Optimization Methods Applied to Network Planning Problems

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I would like to dedicate this thesis to my God and my loves: Karin and Rafaela.

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Abstract

This thesis focuses on the feasibility of solving network planning problems that include non-linear aspects by means of integer linear programming (ILP).

In the specialized literature, most network planning problems solved by applying ILP models do not include non-linear expressions in a direct way. However, non-linear expressions are very common when including constraints related to key network performance metrics as the blocking rate or the availability. To circumvent the difficulties of solving such problems, researchers have usually resorted to not including non-linear aspects or using meta-heuristics and heuristics, which do not guarantee an optimal solution. Such sub-optimal solutions lead to higher budget requirements or under performing networks and thus, as long as the optimal solution can be found in acceptable running times, it is preferred to other alternatives. The use of logarithm functions (to linearize some expressions) and mixed zero-one models have also be used, but not for the problems addressed in this thesis.

In this thesis 3 network planning problems including non-linear expressions were solved by means of ILP. The first problem was the dimensioning of network nodes and links in a dynamic wavelength-division multiplexed (WDM) network equipped with reconfigurable optical add-drop multiplexers (ROADM) as switching nodes. The network had to be dimensioned in such a way that the maximum blocking probability experienced by point-to-point connections would not exceed a maximum threshold. To date, no ILP works have addressed the problem of dimensioning for a specific blocking value. The second problem consisted on dimensioning and configuring the backup resources of a static WDM network using shared-path protection as survivability mechanism. The network had to be dimensioned guaranteeing that the availability of every connection would not decrease under a given target value. A new way of dealing with the non-linear expression for the availability target, the inclusion of an availability-based priority scheme for the access to the shared resources and the equations to consider the wavelength continuity constraint are the main contributions of this work. Finally, the dimensioning of working and backup wavelengths of the dynamic WDM network operating as the physical substrate of a network virtualization system was solved. In this system, virtual networks must be guaranteed a maximum blocking and minimum availability. No previous work has dealt with these constraints.

The strategies used in this thesis to solve non-linear network planning problems could be used as a starting point to solve problems in different network contexts that include important non-linear aspects.

Keywords: *network planning, integer linear programming, mixed zero-one models, WDM networks, blocking, availability, ROADM-based networks, shared path protection, network virtualization.*

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Acronyms

M-WCB: Wavelength Converter Bank of M ports.

AWG: Arrayed Waveguide Grating.

BRKGA: Biased Random-Key Genetic Algorithms.

CDC ROADM: Contentionless, Directionless and Colorless ROADM.

GRASP: Greedy Randomized Adaptive Search Procedure.

ILP: Integer Linear Programming or Integer Linear Program.

INLP: Integer Non Linear Programming or Integer Non Linear Program.

LP: Linear Programming or Linear Program.

MILP: Mixed Integer Linear Programming or Mixed Integer Linear Program.

MINLP: Mixed Integer Non Linear Programming or Mixed Integer Non Linear Program.

OBS: Optical Burst Switching.

OCS: Optical Circuit Switching.

OPS: Optical Packet Switching.

ROADM: Reconfigurable Optical Add Drop Multiplexer.

WC: Wavelength Converter.

WCB: Wavelength Converter Bank.

WDM: Wavelength Division Multiplexing.

WSS: Wavelength Selective Switch.

Common symbols

ρ	Traffic load.
C	Set of connections.
c	Index used to represent a connection.
L	Set of unidirectional links of the network.
l	Index used to represent a link.
$MTTF_l$	Mean Time To Failure of link l.
$MTTF_l$	Mean Time To Repair of link l.
N	Set of nodes of network.
p_l	Availability of link l.
t_{OFF}	Average time a connection is in OFF state.
t_{ON}	Average time a connection is in ON state.

Dimensioning of CDC ROADM-based networks symbols

α_n	Number of connections requiring a transmitter in the add section of node n.
β_w	Number of connections requiring a wavelength converter in WCB w.
δ_n	Number of connections requiring a receiver in the drop section of node n.
ϵ_n	Number of input links of node n.
γ_l	Number of connections requiring a channel of link l

θ_n	Number of output links of node n.
AL_c^{RX}	Value of $F^{RX}(R_{d_c}, \delta_{d_c}))$
AL_c^{TX}	Value of $F^{TX}(T_{s_c}, \alpha_{s_c}))$
AL_w^{WC}	Value of $F^{WC}(WC_w, \beta_w))$
B_c	Blocking probability of connection c.
B_c^{rx}	Blocking probability in the drop section of node d_c.
B_c^{tx}	Blocking probability in the add section of node s_c.
B_l	Blocking probability in link l.
B_w^{wc}	Blocking probability in the wavelength converter bank w.
B_{target}	Maximum value of blocking acceptable for any connection in the network.
C_{net}	Total network cost.
Ch	Number of WDM channels (wavelengths) available to transmit/receive by optical tunable transmitters/receivers in WDM network.
d_c	Destination node of connection c.
$F^{RX}(i,j)$	Value of $\log(1 - B^{rx}(i,j))$; $1 \leq i,j \leq \hat{\beta}_w$
$F^{TX}(i,j)$	Value of $\log(1 - B^{tx}(i,j))$; $1 \leq i,j \leq \hat{\alpha}_n$
$F^{WC}(i,j)$	Value of $\log(1 - B^{wc}(i,j))$; $1 \leq i,j \leq \hat{\beta}_w$
$Ir_{n,k}$	Index used to address R_n and δ_n in table F^{RX}
$It_{n,j}$	Index used to address T_n and α_n in table F^{TX}
$Iwc_{w,i}$	Index used to address WC_w and β_w in table F^{WC}
K^{RX}	Cost of a tunable optical receiver.
$K^{SC}(P^{req})$	Cost of an optical splitter (or coupler) with P^{req} required ports.

K^{TX}	Cost of a tunable optical transmitter.
K^{WC}	Cost of a wavelength converter with full conversion range.
$K^{WSS}(P^{req})$	Cost of a WSS with P^{req} required ports.
L_c	Set of links in route associated to connection c.
N_c	Set of nodes in route associated to connection c.
R_n	Number of tunable optical receivers in node n.
s_c	Source node of connection c.
T_n	Number of tunable optical transmitters in node n.
w	Wavelength converter bank index.
W_c	Set of WCBs used to establish connection c.
WCB_w	Number of wavelength converters in the wavelength converter bank w.

Dimensioning and configuring backup wavelengths symbols

A_c	Availability of connection c operating with sharing path protection.
A_c^B	Availability of backup lightpath of connection c.
A_c^W	Availability of working lightpath of connection c.
A_c^{Target}	Availability target of connection c.
$B_{c,i}$	In the context of the greedy algorithm, is the benefit obtained by sharing a backup wavelength for each pair of connections (c, i).
C_l	Set of connections whose backup routes use the link l.
LP_c^B	Backup lightpath associated to connection c.
LP_c^W	Working lightpath associated to connection c.
R_c^B	Backup route associated to connection c.

R_c^W	Working route associated to connection c.
X_c	Set of connections sharing resources with connection c with higher priority than c.
X_c^{All}	Set of all connections that might share resources with connection c.
$x_{c,i}$	Binary variable that is equal to zero if connection $i \in X_c$.
$y_{l,c,i}$	Binary variable for $l \in L, c \in C_l, i \in C_l$ $(c > i)$, such that $y_{l,c,i} = 1$ when the backup lightpath of connection c shares a wavelength on link l with a higher-priority connection i.
$z_{c,l}$	Binary variable equal to 1 if $l \in (\bigcup_{i \in X_c} R_i^W) \bigcup R_c^B$.

Virtual networks: dimensioning and configuration symbols

λ_l	Number total of wavelengths in physical link l.
λ_l^B	Number of backup wavelengths in physical link l.
λ_l^W	Number of working wavelengths in physical link l.
ρ^V	Traffic load offered by virtual networks.
B_v	Blocking experienced by virtual network v.
B_v^T	Target blocking requested for virtual network v.
B_{l^v}	Blocking experienced by virtual link network l^v.
$B_{L^v}^T$	Blocking threshold value, equal for all $l^v \in L^v$.
L^v	Set of virtual links in virtual network v.
N^v	Set of virtual nodes in virtual network v.
$R_{l^v}^B$	Backup route associated to virtual link l^v.
$R_{l^v}^W$	Working route associated to virtual link l^v.
V	Set of possible virtual topologies in the virtualization system.

v	Index used to represent a virtual network.

Chapter 1

Network Design and Planning Processes

The deployment of a network is a challenging task that must take into account a wide range of aspects to meet technical and economic requirements. Besides the expected connectivity between network nodes, several requirements associated to the levels of service to be delivered by the network (as delay, blocking, availability) must be met. Such levels of service must be achieved considering budget constraints or network cost minimization (initial investment and operational costs) [159; 160]. Finally, environmental constraints, as geographical or regulatory aspects related to civil works, must be considered.

A communication network deployment project strongly depends on several definitions. For example, what kind of network is necessary (long-haul, metropolitan, local area), how it will work (wired or wireless, statically or dynamically) and what equipment will be in place (types of transmitters/receivers, amplifiers, switches, etc.). Usually, in the literature the decision-making related to all these aspects is known as the network design process [38; 121; 162]. In this thesis, however, the concepts of network design and network planning are considered separately to better differentiate the nature of the different activities involved, as in [131].

In this thesis, the network design process defines the type of network to deploy: network topology, network coverage as well as transmission and control plane technologies must be specified in this stage. On the other hand, the network planning process defines the strategies used to comply with service requirements such as blocking rate, delay and availability (all directly affected by the network capacity dimensioning and resource allocation algorithms).

The design and planning network processes are key in the network deployment project, as they provide the information needed during the implementation stage of the network [131]. In addition, without such processes a much required estimation of the deployment cost would not be possible, impacting the feasibility of the whole project.

Because the operation conditions and service requirements considered as input to the design and planning processes could vary on time, usually such processes are part of a continuous improvement cycle, as shown in Fig. 1.1, where the network is continually monitored, re-designed and re-planned to adapt to the changing operative network conditions [55].

For the sake of clarity, the process description illustrated in Fig. 1.1 will focus on wired networks or fixed link wireless networks (thus leaving mobile wireless networks out of the scope of this thesis).

The first step in such cycle is the Requirements Specifications. In it, network performance and cost targets are set. Then, the step of Study of Environmental Information and Forecasts is carried out to identify regulatory and geographically constrains as well as parameters that affect network operation as traffic profile and failure probability of nodes and links. Next, the Network Design stage defines the network topology, operation mode and the technology to be implemented to then start the Network Planning stage, where the resource algorithms in the control plane are defined as well as the network capacity dimensioning and network configuration specification. Later, the steps of Network Installation and Configuration are carried out and the network starts operating under the defined configuration. During this period, the Compliance Assessment step is necessary to verify if the targets defined in the requirement specification are achieved. If not, the Adjustments step is executed to correct any deviation from the parameters set during the Requirements Specifications step. If the requirements or network operation conditions undergo major changes, the entire cycle must be carried out again.

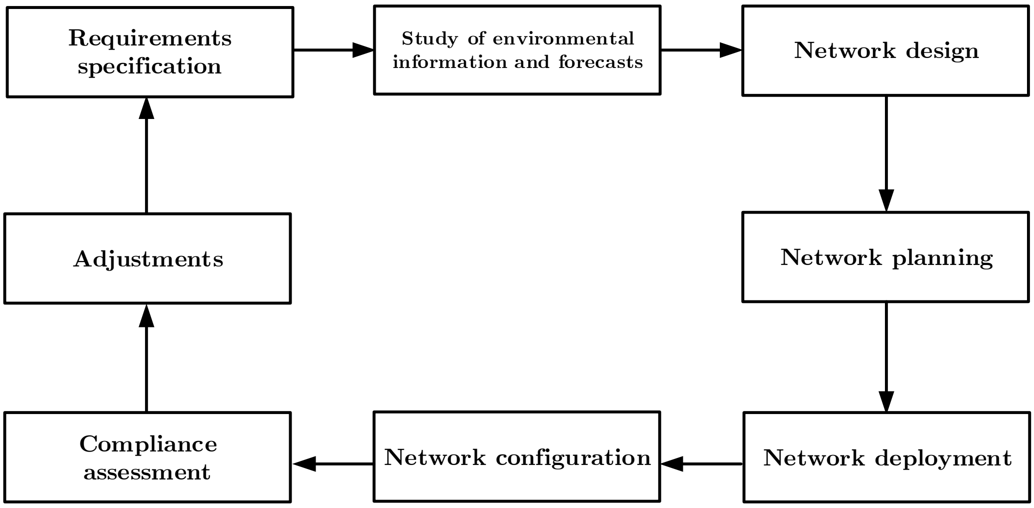


Figure 1.1: Cycle of implementation and continuous improvement of a network

The rest of this chapter focuses on the network design and planning processes and its previous stages, as they produce information relevant to design and planning steps. According to this, the rest of the chapter is as follows: In Sections 1.1 and 1.2 details about the Requirements Specification and Study of Environmental Information and Forecasts steps are given, respectively. Then, in Section 1.3, the aspects of the Network Design step related to topological design, technology selection and control plane are described, whilst in Section 1.4, different aspects of real-time and long-term planning process are discussed. The chapter finalizes with the presentation of the research question of this thesis (Section 1.5), the objectives and contribution to the area of network planning optimization (Section 1.6), a description of the structure of the remaining chapters (Section 1.8) and the list of publications generated during this research work (Section 1.9).

1.1 Requirements specification

In this Section, the typical requirements related to the network services, cost, network coverage and connectivity and quality of service targets are described.

1.1.1 Network services

The network services required by the network will determine, in part, what type of technology the network will be equipped with. This situation derives from the fact that the type of service is closely related to the bandwidth requirements, which in turn, have a high impact on the technology selection. For example, if the network service requires the transmission of data collected by industrial sensors -which only transmit data associated with measurements and status- then, the bandwidth requirement will be low and fieldbus technologies such as Profibus or Modbus (in the case of wired networks) or ZigBee (in the case of wireless networks) [4; 31; 62; 119] are suitable. Instead, if a local area network requires just data file transfer then, the bandwidth requirements are fulfilled with the Ethernet protocol using a wire connection or the WiFi protocol if a wire connection is not feasible. For multimedia services as VoIP, video conferencing or high-definition video on demand, more complex technologies as Gigabit Ethernet [71] for wired connections or WiMax for wireless connections must be implemented [164]. In metropolitan or long-haul networks, where the service of interconnecting local networks is required, high capacity bandwidth technologies as IP over WDM or ATM networks should be considered, that must also have the ability to group/ungroup traffic to/from various sources/destinations [85].

The information provided by this stage must be complemented with the information provided on the next one, Study of environmental information and forecasts stage (Section 1.2) to be able to feed the Network design process.

1.1.2 Cost requirements

One important requirement in any industry project is the maximization of profits, which implies minimizing the costs. In general, either one or the other is looked for to determine the design and planning of a network whilst satisfying the agreed quality of services.

In this step, there are two classes of expenditures that should be considered: capital expenditures (CapEx) and operational expenditures (OpEx). The former contributes to the fixed infrastructure associated to the network and includes the purchase of land and buildings (e.g. to house the personnel), civil work (e.g.

digging to install underground fiber), right-of-ways (to lay fiber on the property of someone else, e.g. along railways), network infrastructure (e.g., transmission media wires, access points, IP routers, transmitters, amplifiers, etc.) and software (e.g. network management system). The latter corresponds to the cost of maintaining the network operational and includes costs for technical and commercial operation. [78; 159; 160].

Table 1.1 shows the wide range of costs associated to OpEx, as discussed in [160]. The first column presents three categories in operational costs: those associated to operate an existing network, those associated to set up a new network and those not related to the technical operation of the network. The second column presents the different costs associated to the three categories just described. The third column lists examples of each type of expenditure.

The resulting OpEx usually grows inversely with the CapEx as more expensive equipment (higher CapEx) might lead to lower maintenance efforts, increased availability and reduced setup time, all of them decreasing OpEx.

Table 1.1: Classification of OpEx, based on [160].

Primary Classification	**Secondary Classification**	**Examples**
Expenditures to operate an existing network	Continuous cost of infrastructure related to the network service	• Floor space • Power and cooling energy • Leasing network equipment (e.g. fiber rental) • Right-of-ways, i.e. the privilege to put fiber on the property of someone else (e.g. along railways).
	Cost of maintaining/operating a network prone to failures	• Monitoring the network equipment and its services. • Stock management (keeping track of the available resources and order equipment if needed). • Security management (keeping track of people trying to violate the system and block resources if needed). • Change management (keeping track of changes in the network) and preventive replacement.
	Failure reparation	• Service interrupts. • Diagnosis and analysis. • Moving technicians to the place of the failure. • Fixing failures and performing the needed tests to verify that the failure is actually repaired.
	Service provisioning and management	• Processing requests, since entering the administration till performing the needed tests to ensure proper operation. • Processing cessation requests, deactivating the circuit, switching off and physically recovering the equipment.
	Pricing and billing	• Sending bills to the customers and ensuring payment. • Collecting information on service usage per customer, calculate cost per customer.
	Operational network planning	• Re-optimization and planning upgrades

Table 1.1 Continued: Classification of OpEx Costs based on [160].

Primary Classification	**Secondary Classification**	**Examples**
OpEx for Setting up a Network	Designing and Planning costs	• Study of environmental information and forecasts. • Designing and planning studies to evaluate the building of a new network. • Introducing a new technology or a new service platform. • Choice of an appropriate equipment vendor.
	Installation of new network equipment	• Installing, connecting and configuring new components in the network. • Testing of new components. • Compliance continuous assessment.
Non telco specific OpEx	Continuous cost of infrastructure	• Buildings to house the personnel. • Energy for desktop PCs, heating, cleaning of buildings.
	Administration costs	• Payment administration for employees. • Payment for secretary and human resources department.

Table 1.2 lists several references where different costs (either CapEx or OpEx) are considered for the network design and planning processes. For each reference, the minimization cost goal is described. The first column identifies the reference whilst the second and third describe the CapEx and OpEx costs considered, respectively.

Table 1.2: Costs requirements by different works focused on network design and planning

REF	CapEx	OpEx
[14]	Not considered	Minimize network equipment energy consumption.
[65]	Minimize the number and the location points of the network nodal equipment	Minimize the the number of PXC fabrics, distributed among the network nodes.
[68]	Minimize pricing and energy consumption costs	Not considered.
[77]	Not considered	Minimize network equipment energy consumption.
[143]	Minimize the total number of wavelengths to be implemented on the network	Not considered
[156]	Minimize the total number of wavelengths to be implemented on the network	Not considered
[171]	Minimize the number of required regenerators	Minimize the number of regeneration sites

1.1.3 Network coverage and connectivity

Network coverage refers to the number and location of network nodes. Network connectivity is a measure of the amount of links used to connect the nodes (the higher the number of links, the higher the connectivity). Together, network coverage and connectivity define the topological network design. In a greenfield scenario [80; 128], where the network must be built from scratch, the sets of nodes and links must be defined according to the geographical coverage target and the degree of connectivity required. In a wire network, the geographical coverage is determined by the population density (that affects the amount of traffic expected in a zone) whilst in a mobile network this is affected by the users movement profile. The connectivity is usually a function of the fault tolerance level required (normally, at least two different paths are required between any pair of nodes to ensure survivability to a single failure).[140]

Usually, there is an interplay between the mentioned requirements and other aspects of this and other stages. For example, the cost increases with the number of nodes/links, the quality of service is affected by the connectivity (higher connectivity leads to higher availability, lower delay and blocking but also increases cost), the technological choices of the design stage are constrained by the distance between nodes and the dimensioning of capacity of links (carried out in the planning stage) is in turn affected by the number of links.

Table 1.3 lists some references where network coverage and connectivity requirements are considered. For each reference, a brief description of the work done is provided along with the requirements considered to define the topological design.

Table 1.3: Revision of network design and network planning works considering connectivity requirements

Reference	**Description**	**Requirements**
[46]	Topological design, minimizing the total line cost.	• Link capacity constraints. • Average packet delay constraints. • Reliability constraint.
[122]	Minimize the number of arcs required to interconnect n nodes.	• Network diameter does not exceed d. • The maximum connectivity degree does not exceed a determined limit. • The network must survive single node failures.
[140]	Topological design of a fault-tolerant network with the aim of minimizing the total link cost.	• Each node must comply with a minimum nodal degree, according to the number of failures the network can survive. • The average packet delay is constrained to be lower than a given threshold

1.1.4 Quality of service targets

For the network services to run properly, a set of performance metrics must be defined along with their acceptable limits. Usual performance metrics are the blocking rate (fraction of connections blocked from being established in the network) and the availability of network (fraction of time during which the network is operative).

The acceptable levels of blocking impact the design of the network in terms of its capacity, as higher capacity (and thus, higher cost) leads to lower blocking and the types of algorithms used to allocate resources. With regard to availability requirements, if a high availability requirement is imposed, network elements with higher availability will be required, leading also to higher cost. This thesis focuses mainly on these two performance metrics, described below.

1.1.4.1 Blocking

The blocking rate is a statistical measure that represents the fraction of connection service requests that could not be served due to the lack of available network resources (e.g. channels on the links and transmission, reception and storage resources in source, destination and intermediate nodes)[8; 152].

The network blocking depends on the network capacity in nodes and links, the traffic generated by users and the provisioning algorithms running on the network.

Due to the complexity of using exact mathematical expressions to model the blocking and using it as an input to the dimensioning process, few works have focused on network dimensioning subject to a limit to the blocking. For example, in [37] such task was carried out by means of simulation.

1.1.4.2 Availability

Availability can be defined as the probability that a given system is available at any time. The availability of a system depends on the availability of each of the elements involved, normally expressed as a function of the time to failure and the time to repair.[161]

To increase the network availability, survivability strategies are used for the network to remain operative in the presence of attacks, failures, or accidents [36; 136; 182]. Protection and restoration are the commonly used network survivability strategies. Protection reserves backup resources when establishing the working connection. Restoration instead is a real-time approach that searches for backup resources once a failure has occurred. As a result of adding survivability strategies, additional resources are necessary to achieve the high availability levels usually required from telecommunication networks. Such backup resources can be complete routes, segments of routes, links or nodes (network devices) [182].

Survivability can be one of the network design requirements. That is, if a survivable network is required, then the level of availability considered as acceptable must be defined. Although different survivable networks might exhibit very different levels of availability [56; 87], most works consider that a network is survivable if it is able to survive single link/node failures [58; 63]. Sometimes, a multiple failure situation (normally, just two simultaneous failures) is also considered [66; 181]. Very few works define a specific level of availability, although this is the normal situation on SLAs where the network provider agrees to comply with values that typically range from 0.99 to 0.9999, depending on the type of network.

Examples of works considering the availability requirements in the network design and planning are the following. In [149] protected optical transport networks are dimensioned considering a minimum value of availability for each connection. To do so, an heuristic method was implemented such that: first the network is dimensioned maximizing the connection availability and then, the network capacity is decreased by adjusting the availability. Then, in [63] the optical metro/core networks with dual-homed access dimensioning considers that 100% survivability is achieved if the network can survive single node failures. To do so, an heuristic method was proposed to restore connections. In [66] the design of logical topologies able to survive multiple failures in IP-over-WDM networks is addressed. For this, and optimization model based on a column generation path formulation [32] is used.

1.2 Study of environmental information and forecasts

The environmental information includes geographic information, movement of people and vehicles, weather and government regulations affecting the area where any part of the communication network will be deployed. This information is very important for the CapEx/OpEx estimations [159; 160] and the technological definitions associated to the transmission media. Table 1.4 lists some examples about the environmental media and its impact in the network design and planning processes.

Considering the environmental information, forecasts related to costs [102; 137], failure risks and the traffic behaviour must be generated [157]. Furthermore, the information associated to the users of the network service (movement of people and vehicles), allows modeling the traffic load that the network will have to accommodate ([117, Section 5.10],[24]). This information is essential for the network dimensioning.

Table 1.4: Examples of environmental information for network design and planning

Type of information	**Examples**	**Impact**
Geographic [99]	• Distance between nodes. • Topographic information.	• Type of transmission media selection. • Network CapEX and OpEx.
Movement of people and vehicles [69; 70]	Movement of people and vehicles	• Wireless channel characterization. • Location of wireless base stations • Network CapEX and OpEx.
Weather [92]	• Precipitation type and intensity • Wind speed and direction	• Requirements of infrastructure of towers (wireless networks). • Wireless channel caracterization. • Installation of aerial optical fiber • Network CapEx and OpEx.
Government regulation [145]	Feasibility of installing network points (wireless towers, fiber optic termination boxes)	Network CapEX and OpEx

1.3 Network Design Process

The Network Design process

> *"encompasses much of the up-front work such as selecting which nodes to include in the network, laying out the topology to interconnect the nodes, selecting what type of transmission and switching systems to deploy (e.g., selecting the line-rate and whether to see optical bypass), what equipment to deploy a particular node."* [131, pag. 14]

In the following, the tasks of defining the network topology, the transmission, switching and control plane technology will be described.

