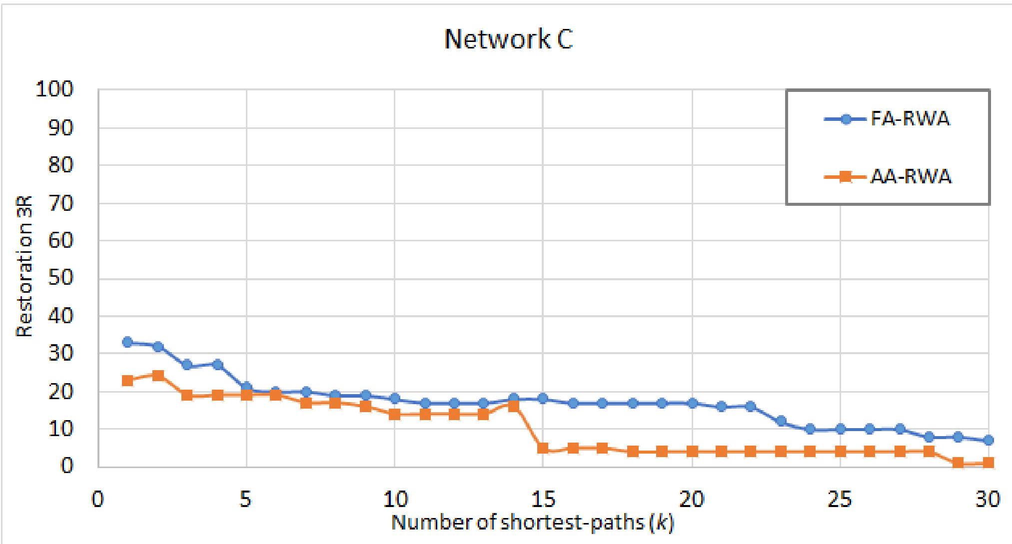


Figure 6.8: *M_1: 3R of restoration allocated for Network C*

with k increasing, because with a higher k each restoration can choose between more competitor paths and then there are more chances to find available restoration 3Rs allocated in the previous FSs;

- the number of restoration 3Rs allocated by both algorithms is higher for less connected networks (Network A) and lower for more connected networks (Network C). This is due to two main reasons. The first is that in more connected networks the k-shortest paths are in average shorter in terms of number of hops than the ones found in a less connected networks, so it is more likely that the restoration paths length is lower than the optical reach and then there is no need to regenerate the signal. The second reason is that even nominal trails are shorter, so one link fault impact less nominal trails and then less demands need to be restored.

Focusing now in a comparison between the output of the two approaches we notice that:

- the proposed tool allocates more or less the same amount of 3R of restoration for less connected networks (Network A), while we highlight an effective saving of 3R for more connected networks (Network B and Network C). This is due to the fact that in less connected networks there is a lower number of paths between a couple of nodes, then in many cases the k-shortest paths chosen are the same for both approaches, while for more connected networks we can include many more available paths for demands between any couple of nodes;
- the advantage of the proposed algorithm (in terms of number of saved 3R) is more important for lower k-values, because it is more likely that the k-shortest paths chosen by the two algorithms are different.

The capability of 3R sharing during the restoration phase depends on the capability of choosing a path for restoration passing through already deployed 3Rs.
This capability is enforced with AA-RWA, while FA-RWA does not provide a path search towards the already deployed 3Rs. For this reason the 3R sharing is higher for the proposed tool, and such sharing allows a lower number of 3Rs for the proposed approach.
The charts in figures 6.9 and 6.10 represents respectively the parameters