1.3.1 Topological design

Given the requirements about the node set and the connectivity level described in Section 1.1.3, the topological design problem can be summarized as the selection of pairs of nodes that are directly connected, irrespective of the transmission media (guided or not).[113]

The topological design task is usually driven by budget constraints. The main costs associated to the topology implementation are civil works [165, pag. 282], the laying of the guided transmission medium (if applicable) and the equipment required in nodes and links.

Table 1.5 lists some works reporting solutions to the problem of topological design in different types of networks. For each work, a brief description of the topology design problem and the cost constraints are given.

Table 1.5: Examples of topological design works

REF	**Description**	**Costs considered**	**Constraints**
[34]	Topology design of IP over WDM networks considering energy efficiency.	Total power consumption.	Minimum nodal degree limit.
[96]	Genetic algorithm for the topological design of survivable optical transport networks.	CapEx: deployment, cost with the WDM terminals, optical amplifiers, and optical fiber and transponders	Survivability considering single-link failure
[178]	Industrial Ethernet network topological design, optimizing the real-time performance while considering the constraint of wiring costs.	Wiring costs	Maximum budget constraint

1.3.2 Transmission and switching technological design

It corresponds to the process of selecting the transmission and switching technology used in the physical layer of the network. This process must ensure that the network will be able to provide the network services established in the requirements definition step (Section 1.1.1) at minimum cost. Also, the environmental information and forecasts (Section 1.2) must be considered in this task.

In this stage each network equipment must be defined as well as the types of links to use. Table 1.6 lists the types of components to define in this stage along with their description and the aspects affecting the decision regarding the technology selected to implement each of them.

1.3.3 Control plane technological system design

It corresponds to the selection of the operating mode of the network that, in turn, determines the necessary technological infrastructure to enable the control plane to execute its tasks.

In relation to the operating mode selection, the network could operate in static mode or dynamic mode. Under static operation, each connection is allocated network resources during a long period of time (months or even years), even though during some periods data is not transmitted [2; 6]. Conversely, under dynamic operation network resources are allocated only while data is actually transmitted. Such resources are released as soon as data transmission ends. [5; 23; 174]. The decision about designing the network to operate in dynamic or static mode depends on the associated network equipment purchase budget and the traffic profile.

Table 1.6: Transmission and switching technological definitions

Network component	**Aspects to define**	**Affected by**
Transmitters and Receivers	• Modulation and demodulation system. • Transmission power level. • In the case of digital transmission, the bit rate used. • For wireless networks, the antennas must be specified (gain, radiation pattern, etc.).	• Signal to noise ratio of physical links. • Distance between nodes. • Topographic characteristics of the land between nodes • Weather conditions. • Interference by other wireless networks.
Switching	• Size of switches • Type of switching (packet switching [123], circuit switching [91, pag. 135], etc).	• Network connectivity • Bandwidth required. • Type of network services required.
Transmission media (Section 6.2.1 on [18])	• Wired media (optical fiber, coaxial cable, UTP) • Wireless media (WiFi, WiMax) .	• Distance between nodes. • Topographic characteristics of the land between nodes. • Bandwidth required
Intermediate transmission equipment	• Type of repeaters required • Type of amplifiers required	• Distance between nodes. • Topographic characteristics of the land between nodes

Regarding the control plane tasks, the resource provisioning task consists on finding a route with available resources (in nodes and links) to serve the request for connection establishment (usually between two nodes) [67; 115; 144]. Upon failure occurrence on any element of the route, the provisioning algorithm should also apply strategies to maintain the connection operative. Such strategies can be of the protection type (switching to backup resources previously configured) or restoration type (performing a new resource provisioning process).

In the case that dynamic operation mode is selected, a signaling system that allows monitoring network status, processing connection requirements and recognize failure events should be implemented. In addition, a software platform for the execution of resource allocation algorithms and restoration should be designed. [48; 79; 147]. In the case of static operation mode, the technological system required is much less complex since a signaling system is not required, because the configurations are established before network operation starts. [78]

1.4 Network Planning Process

The network design and the network planning processes are closely related, as the network planning requires the output of the design process to be carried out. According to [131, pag. 14], in the context of optical networks:

> *"Network planning is more focused on the details of how to accommodate the traffic that will be carried by the network. For example, network planning includes selecting how a particular demand should be routed, protected, and groomed, and what wavelength(s) in the system spectrum should be assigned to carry it."*

That is, the Network Planning process consists on defining the network equipment, network configurations and specifying the algorithms implemented in the control plane in order to meet the service level agreements (see Section 1.1.4). These tasks must be carried out by minimizing the network cost.

Depending on the time scale involved, the network planning problems can be classified as *real-time network planning* and *long-term network planning* [131, pag. 14].

- *In real-time network planning, there is little time between planning and provisioning, and demands are generally processed one at a time. It is assumed that the traffic must be accommodated using whatever equipment is already deployed in the network. Thus, the planning process must take into account any constraints posed by the current state of deployed equipment,* *which, for example, may force a demand to be routed over a sub-optimal path.*

- *In long-term network planning, there is sufficient time between the planning and provisioning processes such that any additional equipment required by the plan can be deployed.*

Note that real-time planning depends on the long-term planning as the capacity available in the network impacts the decisions made during real time operation. In the following, details about these categories are given.

1.4.1 Real-time network planning

During network operation, the real-time network planning process is executed on-demand by the control plane in response to events generated on the network. These events corresponds to the connection requests, failures on the network (on links or nodes) or alarms related to rising traffic levels in parts of the network.

These events, jointly with the network status (updated information about available network devices and traffic level occupancy in nodes and links), are the inputs to the real-time network planning. The output of the real-time network planning corresponds to the configuration required to adapt the network to the generated event.

Depending on the generated event, a different task must be associated to the real-time network planning executed by the network control plane. In the case of a connection request, the resource provisioning algorithm must be executed. Whereas if a failure occurs, the restoration of the affected connections must be carried out. Finally, if unacceptable levels of traffic are reached somewhere in the network, congestion control procedures must be in place. Due to the time constraints associated to the real-time operation, these tasks must have response times suitable to the service requirements.

These tasks are detailed in the following.

1.4.1.1 On-demand resource provisioning

A resource provisioning algorithm must be designed to find and assign the resources necessary to establish a connection [67; 115; 125; 144]. For example, to establish a connection in a WDM network, a routing and wavelength assignment algorithm in charge of finding a route and a WDM channel in each link belonging to the route must be designed [124] (in addition, devices for transmission, reception and transit between nodes through the selected route must be allocated).

Using an efficient resource provisioning algorithm is key to comply with the SLA, specially in terms of blocking probability (see Section 1.1.4.1). Due to this, provisioning algorithms are usually designed to accept as many connection requests as possible [3; 88].

1.4.1.2 Restoration

Restoration is a real-time strategy to keep the network operative (i.e. connections already established can continue transmitting information) in spite of network failures. Restoration consists on finding, on real-time, a new set of operative resources that can be used as a replacement for the failed ones with the aim to maintain network operation [27; 86; 94; 118].

Restoration strategies can be classified as:

- *Path restoration:* the source of the each connection affected by the failed link/node is responsible for initiating the process of restoring the corresponding connection.

- *Link restoration:* the source node of the link failed is in charge of initiating the restoration procedure.

The use of restoration algorithms is key for SLA compliance in terms of availability (see Section 1.1.4.2) as they increase the availability of connections affected by failures.

In the following, some examples of works proposing restoration algorithms are briefly described. In [29] an algorithm to restore connections from double-link failures in all-optical networks is proposed. All disrupted lightpaths by the failure are restored using for the route with the highest possible optical signal-to-noise ratio. In [16] a survivable algorithm able to restore the network from network multi-link failure in elastic optical path networks is proposed. To do so, primary and link-disjoint shared backup paths are pre-computed. Finally, in [49] backup paths are computed dynamically on the basis of link-state information after fault occurrence, and in [107] a restoration technique enabling multipath recovery in an elastic optical network is presented.

1.4.1.3 Network congestion control

If the network applications generate more traffic than the level the network is designed to operate with, congestion arises. Under congestion, harmful situations might occur: new connections cannot be established due to the lack of available resources and, in packet switched networks, the delay of the connections increase significantly due to switch saturation [93; 120; 129].

Congestion can be controlled by balancing traffic load across the network, avoiding retransmissions as much as possible, deflecting traffic around congested zones and discarding data [169].

Congestion control procedures are necessary for the network to comply with the SLA in terms of delay blocking and availability.

1.4.2 Long-term network planning

Once a network is already designed (see Section 1.3), the long-term planning task is in charge of the network static configuration and dimensioning, as explained in the following.

1.4.2.1 Definition of network static configuration

According to the designed control plane (see Section 1.3.3), all aspects of the network that are not operated automatically must be configured in this stage. In the following, the more representative examples are described:

- if the routing algorithm is fixed (that is, a unique route is considered for each possible node pair) or fixed alternate (that is, a set of routes is considered for each possible node pair), then the routing tables must be configured in this stage [83; 84].

- if dynamic channel assignment is not possible during network operation then the channel to be used for each connection must be defined [139; 172].
- if a protection survivability strategy (for links or routes) is selected rather than restoration, the control plane must be configured with the information about the backup resources to use to protect each link or path [42].
- if the control plane does not dynamically adjust power transmission levels during operation, the power levels of each transmitter, repeater and amplifier must be set [74].

1.4.2.2 Network dimensioning

This task is concerned with determining the number of devices in each section of the network (e.g. number of channels and amplifiers in links and number of transmitters/receivers in nodes), in such a way that quality of service requirements are met at the minimum possible cost. Control plane definition and network static configuration must also be taken into account to carry out the dimensioning. [63; 64; 135]

Given that the result of the dimensioning task is the number and type of equipment to be installed, this stage defines an important part of the CapEx. Because of that, efficient dimensioning methods are very much required. Also, as the network configuration also impacts the dimensioning, sometimes both stages (configuration and dimensioning) are carried out jointly with the aim of minimizing the resulting cost whilst meeting the SLA [30; 35; 156].

1.4.3 Solving network planning problems

Network planning problems are solved by using one of the following three methods:

- Mathematical programming: technique that allows finding the optimal solution to a constrained problem with an objective function [11]. Typical objective functions in network planning problems are minimizing cost (either represented by money or resource requirements) [65; 68; 171] or maximizing network performance [59; 149; 168]. Usual constraints include the available budget [19; 167] or a target performance [30; 106]. Obtaining the optimal solution of the problem is the main advantage of this technique, but this comes at the expense of high computational complexity and limitations on the type of mathematical expressions that can be dealt with (usually, linear expressions). The latter is the main reason why many network planning solutions considering non-linear aspects (as blocking or availability) do not resort to mathematical programming.

- Meta-heuristics: algorithmic procedure that provides good quality solutions (there is no guarantee of obtaining the optimal solution) with significantly lower computational complexity than mathematical programming. One of the main advantages, on top of the low solving time, is that the same meta-heuristic can be tuned to be used to solve different problems. Examples of meta-heuristics used to solve network planning problems are: genetic algorithms [30], ant colonies [173] and greedy algorithms [100].
- Heuristics: ad-hoc algorithms specially designed to solve a specific problem, without guarantees on the quality of the solution. Unlike meta-heuristics, different heuristics must be devised to solve different problems. However, they are simpler to implement than mathematical programming or meta-heuristic approaches. Examples of works proposing heuristics used for network planning problems are [27; 63; 67; 115; 149].

1.5 Research question

This thesis focuses on solving network planning problems including requirements on the values of non-linear performance metrics (as blocking and availability) to be able to comply with typical SLA requirements. Usually, such problems are solved by means of meta-heuristics or heuristics, as the non-linear expressions make difficult the application of mathematical programming. However -in discarding the use of mathematical programming- the optimal solution cannot be found, leading to higher cost or worse network performance. Therefore, the research question of this thesis is:

> *“‘Is it possible to solve network planning problems by applying mathematical programming when non-linear performance metrics need to be considered?”*

To answer this research question, in this thesis 3 network planning problems with non-linear expressions for the performance metrics are studied:

- Dimensioning of dynamic WDM networks equipped with ROADM nodes such that minimum CapEx (corresponding of network equipment) are required whilst guaranteeing that no connection exceeds a given value of blocking.
- Dimensioning and configuration of minimum backup resources in a static WDM network such that every connection is guarantee a minimum availability level.
- Dimensioning of minimum working and backup resources of a dynamic WDM network used as the physical substrate of a network virtualization system such that every virtual network has a maximum blocking and minimum availability.

1.6 Objectives of this thesis

- Compiling the information scattered in different publications about the network design and planning processes.
- Deriving mathematical programming formulations that allow including specific non-linear expressions into the model.
- Obtaining the optimal solution to different network planning problems with non-linear expressions applying mathematical programming.

1.7 Contribution of this thesis

The novel contributions of this thesis are the following:

i) A written compilation of the main aspects related to the network design and planning processes.

ii) Formulation and solving of a mathematical programming model that minimizes the network cost in a dynamic WDM network equipped with ROADM nodes, including non-linear constraints of blocking.

iii) Derivation of an expression to estimate the availability of connections in a availability-based priority system for a shared-path protection network.

iv) Formulation and solving of a mathematical programming model that minimizes the backup resources in a shared-path protected optical network (with and without wavelength conversion) such that every connection is guaranteed minimum value of availability.

v) Design of a greedy algorithm to solve the dimensioning problem of minimizing backup resources in a static WDM network under shared-path protection.

vi) Formulation and solving of a mathematical programming model that minimizes resources in the physical substrate of network virtualization problem, such that virtual networks are guaranteed a maximum blocking and minimum availability.

1.8 Chapters distribution

The remaining chapters of this thesis are as follows:

- **Chapter 2:** A review of the main techniques used to solve network planning problems is presented to then introduce the main concepts associated to 3 network problems studied in this thesis, namely: ROADM-based dynamic optical networks, shared-protected optical networks and network virtualization systems. The chapter finishes with a review of previous works using mathematical programming models to solve the network planning problem in each of these types of networks.

- **Chapter 3:** This chapter address the problem of dimensioning a minimum cost Colorless / Directionless/ Contentionless (CDC) ROADM-based network. The network design is constrained by the maximum acceptable value for the blocking probability of every connection. To do so, first a CDC ROADM architecture that allows full wavelength conversion is proposed, as the blocking probability of dynamic networks is strongly affected by the wavelength conversion capability. Next, an ILP model that includes the stochastic nature of traffic demands and aims at minimizing the network cost subject to the blocking probability constraint for each connection is proposed. As a result, for a given maximum acceptable blocking probability per connection, the number of transmitters, receivers and wavelength converters in the CDC-ROADM nodes is determined. Finally, results for a set of realistic topologies with a target blocking value of 10^{-3} are presented.

- **Chapter 4:** In this chapter the problem of determining the backup wavelength requirements of a static optical network operating under shared protection is addressed. The chapter presents the formulation of an ILP model that aims at minimizing the total number of backup wavelengths such that the availability of every connection meets a given target value as well as a heuristic approach to solve the same problem in a shorter time. A modification of the original ILP to consider the wavelength continuity constraint is also presented to evaluate the impact of wavelength conversion. The ILP model identifies the set of connections sharing backup resources in any given network link. Also, a greedy algorithm that solves larger instances in shorter time than the ILP model is proposed. Finally, results for a set of topologies are presented. For each topology two scenarios were evaluated: homogeneous (the same availability target for each connection) an heterogeneous (different availability targets for different connections) scenarios, considering full and no wavelength conversion capability.

- **Chapter 5:** This chapter deals with the dimensioning and configuration of working and backup wavelengths on a network virtualization system (virtual networks are dynamically established on a physical optical substrate). To do so, a first mathematical programming model is presented. The model determines the minimum number of working wavelengths required in the physical substrate of the system such that virtual network blocking does not exceed a given threshold. Then, a second mathematical programming is derived. This model aims at minimizing the number of backup resources required in a shared-path protected substrate network such that the availability of the virtual networks established in the system is guaranteed to achieve a minimum value Results for ring virtual topologies are presented.

- **Chapter 6:** The main findings of this research work along with possible future research lines are discussed.

1.9 Publications and conference presentations

- **Tarifeño-Gajardo, M.**, Beghelli, A., & Moreno, E. (2016). Availability-driven optimal design of shared path protection in WDM networks. Networks, 68(3), 224-237.

- Barra, E., Salinas, R., Mora, F., **Tarifeño, M.**, Beghelli, A., Sambo, N., & Castoldi, P. (2014, July). Virtual network provisioning over multi-line rate networks with fixed or flexible grid. In 2014 16th International Conference on Transparent Optical Networks (ICTON) (pp. 1-4). IEEE.

- Leiva, A., Finochietto, J. M., Huiszoon, B., López, V., **Tarifeño, M.**, Aracil, J., & Beghelli, A. (2011). Comparison in power consumption of static and dynamic WDM networks. Optical Switching and Networking, 8(3), 149-161.

- **Tarifeño, M.**, Beghelli, A., & Moreno, E. (2011, February). Optimal dimensioning of dynamic WDM networks. In Optical Network Design and Modeling (ONDM), 2011 15th International Conference on (pp. 1-5). IEEE.

Chapter 2

WDM Network Planning Problems: A Review

This chapter presents an introduction to the three network planning problems addressed in this thesis, namely: dimensioning of a ROADM-based network, dimensioning of a shared protected optical network and dimensioning of a network virtualization system. To do so, first a description of the main solving methods used for network planning problems is given in Section 2.1 . Then, the main concepts associated to each network planing problem are presented in Secction 2.2 . Finally, Section 2.3 reviews the literature in terms of the methods used and results obtained in solving each network planning problem.

2.1 Modeling and solving network planning problems

The network planning problem is one of the most complex parts of the continuous cycle of network implementation and improvement. In fact, in [95], it is described as a

> *"multi-objective optimization problem which involves clustering the area of interest by minimizing a cost function which includes relevant parameters, such as installation cost, distance between user and base station, supported traffic, quality of received signal, etc."*

As such, it has triggered much theoretical work regarding how to model a network for further mathematical analysis, what aspects of cost should be considered, how to measure the performance of the planned network and what theoretical tools can be used to plan a network. In the following, these four aspects are briefly discussed.

2.1.1 Network modeling

Typically, a network is mathematically modeled as a graph $V = G(L, N)$, where L is the set of links and N the set of nodes. If the links connecting a node pair are identical in each direction, a undirected graph is enough. Otherwise, a directed graph must be used. [13], [154, Section 2.1]

Depending on the objective of the planning task, a weighted graph can also be used where the links can be associated to their length, cost of implementation or other parameters affecting the network cost [54; 89].

2.1.2 Network cost

Once the network design is ready, the network planning process requires a mathematical expression to model the cost in such a way that the objective of keeping the cost as low as possible can be met by using a mathematical approach. Such formula can consider CapEx, OpEx or both.

When considering CapEX, information about network equipment and physical premises costs are required (data collected in the “Forecasts and study of environmental information” stage). The network equipment selection must be done on the basis of the parameters that allowing complying with the SLA (usually defined in the “Requirements” stage of cycle in Figure 1.1) at the minimal possible cost. [72]

When taking OpEx into account, all costs associated to the correct network operation (i.e. complying with the SLA) must be considered. Among these, the equipment maintenance expenses (related to network monitoring and reparation) and energy consumption are the most relevant [17; 78; 160].

2.1.3 Performance metrics

Measuring the performance of the network in terms of relevant aspects (as the blocking probability or availability of network connections) is key to develop a network plan that complies with the SLA. In the network planning stage (where the actual network is not in place and thus, direct measurement is not possible) usually such metrics are estimated by means of some mathematical approach. In this way, the network dimensioning can be adjusted if the performance metric is out of the required range of values. The complexity of the telecommunication system determines the complexity of the method for estimating the performance measures. Typical telecommunications systems are very complex, mostly due to the random nature of traffic. Due to this, event-driven simulation is a possible approach. However, simulation is a time-consuming method for planning purposes and an optimal solution is not guaranteed. Optimization methods are a better choice from the point of view of the optimality of the solution. However, several performance metrics of telecommunication systems (especially those of dynamic nature) are expressed by means of non-linear formulae and this hinders the application of optimization [60; 133]. Details about how optimization models deal with this situation are given in Section 2.1.4.1.

2.1.4 Solving network planning problems

Any network planning solving method must clearly define the following aspects to be able to represent and find an acceptable solution:

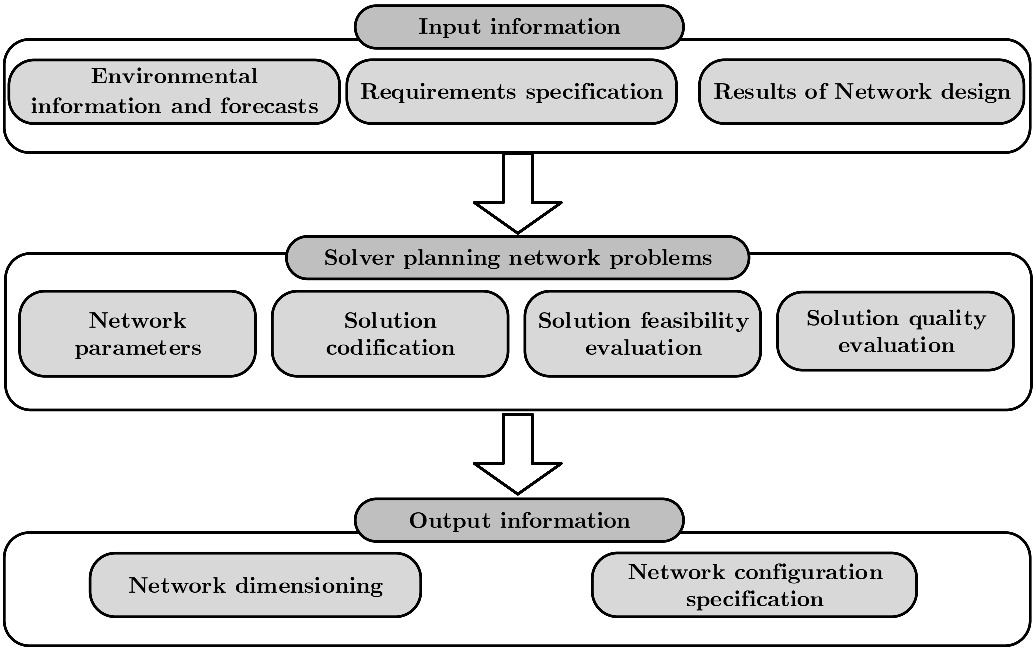


Figure 2.1: Schematic for stages in the network planning solution process

- *network parameters*: these are aspects of the network that affect the cost or complexity of the planning solution but that must be set to specific values during the search for a feasible solution. For example: pre-computed shortest paths, equipment cost, link availability.
- *solution codification:* this is the format used to represent the network planning solution. For example, if the problem is network link dimensioning, then the solution will be codified as a vector with as many elements as network links. Each element in the vector corresponds to the capacity of the corresponding link.
- *solution feasibility:* this is the set of conditions that define whether a solution is feasible or not. For example, the maximum distance between consecutive amplification points or the maximum acceptable value of blocking.
- *solution quality:* this is a function whose evaluation allows determining

whether solution A is better than solution B or not. Usually, this is a function that evaluates the cost of a solution.

Figure 2.1 shows the different stages of the network planning solving process along with their components and expected inputs/outputs. It can be seen that the information required to feed the solver comes from the “Requirements specification”, “Environmental information and forecast” and the results from the “Network design”. All this information is compiled to enter to the solver as the “Network parameters” and defining the solution coding, feasibility and quality. The output information generated by the solver corresponds to the Network dimensioning (long-term planning) and Configuration specification (either for short or long-term planning). In the following, the methods used by a solver are described. They can be classified in 3 main groups: mathematical programming, meta-heuristics and heuristics.

2.1.4.1 Mathematical programming

When using mathematical programming, the optimization model is expressed in terms of an objective function (that determines the solution quality), a set of decision variables (that codify the solution) and a set of constraints modeled as mathematical expressions (that define the solution feasibility). The objective function is expressed in terms of decision variables and network parameters.

The mathematical optimization allows finding an optimal solution within the total set of feasible solutions to a given problem. The optimality of the solution is measured in terms of the minimization/maximization of the objective function, given a set of constraints.[11]

According to the definition of the decision variables, mathematical optimization models can be classified as: continuous optimization models (all decision variables take continuous values), integer optimization models (the values of the decision variables are restricted to integer values) or mixed optimization models (the values of some decision variables are restricted to integer values and others can take continuous values).

On the other hand, optimization models can also be classified as linear and non-linear depending on the operations conducted on the decision variables, either in the objective function or the constraints. In a linear optimization program, the objective function and all constraints are expressed as linear expressions of the decision variables. In non-linear programming models, either the objective function or any of the constraints are expressed as non-linear functions of the decision variables.

In the network planning area the use of integer optimization models is very common because the decision variables usually take discrete values (for example, it is necessary to determine the number of network devices, the number of channels, or whether or not implementing a link). Also, dynamic networks planning problems are represented by non-linear models because of the random nature of traffic and failure occurrence. In this way, the usual methods for network planning problems are either Integer Non-Linear Programming (INLP) or Mixed Integer Non-Linear Programming (MINLP).

Current solving methods for INLP models, that mix the complexity of dealing with integer variables with that of dealing with non-linear expressions, do not exhibit the same solution capabilities of current ILP models [76, pag. 3]. This gap increases with the number of decision variables and constraints. Therefore, a usual strategy is linealizing the non-linear expressions so MILP solvers [76, pag. x] as cutting planes algorithms based on polyhedral combinatorics; enumerative approaches and Branch-and-Bound, Branch-and-Cut and Branch-and-Price; and relaxation and decomposition techniques. [45], [126, part IV] can be applied.

To linealize non-linear expressions several techniques can be used. For example: applying logarithmic function to expressions where decision variables are multiplied (and thus, they become sums) and incorporating new integer variables and constraints using mixed zero-one programming models [44; 50; 105] for functions depending on one or more variables. Linearization techniques usually comes at the expense of adding many auxiliary variables and restrictions to the original MINLP.

Some references of mathematical programming optimization models implemented for long-term planning network are the following. In [151] an ILP model to dimension the number of transceivers in elastic optical networks is derived and solved. In [33] the dimensioning of server resources and network infrastructure to implement a decentralized, big-scale survivable network is carried out by formulating and solving an ILP model. Then, in [22] an ILP model for dimensioning the number of splitters, AWGs (Arrayed Waveguide Grating device) and ports in a Passive Optical Network is presented. Finally in [166], an optimization problem, formulated as a MILNP model, aimed to minimize resource allocation whilst guaranteeing the quality of transmission of every channel is proposed in the context of elastic optical networks. The MILNP though is not solved. The problem is solved by means of a heuristic method.

2.1.4.2 Meta-heuristics

Metaheuristics

> *"... represent a family of approximate optimization techniques [...] They are among the most promising and successful techniques. Metaheuristics provide "acceptable" solutions in a reasonable time for solving hard and complex problems in science and engineering. This explains the significant growth of interest in metaheuristic domain. Unlike exact optimization algorithms, metaheuristics do not guarantee the optimality of the obtained solutions. Instead of approximation algorithms, metaheuristics do not define how close are the obtained solutions from the optimal ones."*
>
> *"The word heuristic has its origin in the old Greek word heuriskein, which means the art of discovering new strategies (rules) to solve problems. The suffix meta, also a Greek word, means "upper level methodology." The term metaheuristic was introduced by F. Glover in the paper [51]. Metaheuristic search methods can be defined as upper level general methodologies (templates) that can be used as guiding strategies in designing underlying heuristics to solve specific optimization problems."*[141, pag. 14]

Unlike mathematical programming, implementing a metaheuristic does not require evaluating the quality of the solutions by means of a mathematical expression. Constraints do not require to be expressed as mathematical equations neither. As a result, when a linear or integer programming model is not possible (either because of non-linear expressions or computational complexity), metaheuristics are an attractive solution technique alternative.

The metaheuristics can be classified in single-solution based and population-based. The single-solution based algorithms manipulate and transform a single solution during the search, intensifying the search in local regions (explotation). Population-based algorithms instead evolve a whole population of solutions allowing a better diversification in the whole search space (exploration) [141, pag. 25]. Some examples for single-solution based are local search, greedy algorithms, tabu search, simulated annealing, threshold accepting, variable neighborhood search, iterated local search, guided local search and GRASP (Greedy Randomized Search Procedure). On the other side, in the population-based algorithms a whole population of solutions is evolved. Some examples for population-based metaheuristics are evolutionary algorithms (genetic algorithms, evolution strategies, genetic programming, evolutionary programming, estimation of distribution algorithms, differential evolution, and coevolutionary algorithms), swarm intelligence-based methods (e.g., ant colonies, particle swarm optimization), scatter search, bee colony and artificial immune systems. [142, pag. xix-xx], [141, pag. 25]

Metaheuristics are not a good solving technique when randomly generating a space solution with feasible solutions is hard (usually because of very complex solution coding or very constrained problems).

In the following, some examples of works using metaheuristics to solve long-term planning network problems are given.

In [30], the routing and dimensioning problem (number of wavelengths required per link) in dynamic WDM networks with fixed routing is solved by means of a genetic algorithm. In [110] the regenerator placement and dimensioning (number of regenerators) problem is solved for an optical network using GRASP and BRKGA (Biased Random-Key Genetic Algorithms).

2.1.4.3 Heuristics

Heuristics are ad-hoc algorithms specially designed to solve a particular problem leveraging on specific knowledge about such problem. As such, they carry out a more constrained exploration in the solution space than mathematical programming and meta-heuristics resulting in shorter execution times. Unlike metaheuristics, a same heuristic cannot be used to solve two different problems. As a result, the solution coding, feasibility and quality are defined specifically for each problem and cannot be adapted to a different problem in an easy way.

Typically, heuristics are used if the network planning problem cannot be solved applying mathematical programming or metaheuristics or if the solving time is constrained. Because of that, run-time network planning problems are usually adressed by means of heuristics.

Examples of the use of heuristics for run-time planning problems are [67; 115; 125; 144] for resource provisioning and [27; 86; 94; 118] for restoration methods.

2.2 Basic concepts

This section presents the main concepts associated to the 3 long-term network planning problems solved in this thesis. Section 2.2.1 introduces the concept of WDM networks. Section 2.2.2 describes the main characteristics of a Reconfigurable Optical Add Drop Multiplexer (ROADM) and the advantages of a ROAD-based WDM network. Section 2.2.3 describes the survivability methods of dedicated path protection and shared path protection. Finally, Section 2.2.3 presents the main concepts associates to a network virtualization system.

2.2.1 WDM Networks

An optical WDM network uses optical fiber as transmission medium and wavelength-division multiplexing as a sharing technique to the multiple point-to-point connections that transmit using the same optical fiber. That is, every different connection is allocated a different wavelength in an optical fiber link to achieve simultaneous data transmission of different connections. The physical principles that make optical transmission possible are explained in [10].

Currently, WDM networks are the dominant technology in transport networks due to its high transmission rate (250 Gbps [81]) and low signal attenuation $0.2\frac{dB}{Km}$, allowing transmission without amplification over long distances [131, pag. 12]. The spectrum bands used by WDM networks are known as the C band (wavelengths from $1530nm$ to $1565nm$) and L band (wavelengths from $1565nm$

to 1625nm). Although wavelengths used for optical transmission are in the non-visible part of the spectrum, in this thesis different wavelengths are identified with different colors just for the sake of understanding.

To establish a point-to-point connection between a source node and a destination node, a route and a wavelength in each link along the route must be allocated [15] . To do so, a wavelength cannot be used by more than one connection at each network link. The allocation of wavelengths is very much affected by the existence of wavelength conversion capability (i.e., the capability of transmitting the data of a connection using different wavelengths along the route). Such capability is implemented in the network nodes, that must be able to switch an incoming signal to an output port using a wavelength different than that used to receive the data [25; 170]. If network nodes are not equipped with wavelength conversion, the same wavelength must be used along the route. This is known as the wavelength continutiy constraint [12; 57]. Conversely, if nodes are equipped with full wavelength conversion, different wavelengths can be used along a route. In either case, the specification of a route and the wavelength(s) used along that route make a lightpath.

Figure 2.2 shows an schematic of a WDM network , made of 5 nodes and 12 unidirectional links. Two lightpaths are established in the network: one to transmit data from node A to C (segmented line), implementing connection c_0; and a second one to transmit data from node B to E (dotted line), implementing connection c_1. The lightpath for c_0 is associated to the route (l_7, l_5) and the blue wavelength in both links. The lightpath for c_1 is associated to the route (l_1, l_7, l_{11}) and the blue wavelength only in links l_1 y l_{11}; in link l_7 the orange wavelength is used as the bluw one is already allocated to c_0. To achieve such configuration, at least nodes A y D must be equipped with the wavelength conversion capability.

2.2.2 ROADM and ROADM-based WDM Networks

A Reconfigurable Optical Add Drop Multiplexer (ROADM) is an optical commutation device capable of automatically switching any wavelength coming from any input link to any output link. If equipped with wavelength conversion, the switching could be done from any wavelength coming from any input link to any

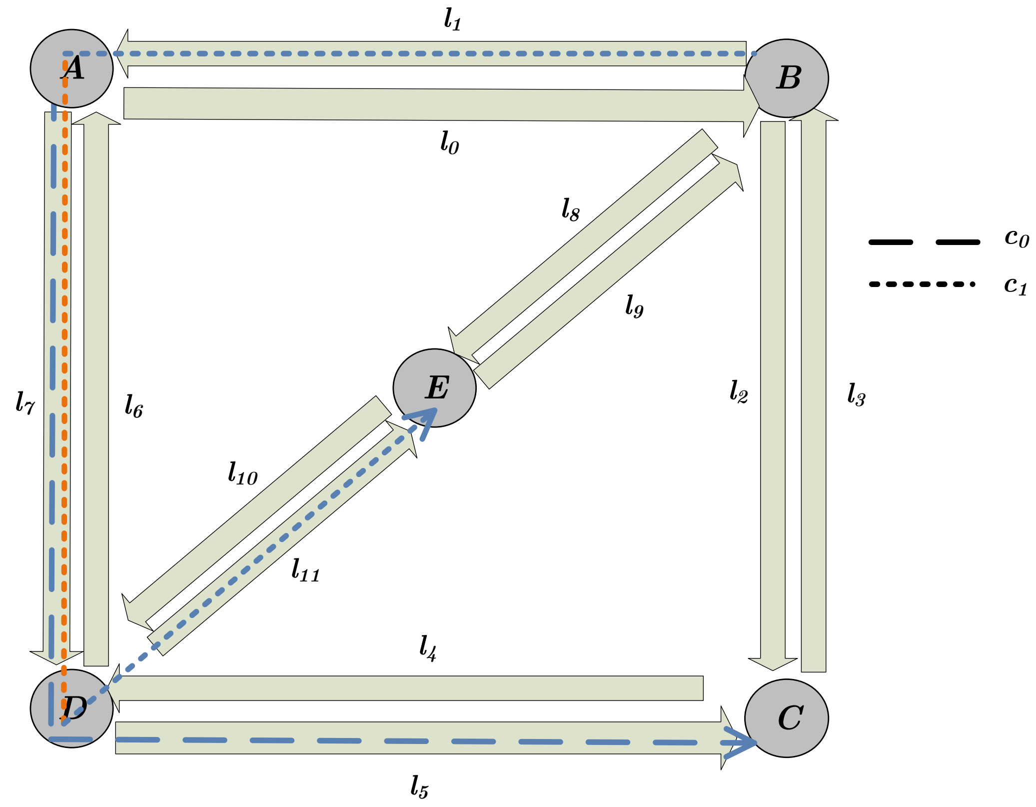


Figure 2.2: Routing and wavelength assignment example in WDM networks.

wavelength in the output link [131, pag. 27], [132].

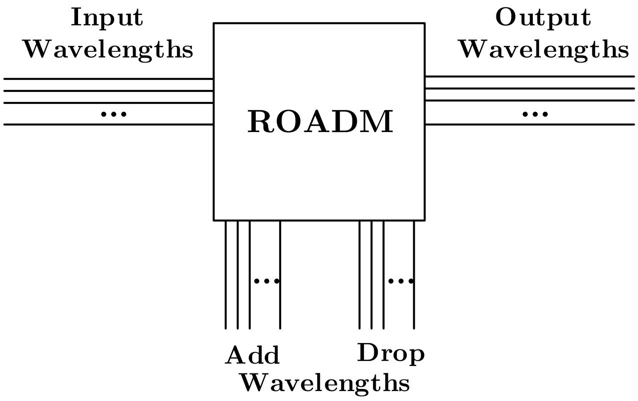


Figure 2.3: ROADM schematic, extracted from [26, pag. 24].

Figure 2.3 shows a generic black-box schematic of a ROADM: input wavelengths (carrying incoming traffic from other network nodes) can either be transmitted to the output wavelengths (carrying data directed to other network nodes) or to the drop wavelengths (carrying data directed to this node). Analogously, output wavelengths can be fed from input wavelengths or add wavelengths (carrying traffic generated at this node and directed to other network nodes). Three main sections can be distinguished in a ROADM: add section, drop section and transit section. In the add section, the information generated at the electronic layer of the local node is transformed into an optical signal and inserted into the right output channel. In the drop section, the incoming optical signals whose destination is the local node are received, transformed into electronic signals and sent to the electronic layer of the local node. Finally, in the transit section all data from input/add wavelengths that must be directed to other network nodes is switched into their corresponding output/drop wavelengths.

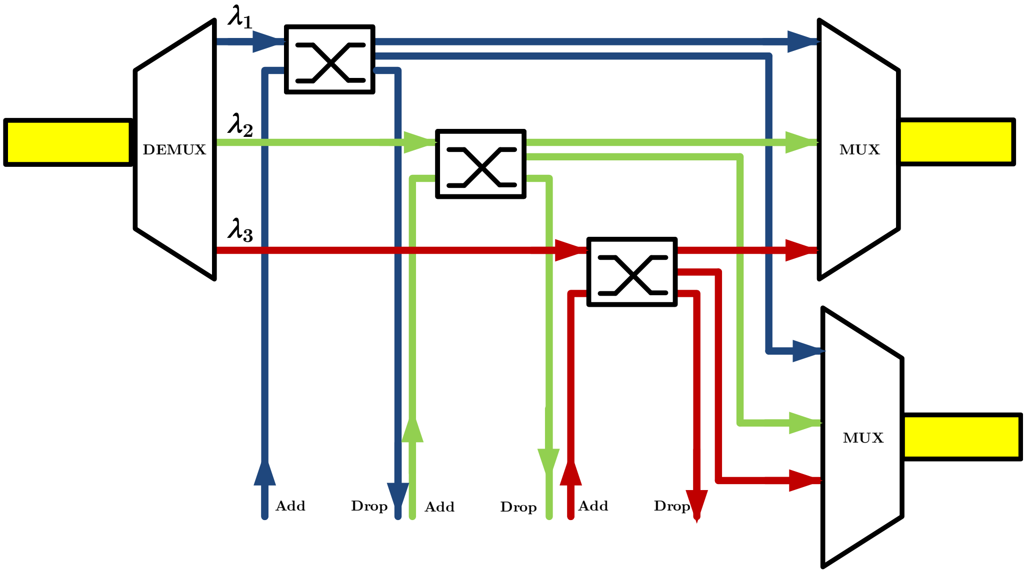


Figure 2.4: Internal configuration of a 3-wavelength ROADM, based on [53, pag. 79].

Figure 2.4 shows an schematic of the internal configuration of a simple 3-wavelength ROADM. The ROADM has one input port (where the 3 input wavelengths are received) and two output ports (each associated to an optical fiber carrying 3 output wavelengths each). The demultiplexer at the entrance of the node decomposes the input signal in 3 different wavelengths. Each of them is directed to a conmutation device in charge of selecting what input/add wavelength is directed to what output/drop wavelength. The 2 sets of output wavelengths are bundled together by means of two multiplexers connected to the output ports. Internally, a ROADM can exhibit any combination of the following three capabilities.

A colorless ROADM allows any transmitter/receiver in the add/drop Section transmitting/receiving in any wavelength channel. Without this capability, each transmitter/receiver can transmit/receive only in a specific wavelength, leading to an increase in the network blocking probability due to wavelength contention in the transmitter/receiver pools [1; 82; 101; 130].

In a directionless ROADM node every transmitter in the add Section can transmit to any output link. Analogously, every receiver in the drop Section can receive information from any input link. In a directed ROADM node instead (i.e. without the directionless capability) each transmitter/receiver can transmit/receive only to/ from a given output/input link. Thus, to achieve the same blocking performance that a directionless ROADM, a higher number of (underutilized) transmitter/receivers will be required [1; 82; 101; 130].

Finally, in a contentionless ROADM node a wavelength channel can be used by more than one transmitter in the add Section (or receiver in drop Section), as long as they are directed to different output links (or coming from different input links). A ROADM without the contentionless capability exhibits a higher blocking probability, as “available” wavelengths cannot be used for transmission of data [1; 82; 101; 130].

To deploy an efficient dynamic WDM network, nodes implemented as Colorless, Directionless and Contentionless ROADMs (CDC ROADM) are required. Otherwise not only the blocking performance of the network degrades but also network operation complexity increases due to the additional constraints on the lightpath allocation task. Several architectures of CDC ROADM have been proposed in the literature [1; 52; 82; 101; 130; 138; 153].

Given that ROADMs are a key component of automatically switched optical networks and that wavelength conversion has been shown to play an important role on decreasing the blocking performance of dynamic WDM networks [174], [47; 116] by relaxing the wavelength continuity constraint, wavelength conversion capability emerges as an attractive feature of CDC ROADM nodes. Thus, this thesis focuses on the dimensioning of a CDC ROADM-based WDM network, where the ROADM nodes are equipped with full wavelength conversion.

2.2.3 Protection on WDM networks

Sometimes, the required level of availability for a given connection (an optical communication channel between a source and destination node) can be provided with a single lightpath, however, the usual situation is that the availability provided by a single lightpath is not enough. In this case, the path protection strategy can be used, where one or more backup lightpaths are associated to a working lightpath (the lightpath normally used to transmit data). Thus, when a failure renders the working lightpath inoperative, the information can still reach the destination node using a backup lightpath. As a result, in spite of the occurrence of a failure, the user perceives the network service as operative. There are two path protected strategies: dedicated and shared path protection. They are described in the following.

2.2.3.1 Dedicated path protection

Under dedicated path protection, resources (wavelengths in links) must be exclusively reserved in every link of the routes of working and backup lightpaths. Wavelengths reserved in the working routes are used under normal operation and wavelengths reserved in the backup routes are only used when the corresponding working route fails.

As a way of illustration, in Figure 2.5 a 9-node mesh network with two established connections (solid black and gray lines) is shown. The working lightpath of connection 1 (from node 0 to node 2) follows the route made of the nodes 0-1-2 whilst the working lightpath of connection 2 (from node 3 to node 5) follows the route made of the nodes 3-4-5. The backup lightpaths of connections 1 and 2 follow the routes made of nodes 0-3-6-7-8-5-2 and 3-6-7-8-5, respectively (dashed lines).

Under this type of protection, it must be ensured that lightpaths with common links (e.g. both backup lightpaths in Figure 2.5 use links 3-6, 6-7, 7-8 and 8-5) use different wavelengths in those links.

The main drawback of dedicated path protection is that backup lightpaths of connections using dedicated path protection are seldom utilized to transmit information. For example, according to the failure statistics reported in [175], a 1609.34[Km] working lightpath would fail, in average, 0.012 times every year. If the cut occurs in a terrestrial link, its reparation time would take 12 hours. This leads to an average downtime of 8.64 min per year. As a result, if a backup lightpath was necessary (due to the availability requirements established in the SLA), then it would be used just 8.66 min per year, being idle the rest of the time. From the network operator perspective, given that network resources (as backup lightpaths) are expensive, having them reserved but idle should be avoided as much as possible.

2.2.3.2 Shared path protection

To increase the backup network resource usage, a technique called shared path protection is used. Under shared path protection, different connections share their backup network resources. Thus, backup resources are used a higher fraction of time as they act as a backup of several connections. However, this comes at the expense of a decreased availability with respect to dedicated protection, highlighting a trade-off between availability and backup resource usage. Thus, shared protection might not be an attractive solution for services for which network connectivity is a mission-critical factor (e.g., banks or stock markets) but it could be a very good option for customers not affected by lower levels of availability (residential customers, educational institutions, mining companies, etc).

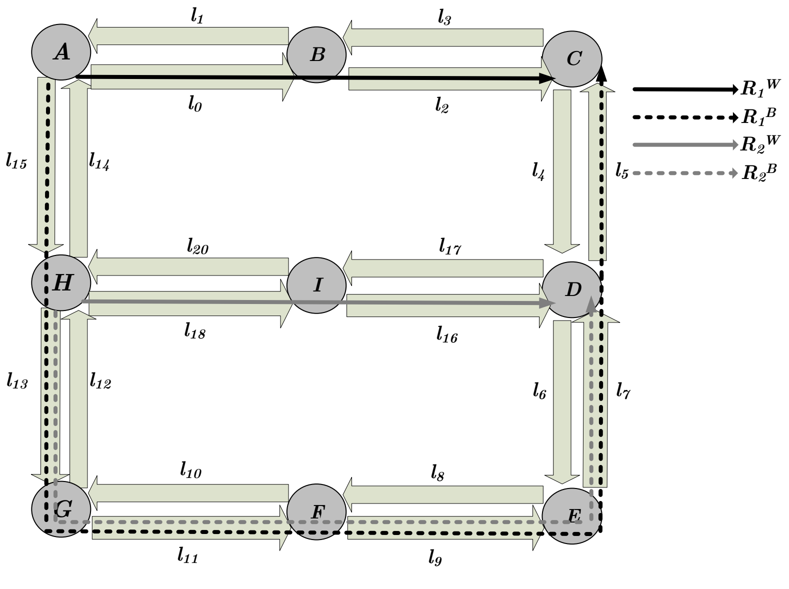


Figure 2.5: Working an backup ligthpaths for under shared path protection.

Under shared path protection the same backup wavelength can be shared among several backup lightpaths. In the example of Figure 2.5, the same wavelength in links 3-6, 6-7, 7-8 and 8-5 could be allocated as backup to both working lightpaths. As a result of sharing, wavelength contention might arise if more than one working lightpath sharing backup resources fails. That is, a backup wavelength could be required to be used by more than one backup lightpath simultaneously. In case of a single link failure, backup wavelength contention is eliminated if the corresponding working lightpaths of the connections sharing backup wavelengths are link-disjoint. In case of multiple link failures, backup wavelength contention cannot be efficiently eliminated and thus, a priority system for the access to the backup wavelengths must be defined.

As a way of illustration of a backup wavelength contention situation, consider again Fig. 2.5. Assume that only link 0-1 fails. In that case, because working lightpaths are link-disjoint, only one of them is affected by the single link failure and no backup wavelength contention arises. Instead, if link 3-4 fails while link 0-1 is still under reparation, backup wavelength contention arises as both working lightpaths require using the shared backup wavelengths in links 3-6, 6-7, 7-8 and 8-5. In that case, if connection 1 has higher priority than connection 2, the shared backup wavelengths will be allocated to connection 1 and connection 2 becomes non-operative.

2.2.4 Concepts about network virtualization systems

Extending the concept of server virtualization to networks, in a network virtualization system several virtual networks can co-exist independently over a common substrate (physical) network. Thus, each virtual network is

> *"a collection of virtual nodes and virtual links [...] implemented over a subset of the underlying physical network resources"* [21]

Thus, the physical network is a collection of physical resources used to establish several virtual networks. The establishment of a virtual network requires solving two problems: those of virtual nodes and links embedding (what physical nodes/links are used to host the virtual nodes/links). For node embedding, the resource requirements of the virtual nodes as well as the availability of resources in the physical nodes must be taken into account (e.g. a virtual node requiring more storage than that available at a certain physical node could not be mapped on that physical node). For link embedding, usually a routing algorithm must be considered as the virtual link might need to connect two physical nodes not directly connected in the physical network. To do, bandwidth requirements of the virtual links and bandwidth availability of physical links must be considered (along with additional constraints of the specific physical substrate, as wavelength continuity constraint in WDM networks without conversion capability). In [20; 61; 183] the problem of resource provisioning for virtual networks is studied.

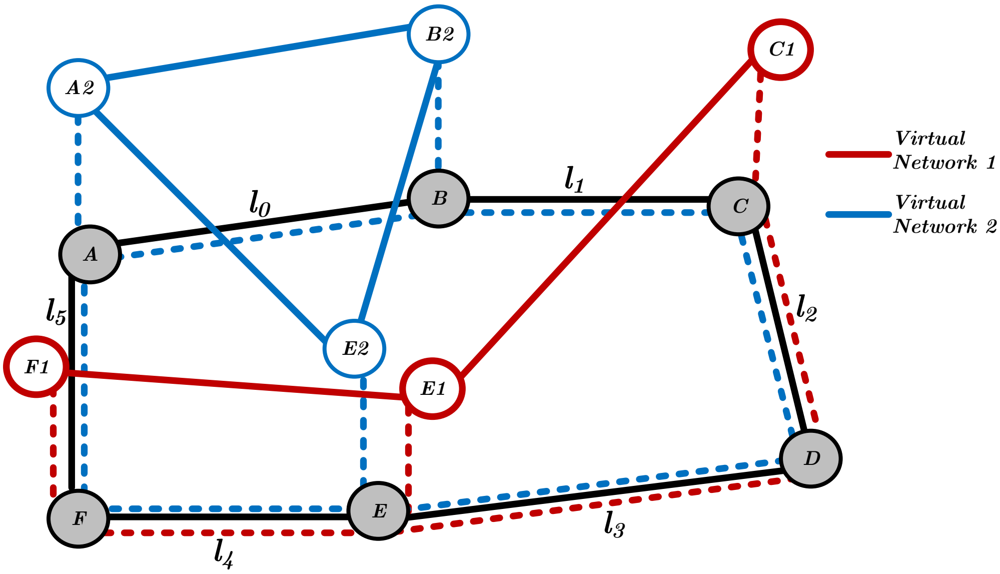


Figure 2.6: Example of a network virtualization system in a 6-node ring physical network with two virtual networks established.