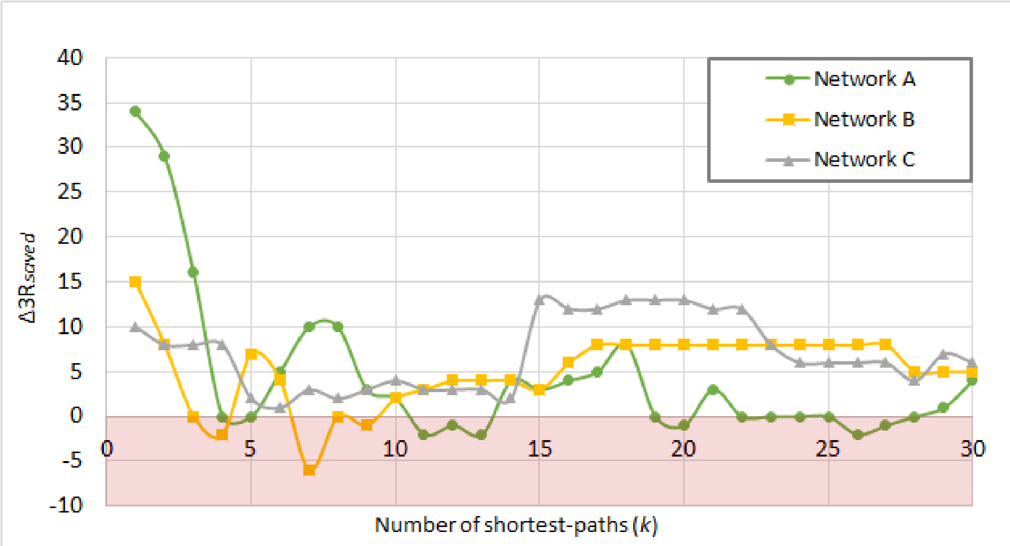


Figure 6.9: M_1: $\Delta 3R_{saved}$

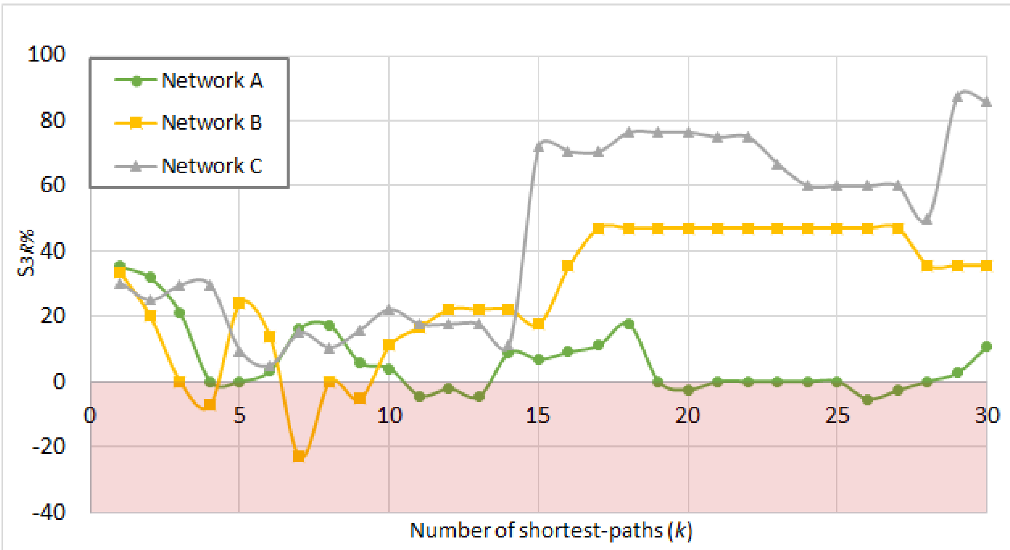


Figure 6.10: M_1: $S_{3R\%}$

Δ3R$_{saved}$ and S$_{3R\%}$ with respect to k.

The chart in Fig. 6.9 shows the absolute number of restoration 3Rs saved but it does not take in account the total number of restoration 3Rs allocated, while S$_{3R\%}$ in Fig. 6.10 does it.

We retain that the percentage values are important because they allow to

have an idea of the impact of the saving in the whole network solution. The higher percentage of saving 3Rs observed for Network C (Fig. 6.10) is related to the smaller use of restoration 3R for both approaches. In this case even one saved 3R provides a large percentage of saving.
The proposed AA-RWA can present a possible disadvantage: it may use more optical channels than FA-RWA for the restoration phase because likely its restoration paths are routed over longer paths passing through more links. In Fig. 6.11, the average number of occupied optical channels per link for both approaches and for the three case studies is shown.

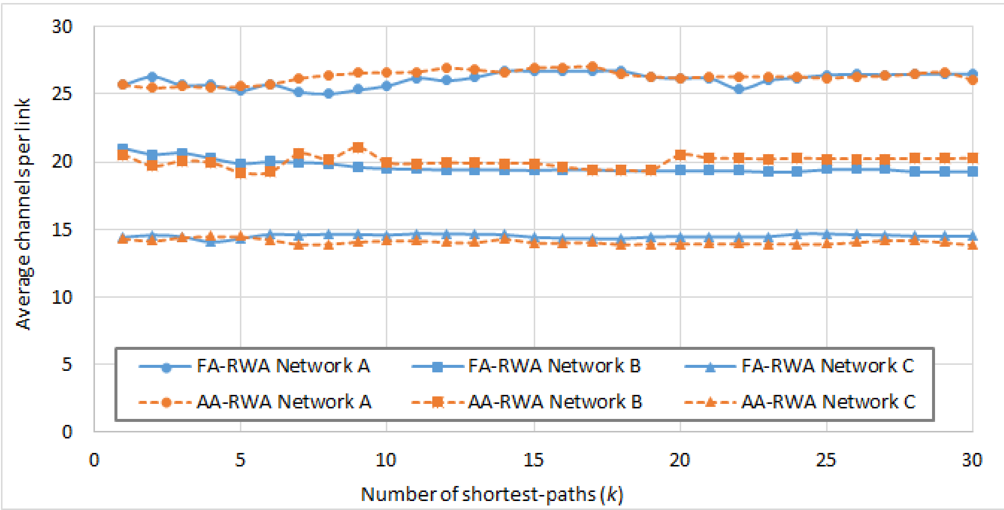


Figure 6.11: *M_1: average number of channels allocated per link*

We see that for Network A and Network B the number of channels allocated per link is almost the same for the two approaches, while for Network C the number of occupied optical channels is lower with the proposed algorithm. Indeed the proposed algorithm allows also a better sharing of optical channels that during the restoration phase can be used by different optical paths when they do not belong to the same FS. Optical channels like 3R reserved during restoration phase are not dedicated resources as for the nominal phase.
The results of the simulator (Tab. 6.4) are quite good for networks B and C, where the simulator can restore all the failed demands for all the failure

scenarios. Only in Network A the simulator cannot restore 31 out of 11940 broken demands (including all the 30 values of k and all the broken demands for all the FS, 398), so the simulator is not able to restore only 0,0026 % of the failed demands for Network A.

Table 6.4: *M_1: simulator results about blocked restorations*

Network	Algorithm	n. rest. needed	n. rest. blocked	% of rest. blocked
Network A	FA-RWA	11940	0	0 %
	AA-RWA	11940	31	0,0026 %
Network B	FA-RWA	9510	0	0 %
	AA-RWA	9510	0	0 %
Network C	FA-RWA	8880	0	0 %
	AA-RWA	8880	0	0 %

6.3.2 Average results over the 30 traffic matrices

The results obtained in section 6.3.1 show the reduction on network cost for the three network topologies in figures 6.6, 6.7 and 6.8, where only traffic matrix M_1 is used. But a more reliable analysis has to be performed for deducing the advantages of the proposed algorithm. So we used 30 traffic matrices made of sixty 100 Gbit/s demands, randomly chosen between all the couple of nodes in the network.
Applying 30 traffic matrices to the three network topologies gives 90 case studies to be tested by the two algorithms, and this would require a large amount of time to provide results for all the possible values of k. To save time we decided to test each case study only for a limited set of values of the parameter k: 1, 5, 10, 15, 20, 30.
In the following, we repete the same comparison as in the previous section on:

- the number of restoration 3Rs allocated in the network;

- $\Delta 3R_{saved}$;
- $S_{3R\%}$;
- Average number of optical channels allocated per link;
- Percentage of blocked restorations found by the simulator ($P_{blocked_{Rest}}$).