Figure 2.6 shows an schematic of a physical network made of 6 nodes (A, B, C, D, E, F) and 6 bidirectional links. On top of the physical network, two virtual networks have been established. Virtual network 1 is a 3-node bus topology using the physical nodes (C, E, F) to embed the virtual nodes ($C1, E1, F1$). To interconnect such virtual nodes in a bus topology, virtual links ($C1 - E1$) and ($E1 - F1$) are established using the physical routes made of the physical links ($l_2 - l_3$) and (l_4), respectively. Virtual network 2 is a 3-node ring topology. Virtual nodes ($A2, B2, E2$) have been established on the physical nodes (A, B, E). Virtual links ($A2 - B2$), ($B2 - E2$) and ($E2 - A2$) are implemented using the routes (l_0),

$(l_1 - l_2 - l_3)$ and $(l_4 - l_5)$, respectively . It can be seen that the same physical node can host several virtual nodes and the same physical link can host several virtual links (as long as the physical node/link has enough resources to host the virtual nodes/links).

2.3 State of art for optical network planning problems

In this section a review of the solutions proposed to each long-term network planning problem addressed in this thesis is presented. Section 2.3.1 reviews the literature in the area of dynamic WDM networks dimensioning. Next, in Section 2.3.2 a survey on the problem of dimensioning and configuring backup wavelengths in a static WDM network using shared path protection with availability guarantees is presented. Finally, in Section 2.3.3, a review on the long-term network planning of network virtualization systems is presented.

2.3.1 Review of ROADM networks dimensioning

When dimensioning and operating a network, it is necessary to comply with some quality of service requirements whilst making sure that network resources are efficiently used. In an automatically switched network, the level of blocking is one of the most important parameters related to quality of service. However, the optimal dimensioning of a network that must deal with dynamic lightpath provisioning is a challenging task due to the stochastic nature of lightpath demands. The easiest method to ensure the best possible blocking performance in such a dynamic network is to allocate as many resources as required in the worst case (i.e., zero blocking). That is, resources are allocated to connections during the whole network operation period, irrespective of when they actually require the network resources for data transmission. However, this worst-case dimensioning method leads to inefficient use of expensive network resources. To date, previous proposals dealing with ROADM-based network dimensioning [97; 109; 114] have considered variants of this worst-case approach, not taking the stochastic nature of traffic demands into account. All of them assume that connection requests are known in advance and that circuits must be established for them in a permanent basis, which does not exploit the reconfigurable capability of ROADMs. The few works addressing stochastic traffic demands in ROADM-based networks [40; 155] do not solve the dimensioning problem, but rather evaluate (by means of simulation) the impact of different network configurations on the blocking ratio.

Table 2.1 2.1 lists the few works reported on the dimensioning of ROADM-based networks. For each, the dimensioning target, the method used, the scenario evaluated and the main assumptions are given.

Table 2.1: Literature revision about dimensioning ROADM networks

REF	**Description**
[97]	***Dimensioning:*** Minimization of the overall network cost due to the switching modules required at the input and output links of the OXCs (optical cross-connects devices). ***Method:*** ILP and heuristic. ***Scenario:*** Static operation in an elastic optical network. Blocking is not considered. After dimensioning, blocking is evaluated as a function of the traffic load. ***Technological assumptions:*** Elastic networks y uso de CDC ROADM-based network.
[109]	***Dimensioning:*** Number of add/drop banks in a directionless contention ROADM, such that same performance of directionless & contentionless ROADM is achieved. ***Method:*** For each possible contention factor, an ILP and a heuristic are executed. ***Scenario:*** Static case is solved, performance evaluated in dynamic scenario for unprotected and protected cases. ***Technological assumptions:*** Full wavelength conversion, contention ROADMs.
[114]	***Dimensioning:*** Dimensioning of transponders and client-cards is addressed. The objective of the dimensioning is to minimize the overall power consumption. ***Method:*** MILP and heuristic ***Scenario:*** Static operation. ***Assumptions:*** Maximum traffic requirement (not a statistical characterization of the traffic profile).

2.3.2 Review of configuration and dimensioning backup wavelengths in static WDM networks

Among the different quality metrics considered in the network planning and design process, availability is one of fundamental importance as it measures the capacity of the network to be operative in spite of the occurrence of failures. In fact, most SLAs (Service Level Agreements) established between network providers and their customers specify a minimum level of network availability, defined as the fraction of time the network service is required to be operative.

The number of backup lightpaths and the type of protection provided to the connections (dedicated or shared) must be defined during the network planning stage. To do so, two different approaches are commonly used: a) providing every network connection with the same number of backup lightpaths or type of protection, as in [103; 104; 146] or b) providing every network connection with the number of backup lightpaths or type of protection that ensures the level of availability required by that connection. The latter approach is known as availability-guaranteed or availability-aware network planning process and the task of actually establishing the corresponding working and backup lightpaths is carried out by availability-aware provisioning algorithms.

Availability-aware provisioning algorithms can be classified as dynamic or static. Dynamic ones must establish the working/backup lightpaths on demand and thus, there is not much time to compute the lightpath allocation. For that reason, heuristics are the most used approach to solve the problem, as in [90; 98; 106; 148]. In a static scenario instead, the set of connections to establish are known *a priori* and there is enough time to run optimization techniques such as integer linear programming (ILP) models. In [176; 177] an ILP model was proposed to solve the problem of minimizing the number of backup wavelengths with availability guarantees. However, only the dedicated protection case is analyzed.

The complexity that a shared protection scheme introduces in the ILP model is not addressed. The same case of dedicated protection with availability guarantees is also studied in [179; 180], but only heuristic approaches are applied. Finally, in [39] an ILP to evaluate the wavelength requirements of shared and dedicated protected connections is studied. To deal with the non-linear expression for the availability constraint, such an equation is dropped and the objective function is changed to maximize the availability of paths. In all the static cases, full wavelength conversion is assumed.

Table 2.2 summarises the references on availability-guaranteed provisioning.

Table 2.2: Comparison of previous works on availability-guaranteed provisioning.

REF	**Shared**	**Dedicated**	**Method**	**Scenario**	**Types of failure**	**Full wavelength conversion ?**
[39]	Yes	Yes	ILP and Heuristic	Static	Multiple	Yes
[90]	Yes	No	Heuristic	Dynamic	Double link failure	Yes
[98]	Yes	No	Heuristic	Dynamic	Multiple	Yes
[106]	Yes	No	Heuristic	Dynamic	Multiple (link & node) failures	No
[148]	Yes	Yes	Heuristic	Dynamic	Double link failure	Yes
[176]	Yes	Yes	ILP (only for unprotected and dedicated protected connections) and Heuristic (for unprotected, dedicated and shared protected connections)	Static	Multiple	Yes
[177]	No	Yes	ILP (only for unprotected and dedicated protection connections)	Static	Up to 10 link failures	Yes
[179]	No	Yes	Heuristic	Static	Multiple	Yes
[180]	No	Yes	Heuristic	Static	Multiple	Yes

2.3.3 Revision of literature about dimensioning in WDM networks used for virtualization network systems

In network virtualization systems the most common problem addressed has been the run-time network planning in terms of resource provisioning. That is, designing mechanisms to find and allocate the necessary resources when a virtual networks establishment request is received.

In the different works published [9; 73; 108; 134] MILP, ILP and heuristics have been proposed to solve the dimensioning problem with the aim of either minimizing the resource usage or the energy consumption, considering different network scenarios and technological assumptions. However, works that directly propose dimensioning methods for the physical infrastructure guaranteeing given levels of blocking or availability are inexistent. In spite of this, the methods used in them can be considered to solve the type of long-term planning problem addressed in 5.

Table 2.3 gives details about the planning problem addressed by each work, the solving method used, the scenario an the technological assumptions.

Table 2.3: Literature revision about planning virtual networks

REF	**Description**
[9]	***Planning problem:*** Virtual network requests embedding in a reduced group of physical network equipment, minimizing energy consumption. ***Method:*** ILP. ***Scenario:*** Dynamic scenario. ***Technological assumptions:*** No specification regarding the type of physical substrate is given.
[73]	***Planning problem:*** Configuration of physical routes used by virtual links, minimizing the number of wavelengths in the physical substrate. For each virtual link, a minimum quality of service is considered in terms of burst losses. ***Method:*** MILP, ILP and a heuristic method are proposed. Erlang-B is used to model the traffic. A zero-one program is used. ***Scenario:*** Dynamic operation, considering traffic load models. ***Technological assumptions:*** Optical Burst Switching optical network.
[75]	***Planning problem:*** Flow allocations in the infraestructure layer and determining link capacity minimizing the network cost. ***Method:*** LP and MILP. ***Scenario:*** Static operation, traffic load is not considered, neither failures in nodes or links. Not availability or blocking requirements are considered. ***Technological assumptions:*** Transport network (type of technology is not specified).
[108]	***Planning problem:*** Configuring an optimal fixed virtual topology, and the associated traffic flow routing on top of it, which is capable of fully carrying the given traffic in all time slots. Minimization of transceivers (network cost). ***Method:*** ILP, MILP and heuristics for larger instances. ***Scenario:*** Static operation. ***Technological assumptions:*** Transparent WDM network. Splitable flow.
[134]	***Planning problem:*** Minimizing number of transceivers to establish virtual networks. ***Method:*** ILP and Heuristic. ***Scenario:*** Dynamic physical network, static traffic for each virtual network. ***Technological assumptions:*** WDM network. Blocking and traffic load not considered.

Chapter 3

Dimensioning of CDC ROADM-based networks with blocking probability guarantees

In this chapter the work in [143] is extended, by proposing a CDC&WC ROADM architecture and then formulating and solving an ILP model to dimension the add, drop and transit sections of all the CDC&WC ROADM nodes of a dynamic network where lightpath requests arrive randomly and whose lifetime is also random. The dimensioning aims at minimizing the network cost whilst guaranteeing that the maximum blocking probability of each connection does not exceed a threshold.

The rest of this chapter is as follows: in Section 3.1 the network and traffic models assumed in this chapter are presented; Section 3.2 describes the CDC&WC ROADM architecture proposed; Sections 3.3 and 3.4 describe the mathematical model used to compute the probability blocking of connections and the network cost model, respectively. Then, in Section 3.5, the ILP model that allows dimensioning a CDC&WC ROADM-based network is formulated. Section 3.6 presents the numerical results and finally Section 3.7 concludes the work presented in this chapter.

3.1 Network and traffic models

For this work, an end-to-end dynamic WDM network (e.g. a PCE-based architecture [127] or an optical circuit switching network [111]) with full wavelength conversion is considered. Full wavelength conversion is key to maintain a low value for the blocking rate [158].

Also, if the network has wavenlength conversion capability, the mathematical modeling of the network is less complex because that the wavelength continuity constraint is not considered.

In such a dynamic network, once a lightpath request is generated, a control packet is sent across the network to reserve the network resources needed to establish the end-to-end optical connection from source to destination. If resources cannot be reserved from source to destination, then a reject message is sent to the source node and the request is blocked. If resources are successfully reserved, an ACK message is sent to the source node and the corresponding ROADMs are configured so the lightpath is established. Upon reception of the ACK message, data transmission starts.

Here a dynamic routing algorithm based on routes computed *a priori* is considered. This strategy is called fixed-path routing and is selected here because is a simple and very much used strategy that does not require any real-time computation in the network nodes.

The network is represented by a graph $G = (N, L)$, where N is the set of nodes and L is the set of unidirectional links. In every node $n \in N$, there are θ_n output links and ϵ_n input links.

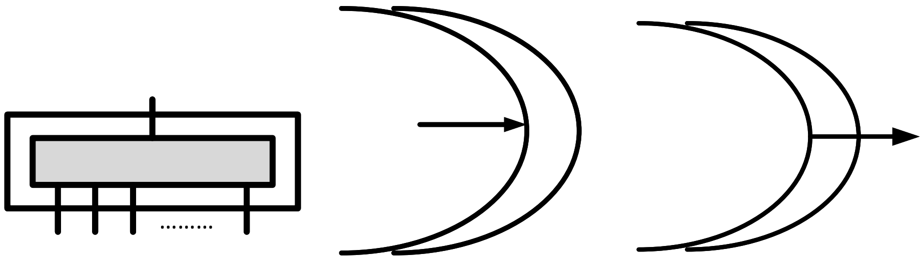
Let C be the set of all connections that can be established in the network. Let s_c and d_c be the source and destination nodes of connection $c \in C$, respectively. Each connection c has a fixed route associated to it. The sets of links and nodes on the route from s_c to d_c are denoted by L_c and N_c, respectively.

The traffic offered to the network by each source-destination pair is governed by an ON-OFF process. During the ON period, the source is assumed to transmit at the transmission rate of one wavelength. During the OFF period, the source does not transmit data. The mean duration of the ON and OFF periods is denoted by t_{ON} and t_{OFF}, respectively. Identical values of t_{ON} and t_{OFF} for all node pairs are assumed. Therefore, the traffic load of any connection is given by:

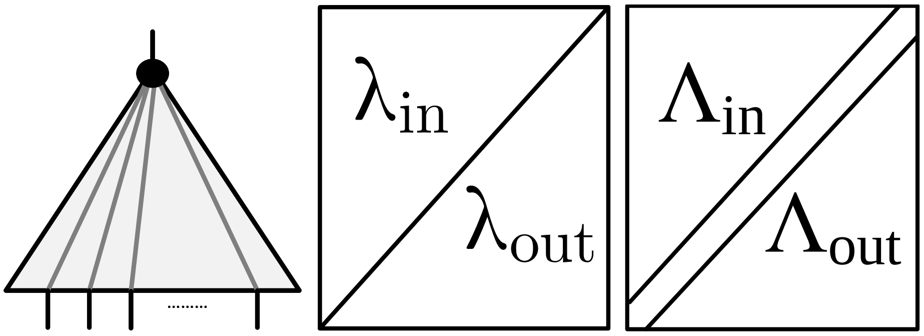
$$\rho = \frac{t_{ON}}{t_{ON} + t_{OFF}} \tag{3.1}$$

3.2 CDC&WC ROADM node architecture

Figure 3.1 shows the basic optical components required to build a CDC&WC ROADM. The symbol shown in 3.1(a) represents a $1 \times M$ wavelength selective switch (WSS), that can select specific wavelengths from the input WDM signal to be directed to specific output ports. Figure 3.1(b) and 3.1(c) show the symbols used to represent a tunable optical transmitter and receiver, respectively. They allow data transmission/reception in one of several possible wavelengths. Figure 3.1(d) shows the symbol for a passive $M \times 1$ optical coupler, that can also be used as a passive 1xM optical splitter. Figure 3.1(e) represents a wavelength converter device, able to convert any input wavelength to any output wavelength. Finally, Figure 3.1(f) symbolizes a wavelength converter bank (WCB) made of M wavelength converters (conforming a M-wavelength converter bank, M-WCB)



(a) $1 \times M$ or $M \times 1$ Wavelength Selective Switch (b) Tunable optical receiver (c) Tunable optical transmitter



(d) $1 \times M$ optical splitter or $M \times 1$ optical coupler (e) Wavelength converter (f) Wavelength converter bank

Figure 3.1: Optical network devices.

The Figure 3.2 shows an M-WCB composed by a $1 \times M$ WSS, a set of M wavelength converters and a passive $M \times 1$ optical coupler. The input WDM signal that enters the WSS of the wavelength converter bank is made of a given number of wavelength channels. The WSS allows selecting some individual input wavelength channels -from the input signal- to be sent to different M wavelength converters, where they can be converted from wavelength λ_{in} to wavelength λ_{out}, if necessary. This set of M wavelength channels are then combined together again in a single WDM signal by the coupler.

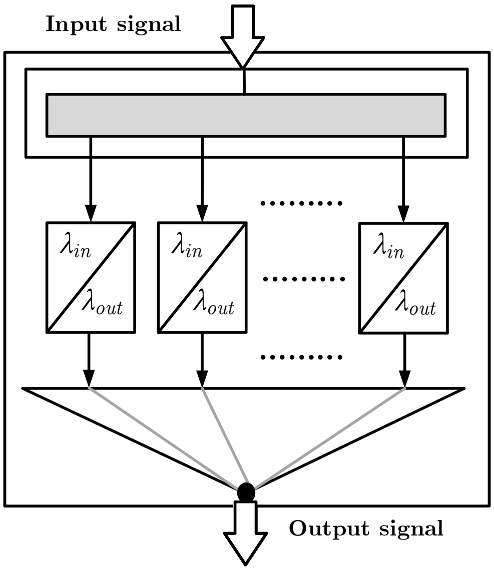


Figure 3.2: Internal view of a wavelength converter bank.

Figure 3.3 shows a proposal for a 4-degree CDC&WC ROADM node. As any commutation node, it consists of an add section, a transit section and a drop section. Unlike the architecture proposed in the literature, this CDC ROADM is equipped with full wavelength conversion.

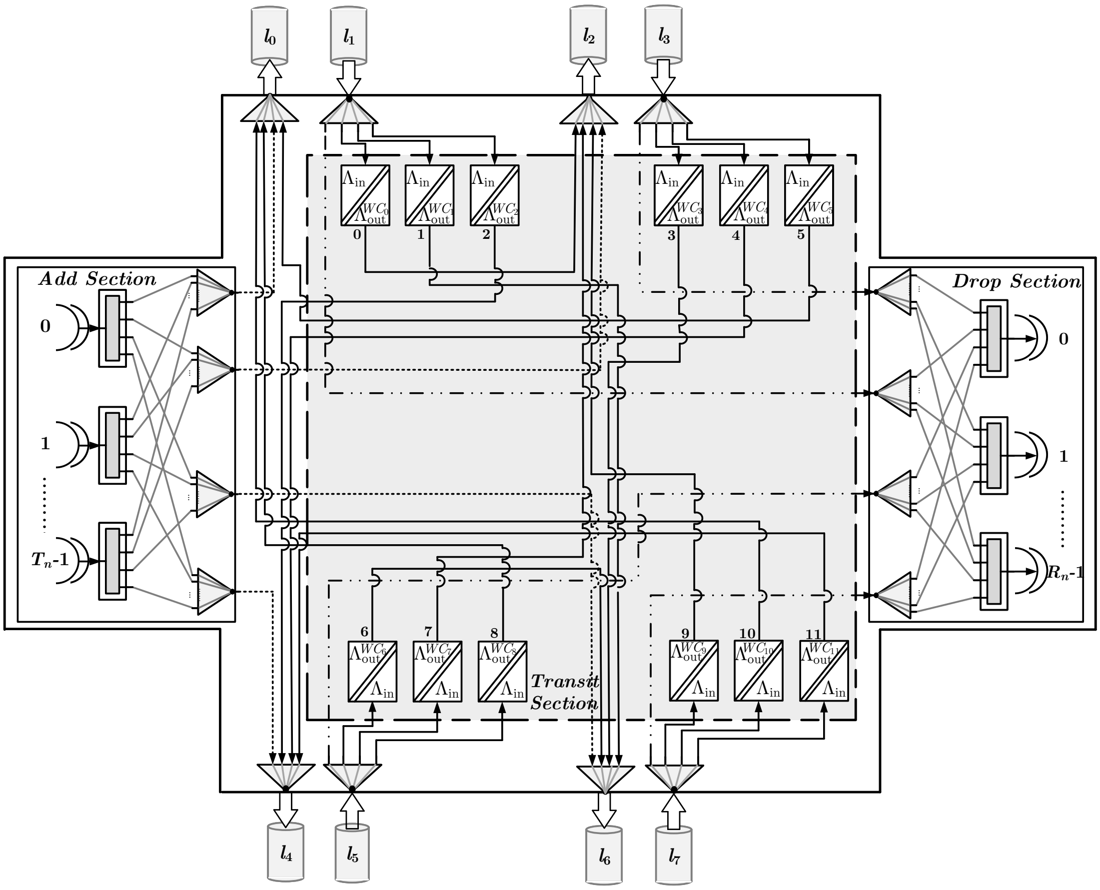


Figure 3.3: Architecture of 4-degree colorless, directionless and contentionless ROADM with wavelength conversion capability.

The connections originated in the node are generated by the set of T_n tunable optical transmitters in the add Section (left side in Figure 3.3). The output optical signal of each tunable transmitter is connected to the input of one of T_n WSSs (one WSS per optical transmitter), used to select the optical coupler to which the optical signal is sent. There is one optical coupler per output link. Thus, any tunable optical transmitter can add the optical signal to any output link in any WDM channel, considering only the wavelength collision constraints.

The optical signal entering the node from any input link (l_1, l_3, l_5 and l_7 in Fig. 3.3) might include wavelength channels transporting information directed to the node as well as other nodes. Thus, the incoming optical signals are repeated using an optical splitter. One of the optical splitter output signals is sent towards the drop section (segmented line) to process the data of the wavelength channels directed to the node. The rest is sent towards the set of wavelength converter banks in the transit section.

In the transit Section, there are $\theta_n - 1$ wavelength converter banks for every input link (one wavelength converter bank per output link, except the output link leading to the node directly connected to the input link). Let W be the set of wavelength converter banks in the network, W_c the set of wavelength converter banks used by connection c and WC_w the number of wavelength converters in the wavelength converter bank w. Before finally exiting the node through the output link, the optical signal from the WCB is sent to an optical coupler, where it is combined with the wavelength channels coming from couplers of the add section.

The drop section (right side of Figure 3.3) of the proposed ROADM architecture consists of ϵ_n optical splitters (one per input link), R_n WSSs (one per optical receiver) and R_n optical receivers. Each optical splitter repeats the WDM optical signal from its corresponding input link to each of the WSS. Each WSS selects one WDM channel from a specific input optical signal to be sent to the tunable optical receiver. In this way, any tunable optical receiver can receive any WDM channel from any input link.

Table 3.1 lists the devices required to implement the CDC&WC ROADM node. The first column identifies the name of the device whilst the remaining columns identify the section of the node the device belongs to (add, transit or drop), the number of this type of device the node is equipped with and the main features of the device. Table 3.2 lists the devices necessary to implement a wavelength converter bank.

Table 3.1: Components in node $n \in N$

Optical device	**Section**	**Quantity**	**Features**
Tunable optical transmitter	Add	T_n	Whole tunable range
WSS	Add	T_n	$1 \times \theta$ ports
Optical coupler	Add	θ_n	$T_n \times 1$ ports
Tunable optical receiver	Drop	R_n	Whole tunable range
WSS	Drop	R_n	$\epsilon \times 1$ ports
Optical splitter	Drop	ϵ_n	$1 \times R_n$ ports
Optical splitter	Input links	ϵ_n	$1 \times \theta_n$ ports
Optical coupler	Output links	θ_n	$1 \times \epsilon_n$ ports
WCB	Transit	$\epsilon_n(\theta_n - 1)$	See Table 3.2

Table 3.2: Components in a WCB $w \in W$

Optical device	**Quantity**	**Features**
WSS	1	$1 \times WC_w$ ports
Wavelength converter	WC_w	Full conversion range
Optical coupler	1	$WC_w \times 1$ ports

In the following, an ILP formulation used to dimension a CDC&WC ROADM-based dynamic network is presented (Section 3.5). As the ILP formulation uses non-trivial expressions for the blocking probability of connections and the network cost, they are previously derived in the following subsections.

3.3 Connection blocking probability evaluation in a CDC&WC ROADM-based network

To establish connection c from node s_c to node d_c, it is necessary to successfully allocate the following resources: one transmitter in the add section of the source node s_c; wavelength converters in the transit sections of the intermediate ROADM nodes, one wavelength in every link of the route and a receiver at the drop section of the destination node d_c.

Let α_{s_c} be the number of connections that start at node s_c. Thus, connection c must contend with the remaining $\alpha_{s_c} - 1$ connections for one of the T_{s_c} tunable optical transmitters. Note that if $T_{s_c} < \alpha_{s_c}$, connection c might be blocked due to unavailability of tunable transmitters in node s_c.

Next, connection c must contend for resources in the transit sections of the intermediate CDC&WC ROADM nodes as well as for a wavelength channel in every link $l \in L_c$. Let β_w be the number of connections requiring a wavelength converter of WCB w. If $WC_w < \beta_w$, then the connection c might be blocked due to unavailability of wavelength converters in WCB w,$\forall w \in W_c$. Let Ch be the number of wavelengths per link and γ_l the number of connections requiring link l. If $Ch < \gamma_l$, then connection c might be blocked due to unavailability of wavelengths in link l.

Finally, let δ_{d_c} be the number of connections that require ending at destination node d_c. Thus, in the reception stage (drop section of node d_c) connection c must contend with the other $\delta_{d_c} - 1$ connections destined to d_c, for one of the R_{d_c} tunable optical receivers. Note that if $R_{d_c} < \delta_{d_c}$ then the connection c might be blocked due to unavailability of tunable receivers in node d_c.