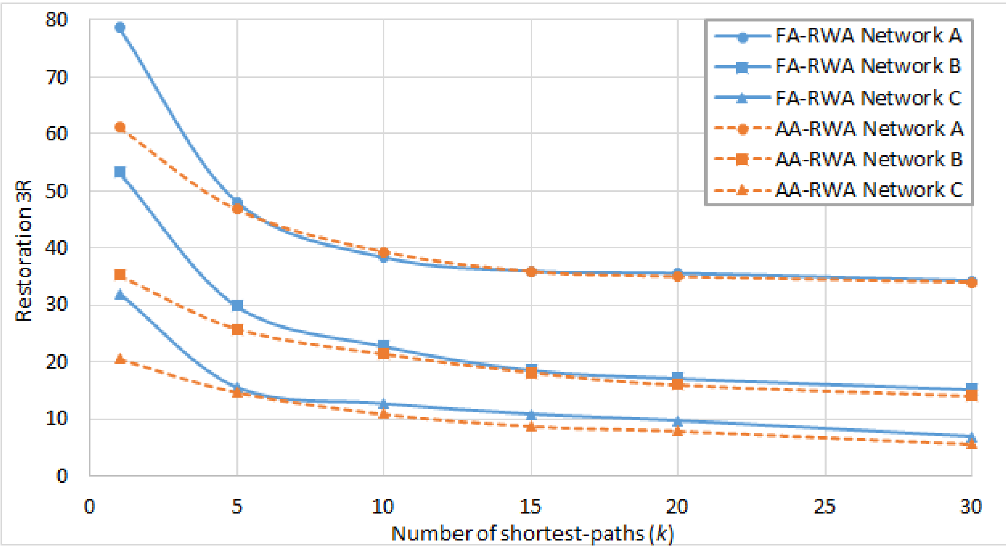


***Figure 6.12:** Average restoration 3Rs allocated*

In the following we repropose the same figures than in section 6.3.1, but now the presented curves are achieved by averaging the results obtained for the 30 traffic matrices.
These results confirm the trend observed in Fig. 6.9, that greater savings are observed for more connected networks and lower values of k.
It is important to remark that both algorithms are able to restore all the failed demands for all the FS, so we have the same restoration capability while using less restoration 3Rs. All the considerations done in section 6.3.1 have been validated by these averaged results.
All the considerations from section 3.1 about the charts of $\Delta 3R_{saved}$ and $S_{3R\%}$ are here confirmed. Indeed, we see that more connected networks (networks B and C) shows a saving of restoration 3Rs using the proposed

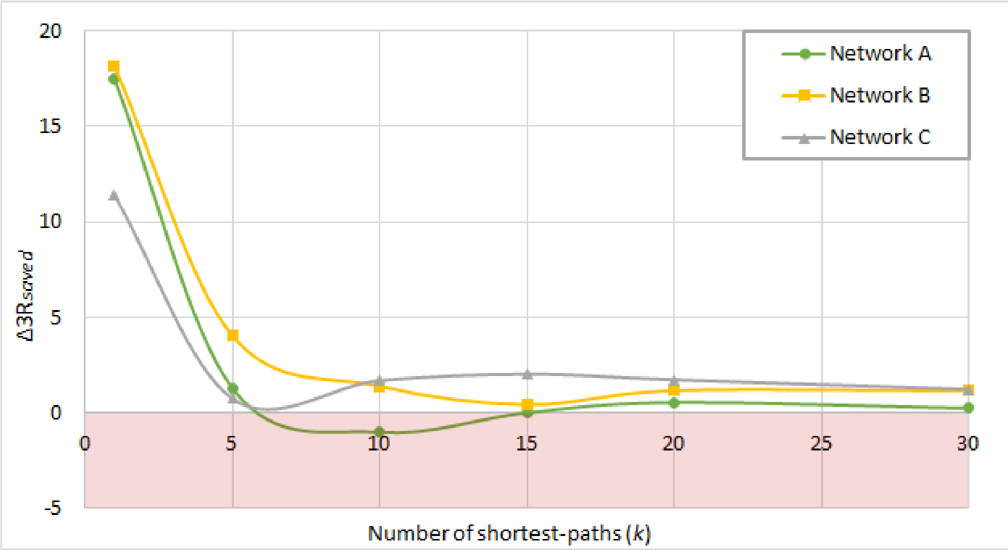


Figure 6.13: *Average* $\Delta 3R_{saved}$

tool regardless of of k used, with a better impact about $S_{3R\%}$ for Network C as there are less restoration 3Rs allocated than the number of restoration 3Rs allocated for the other networks. Network A does not show a saving of 3R except for low values of k.

In Fig. 6.15 is represented the average number of optical channels allocated for each one of the three network topologies using the two approaches.

The first observation is that the average number of channels allocated per link is higher for less connected networks. This is due to two main reasons:

- as explained in the previous section 6.3.1 networks (with the same number of nodes) less connected need a higher number of restorations;
- less connected networks have less links, so the total number of channels allocated are less spread over the network.

Coming back to the comparison between the two approaches, we see that for Network A AA-RWA allocates slightly more channels than FA-RWA, while for Network C the opposite is true. We deduce that the average number of channels allocated per link requested by AA-RWA is lower than the one required by FA-RWA when the network connectivity degree increases. This