It is assumed that there is no blocking due to unavailability of resources such as WSSs, couplers and splitters in the ROADM nodes. The quantity and number of ports of these devices are selected considering the topology, the number of transmitters, receivers and wavelength converters in each node.

Assuming that the blocking experienced by connection c in any of these stages is independent of the blocking experienced in any other stage, the blocking probability of connection c can be estimated as:

$$B_c = 1 - ((1 - B_c^{tx}) \prod_{\forall w \in W_c} (1 - B_w^{wc}) \prod_{\forall l \in L_c} (1 - B_l)(1 - B_c^{rx})) \tag{3.2}$$

where B_c^{tx} is the blocking probability in the add section of node s_c due to the unavailability of tunable transmitters; B_w^{wc} is the blocking probability in the wavelength converter bank w in the transit section of every intermediate node $n \in N_c$ due to the unavailability of wavelength converters, B_l is the blocking probability in link l due to the unavailability of wavelength channels; finally B_c^{rx} is the blocking probability in the drop section of node d_c due to the unavailability of tunable receivers.

To evaluate B_c^{tx}, B_w^{wc}, B_l and B_c^{rx} in 3.2, the Engset formula [163] is used, given that the number of connections using the transmission, transit and reception resources cannot be considered as infinite (as done when applying the Erlang model). In its generic form, the Engset formula establishes that the blocking probability B experienced by a set of y clients that arrive at mean rate λ (clients/time unit) at a pool of x servers that serve the clients at mean rate μ (clients/time unit) is given by:

$$B(x,y) = \frac{\binom{y}{x}(\frac{\rho}{\rho-1})^x}{\sum_{i=0}^{x}\binom{y}{i}(\frac{\rho}{\rho-1})^i} \tag{3.3}$$

where $\rho = \frac{\lambda}{\mu}$ is the traffic load offered by the clients to the pool of servers. Thus:

$$B_c^{tx} = B(T_{s_c}, \alpha_{s_c}) = \frac{\binom{\alpha_{s_c}}{T_{s_c}}(\frac{\rho}{\rho-1})^T_{s_c}}{\sum_{i=0}^{T_{s_c}}\binom{\alpha_{s_c}}{i}(\frac{\rho}{\rho-1})^i} \tag{3.4}$$

$$B_w^{wc} = B(WC_w, \beta_w) = \frac{\binom{\beta_w}{WC_w}(\frac{\rho}{\rho-1})^{WC_w}}{\sum_{i=0}^{WC_w}\binom{\beta_w}{i}(\frac{\rho}{\rho-1})^i} \tag{3.5}$$

$$B_l = B(Ch, \gamma_l) = \frac{\binom{\gamma_l}{Ch}(\frac{\rho}{\rho-1})^{Ch}}{\sum_{i=0}^{Ch}\binom{\gamma_l}{i}(\frac{\rho}{\rho-1})^i} \tag{3.6}$$

$$B_c^{rx} = B(R_{d_c}, \delta_{d_c}) = \frac{\binom{\delta_{d_c}}{R_{d_c}}(\frac{\rho}{\rho-1})^{R_{d_c}}}{\sum_{i=0}^{R_{d_c}}\binom{\delta_{d_c}}{i}(\frac{\rho}{\rho-1})^i} \tag{3.7}$$

Note that, besides traffic load, equations (3.4)-(3.7) depend on the number of resources (transmitters, wavelength converters, wavelengths and receivers) and the number of connections requiring those resources. The problem is determining the number of transmitters, wavelength converters and receivers at each node of the network such that the maximum blocking probability of every network connection does not exceed a given threshold. The number of wavelengths is assumed a known parameter given by the physical characteristics of the network components (e.g. tunability range of transmitters/receivers).

3.4 Cost model of a CDC&WC ROADM-based network

For the networks considered all the network links are assumed already deployed. Thus, in the work reported in this chapter the cost of the network is given only by the cost of nodes.

The symbols used to represent the cost of every device is as follows: K^{TX} and K^{RX} are the fixed costs of a tunable optical transmitter and a tunable optical receiver, respectively; $K^{SC}[P^{req}]$ and $K^{WSS}[P^{req}]$ are the costs of an optical splitter/coupler and the cost of a WSS respectively, both as a function of the number of ports required P^{req}, where $P^{req} \leq P^{total}$. P^{total} is the number of ports of a commercially available WSS or optical splitter/coupler; K^{WC} is the fixed cost of a wavelength converter with full conversion range.

Therefore, the following expression to evaluate the total network cost, denoted by C_{net}, is used:

$$\begin{aligned} C_{net} = \sum_{\forall n \in N} &[(K^{TX} + K^{WSS}(\theta_n))T_n + \theta_n K^{SC}(T_n)] + \\ &\sum_{\forall w \in W} [K^{WC} WC_w + (K^{WSS}(WC_w) + K^{SC}(WC_w))] + \\ &\qquad \sum_{\forall n \in N} [(K^{RX} + K^{WSS}(\epsilon_n))R_n + \epsilon_n K^{SC}(R_n)] \end{aligned} \tag{3.8}$$

The first summation in (3.8) is the total cost of the add sections of all nodes in the network. The second summation corresponds to the sum of the cost of the transit sections of all the WCBs in the network. Finally, the third summation corresponds to total cost of the drop section for all the network nodes. Note that the cost of optical splitters/couplers associated to the input/output links is not considered because this is determined by the network topology not by the traffic pattern or the blocking probability.

3.5 An integer linear programming formulation for dimensioning of CDC&WC ROADM-based network

The problem of efficient dimensioning of a dynamic CDC&WC ROADM-based network can be formulated as follows:

$$\begin{aligned} &\min \ C_{net} \\ &\text{subject to:} \\ &B_c \leq B_{target}, \forall c \in C \end{aligned} \tag{3.9}$$

where C_{net} is the network cost, B_c is the blocking probability experienced by connection c (evaluated as explained in Section 3.4) and B_{target} is the maximum value of blocking acceptable for any connection in the network. Thus, the network must be dimensioned at minimum cost whilst guaranteeing a given value of probability blocking per connection.

Note that the term B_c is a non-linear function of T_n, R_n and WC_w. Thus, the main difficulty of the problem lies in incorporating these non-linear terms. To be able to use linear integer programming techniques, the problem must be formulated in an alternative way that uses linear operations. Replacing B_c by equation (3.2), regrouping the terms and applying the logarithm function to each side of the resulting inequation, the expression $B_c \leq B_{target}$ can be re-written in the following way:

$$\log(1-B_c^{tx}) + \sum_{\forall w \in W_c} \log(1-B_w^{wc}) + \log(1-B_c^{rx}) \geq \log\left(\frac{1-B_{target}}{\prod_{\forall l \in L_c}(1-B_l)}\right) \tag{3.10}$$

Even if this expression is still non-linear, the values of $\log(1-B_c^{tx})$, $\log(1-B_c^{rx})$ and $\log(1-B_w^{wc})$ can be pre-computed for the different values of T_n, R_n and WC_w, respectively.

More precisely, for a given value of traffic load, ρ, the following formulas are computed:

$$F^{TX}(i,j) = \log(1 - B^{tx}(i,j)); 1 \leq i,j \leq \hat{\alpha}_n \tag{3.11}$$

$$F^{WC}(i,j) = \log(1 - B^{wc}(i,j)); 1 \leq i,j \leq \hat{\beta}_w \tag{3.12}$$

$$F^{RX}(i,j) = \log(1 - B^{rx}(i,j)); 1 \leq i,j \leq \hat{\delta}_n \tag{3.13}$$

Using the pre-computed values of equations (3.11)-(3.13), it is possible to formulate an integer linear programming model for network dimensioning as follows:

Sets and indexes

- N: set of network nodes.
- L_c: set of links conforming the route used to establish connection c.
- W: set of wavelength converter banks of the network.
- W_c: set of wavelength converter banks used to establish connection c.
- n: index used to traverse set N.
- l: index used to traverse sets of links (L and L_c).
- w: index used to traverse the sets of wavelength converter banks (W and W_c).
- i: index used to traverse the α_n connections at the add section for each node n.
- j: index used to traverse the β_w connections at wavelength converter bank w.
- k: index used to traverse the δ_n connections at the drop section for each node n.

Parameters

- K^{TX}: cost of a tunable optical transmitter.

- K^{WC}: cost of a wavelength converter.
- K^{RX}: cost of a tunable optical receiver.
- K^{WSS}: cost of a wavelength selective switch.
- K^{SC}: cost of an optical splitter or an optical couple.
- θ_n: number of output links of node n.
- ϵ_n: number of input links of node n.
- B_{target}: maximum value of blocking acceptable for any connection in the network.
- B_l: blocking probability in link l.
- α_n: number of connections requiring a transmitter in the add section of node n.
- β_w: number of connections requiring a wavelength converter in wavelength converter bank w.
- δ_n: number of connections requiring a receiver in the drop section of node n.

Decision variables

- T_n: integer decision variable that represents the number of tunable transmitters required for node n.
- WC_w: integer decision variable that represents the number of wavelength converters required for wavelength converter bank w.
- R_n: integer decision variable that represents the number of tunable receivers required for node n.
- AL_c^{TX}: continuous decision variable that takes the value of $F^{TX}(WC_w, T_n)$ addressed using the binary decision variable $It_{n,i}$.

- AL_w^{WC}:continuous decision variable that takes the value of $F^{WC}(\beta_w, WC_w)$ addressed using the binary decision variable $Iwc_{w,j}$.
- AL_c^{RX}:continuous decision variable that takes the value of $F^{RX}(\delta_n, R_n)$ addressed using the binary decision variable $Ir_{n,k}$.
- $It_{n,i}$: binary decision variable that takes value 1, $\forall n \in N$, if $i = T_n$, and value 0 otherwise.
- $Iwc_{w,j}$: binary decision variable that takes value 1, $\forall w \in W$, if $j = WC_w$, and value 0 otherwise.
- $Ir_{n,k}$: binary decision variable that takes value 1, $\forall n \in N$, if $k = R_n$, and value 0 otherwise.

Minimize

$$\begin{aligned} &\sum_{\forall w \in W} [K^{WC} \times WC_w + \sum_{j=1}^{\beta_w}((K^{WSS}(j) + K^{SC}(j))Iwc_{w,j})]+ \\ &\sum_{\forall n \in N} [(K^{TX} + K^{WSS}(\theta_n))T_n + (K^{RX} + K^{WSS}(\epsilon_n))R_n + \\ &\sum_{i=1}^{\alpha_n}(\theta_n K^{SC}(i)It_{n,i}) + \sum_{k=1}^{\delta_n}(\epsilon_n K^{SC}(k)Ir_{n,k})] \end{aligned} \tag{3.14}$$

Subject to

$$AL_c^{TX} + AL_c^{RX} + \sum_{\forall w \in W_c} AL_w^{WC} \geq \log\left(\frac{1 - B_{target}}{\prod_{\forall l \in L_c}(1 - B_l)}\right); \forall c \in C \tag{3.15}$$

$$AL_c^{TX} = \sum_{i=1}^{\alpha_n} F^{TX}(i, \alpha_n) \times It_{s_c,i}; \forall c \in C \tag{3.16}$$

$$AL_w^{WC} = \sum_{j=1}^{\beta_w} F^{WC}(j, \beta_w) \times Iwc_{w,j}; \forall w \in W \tag{3.17}$$

$$AL_c^{RX} = \sum_{k=1}^{\delta_n} F^{RX}(k, \delta_n) \times Ir_{d_c,k}; \forall c \in C \tag{3.18}$$

$$\sum_{i=1}^{\alpha_n} It_{n,i} = 1; \forall n \in N \tag{3.19}$$

$$\sum_{j=1}^{\beta_w} Iwc_{w,j} = 1; \forall n \in N \tag{3.20}$$

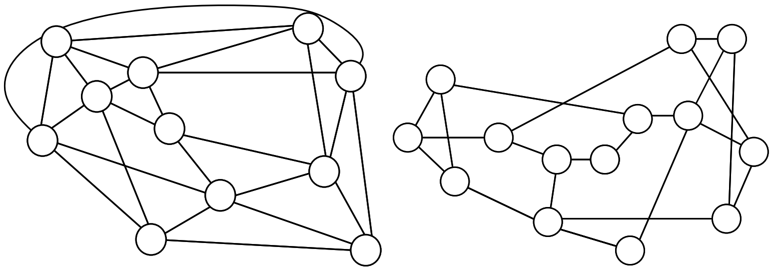
$$\sum_{k=1}^{\delta_n} Ir_{n,k} = 1; \forall n \in N \tag{3.21}$$

$$T_n = \sum_{i=1}^{\alpha_n} i \times It_{n,i}; \forall n \in N \tag{3.22}$$

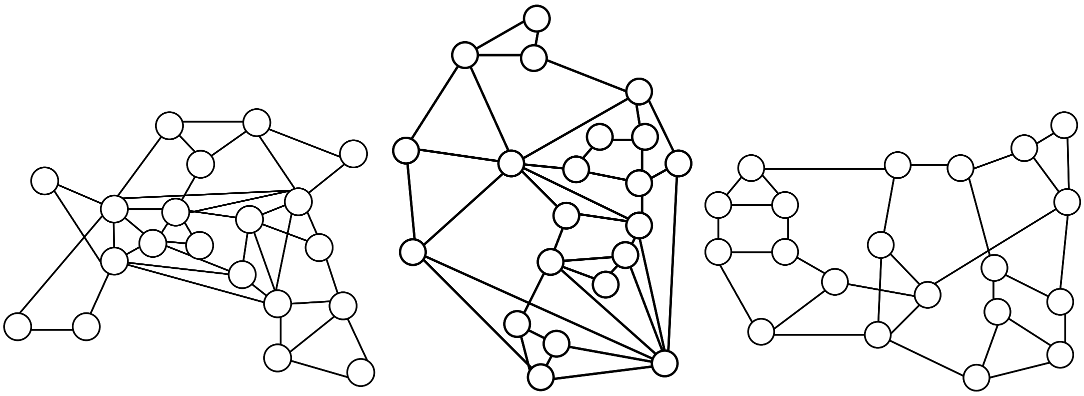
$$WC_w = \sum_{j=1}^{\beta_w} j \times Iwc_{w,j}; \forall w \in W \tag{3.23}$$

$$R_n = \sum_{k=1}^{\delta_n} k \times Ir_{n,k}; \forall n \in N \tag{3.24}$$

The objective function -Eq. (3.14)- represents the network cost in terms of the number of transmitters, receivers and wavelength converters. Equation (3.15) establishes the condition on the blocking probability of each connection. The values of AL_c^{TX}, AL_w^{WC} and AL_c^{RX} -in Eq.(3.15)- are computed using Eqs. (3.16), (3.17) and (3.18), respectively. This is done using the pre-computed values of F^{TX}, F^{WC} and F^{RX} together with the auxiliary decision variables $It_{n,j}$, $Iwc_{w,i}$, $Ir_{n,k}$. These auxiliary decision variables are calculated in Eqs. (3.19), (3.20) and



(a) Eurocore, 11 nodes and 50 links (b) NSFNet, 14 nodes and 42 links



(c) EON, 20 nodes and 78 links (d) UKNet, 21 nodes and 78 links (e) ARPANet, 20 nodes and 62 links

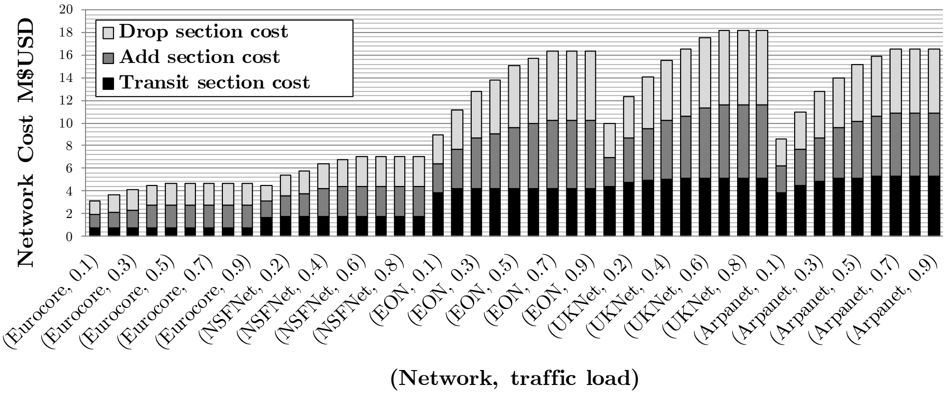
Figure 3.4: Study topologies.

(3.21). Constraints (3.22), (3.23) and (3.24) establish the conditions to evaluate the decision variables T_n, WC_w, and R_n, respectively. Binary variables $It_{n,j}$, $Iwc_{w,i}$, and $Ir_{n,k}$, together with constraints (3.19)-(3.24), allows that $It_{n,j} = 1$ (respectively, $Iwc_{w,i} = 1$ and $Ir_{n,k} = 1$) if and only if $T_n = j$ ($WC_w = i$ and $R_n = k$, respectively).

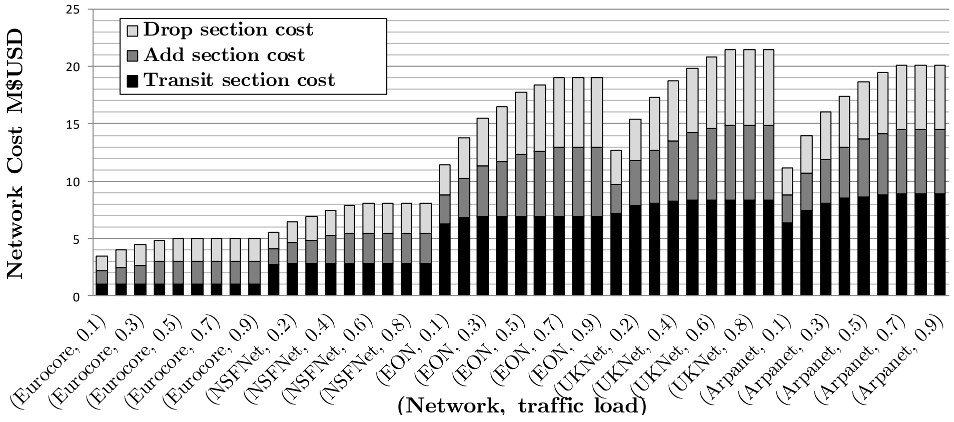
3.6 Numerical results

The integer linear programming model was solved using the IBM ILOG OPL Optimization Suite v6.3 in an Intel Dual- Core 2,2GHz and 3Gbyte of RAM.

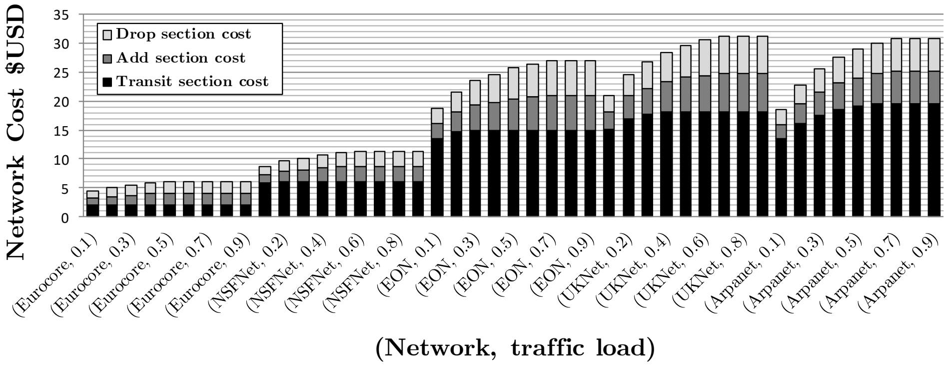
Figure 3.4 shows the five network topologies studied, ordered from highest



(a) $K^{WC} = K^{TX} = K^{RX}$ cost case



(b) $K^{WC} = 2K^{TX} = 2K^{RX}$ cost case



(c) $K^{WC} = 5K^{TX} = 5K^{RX}$ cost case

Figure 3.5: Network cost to three cases of wavelength converter in function of topology and traffic load, with $B_{target} = 10^{-3}$.

to lowest physical connectivity η (defined as the number of unidirectional links divided by $|N|(|N|-1)$, where $|N|$ is the number of network nodes): Eurocore ($\eta = 0.45$), NSFNet ($\eta = 0.23$), EON ($\eta = 0.21$), UKNet ($\eta = 0.19$) and Arpanet ($\eta = 0.16$). For each topology, one connection for every node pair and the shortest path route (in terms of number of hops) for every connection is considered.

The numerical values of the component costs were obtained using the cost functions $K^{WSS}(P^{req})$ and $K^{SC}(P^{req})$ published in [28], where the values of 1×2, 1×4 and 1×8 WSS are equal to USD 5850, USD 9750 and USD 16250, respectively. If P^{req} for any WSS is greater than 8, the number of WSS and couplers to satisfy the number of ports required is increased. The cost of splitters/couplers with P^{req} ports, $K^{SC}(P^{req})$, is given by USD $5.2P^{req}$. In this work $K^{TX} = K^{RX}$= USD 5200 is considered and three cases for the cost of a wavelength converter in comparison with the cost of a tunable optical transmitter/receiver: $K^{WC} = K^{TX} = K^{RX}$=USD 5200, $K^{WC} = 2K^{TX} = 2K^{RX}$=USD 10400 and $K^{WC} = 5K^{TX} = 5K^{RX}$=USD 26000.

For each topology and for each of the three cost cases of a wavelength converter, the ILP model was run for traffic load values from 0.1 to 0.9 Erlangs (135 instances). The target blocking probability per connection was set to 10^{-3}. The maximum time required to solve each instance of the model was shorter than 2 minutes.

Table 3.3: Number of components required in the Eurocore topology for different traffic load values and cost scenarios

Cost case	**Device**	**0.1**	**0.3**	**0.5**	**0.7**
$K^{WC} = K^{TX} = K^{RX}$	Transmitters	66	88	110	110
	Receivers	66	99	110	110
	Wavelength Converters	64	64	64	64
$K^{WC} = 2K^{TX} = 2K^{RX}$	Transmitters	66	88	110	110
	Receivers	66	99	110	110
	Wavelength Converters	64	64	64	64
$K^{WC} = 5K^{TX} = 5K^{RX}$	Transmitters	66	88	110	110
	Receivers	66	99	110	110
	Wavelength Converters	64	64	64	64

Table 3.4: Number of components required in the Arpanet topology for different traffic load values and cost scenarios

Cost case	**Device**	**0.1**	**0.3**	**0.5**	**0.7**
$K^{WC} = K^{TX} = K^{RX}$	Transmitters	160	260	340	380
	Receivers	160	280	340	380
	Wavelength Converters	492	624	668	686
$K^{WC} = 2K^{TX} = 2K^{RX}$	Transmitters	161	260	340	380
	Receivers	161	280	340	380
	Wavelength Converters	490	624	668	686
$K^{WC} = 5K^{TX} = 5K^{RX}$	Transmitters	173	280	340	380
	Receivers	173	275	340	380
	Wavelength Converters	468	611	668	686

In Tables 3.3 and 3.4 the dimensioning results are shown for different values of traffic loads and wavelength converter cost scenarios for the Eurocore and Arpanet topologies, respectively. These topologies were selected as they represent extreme cases of physical connectivity. As expected, for both network topologies there are significant savings (up to 60%) in terms of the number of transmitters/receivers for low traffic loads. It can also be seen that the saving in the number of wavelength converters is null for the Eurocore topology. This is due to its high physical connectivity which leads to every wavelength converter bank having a low number of connections passing through it. Instead, in the case of Arpanet topology, a high saving in terms of wavelength converters is achieved. This happens as every wavelength converter bank is used by a high number of connections (due to the low physical connectivity of this topology), leading to a better statistical gain. Figure 3.5 shows the total network cost (in million USD) as a function of the topology and the traffic load. Each bar in the figure is divided in three sections (light gray, dark gray and black) to show the contribution of the add, drop and transit Sections of the CDC&WC ROADM nodes to the total network cost, respectively. It can be seen that, for each topology, the network cost increases up to a traffic load equal to 0.5 for the Eurocore case, 0.6 for the NSFNet case and 0.7 for the remaining topologies, for all the cases of wavelength converter costs. For higher traffic loads, the network cost does not increase as the network is already fully equipped. That is, each node n is equipped with α_n and δ_n transmitters and receivers, respectively ($|N| - 1$ in this case), and every

WCB w, is equipped with β_w wavelength converters. The network cost obtained in the case where the network node must be equipped with the maximum number of components (transmitters, receivers and wavelength converters) is namely the worst case cost.