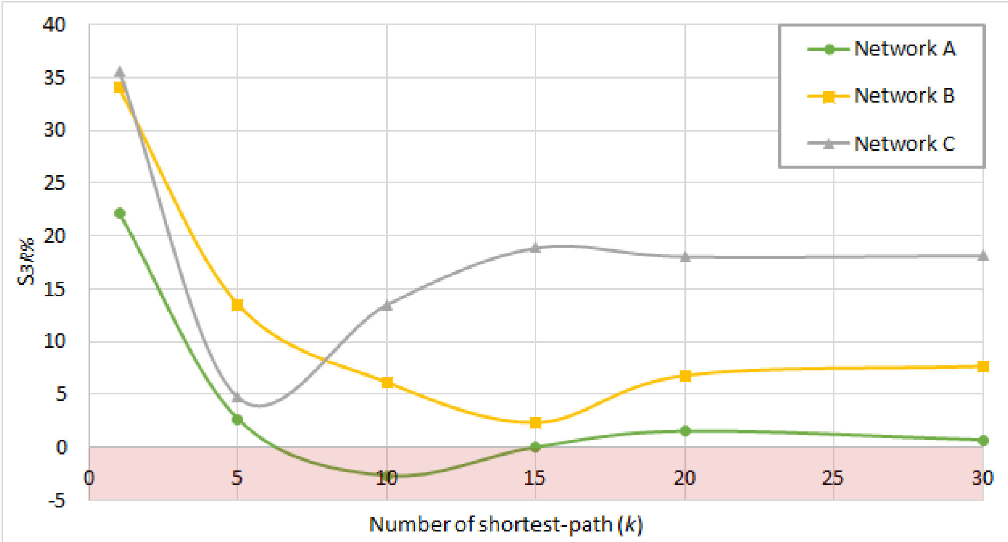


Figure 6.14: *Average* $S_{3R\%}$

is due to a better sharing of channels allocated for the restorations by the proposed algorithm. However, the difference between the two approaches for this parameter is negligible.

Now we use the simulator to validate the solution of each case study. The sum of the number of restorations calculated by both algorithms over the 30 traffic matrices and over all the k used is respectively:

- 63810 for Network A;
- 55158 for Network B;
- 48870 for Network C.

Tab. 6.5 presents the percentages of blocked restorations found by the simulator, these numbers are very low. For Network A and Network B this percentage is almost the same for both approaches, while for Network C AA-RWA presents more restorations blocked by the simulator than FA-RWA, but even here the number of restorations calculated by the tool is so high that the percentage of blocked restorations in the simulation is very low (0,094 %).

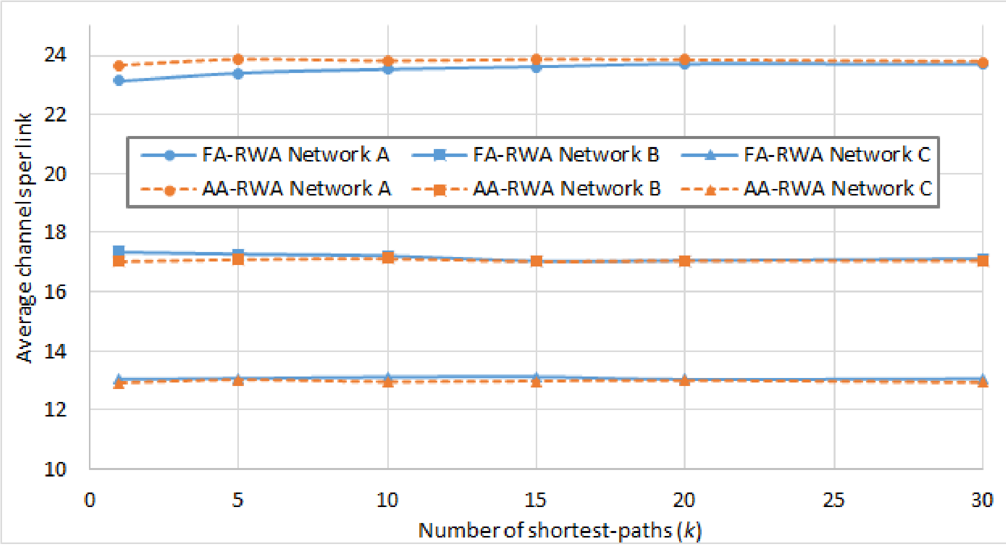


Figure 6.15: *Average number of channels allocated per link*

6.3.3 Customers' networks

We conclude this chapter with the results obtained from testing two customers' networks, so as to have an idea of the behavior of the proposed AA-RWA algorithm compared to the FA-RWA one in the design of real networks. The two network topologies (named Customer A and Customer B) and traffic matrices are described in section 6.2.1. Again, we tested these networks for all the possible values of the parameter k, from 1 to 30.

We can see from Fig. 6.16 and Fig. 6.17 that AA-RWA allocates a fewer number of 3Rs than FA-RWA, whatever k. Customer A is less connected than Customer B, as many nodes have a degree of connection equals to 2. Due to the different physical impairments of the networks, Customer A needs many more restoration 3Rs than Customer B.

As Customer B has a high connectivity degree, δ = 3,75 , we expect the modified tool to have a bigger impact than it would have on Customer A, where δ = 2,38 , and figures confirm conclusions of section 6.3.2: AA-RWA uses less resources than AA-RWA for both customers' networks.

About the average number of channels per link, we observe from Fig. 6.18 and 6.19 that the two approaches require approximately the same num-

Table 6.5: Simulator results about blocked restorations

Network	Algorithm	n. rest. needed	n. rest. blocked	Percentage of rest. blocked
Network A	FA-RWA	63180	6	0,0095 %
	AA-RWA	63180	6	0,0095 %
Network B	FA-RWA	55158	5	0,009 %
	AA-RWA	55158	16	0,029 %
Network C	FA-RWA	48870	0	0 %
	AA-RWA	48870	46	0,094 %

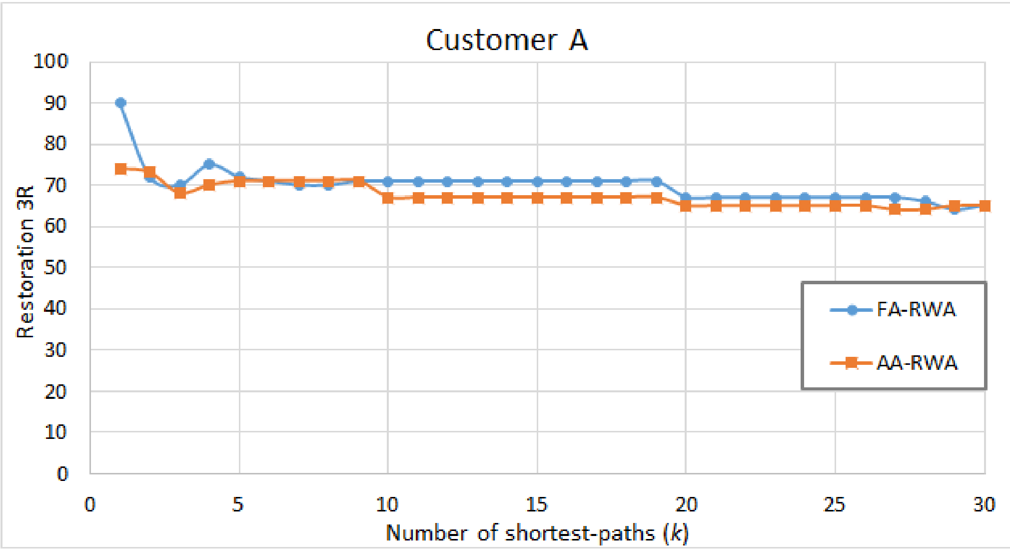


Figure 6.16: Customer A: restoration 3Rs allocated

ber of optical channels. Better results are observed for Customer B, where the average number of optical channels per link required using AA-RWA is slightly lower than the one required using FA-RWA.

Tab. 6.6 shows the simulator results for the customers' networks.

We observe that the number of restorations calculated by the two algorithms are the same for the two customers' networks. For Customer B the simulator is able to restore all demands with the nominal trail failed by the FS for all the failure scenarios. For Customer A we can observe the simulator