From Fig. 3.5 it can also be seen that, for all the cases studied, the contribution of the add section is the same as the contribution of the drop section. Additionally, with the exception of the Eurocore case, the transit Section contributes as much as the add and drop section together. Table 3.5 details the percentage of the network cost represented by the transit Section, averaged over all traffic loads, for each cost case ($K^{WC} = K^{TX} = K^{RX}$, $K^{WC} = 2K^{TX} = 2K^{RX}$, $K^{WC} = 5K^{TX} = 5K^{RX}$). It can be seen that the contribution of the transit Section is significant in the topologies with lower connectivity (mainly, EON, UKNet and ARPANet). This is an expected result, as low connected topologies require longer routes than highly connected topologies (e.g., the mean number of hops of routes in ARPAnet is 2.81, whilst this number is equal to 1.58 for Eurocore). Thus, more transit components are required to establish the lightpaths. Also, as expected, the percentage of transit section in comparison with the total network cost increases with the cost of wavelength converters.

Table 3.5: Average network cost percentages of transit Section in a CDC&WC ROADM-based network

Cost case Topology	$K^{WC} = K^{TX} = K^{RX}$	$K^{WC} = 2K^{TX} = 2K^{RX}$	$K^{WC} = 5K^{TX} = 5K^{RX}$
Eurocore	16	23	36
NSFnet	28	39	57
EON	31	42	61
UKnet	33	44	63
Arpanet	36	48	67

To compare the savings achieved by the dimensioning method presented in this chapter, the normalized saving is computed: worst case cost minus the network cost obtained here divided by the worst case cost. Figures 3.6, 3.7 and 3.8 show the value of the normalized savings as a function of traffic load for the five topologies studied, for each cost scenario, respectively. It can be seen that up to 50% savings can be achieved and that the saving is higher for topologies with low connectivity. Again, the longer routes of low connected topologies highlight the fact that an efficient dimensioning of the transit resources is of fundamental importance.

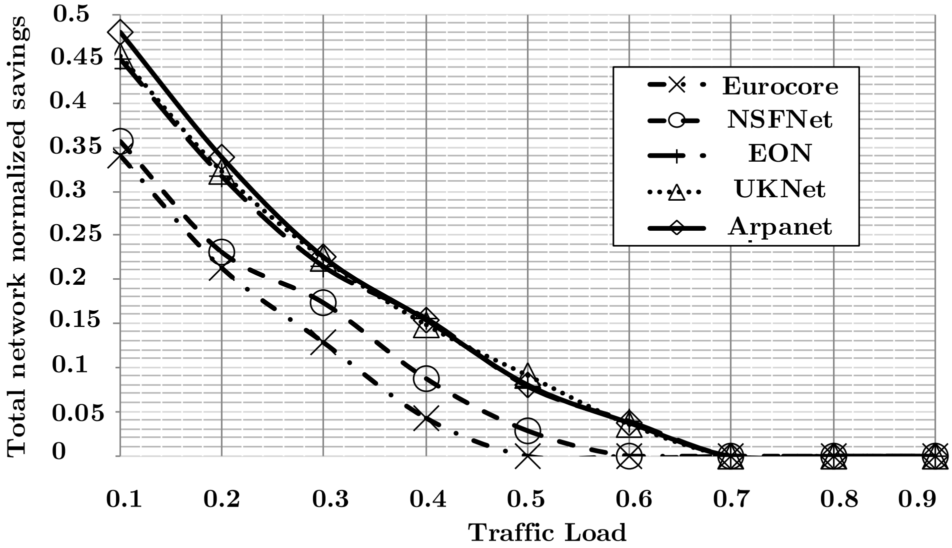


Figure 3.6: Normalized saving network as function of traffic load, case $K^{WC} = K^{TX} = K^{RX}$, with $B_{target} = 10^{-3}$.

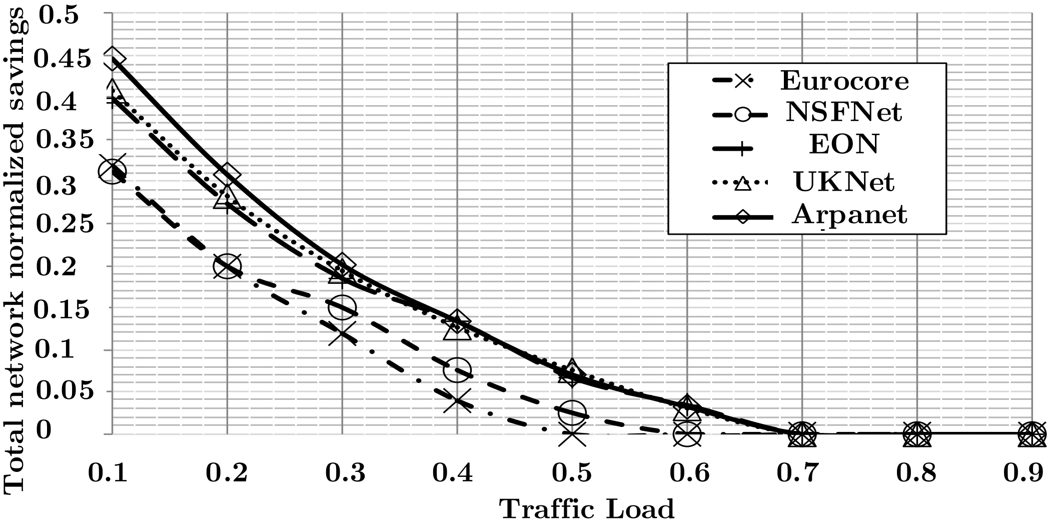


Figure 3.7: Normalized saving network as function of traffic load, case $K^{WC} = 2K^{TX} = 2K^{RX}$, with $B_{target} = 10^{-3}$.

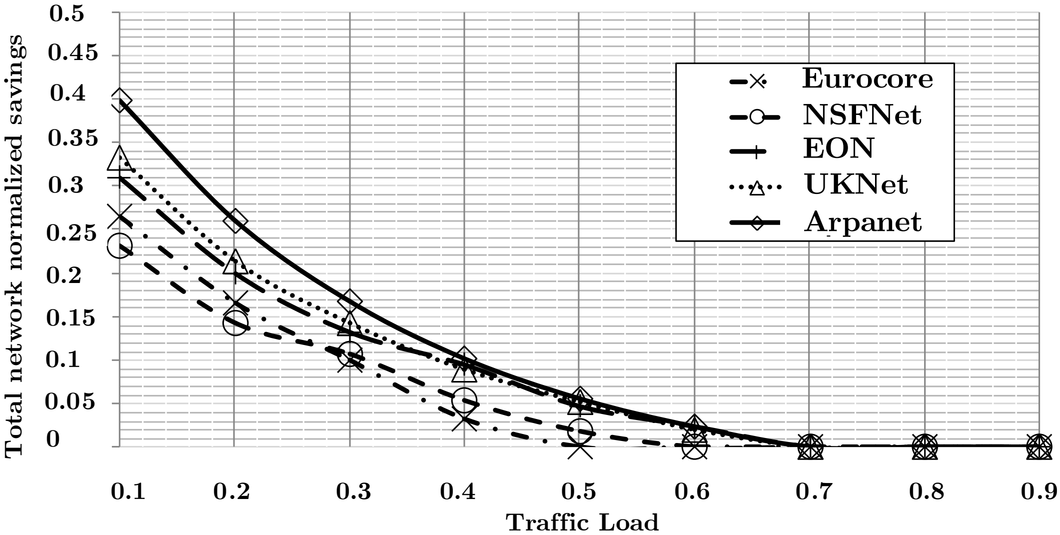


Figure 3.8: Normalized saving network as function of traffic load, case $K^{WC} = 5K^{TX} = 5K^{RX}$, with $B_{target} = 10^{-3}$.

Compliance of the ILP model results with the restriction of maximum blocking probability for each connection was verified by simulation. To do so, an ad-hoc event-driven simulator programmed in C language was developed. For each topology, the number of transmitters, receivers and wavelength converters resulting from solving the ILP model were incorporated to the data structures storing the network nodes information. Then, 50 simulation runs, each one with 10^6 connections requests uniformly distributed among the different node pairs, were executed. The ratio between the blocked requests of a particular connection (node pair) and the total number of connections requests generated by that node pair was recorded. Simulation results show that the model was successful in guaranteeing a maximum blocking probability of connections as 100% of connections in the Eurocore, NSFNet, UKNet and ARPANet topologies and 99% of connections in the EON topology experienced a blocking lower than the target.

3.7 Conclusions

In this chapter, an ILP formulation for solving the problem of determining the number of components in the add, drop and transit sections of a CDC&WC ROADM architecture whilst minimizing the network cost subject to a blocking constraint per connection was proposed.

The main difficulty in doing so was including the stochastic nature of lightpath arrival/departure process in the ILP model, which leads to a non-linear constraint because of the blocking equation. This problem was solved by applying the logarithm function to the formula for blocking and the still non-linear resulting terms were made linear by introducing tabulated parameters in the model.

Results, validated by simulation, show that depending on the topology and the value of the traffic load, up to 50% savings can be achieved by applying the presented method with respect to the worst case dimensioning. The highest savings are obtained at low loads in low connected networks. Additionally, the impact of the transit sections in the total network cost is higher in low connected networks, as routes are longer than in high connected topologies, leading to an increase of the number of intermediate nodes used to transfer the information across the network.

Studying the impact that the elimination of wavelength conversion has on the dimensioning of a CDC ROADM-based network is part of future research.

Chapter 4

Dimensioning and configuring backup wavelengths on WDM Networks with availability guarantees.

In this chapter the problem of determining the backup wavelength requirements of a static optical network operating under shared protection is addressed. The contribution of this research work are: a novel way of dealing with the non-linear expression for the availability constraint and derivation of new numerical results based on that constraint; studying the impact of a new availability-aware priority mechanism on availability equations and results; defining variables that allow identifying which wavelength is shared by which connections in every network link; and a new set of equations capturing the wavelength continuity constraint and its impact on the number of backup wavelengths. The problem of planning a static WDM network with availability guarantees under shared protection is addressed as follows:

- First, the set of connections that are to be allocated a backup lightpath to meet the availability requirement is determined.
- Next, for the set of connections determined in the first step, an ILP that aims at minimizing the total number of backup wavelengths such that the

availability of every connection meets a given target value is formulated and solved. The input data are the working/backup routes and the availability requirements of the set of connections determined in the first step. The proposed ILP model considers an availability-based priority scheme for the access to the shared resources and also allows identifying which connections can share backup resources in every network link.

- Finally, a heuristic approach to solve the same problem in a shorter time is implemented and a modification of the original ILP to consider the wavelength continuity constraint is presented.

Unlike previous work in the area of shared protection in WDM networks, that only provide the number of backup wavelengths required by the whole network but not how to exactly configure the backup resources of each link, this work provides essential information about the set of connections that share a backup wavelength in every network link. In this way, results relevant to the network operators who need to know how to exactly configure their backup wavelengths to provide the availability requested by the customers (as just providing the number of backup resources does not allow one to configure the network) are produced. To diminish the amount of information that must be processed, instead of storing connection-by-connection information, link-by-link information is stored.

In this chapter the design problem of a WDM network operating in shared path protection mode so as to be capable of to give guarantees for a determined availability requirement for its connections is considered. This problem is solved formulating an integer linear program (ILP) where an availability not linear model is included and the number of WDM channels required to meet the availability requirement imposed to the network service is minimized. The ILP give the configuration of backup lightpaths sharing WDM channels.

This chapter is organized as follows. In Section 4.1 the network and failure models are presented. In Section 4.2 dedicated and shared path protection schemes are described. Next, in Section 4.3, the expression for availability of connections operating under shared path protection scheme is derived. Then, the proposed ILP model and the greedy heuristic are given in Sections 4.4 and 4.5, respectively. Section 4.6 presents the numerical results obtained with the ILP model and the heuristic along with upper and lower bounds on the number of backup wavelengths required. Finally, Section 4.9 concludes this work.

4.1 Network and failure model

The network is represented by a graph $G = (N, L)$ where N is the set of nodes and L the set of unidirectional links. The number of elements in the sets N and L is denoted by $|N|$ and $|L|$, respectively.

Every network link $l \in L$ can be either in operative or non-operative state. The mean time link l is in operative state is denoted by $MTTF_l$ (Mean Time To Failure). The mean time link l is under failure is denoted by $MTTR_l$ (Mean Time To Repair). The mean time between two consecutive failures on link l is denoted by $MTBF_l$ (Mean Time Between Failure) and is equal to the sum of $MTTF_l$ and $MTTR_l$. Also, independent failure links and that the network is in steady state is assumed. Therefore, the probability that link l is in operative state, denoted by p_l, is given by:

$$p_l = \frac{MTTF_l}{MTTF_l + MTTR_l} \tag{4.1}$$

According to the statistics reported in [175], the unavailability due to link failures is 3 orders of magnitude higher than that due to equipment failures at the nodes. Therefore, in this paper it is assumed that a lightpath may not be available due to link failures only.

Let C be the set of all point-to-point connections that might be established in the network. The maximum number of elements in C is equal to $|N|(|N|-1)$, and each one is defined by its source and destination node. Once established, it is assumed that a connection remains in place for a long time (weeks to years), configuring a static scenario. To establish a connection at least a working lightpath must be implemented. Let LP_c^W be the working lightpath of connection c. LP_c^W is defined by: a) a route (given as input data), denoted as R_c^W, corresponding to the ordered set of links starting at the source node and ending at the destination node of connection c and b) a wavelength in each link in R_c^W (not necessarily the same, if full wavelength conversion is assumed).

If A_c^{Target}, the target availability required for the connection c, cannot be provided by the working lightpath alone, then a backup lightpath must be implemented. Let LP_c^B be the backup lightpath of connection c, defined by a route (given as input data) and a wavelength in each link. The set of links used by LP_c^B is denoted by R_c^B and C_l is defined as the set of connections whose backup routes use the link l.

To ensure that a link failure does not affect simultaneously the working and backup lightpaths of a connection, R_c^W and R_c^B are assumed to be link-disjoint.

4.2 Prioritization of connections

In a WDM network it must be ensured that two lightpaths in the same link do not use the same wavelength. Besides this requirement, additional constraints must be met depending on the type of protection used. They are described in the next subsections.

In this study the following availability-based priority system to deal with the problem of backup wavelength contention is defined: among all working connections sharing the same backup wavelength, the connection with the lowest value of availability under dedicated protection has the higher priority to access the shared backup resources. The connection with the second lowest availability level under dedicated protection has the second highest priority to access the shared resource and so on. In this way, as shared protection reduces the availability of all connections sharing backup resources, the connections most likely to have difficulties meeting the target availability under shared protection are less affected by the availability reduction. Because of mathematical convenience, in this paper it is assumed that if $i >$j, then connection i has lower priority than connection j.

4.3 Availability of connections under prioritized shared protection

The availability of connection c operating with a protection scheme is denoted by A_c and it is given by:

$$A_c = \Pr\{LP_c^W \text{ is available}\} + \Pr\{LP_c^W \text{ is unavailable and } LP_c^B \text{ is available}\} \tag{4.2}$$

Denoting by A_c^W and A_c^B the availability of the working and backup lightpath for connection c, respectively, and since paths LP_c^W and LP_c^B are link disjoint, then

$$A_c = A_c^W + (1 - A_c^W) \times A_c^B \tag{4.3}$$

The availability of a lightpath depends not only on the availability of the links along its route but also on the availability of the wavelength to be used. In this paper, that a particular wavelength is unavailable for a given connection only when it is used by another connection or when the corresponding link is under failure (in which case, all wavelengths in that link become unavailable) is assumed. Wavelength unavailability due to hardware malfunctioning (e.g. laser failure) is not considered here. Thus, the availability of the working lightpath R_c^W (where the wavelengths are always available unless the link fails) reduces to:

$$A_c^W = \Pr\{LP_c^W \text{ is available}\} = \prod_{l \in R_c^W} p_l \tag{4.4}$$

The expression for $\Pr\{LP_c^B$ is available$\}$ under shared protection can be evaluated as:

$$A_c^B = \Pr\{R_c^B \text{ and } R_i^W \text{ are available } \forall i \in X_c\} \tag{4.5}$$

where $X_c \subseteq X_c^{All}$, where X_c^{All} is the set of all connections that might share resources with connection c such that:

- the backup lightpaths of connections c and i use the same wavelength in at least one link of their corresponding routes.

- connection i has higher priority than connection c to access the common wavelength(s).
- the working lightpath of connection i does not have links in common with the backup lightpath of connection c

Mathematically, X_c^{All} is defined as:

$$X_c^{All} := \{i \in C : c > i \wedge R_i^B \cap R_c^B \neq \emptyset \wedge R_i^W \cap R_c^B \neq \emptyset\}$$

On the other hand, X_c is the set of connections that actually share resources with connection c.

Equation (4.5) states that, for the backup lightpath of connection c to be available, not only all the links along its route must be operative but also all the working lightpaths of connections sharing backup wavelengths with connection c and that have higher priority than connection c must be operative.

Note that (4.5) is an approximation, as it does not consider the low-probability case where the wavelengths for R_c^B are available although at least one working path i ($\forall i \in X_c$) is unavailable. This occurs when the working path of connection i failed, but also did its backup connection due to a failure in a link that is not shared with connection c.

Note also that the set R_c^W is link-disjoint with sets R_c^B and R_i^W ($\forall i \in X_c$), and that R_i^W is not necessarily link-disjoint with R_c^B. Then

$$A_c^B = \prod_{l \in (\bigcup_{i \in X_c} R_i^W) \bigcup R_c^B} p_l \tag{4.6}$$

According to this, the availability of connection c under shared protection depends on the set of shared connections X_c, and can be expressed as:

$$A_c(X_c) = A_c^W + (1 - A_c^W) \times \prod_{l \in (\bigcup_{i \in X_c} R_i^W) \bigcup R_c^B} p_l \tag{4.7}$$

It can be seen that the key element to decide is the set of shared connections X_c for all $c \in C$. The dedicated path protection is obtained when $X_c = \emptyset$ for all $c \in C$, so the maximum availability is obtained, but this requires a large number of wavelengths available at each link. On the contrary, if as many connections as possible are grouped, then $X_c = X_c^{All}$. In such case, several wavelengths can be saved, but the resulting availability A_c can be too low.

So, the natural problem to study is how to minimize the total number of backup wavelengths subject to guaranteeing a target availability for every network connection in a WDM network using shared protection. That is:

$$\text{minimize} \sum_{l \in L} (\text{number of backup wavelengths used in link } l) \tag{4.8}$$

$$\text{subject to } A_c(X_c) \geq A_c^{Target}, \forall c \in C \tag{4.9}$$

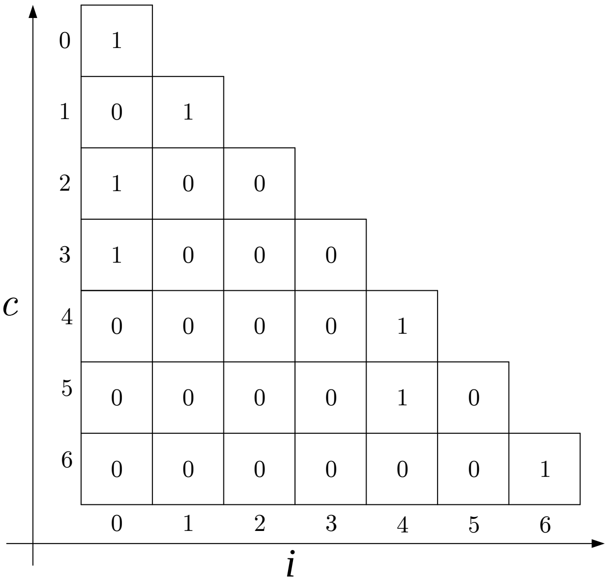
Note that even for a given set of allowed shared connections X_c for all $c \in C$, to evaluate the minimum number of backup wavelengths required in each link is an NP-hard problem. In fact, this problem is equivalent to find the MINIMUM CLIQUE PARTITION (see Section 4.7). In the following Section, an ILP model that aims at minimizing the number of backup wavelengths used under shared protection is presented.

4.4 The integer linear programming model

The ILP model uses binary decision variables $x_{c,i}$ for each $c \in C$ and $i \in C (i < c)$ such that $x_{c,i} = 1$ if $i \in X_c$ and $x_{c,i} = 0$ if $i \notin X_c$.

As the number of wavelengths required in each link cannot be obtained directly from the set X_c, it is necessary to decide, at each link, which connections share the same wavelength.

Let $y_{l,c,i}$ be a binary decision variable for $l \in L, c \in C_l, i \in C_l$ $(c > i)$, such that $y_{l,c,i} = 1$ when the backup lightpath of connection c shares a wavelength on link l with a higher-priority connection i. A unique representative connection is selected for each group of connections sharing a backup wavelength in a link. The representative connection is the one with the highest priority in the group. All remaining connections in a group only need to be associated to this representative



$c \backslash i$	0	1	2	3	4	5	6
0	1						
1	0	1					
2	1	0	0				
3	1	0	0	0			
4	0	0	0	0	1		
5	0	0	0	0	1	0	
6	0	0	0	0	0	0	1

Figure 4.1: Variable structure $y_{l,c,i}$ for a link l.

connection to indicate they belong to the same group. Thus, if connections i, j and k (in descending order of priority) share a wavelength on link l, then connection i is the representative connection of this group. This is indicated by making $y_{l,i,i} = 1$. To indicate that connections j and k are part of this group, $y_{l,i,j} = 1$ and $y_{l,i,k} = 1$ are defined. No more elements must be made equal to 1 to represent this group.

Fig. 4.1 illustrates the behavior of variable $y_{l,c,i}$ for a determined link l. In the figure, the inferior triangular Section of matrix Y_l, of size $|C_l| \times |C_l|$, is shown, where $|C_l|$ is the number of connections whose backup routes use link l. The lower the number of the row/column, the higher the priority of the connection. In this particular example, the backup lightpaths of connections $0-6$ use the link under study, with connection 0 having the highest priority. Each element in the matrix represents the value of the binary decision $y_{l,c,i}$, with c having lower priority than connection i. The meaning of the elements of matrix Y_l is as follows:

- *Column*: the elements (c, i) in column i that are equal to 1 belong to a group of connections sharing a backup wavelength in link l whose representative connection (the connection with the highest priority) is connection i. In the example, four groups can be observed: *a*) the group represented by connection 0 that contains connections 0, 2 and 3, *b*) the group represented by connection 1 that only contains this connection (that is, connection 1 does not share backup wavelengths with any other connection in link l), *c*) the group represented by connection 4, containing connections 4 and 5 and *d*) the group represented by connection 6, containing only this connection.

- *Row*: each row can have only one element different from 0. For each row r, the column where a value equal to 1 is found corresponds to the identification of the connection representing the group to which connection r belongs. In the example, connections 0, 1, 2, 3, 4, 5 and 6 are represented by connections 0, 1, 0, 0, 4, 4 and 6, respectively.

The decision of selecting a representative for each group has been made in order to avoid symmetry problems in the final ILP model.

Note that the total number of backup wavelengths corresponds to the number of groups of connections sharing a wavelengths in each link. Hence, the number of wavelengths required at each link can be counted as the number of representative connections with $y_{l,c,c} = 1$. This allows formulating the objective function as:

$$\text{minimize} \sum_{l \in L} \sum_{c \in C_l} y_{l,c,c} \tag{4.10}$$

The selection of a representative connection at each link for each group is obtained by the following constraints:

$$\sum_{i \in C_l : c \geq i} y_{l,c,i} = 1 \qquad \forall l \in L, \forall c \in C_l \tag{4.11}$$

$$y_{l,c,i} \leq y_{l,c,c} \quad \forall l \in L, \forall c \in C_l, \forall i \in C_l : c > i \tag{4.12}$$

The first equation makes sure that, for a given link l and connection c, each connection i ($\forall i \in C_l$) can be either the representative connection of only one group of connections (that is, $y_{l,i,i} = 1$ and $y_{l,c,i} = 0$ for the rest of elements of row c such that $c > i$) or be part of at most one group represented by another connection c with higher priority (that is, $y_{l,c,i} = 1$).

The second expression ensures that, if the backup lightpaths of connections i and c share a wavelength at least in one link of their backup routes (that is, if $y_{l,c,i} = 1$), then c must be the representative connection of this group of backup lightpaths using this wavelength. That is, if $y_{l,c,i} = 1$, then $y_{l,c,c}$ must be also 1.

Note that although connections k and j can share a wavelength (then $x_{k,j} = 1$) $y_{l,j,k}$ can be equal to 0 if connection j is not the representative connection of this group.

To ensure that the decision variable $y_{l,c,i}$ allows modeling the grouping of connections per link in a correct way, constraints linking variables $y_{l,c,i}$ and $x_{c,i}$ are required.