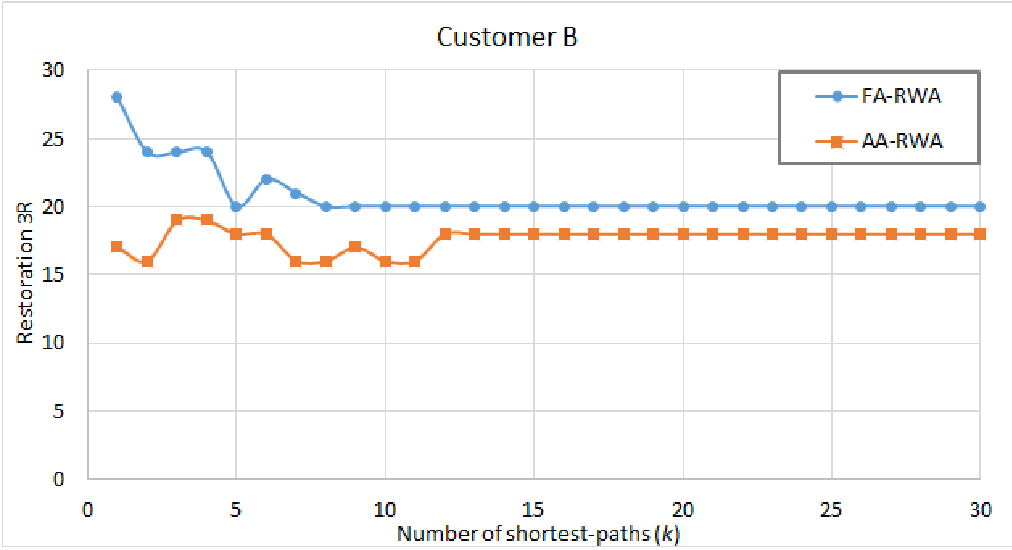


Figure 6.17: *Customer B: restoration 3Rs allocated*

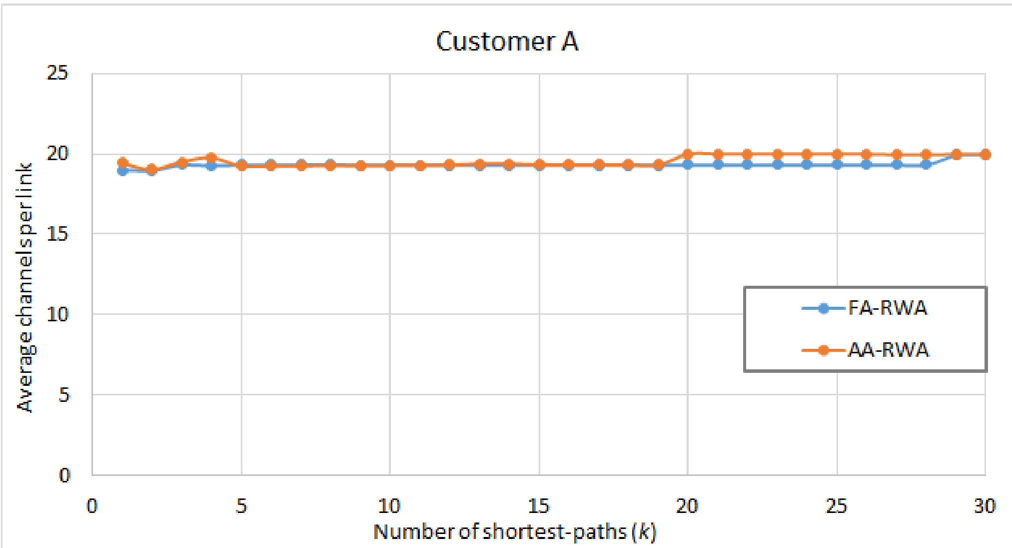


Figure 6.18: *Customer A: average number of channels allocated per link*

is not able to restore all the demands failed, but AA-RWA shows a better behavior because it has more demands restored by the simulator than what FA-RWA has.

These results show that the modified tool is reliable even when network topologies and traffic matrices of the customers are considered.

Figure 6.19: Customer B: average number of channels allocated per link

Table 6.6: Customers' networks: restorations blocked by the simulator

Network	Algorithm	n. rest. needed	n. rest. blocked	Percentage of rest. blocked
Customer A	FA-RWA	12150	204	1,67 %
	AA-RWA	12150	165	1,35 %
Customer B	FA-RWA	5160	0	0 %
	AA-RWA	5160	0	0 %

Finally, it is important to keep in consideration that the traffic matrices used are the original traffic matrices of the customers and that we only changed the type of the used OTs (as explained in section 6.2.2.1, all the OT of the networks tested are 130SNX10(LN)). As a next step, it would be interesting to test the proposed AA-RWA with various types of OTs in a network able to satisfy demands at different bit rates, but in order to achieve it we should solve many constraints related to nodes architecture and the devices belonging to them.

Chapter 7

Conclusions

7.1 Conclusions

In optical backbone networks opto-electronic devices are very costly due to the complex conversion from optical to electrical domain (and vice-versa) at a very high rate. Such devices are used for emetting/receiving the signals and regenerate them. To reduce the overall network cost, operators' aim is to reduce the number of regenerators (called 3Rs) without generating signal blocking due to physical impairments or wavelength continuity, neither for nominal nor for restoration paths.
Nominal 3Rs are dedicated to nominal paths, which are already routed with an efficient alternative routing based on Yen's algorithm. While restoration 3Rs are sharable between different restoration paths occurring for different Failure Scenarios (FSs). Then a smart technique to achieve a reduction of deployed restoration 3Rs is to exploit the 3R sharing.
In this work we used the Nokia planning tool named 1830 PSS Engineering and Planning Tool for dimensioning optical backbone networks for a given network topology and a traffic matrix. For restorable networks, the planning tool needs to know the set of network resources that can be affected at the same time by a failure.
The Routing and Wavelength Allocation routine implemented in the plan-

ning tool is based on a heuristic algorithm which considers sequentially the demands to route, as a consequence the resource allocation is incremental. Each demand is routed by using a fixed alternative routing algorithm (called FA-RWA); where alternative means that the demand can choose its route among k different paths; while fixed highlights that these k shortest paths are calculated by considering a static set of parameters describing the network.