If $i \notin X_c$ ($x_{c,i} = 0$), then $y_{l,c,i} = 0$ for every link l. This is forced with the next constraint:

$$y_{l,c,i} \leq x_{c,i} \quad \forall l \in L, \forall c \in C_l, \forall i \in C_l : c > i \tag{4.13}$$

Note that sharing a wavelength is not a transitive operation. For example if $x_{i,j} = 1$, $x_{i,k} = 1$, and if backup routes R^B_j and R^B_k are disjoint, then $x_{j,k} = 0$. However, if the backup lightpaths of three connections have in common at least one link (also that their primary routes R^W_i, R^W_j and R^W_k are disjoint), then in this case the transitivity applies: that is $x_{i,j} = 1$, $x_{i,k} = 1$ then $x_{j,k} = 1$, if $j \in X_i$, $k \in X_i$ and $k \in X_j$. Hence, the definition of the sharing of wavelengths at a link level is required. Hence, the following condition must be met:

$$y_{l,i,k} + y_{l,j,k} \leq 1 + x_{i,j} \quad \forall l \in L, \forall k \in C_l, \forall i \in C_l, \forall j \in C_l : j < i \wedge k < i \wedge k < j$$

This constraint forces to set $x_{i,j}$ to 1 if the connections i and j are in a group represented by connection k. This inequality also implies that if $x_{i,j} = 0$, then the connection i or connection j might be part of the group represented by connection k, but not represented by i and j. Note that in this case ($x_{i,j} = 0$), connection i could belong to the group represented by connection k and not containing connection j at a given link, whilst in another link connection j could belong to the group represented by and not containing connection i. This is equivalent to change the backup wavelength used along the backup routes.

Variables $x_{i,j}$ requires additional bound constraints. The first, for variables $x_{c,i}$, is to set $x_{c,i} = 0$ if the connections c and i can not share wavelengths (because its backup routes are disjoint or its working routes are not disjoint). This is formulated as:

$$x_{c,i} = 0 \quad \forall c \in C, \forall i \in C : c > i \wedge i \notin X_c^{All} \tag{4.14}$$

Finally to model the availability constraint in (4.9) -recall that p_l is the probability that link l is in operative state-, reordering the terms in (4.7) and applying the logarithmic function to each term is obtained

$$\sum_{l \in (\bigcup_{i \in X_c} R_i^W) \bigcup R_c^B} \log(p_l) \geq \log\left(\frac{A_c^{Target} - A_c^W}{1 - A_c^W}\right) \quad \forall c \in C \tag{4.15}$$

Considering that the expression (4.15) is only for connections operating with a working and backup lightpaths, the values for A_c^{Target} must satisfy that:

$$A_c^W < A_c^{Target} < A_c(\emptyset) \tag{4.16}$$

The condition $A_c^W < A_c^{Target}$ establishes that at least a backup lightpath is required to satisfy the target availability. The condition $A_c^{Target} < A_c(\emptyset)$ requires that the availability requirement must be achievable operating under dedicated protection scheme.

To write (4.15) as a linear constraint, selecting the set of links $(\bigcup_{i \in X_c} R_i^W) \bigcup R_c^B$ for X_c is required. To do so, a binary variable $z_{c,l}$ such that $z_{c,l} = 1$ if $l \in (\bigcup_{i \in X_c} R_i^W) \bigcup R_c^B$ is defined. In order to do that, two set of inequalities are required:

$$z_{c,l} = 1 \qquad \forall c \in C, \forall l \in R_c^B \tag{4.17}$$

$$z_{c,l} \geq x_{c,i} \qquad \forall c \in C, \forall l \in R_i^W, \forall i \in C : c > i \tag{4.18}$$

Using these new variables, (4.15) can be formulated as

$$\sum_{l \in L} z_{c,l} \times \log(p_l) \geq \log\left(\frac{A_c^{Target} - A_c^W}{1 - A_c^W}\right) \quad \forall c \in C \tag{4.19}$$

In summary, the final linear integer programming model is given by:

Sets and indexes

- L: set of network links.
- C: set of network connections.
- C_l: set of connections using link l.
- R_c^W: set of links conforming the working route of connection c.
- R_c^B: set of links conforming the backup route of connection c.
- X_c^{All}: set of connections that could share backup wavelengths with connection c.
- l: index used to traverse the sets of links L, R_c^W and R_c^B.
- c: index used to traverse the sets of connections C and C_l.
- i: index used to traverse the sets of connections C, C_l and X_c^{All}.
- j: index used to traverse the sets of connections C and C_l.
- k: index used to traverse the sets of connections C and C_l.

Parameters

- p_l: availability of link l.
- A_c^{Target}: availability target for connection c.
- A_c^W: availability of working lightpath of connection c.

Decision variables

- $x_{c,i}$: binary variable that is equal to zero if connection $i \in X_c$ ((i.e. i has higher priority than connection c and shares backup wavelengths with it).

- $y_{l,i,j}$: binary variable that takes value 1 when the backup lightpath of connection c shares a wavelength on link l with a higher-priority connection i.
- $z_{c,l}$: binary variable equal to 1 if $l \in (\bigcup_{i \in X_c} R_i^W) \bigcup R_c^B$.

Minimize

$$\sum_{l \in L} \sum_{c \in C_l} y_{l,c,c} \tag{4.20}$$

Subject to

$$\sum_{l \in L} z_{c,l} \times \log(p_l) \geq \log\left(\frac{A_c^{Target} - A_c^W}{1 - A_c^W}\right), \forall c \in C \tag{4.21}$$

$$z_{c,l} = 1 \quad , \forall c \in C, \forall l \in R_c^B \tag{4.22}$$

$$z_{c,l} \geq x_{c,i} \quad , \forall c \in C, \forall i \in X_c^{All} \quad , \forall l \in R_i^W : c > i \tag{4.23}$$

$$x_{c,i} = 0 \quad , \forall c, i \in C : i \notin X_c^{All}, \quad c > i \tag{4.24}$$

$$y_{l,c,i} \leq x_{c,i} \quad , \forall l \in L, \forall c, i \in C_l \quad : c > i \tag{4.25}$$

$$\sum_{i \in C_l : c \geq i} y_{l,c,i} = 1 \quad , \forall l \in L, \forall c \in C_l \tag{4.26}$$

$$y_{l,c,i} \leq y_{l,i,i} \quad , \forall l \in L, \forall c, i \in C_l \quad : c > i \tag{4.27}$$

$$y_{l,i,k} + y_{l,j,k} \leq 1 + x_{i,j} \quad , \forall l \in L, \forall k, i, j \in C_l \quad : j < i \wedge k < i \wedge k < j \tag{4.28}$$

$$x_{c,i} \in \{0,1\} \quad , \forall c, i \in C \quad : c > i \tag{4.29}$$

$$y_{l,c,i} \in \{0,1\} \quad , \forall l \in L, \forall c, i \in C_l \quad : c > i \tag{4.30}$$

$$z_{c,l} \in \{0,1\} \quad , \forall l \in L, c \in C_l \tag{4.31}$$

4.5 A greedy heuristic

The previous ILP model can be hard to solve, specially on large instances of the problem. To be able to solve large instances, in this section a heuristic solution is presented. Such solution is obtained using a greedy algorithm that, starting from $X_c = \emptyset$ for all $c \in C$, iteratively groups two connections (i.e. $x_{c,i} = 1$), reducing the number of required wavelengths, until no more grouping is possible without violating the required availability for each connection A_c^{Target}.

Remember that given a set of allowed shared connections X_c, the availability of each connection $A_c(X_c)$ can be obtained directly from (4.7), but the minimum number of required wavelengths at each link is NP-hard to compute. Hence, a different objective to select the "best" pair of connections to be grouped in each iteration is used: for each pair of connections (c, i), the benefit obtained by sharing a backup wavelength is defined by:

$$B_{c,i} = \left(A_i(X_i) - A_i^{Target}\right) \times \left|R_i^B \bigcap R_c^B\right| \tag{4.32}$$

where the first term of the right side corresponds to the difference between the target availability of connection i (the one with lowest priority) and its resulting availability under shared protection (resulting from making connections c and i sharing a backup wavelength in all their common backup links). The higher the positive value of this difference, the higher the potential of backup wavelength sharing and thus, the higher the probability of including another connection in this group. The second term in (4.32) is the number of common links in the backup routes of connections c and i. Thus, the higher the value of this term, the higher the backup resource savings obtained by allowing these two connections to share backup resources.

Hence, the heuristic finds, at each iteration, the pair of connections (c, i) with $i \in X_c^{All}$ that attains the maximum benefit $B_{c,i}$ as a candidate to share backup wavelengths. Next, to ensure that the all connections meet the availability constraint formulated in (4.9), for each iteration of the greedy algorithm the fulfillment of the following expression is evaluated:

$$A_i(X_i) \geq A_i^{Target} \tag{4.33}$$

where i is the connection with lower priority of the pair (c, i) (the availability of connection c does not change). If the condition established by (4.33) is not met, then the candidate is not considered part of solution (i.e. $x_{c,i} = 0$) and it is not further considered in the following iterations of the greedy heuristic.

When there are no more candidates that meet the expression (4.33), the greedy algorithm stops and the solution for each variable $x_{i,j}$ is stored in matrix X.

Next, to correctly find the groups of backup routes that share the same wavelength in each link, *i.e.* to evaluate the minimum number of wavelengths required in each link, solving an ILP is required. But, as the values of X_c are fixed, the general problem becomes separable and thus, less complex. For each link $l \in L$, the following ILP is solved:

$$
\begin{aligned}
L_l(X) := \text{minimize} \sum_{\forall c \in C_l} & y_{c,c} && && (4.34)\\
\text{subject to } & y_{c,i} = 0 && , \forall c \in C_l, \forall i \in C_l : x_{c,i} = 0 && (4.35)\\
& \sum_{i \in C_l : c \geq i} y_{c,i} = 1 && , \forall c \in C_l && (4.36)\\
& y_{c,i} \leq y_{i,i} && , \forall c \in C_l, \forall i \in C_l : c > i && (4.37)\\
& y_{i,k} + y_{j,k} \leq 1 && , \forall i, j, k \in C_l && (4.38)\\
& && : j < i \wedge k < i \wedge k < j : x_{i,j} = 0 &&\\
& y_{c,i} \in \{0, 1\} && , \forall c \in C_l, \forall i \in C_l && (4.39)
\end{aligned}
$$

which is equivalent to the ILP problem in the previous Section for a fixed value of X_c for all $c \in C$.

The pseudocode of the heuristic is described in Algorithm 1.

Algorithm 4.1 Greedy for backup wavelengths configuration for networks operating under shared protection scheme with availability requirement

```
Input: sets $L$, $N$ and $C$.
Input: $R_c^W$, $R_c^B$ for every $c \in C$.
Input: $p_l$, for every $l \in L$.
Input: $A_c^{Target}$, for every $c \in C$.
Input: $X^{base}$ (Matrix of zeros)
Define $sw = 1$ (auxiliary variable)
Define $X = X^{base}$
Define $Candidates\_set$ like the set of pairs of connections $(i, j)$ such as $x_{i,j}^{base} = 1$ (where connection $i$ has lower priority than connection $j$)
while $sw = 1$ do
    (loop to modify matrix $X$ to find the solution)
    $sw = 0$, $B^{MAX} = 0$
    for all $(i, j) \in Candidates\_set$ do
        (in this loop, the benefit of all candidates is evaluated and the next candidate to be incorporated to the solution is selected)
        $x_{i,j} = 1$
        Compute $A_i$, $B_{i,j}$
        (In the next, the availability requirement is evaluated for connection $i$, the connection with lower priority of the pair)
        if $A_i \geq A_i^{Target}$ then
            if $(B_{i,j} > B^{MAX})$ then
                (if the availability requirement is met for connection $i$ and the benefit of candidate evaluated is higher than the previous candidates in $Candidates\_set$ , then the variables $B^{MAX}$, $i^{MAX}$, $j^{MAX}$ and $sw = 1$ are updated)
                $B^{MAX} = B_{i,j}$, $i^{MAX} = i$, $j^{MAX} = j$, $sw = 1$
            end if
        else
            (if the availability requirement is not met, then the candidate is dropped from the list of possible candidates )
            Delete $(i, j)$ from $Candidates\_set$
        end if
        $x_{i,j} = 0$
        Compute $A_i$
    end for
    if $sw == 1$ then
        (if any candidate meet the availability requirement, then the position associated to candidate selected is change to 1 in matrix $X$ )
        $X[i^{MAX}, j^{MAX}] = 1$
    end if
end while
```

Algorithm 4.1 Greedy for backup wavelengths configuration for networks operating under shared protection scheme with availability requirement (continued)

```
  (The next loop is to compute the total backup wavelengths)
  $w_{total} = 0$
  for all $l \in L$ do
    execute the ILP formulated in (4.34)- (4.38) for $l \in L$
    $w_{total} = \sum_{c \in C_l} y^l_{c,c} + w_{total}$
  end for
Ensure: $X$ (matrix with information about that connections share its backup
  resources with each connection)
Ensure: $Y_l$ for each link (matrix with information about the groupings of con-
  nections sharing backup wavelengths in each link)
Ensure: $w_{total}$ (the total number of backup wavelength required)
```

4.6 Numerical results and discussion

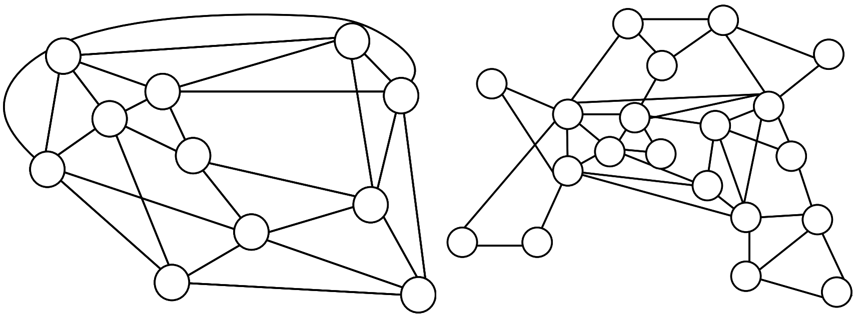
The ILP model and heuristic solution were solved using the IBM ILOG OPL Optimization Suite v6.3 in an CPU 2x Xeon E5-2670 2.0 Ghz, 20M Cache, 2.00 GHz, 8.00 GT/s Intel(R) QPI, 8 cores, RAM of 128 Gb, with the total memory assigned for each instance.

The topologies studied are shown in Fig. 4.2. The working route R_c^W for each connection $c \in C$ corresponds to the most reliable route between the source and destination node of c, assuming link failure independence. Similarly, each backup route R_c^B corresponds to the most reliable route that is arc-disjoint with R_c^W. However, it is worth noticing that the proposed methodology can be applied to any pair of working/backup routes, and other criteria can be applied to select these pairs of routes.

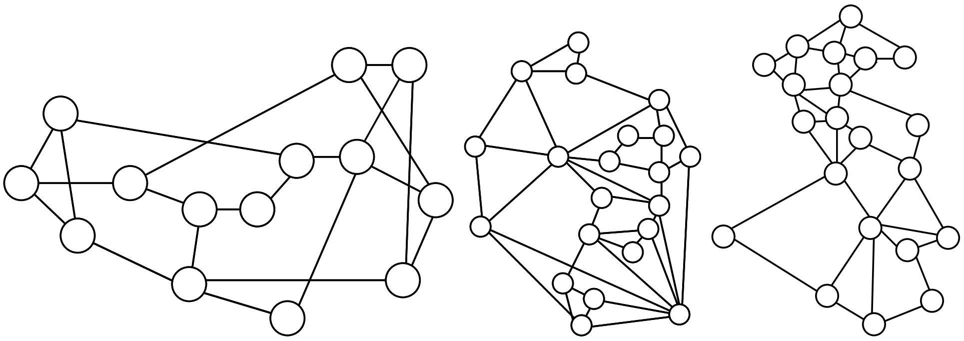
For each topology two scenarios were evaluated. In the first scenario (homogeneous scenario), all connections require the same value of availability with three possible values: 0.999, 0.9999, 0.99999. That is, $A_c^{Target} = A^{Target}, \forall c \in C$. In this scenario it might happen that some connections achieve the required availability using only the working lightpath and thus, they are excluded from further consideration (as they do not required backup resources). On the other side, some connections could not achieve the required availability even with dedicated protection. They are also excluded from consideration. Therefore, the set of connections C (problem size) might have a number of elements lower than $|N| \times (|N| - 1)$ as it is made of the connections that need to operate with exactly one backup lightpath to reach the target availability. Given the target availability, this set is unique.

In the second scenario (heterogeneous scenario), the concept of differentiated reliability (introduced in [41]) is used, where every connection requires a different target availability, corresponding to a fraction of the availability obtained under dedicated protection (heterogeneous scenario). That is, $A_c^{Target} = \alpha \cdot A_c(\emptyset)$, $\forall c \in C$. In this case, no connection requires more than one backup lightpath to achieve the target availability. Thus, only those connections that achieve their required availability using just the working lightpath are excluded from the set C.

Tables 4.1 and 4.2 show the results for the homogeneous and heterogeneous scenarios, respectively. The first column of each table corresponds to the name of the network analyzed. Under the name, in brackets, the average number of hops of the working and backup lightpaths and the average availability of their links are given. The availability of each link, used to obtain the average availability of the network links, is evaluated according to (4.1). The MTTF of each link is calculated by multiplying the length of the link by the failure rate per length unit, equal to $2.73 \times 10^{-3}[\mathrm{yr}^{-1} \times \mathrm{km}^{-1}]$ for terrestrial links, as reported in [175], and equal to $1 \times 10^{-4}[\mathrm{yr}^{-1} \times \mathrm{km}^{-1}]$ for submarine links, as reported in [150]. The MTTR is assumed equal to 12[hr] and 336[hr] for terrestrial and submarine links, respectively.



(a) Eurocore, 11 nodes and 50 links (b) EON, 20 nodes and 78 links



(c) NSFNet, 14 nodes and 42 links (d) UKNet, 21 nodes and 78 links (e) Italnet, 21 nodes and 72 links

Figure 4.2: Studied topologies.

The second column shows the target availability value (homogeneous scenario) or the value of α (heterogeneous scenario). The third column shows PS (problem size), equal to the number of connections considered in the problem (out of a total of $|N| \times (|N| - 1)$). These are the connections that need to operate with exactly one backup lightpath to reach the target availability. The next four columns present the results in terms of number of backup wavelengths required in 4 cases (from left to right):

- LB: a scenario where the availability constraint in the ILP model is relaxed. That is, $X_c = X_c^{All}$ for all $c \in C$. Thus, this is a lower bound for the number of backup wavelengths.
- ILP: the results for the complete ILP model.

Table 4.1: Number of backup wavelengths for the homogeneous scenario

Topology			Number of backup wavelengths			
$[\|\bar{R}\|; \bar{p_l}]$	A^{Target}	PS	LB	ILP $[\delta^{LB}_{ILP};\delta^{UB}_{ILP}]$	Greedy $[\delta^{ILP}_{Greedy};\delta^{UB}_{Greedy}]$	UB
Eurocore [2.8; 0.9984]	0.999	98	124	124 [0; 44.1]	124 [0; 44.1]	222
	0.9999	110	126	126 [0; 48.7]	126 [0; 48.7]	246
	0.99999	76	84	98 [16.7; 38]	102 [4.1; 35.4]	158
EON [3.02; 0.997]	0.999	372	768	768 [0; 40.3]	768 [0; 40.3]	1286
	0.9999	298	502	555* [10.6; 38.2]	585 [5.4; 34.9]	898
	0.99999	52	58	74 [27.6; 30.2]	76 [2.7; 28.3]	106
NSFNet [3.25; 0.9981]	0.999	172	295	295 [0; 53.3]	295 [0; 53.3]	632
	0.9999	182	303	303 [0; 54.6]	311 [2.6; 53.4]	668
	0.99999	34	52	62 [19.2; 46.6]	66 [6.5; 43.1]	116
UKNet [3.25; 0.9995]	0.999	230	603	603 [0; 36.6]	603 [0; 36.6]	951
	0.9999	416	920	920 [0; 39.1]	920 [0; 39.1]	1511
	0.99999	420	922	922 [1; 38.8]	951 [2.1; 37.5]	1521
ItalNet [3.64; 0.9994]	0.999	294	988	988 [0; 32]	988 [0; 32]	1453
	0.9999	420	1115	1115 [0; 38.2]	1115 [0; 38.2]	1803
	0.99999	342	720	776* [7.8; 39.4]	791 [1.9; 38.3]	1281

(*) Best solution after memory limit.

- Greedy: the results obtained by applying the greedy heuristic.
- UB: a scenario where full dedicated protection is used. That is, $X_c = \emptyset$ for all $c \in C$. Thus, this is an upper bound for the number of backup wavelengths.

In the ILP column, the percentage of additional resources required by the ILP model with respect to the LB, denoted by δ^{LB}_{ILP}, and the percentage of additional resources defined by the UB with respect to the ILP model, denoted by δ^{UB}_{ILP}, are given (first and second number between brackets, respectively). In the Greedy column, the percentage of additional resources required by the Greedy heuristic with respect to the ILP, denoted by δ^{ILP}_{Greedy}, and the percentage of additional resources required by the UB with respect to the Greedy heuristic δ^{UB}_{Greedy}, are also given.

From Table 4.1, it can be seen that in most cases, the problem size increases with the target availability value because connections that required only a working lightpath to achieve a low availability value need to include a backup lightpath to meet higher availability levels. However, it can also be seen that in some cases the problem size decreases with the target availability value because when such value becomes too high it is not possible meeting condition (4.16). Thus, those connections whose target availability cannot be achieved even with dedicated protection are removed from analysis. The only network where the problem size always increases with the target availability value is the UKNet topology, due to its high link reliability (because of short length of links). As a result, even high values of availability can be achieved with a single backup lightpath.

It can also be seen that in 66% of the cases studied, the values in the LB and ILP columns are exactly the same, highlighting the fact that for low levels of availability requirements (e.g. 0.999) or for topologies with highly available links (e.g. UKNet) all backup wavelengths in a link can be shared without violating the availability requirements. In the remaining cases, the target availability is so high (0.99999) that to guarantee such value, the level of sharing of backup resources must decrease, leading to a higher requirement in the number of backup wavelengths. In these cases, the approach of simply sharing as much as possible, as usually done (e.g. [112]) is not good enough to ensure the required availability levels.

In Table 4.1 two cases where the optimal solution was not achieved, due to memory exhaustion, have been marked (with *). For these cases, the resulting GAP was of 1.2% for EON with $A^{Target} = 0.9999$ and 0.35% for ItalNet with $A^{Target} = 0.99999$. For the heterogeneous scenario, the optimal solution was reached in all cases.

Regarding the performance of the greedy heuristic, it can be seen that in the cases where it requires more backup wavelengths than the ILP solution, the maximum difference was just 15.7%. In Table 4.3 the running time (in seconds) for the ILP (RTI column) and the Greedy heuristic (RTG) is given. It can be seen that in most cases, the ILP solver takes much shorter times than the heuristic. However, there are a few cases where the ILP solver takes very long times (between 12 and 48 hours) and in some of them it could not find the optimum as it ran out of memory. Such different running times exhibited by the ILP solver for the same network is caused by the nature of the solution provided by the linear relaxation of the problem, which is the first step of the Branch&Bound algorithm. If such solution is integer (or almost integer), usually the solver ends its execution very quickly. Instead, is most of the solution is fractional, then the Branch&Bound algorithm could lead to exhibit a very bad performance. The heuristic instead, took less than 2 minutes for all the studied cases.

Table 4.2: Number of backup wavelengths for the heterogeneous scenario

Topology			Number of backup wavelengths			
$[\lvert\bar{R}\rvert;\bar{p_l}]$	α	PS	LB	ILP [δ^{LB}_{ILP};δ^{UB}_{ILP}]	Greedy [δ^{ILP}_{Greedy};δ^{UB}_{Greedy}]	UB
Eurocore [2.8; 0.9984]	0.999	98	124	124 [0; 44.1]	124 [0; 44.1]	222
	0.9999	110	126	126 [0; 48.8]	126 [0; 48.8]	246
	0.99999	110	126	140 [11.1; 43.1]	162 [15.7; 34.1]	246
EON [3.02; 0.997]	0.999	372	768	768 [0; 40.9]	768 [0; 40.9]	1286
	0.9999	380	772	796* [3.1; 40]	885 [11.2; 32.1]	1304
	0.99999	380	772	1206 [56; 7.5]	1224 [1.5; 6.1]	1304
NSFNet [3.25; 0.9981]	0.999	172	295	295 [0; 53.3]	295 [0; 53.3]	632
	0.9999	182	303	303 [0; 54.6]	303 [0; 54.6]	668
	0.99999	182	303	474 [56.4; 29]	536 [13.1; 19.8]	668
UKNet [3.25; 0.9995]	0.999	230	603	603 [0; 26.6]	603 [0; 26.6]	951
	0.9999	416	920	920 [0; 39.1]	920 [0; 39.1]	1511
	0.99999	420	922	922 [0; 39.4]	931 [1; 38.8]	1521
ItalNet [3.64; 0.9994]	0.999	294	988	988 [0; 32]	988 [0; 32]	1453
	0.9999	420	1115	1115 [0; 38.2]	1115 [0; 38.2]	1803
	0.99999	420	1115	1127* [1.1; 37.5]	1193 [5.9; 33.8]	1803

(*) Best objective after memory limit.