In order to better exploit the available restoration 3Rs deployed for previous FSs, we proposed an alternative adaptive routing algorithm (AA-RWA) for RWA used in restoration phase, where adaptive means that when a new demand has to be routed all the network resources weigths are updated according to the availability of restoration 3Rs in the nodes. By performing this update mechanism before routing a demand, the routing algorithm becomes network-aware and favor the paths passing through available 3Rs already placed in the network.

The weight of resources associated to the available 3Rs is updated with lower values, so the k shortest paths calculated with the new weigths are forced to exploit available restoration 3Rs, which are sharable because deployed for previous FSs.

We compared the two routing algorithm (AA-RWA and FA-RWA) by dimensioning some case studies and customers' networks, in order to validate the proposed algorithm AA-RWA and check its networks design with respect to the legacy routing algorithm FA-RWA used by the 1830 PSS EPT. The case studies were obtained by dimensioning three network topologies with 30 different traffic matrices composed by the same number of demands. The three network topologies are composed by the same number of nodes (30), but they have different connectivity degree in order to estimate its impact on the needs of restoration 3Rs. Moreover, on each network we also considered the impact of k-value on the total number of 3Rs required for the restoration purpose.

Results showed that generally the proposed AA-RWA performs better than FA-RWA because less restoration 3Rs are computed, while the blocking probability remains unchanged. The advantages of AA-RWA are observed above all for low values of k, whatever the network topology.

When network topologies have high connectivity degree, the number of paths that can exploit the already deployed 3Rs when the weigths of network resources is changed is more important, so AA-RWA provides better results.

Generally, by considering all the case studies, AA-RWA required, in average, fewer restoration 3Rs than FA-RWA.

Eventually we validated using the Nokia network simulator (which emulates the real behavior of optical networks in the field) the obtained results, finding out that the two algorithms almost have the same overall blocking probability for the dimensioned networks.

This confirms that saved 3Rs do not jeopardize the correct operation of the network. As a conclusion, the proposed AA-RWA algorithm succeeded in its aim: reduce the overall network cost without impacting the correct network operations.

7.2 Future works

In this work we dealt with the software tools actually used in the field to dimension optical networks. These tools are very accurate and well optimized for providing a complete network dimensioning while minimizing the overall network cost.

Nevertheless, the greedy approach used by the network planning tool allowed us to propose an adaptive algorithm for providing a better sharing of restoration 3Rs.

The adaptive algorithms are the most promising solution to develop in future works. Further enhancements of the proposed AA-RWA algorithm can be performed in order to better exploit available 3Rs, for example using a more accurate weight for resources update.

If the main purpose is minimizing the links congestion, adaptive routing algorithms can be exploited dynamically associating higher weights to con-

gested links in order to discourage the next demands to further overload congested links, the k-shortest paths would change consequently.
Another important enhancement that can be performed during the restoration phase is ordering the failed demands by number of hops, because we know that long nominal trails require longer restoration paths. Doing so, there is a higher probability to route as first restoration paths needing regeneration, giving them the chance to re-use available restoration 3Rs deployed in previous FSs.

Glossary

AA-RWA Adaptive Alternative RWA

AWG Arrayed Waveguide Grating

BER Bit Error Rate

BOM Bill of Material

CD Coloreless Directionless

CDC Colorless Directionless Contentionless

CNF Centered Node First

EPT Engineering and Planning Tool

FA-RWA Fixed Alternative RWA

FEC Forward Error Correction

FS Failure Scenario

GMPLS Generalized Multi-Protocol Label Switching

GT Glass Through

IA Impairments Aware

ILA In-Line Amplifier

ILP Integer Linear Programming

ITU International Telecommunication Union

MCS Multicast Switch

MLR-RSSRP Mixed Line Rate Regenerator Site Selection and Regenerator Placement

NDF Nodal Degree First

OT Optical Transponder

OTN Optical Transport Network

PLC Planar Lightwave Circuit

PLI Physical Layer Impairments

ROADM Reconfigurable Optical Add Drop Multiplexer

RPP Regenerator Placement Problem

RS-RWA Random Search RWA

RSS Regenerator Site Selection

RWA Routing and Wavelength Assignment

SD-FEC Soft Decision Forward Error Correction

TI Transparent Island

WA Wavelength Assignment

WDM Wavelength Division Multiplexing

WSS Wavelength Selective Switch

3R Re-amplification, Re-shaping, Re-timing

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