Table 4.3: Running time for cases of ILP and Greedy

		Homogeneous case			Heterogeneous case		
Topology	α/A^T	PS	RTI[s]	RTG[s]	PS	RTI[s]	RTG[s]
Eurocore	0.999	98	0.06	0.452	98	0	0.252
	0.9999	110	0.06	0.38	110	0	0.332
	0.99999	76	0.05	0.12	110	0.85	0.231
EON	0.999	372	0.76	22.088	372	0.09	19.765
	0.9999	298	44268.39*	4.344	380	172804.48*	12.375
	0.99999	52	0.02	0.146	380	0.05	4.356
NSFNet	0.999	172	0.19	4.094	172	0.07	3.949
	0.9999	182	175.62	4.462	182	1.02	5.478
	0.99999	34	0.13	0.15	182	48.26	1.197
UKNet	0.999	230	0.25	6.094	230	0.01	6.415
	0.9999	416	0.64	44.37	416	0.03	42.806
	0.99999	420	54.04	40.339	420	6.74	42.733
ItalNet	0.999	294	0.57	31.331	294	0.01	31.38
	0.9999	420	1.29	104.224	420	0.06	95.076
	0.99999	342	65240.54*	22.185	420	172802.46*	61.19

(*) Running time after memory limit.

In Table 4.2 the same information shown for the homogeneous case is given for the heterogeneous case. As the target values for availability are now a fraction of the dedicated protection availability values, it is always possible guaranteeing the constraint (4.16). For this reason, PS increases with the value of α.

In this case, in the 73% of the cases studied the ILP model achieved the same results that the lower bound in the cases of low availability requirements or networks with links with high availability values (UKNet and ItalNet, both with short links). In the remaining cases, it can be seen a small difference with the lower bound, except in two cases: EON and NSFNet for $\alpha = 0.99999$. This is because, compared to other topologies, these two exhibit the lowest values of link availability and longest routes.

For the 4 cases where the ILP computation time was in the order of days, the optimality gap was modified to 2% to verify whether a good solution could be found in shorter time. Even so, there were still 2 cases where the time limit was exceeded, highlighting the usefulness of devising a heuristic to deal with those cases.

In Section 4.8 the case without wavelength conversion is briefly explored.

4.7 Proof of NP-completeness for the minimum number of wavelengths required for a link.

Lemma 1 *Let* Ψ_c *be a set of allowed shared connections for each* $c \in C$ *and let* Ω_l *be the set of connections using a given link* $l \in L$*. Then, to determine the minimum number of required wavelengths in a link* l *is an NP-hard problem.*

Prof. A reduction of Minimum Clique Partition problem [43] is used. Given a graph $G = (V, E)$an instance of the problem where $\Omega_l = V$ (i.e., each vertex of G is a connection in Ω_l) and two connections $u, v \in V$ can be grouped if and only if $\{u, v\} \in E$ can be constructed. Recall that two connections u and v can be grouped in a same wavelength if and only if $u \in \Psi_v$ and $v \in \Psi_u$. Hence, if it is possible to assign a subset S of connections into one wavelength, then the corresponding subset of nodes S forms an induced clique in G. Also, since each connection requires an assigned wavelength, then an assignment of wavelengths to Ω_l is equivalent to a clique partition of the graph G. Hence, a minimum assignment of wavelength to Ω_l is equivalent to a minimum partition of G into cliques.

4.8 Extension to the case without wavelength conversion

For the case of lack of wavelength conversion, in the ILP model (5.40) can be replaced by the following constraints:

$$
\begin{aligned}
x_{i,j} \geq x_{i,c} + x_{j,c} - 1 \ &, \forall c \in C, \forall i \in C \\
&, \forall j \in C | c < i \wedge c < j \wedge j < i \\
&, R_i^B \cap R_j^B \neq \emptyset, R_i^B \cap R_c^B \neq \emptyset \\
&, R_j^B \cap R_c^B \neq \emptyset
\end{aligned}
\tag{4.40}
$$

$$
\begin{aligned}
x_{i,j} \leq 1 + (x_{j,c} - x_{i,c}) \ &, \forall c \in C, \forall i \in C \\
&, \forall j \in C | c < i \wedge c < j \wedge j < i \\
&, R_i^B \cap R_j^B \neq \emptyset, R_i^B \cap R_c^B \neq \emptyset \\
&, R_j^B \cap R_c^B \neq \emptyset
\end{aligned}
\tag{4.41}
$$

$$
\begin{aligned}
x_{i,j} \leq 1 + (x_{i,c} - x_{j,c}) \ &, \forall c \in C, \forall i \in C \\
&, \forall j \in C | c < i \wedge c < j \wedge j < i \\
&, R_i^B \cap R_j^B \neq \emptyset, R_i^B \cap R_c^B \neq \emptyset \\
&, R_j^B \cap R_c^B \neq \emptyset
\end{aligned}
\tag{4.42}
$$

Constraints (4.40), (4.41) and (4.42) guarantee a coherent behavior among different links. For example, if connections i and j share the same wavelength with connection c at some different links, then i and j also would share backup resources, because i, j and c are using the same wavelength.

The results for homogeneous and heterogeneous scenarios are presented in Tables 4.4 and 4.5, respectively. As in the previous case, the lower bound (LB) is obtained by removing the availability constraint.

Table 4.4: The homogeneous scenario for networks without wavelength conversion.

Topology $[\|\bar{R}\|;\bar{p_l}]$	A^{Target}	PS	GAP%	RT[s]	Number of backup wavelengths		
					LB	ILP[δ^{LB}_{ILP};δ^{UB}_{ILP}]	UB
Eurocore [2.8; 0.9984]	0.999	98	0	0.28	124	124 [0; 44.1]	222
	0.9999	110	0	0.45	126	126 [0; 48.7]	246
	0.99999	76	0	0.1	84	98 [16.7; 38]	158
EON [3.02; 0.997]	0.999	372	0.77	108011.9	768*	768 [0; 40.3]	1286
	0.9999	298	0.26	108000.06	504*	518 [2.8; 42.3]	898
	0.99999	52	0	0.03	58	74 [27.6; 30.2]	106
NSFNet [3.25; 0.9981]	0.999	172	0	7194.62	295	295 [0; 53.3]	632
	0.9999	182	0.65	108006.36	303	303 [0; 54.6]	668
	0.99999	34	0	0.14	52	64 [23.1; 44.9]	116
UKNet [3.25; 0.9995]	0.999	230	0.17	108000.1	605*	605 [0; 36.4]	951
	0.9999	416	4.38	108000.11	920*	922 [0.2; 39]	1511
	0.99999	420	4.5	108000.38	922*	926 [0.4; 39.1]	1521
ItalNet [3.64; 0.9994]	0.999	294	0.4	108004.69	988*	988 [0; 32]	1453
	0.9999	420	1.99	108000.15	1115*	1116 [0.1; 38.1]	1803
	0.99999	342	0.96	108000.17	721*	742 [2.9; 42.1]	1281

(*) Best objective obtained after time-limit (30 hours).

Table 4.5: The heterogeneous scenario for networks without wavelength conversion

Topology $[\|\bar{R}\|;\bar{p_l}]$	A^{Target}	PS	GAP%	RT[s]	Number of backup wavelengths		
					LB	ILP[δ^{LB}_{ILP};δ^{UB}_{ILP}]	UB
Eurocore [2.8; 0.9984]	0.999	98	0	0.27	124	124 [0; 44.1]	222
	0.9999	110	0	0.27	126	126 [0; 48.8]	246
	0.99999	110	0.9	1.5	126	140 [11.1; 43.1]	246
EON [3.02; 0.997]	0.999	372	0.66	108009.32	768*	768 [0; 40.3]	1286
	0.9999	380	2.83	108000.58	772*	796 [3.1; 39]	1304
	0.99999	380	0	1.29	772*	1210 [56.7; 7.2]	1304
NSFNet [3.25; 0.9981]	0.999	172	0	27736.46	295*	295 [0; 53.3]	632
	0.9999	182	0.33	65899.95	303*	303 [0; 54.6]	668
	0.99999	182	0.21	39657.23	303*	504 [66.3; 24.6]	668
UKNet [3.25; 0.9995]	0.999	230	0.29	108022.18	605	605 [0; 36.4]	951
	0.9999	416	5.73	108000.85	920*	926 [0.6; 38.7]	1511
	0.99999	420	4.96	108000.82	922*	926 [0.4; 39.1]	1521
ItalNet [3.64; 0.9994]	0.999	294	0.35	108005.54	988*	988 [0; 32]	1453
	0.9999	420	2.09	108000.77	1115*	1115 [0; 38.2]	1803
	0.99999	420	2.73	108000.3	1115*	1122 [0.6; 37.8]	1803

(*) Best objective obtained after time-limit (30 hours).

It can be seen that the homogeneous and heterogeneous cases including the wavelength continuity constraint behave similarly to the corresponding cases with wavelength conversion. The most important observation is that taking the wavelength continuity into account does not significantly increase the backup wavelength requirements. Such an observation was also made in the context of routing and wavelength assignment algorithms, with and without failure restoration capability [7]. This behavior highlights the fact that, given the time to find an optimal solution, significant savings in wavelength converters could be made when designing availability-aware networks.

Further research on the implications of the results presented in Tables 4.4 and 4.5 is part of future work.

4.9 Conclusions

An ILP model to solve the problem of configuration of shared backup routes with an availability target was proposed and solved. To do so, unlike previous work, the ILP model included modeling the availability constraint as linear expression and the solution allowed identifying the connections sharing resources in different links. The results obtained by solving the ILP model were equal that the lower bound (ILP without availability guarantees) for network with high link availability and low number of hops in the routes. However, in networks with low levels of link availability or longer routes, the results in a scenario with availability requirements was different from the lower bound, highlighting the importance of considering the availability requirements when designing the network. At the best of the knowledge of the author of this thesis, this approach of guaranteeing availability levels to the connections in a network operating under shared protection was not addressed before.

To solve instances where the ILP takes significant time to get to a solution (in the order of days), a greedy heuristic approach that showed a very good performance was proposed: an average and maximum relative error of 2.46% and 15.7%, with execution times lower than 1 hour.

The modifications necessary for the ILP model to include the wavelength continuity constraint and obtained results for that case were also explored. Further analysis on this area as well as the impact of modifying assumptions on the input routes and the link failure independence is part of future research.

Chapter 5

Virtual networks: dimensioning and configuration of wavelengths with blocking and availability guarantees.

This chapter describes the modeling and formulation of two ILP models to plan a dynamic WDM network used as the physical infrastructure of a network virtualization system. The first ILP model deals with the dimensioning of the working wavelengths whilst the second with the dimensioning of the backup wavelengths and their configuration under shared protection.

The network planning process detailed in this chapter considers the blocking rate of virtual network requests and the availability of established virtual networks as the parameters used to define the quality of service offered to the clients. The acceptable value for the first performance measure (blocking) makes the network planning process to minimize the number of working wavelengths required in such a way that the blocking rate of each virtual network is under a pre-specified target. On the other hand, the target availability value makes the network planning process to determine the number of backup wavelengths and its sharing configuration in such a way that each virtual network is guaranteed a given availability value.

The rest of this chapter is organized as follows: Section 5.1 presents the model for the physical and virtual layer of the network virtualization system. Next, in Section 5.2, the traffic model used to represent the arrival of virtual network requests is described. Then, the formulation of the ILP model for dimensioning of the working ligthpaths, considering the blocking probability target, is derived in Section 5.3, whereas in Section 5.4 the ILP model for the dimensioning and configuration of the backup wavelengths is formulated. Finally, in Section 5.5, results obtained after solving the ILP models are presented and in Section 5.6 conclusions are drawn.

5.1 Network virtualization system model

A virtualization network system consists in two parts: the virtual layer, where virtual networks operate according to the users requirements; and the physical layer, a dynamic WDM network where the virtual nodes and links of virtual networks are mapped.

The physical network is modeled as a graph $G(N, L)$ where N and L are the sets of physical nodes and links respectively. Each node n in N has a finite amount of resources (e.g. processing or storage resources) denoted by r_n. Each link l in L has a finite amount of wavelengths, denoted by λ_l.

A virtual network request is defined by its topology, the resource requirements of its nodes and links and the availability required by each link. The set of possible virtual topologies is denoted by V. The virtual network topology v in V is also modeled by graph $G^v(N^v, L^v)$ where N^v is the set of virtual nodes and L^v the set of virtual links. Every virtual node and link is associated to a specific resource requirement denoted by r_{n^v} and r_{l^v}, respectively.

To map a virtual network to the physical substrate, each virtual node must be mapped to a physical node with enough resources (that is, a physical node such that $r_n \geq r_{n^v}$) and every virtual link $l^v \in L^v$ must be mapped to a physical lightpath that connects the pair of physical nodes where the virtual nodes at the extremes of the virtual link have been mapped. Such lightpath is defined by a working route $R^W_{l^v}$ and one wavelength in each link $l \in R^W_{l^v}$. If a given value of availability is required, a backup lightpath might be associated to each working lightpath. The backup lightpath is defined by its route R_{lv}^{B} and one wavelength is required in each link $l \in R_{lv}^{B}$.

Let λ_l^W be the number of wavelengths required in physical link l to establish the working routes associated to their corresponding virtual links and λ_l^B the number of backup wavelengths required to guarantee the required availability of the virtual links. Then, the total number of wavelengths in each link l is given by $\lambda_l = \lambda_l^W + \lambda_l^B$.

In this chapter, the following assumptions are made:

- each virtual node requires to be mapped to a specific physical node and that physical nodes have enough resources to accommodate as many virtual nodes as required.
- fixed routing (i.e. a pre.computed route) is used to define R_{lv}^{W} and R_{lv}^{B}. The routes with the highest and second highest availability are selected as working and backup routes for each virtual link.
- fixed routing (i.e. a pre.computed route) is used to define R_{lv}^{W} and R_{lv}^{B}. The routes with the highest and second highest availability are selected as working and backup routes for each virtual link.
- the physical network operates under shared path protection, to decrease backup wavelength requirements (see Section 2.2.3.2). That is, for every virtual link established a backup lightpath sharing wavelengths with other backup lightpaths might be in place.
- an availability-based priority system to access shared resources is in place. That is, if two working lightpaths sharing backup wavelengths fail simultaneously, the one with lowest availability (in the dedicated protection case) is granted access to the backup resources.
- bandwidth requirements of virtual links are met with one wavelength.
- only links fail, according to the same failure model described in subsection 4.1. Link l fails with probability $(1 - p_l)$.

5.2 Traffic model

The traffic offered to the physical network by each virtual network v is governed by an ON-OFF process. During the ON period, the virtual network v is assumed to transmit date over each of its virtual links at the permitted transmission rate. During the OFF period, the virtual network is not established, so it does not transmit data. The mean duration of the ON and OFF periods is denoted by t^v_{ON} and t^v_{OFF}, respectively. Identical values of t^v_{ON} and t^v_{OFF} are assumed for all virtual networks. Therefore, the traffic load of any virtual network is given by:

$$\rho^v = \frac{t^v_{ON}}{t^v_{ON} + t^v_{OFF}} \tag{5.1}$$

5.3 Dimensioning the working wavelengths capacity

Given:

- The physical topology defined by the sets L and N.
- V, the set of virtual topologies.
- The path (in the physical substrate) $R^W_{l^V}$ to establish the working route for every virtual link $l^v \in V$.
- The traffic load ρ^V, offered by virtual networks (equal for all virtual networks, i.e., $\rho^v = \rho^V, \forall v \in V$).

The objective is minimizing the amount of physical resources (wavelengths used for the working lightpaths) required in the physical substrate, subject to the blocking of each virtual network does not exceed a threshold. That is:

$$\text{minimize} \sum_{l \in L} \lambda^W_l \tag{5.2}$$

$$\text{subject to } B_v \leq B^T_v, \forall v \in V \tag{5.3}$$

where:

- B_v is the blocking experienced by virtual network v
- B_v^T is the target blocking requested for virtual network v

Assuming blocking independence among virtual links, B_v can be calculated as as follows:

$$B_v = 1 - \prod_{\forall l^v \in L^v} (1 - B_{l^v}) \tag{5.4}$$

Where B_{l^v} is the blocking experienced by virtual link l^v. Replacing (5.4) in (5.3) the next expression is formulated:

$$1 - \prod_{\forall l^v \in L^v} (1 - B_{l^v}) \leq B_v^T ; \forall v \in V \tag{5.5}$$

Inequality (5.5) is now dependant on the virtual link blocking values. To determine the maximum values of $B_{l^v} \forall l^v \in L^v$ (where $L^V = \bigcup_{v \in V} L^v$, the set of all virtual links of all virtual networks) in a simple manner whilst meeting inequality (5.5), a threshold for the values of B_{l^v} is set, such that:

$$B_{l^v} \leq B_{L^v}^T \tag{5.6}$$

Let $B_{L^v}^T$ be this threshold value, equal for all $l^v \in L^v$. Then:

$$1 - (1 - B_{L^v}^T)^{|L^v|} \leq B_v^T \tag{5.7}$$

Reordering (5.7), the threshold value can be determined as:

$$B_{L^v}^T = 1 - \sqrt[|L^v|]{1 - B_v^T} \tag{5.8}$$

Assuming blocking independence among physical links, the virtual link blocking can be estimated as:

$$B_{l^v} = 1 - \prod_{\forall l \in R_{l^v}^W} (1 - B_l) \tag{5.9}$$

where B_l is the blocking of physical link l. Joining (5.8) and (5.9) the following expression is obtained:

$$1 - \prod_{\forall l \in R_{lv}^W} (1 - B_l) \leq B_{L^v}^T \tag{5.10}$$

Given that B_l depends on the decision variable λ_l^W, then inequation 5.10 is non-linear. Thus, to be able to include this inequation in a linear model, logarithm is applied to both sides of it and after reordering, the fallowing expression is obtained:

$$\sum_{\forall l \in R_{lv}^W} \log(1 - B_l) \geq \log(1 - B_{L^v}^T) \tag{5.11}$$

and then $\log(1 - B_l)$ is defined as a decision variable, denoted as AL_l. AL_l depends on B_l, that on turn can be calculated using the Engset formula, as explained in the Chapter 3 (Section 3.1, Eq. (3.3)).

Reminding the definition given in Chapter 3, the Engset formula allows calculating the blocking probability experienced by a set of y clients that arrive at mean rate λ^v (clients/time unit) at a pool of x servers that serve the clients at mean rate μ^v (clients/time unit).

In this case, the set of clients corresponds to the set of virtual links (regardless of which virtual network) that could use the physical link l. Then, the number of elements of this set of virtual links is denoted by $|L_l^{V,W}|$ (where $L_l^{V,W}$ is the set all virtual links that could be activated using the physical link $l \in L$ in its working route). The pool of servers correspond to the wavelengths in the physical link, dimensioned to operate under failure free conditions. Furthermore, the number of wavelengths in physical link l is denoted by λ_l^W. By replacing $|L_l^{V,W}|$ and λ_l^W in (3.3), the expression for the blocking of physical link is given by:

$$B_l(\lambda_l^W, |L_l^{V,W}|) = B(\lambda_l^W, |L_l^{V,W}|) = \frac{\binom{|L_l^{V,W}|}{\lambda_l^W} (\frac{\rho^V}{\rho^V - 1})^{\lambda_l^W}}{\sum_{i=0}^{\lambda_l^W} \binom{|L_l^{V,W}|}{i} (\frac{\rho^V}{\rho^V - 1})^i} \tag{5.12}$$

As the Engset formula is non-linear, to be able to use it in a integer linear programming model, AL_l is pre-calculated for all values of $|R_l^W|$ and λ^v (ρ^V is an input parameters of the model), then values are stored in table $FL(x, y) = \log(1 - B_l(x, y))$, where x corresponds to the to the number of servers, while y corresponds to the number of clients. By doing so, the expression for AL_l can be re-written as:

$$AL_l(\lambda_l^W, |L_l^{V,W}|) = \sum_{i=1}^{|L_l^{V,W}|} FL(|L_l^{V,W}|, i) \times I_{l,i}^{AL} \tag{5.13}$$

Now, AL_l is formulated only in function of parameters FL and binary variables $I_{l,i}^{AL}$, where $I_{l,i}^{AL}$ is used as index such that $I_{l,i}^{AL} = 1$ if $i = \lambda_l^W$ and $I_{l,i}^{AL} = 0$ if not ($\forall l \in L$).

The linearized model can be expressed as:

Sets and indexes

- L^V: set of virtual links considering all virtual topologies in V.
- L: set of physical links.
- $R_{l^v}^W$: set of physical links used to implement the working route of virtual link l^v.
- l: index used to traverse sets of physical links (L and $R_{l^v}^W$).
- i: index used to traverse virtual links using each physical link.

Parameters

- $B_{L^v}^T$: target value for the blocking probability of all virtual links in virtual network v.
- $FL(x, y)$: array with the pre-calculated values of function $\log(1 - B_l(x, y))$ according to (5.12).
- $|L_l^{V,W}|$: number of virtual links whose working routes use the physical link l.

Decision variables

- λ_l^W: integer decision variable that represents the number of working wavelengths required in physical link l.
- AL_l: continuous decision variable that takes the value of $FL(|L_l^{V,W}|, \lambda_l^W)$, addressed using the binary decision variable $I_{l,i}$.
- $I_{l,i}$: binary decision variable that takes the value 1, $\forall l \in L$, if $i = \lambda_l^W$, and value 0 in other cases.

Minimize

$$\sum_{\forall l \in L} \lambda_l^W \tag{5.14}$$

Subject to

$$\sum_{l \in R_{l^v}^W} AL_l \geq \log(1 - B_{L^v}^T) \quad , \forall l^v \in L^V \tag{5.15}$$

$$AL_l = \sum_{i=1}^{|L_l^{V,W}|} FL(|L_l^{V,W}|, \lambda_l^W) \times I_{l,i} \ , \forall l \in L \tag{5.16}$$

$$\lambda_l^W = \sum_{i=1}^{|L_l^{V,W}|} i \times I_{l,i} \quad , \forall l \in L \tag{5.17}$$

$$\sum_{i=1}^{|L_l^{V,W}|} I_{l,i} = 1 \quad , \forall l \in L \tag{5.18}$$

$$I_{i,l} \in \{0,1\} \quad , \forall l \in L, 1 \leq i \leq |L_l^{V,W}| \tag{5.19}$$

5.4 Dimensioning and configuration of backup wavelengths

Given:

- The physical topology defined by the sets L and N.

- V, the set of virtual topologies.
- The path (in the physical substrate) $R^W_{l^V}$ to establish the working route for every virtual link $l^v \in V$.
- The path (in the physical substrate) $R^B_{l^V}$ to establish the backup route for every virtual link $l^v \in V$, link-disjoint from $R^W_{l^V}$.

The objective is minimizing the amount of backup physical resources (wavelengths used for backup lightpaths) required in the physical substrate, subject to the availability of each virtual network does not exceed a threshold. That is:

$$\text{minimize} \sum_{l \in L} \lambda^B_l \tag{5.20}$$

$$\text{subject to } A_v \geq A^T_v, \forall v \in V \tag{5.21}$$

where:

- λ^B_l is the number of backup wavelengths required in link l when the network is prone to link failure
- A_v is the availability of virtual network v
- A^T_v is the target availability requested for virtual network v

To ensure meeting the availability target of all virtual networks, a worst case is considered. That is, it is assumed that all virtual networks are active simultaneously.

A_v can be calculated as:

$$A_v = \prod_{\forall l^v \in L^v} A_{l^v} \tag{5.22}$$

where A_{l^v} is the availability of virtual link l in virtual network v. Then, joining (5.21) and (5.22) next inequality is formulated:

$$\prod_{\forall l^v \in L^v} A_{l^v} \geq A^T_v \tag{5.23}$$

Eq. (5.23) is now dependent on the virtual link availability values. To determine in a simple manner the maximum values of each A_{l^v} ($\forall l^v \in L^v$), whilst meeting inequality (5.21), a threshold for the values of A_l^v is set, such that:

$$A_{l^v} \geq A_{L^v}^T, \forall l^v \in L^v \tag{5.24}$$

Let $A_{L^v}^T$ be this threshold value. Then:

$$A_{L^v}^T = \sqrt[|L^v|]{A_v^T}, \forall v \in V \tag{5.25}$$

It is worth noticing that in some cases a virtual link might achieve the required availability target without protection (that is, the working lightpath associated to the virtual link alone is enough to provide the required availability). It could also happen that even using dedicated protection, a virtual link from the same virtual network could not achieve the required availability. To compensate these cases, the target availability of each virtual link must be adjusted considering the following expression:

$$A_{L^v}^T = \sqrt[|L^v|^{Sh}]{\frac{A_v^T}{A_{l^v}^D \times A_{l^v}^U}}, \forall v \in V \tag{5.26}$$

where $|L^v|^{Sh}$ is the number of virtual links (belonging to the virtual network v) operating with shared protection, $A_{l^v}^D$ is the multiplication of the availability values of the virtual links (belonging to the virtual network v) using dedicated protection and $A_{l^v}^U$ is is the multiplication of the availability values of the unprotected virtual links (belonging to the virtual network v). The target value is iteratively adjusted until no changes are recorded from one iteration to the next (that is, the set of virtual links operating with shared protection does not change).

Then, A_{l^v} can be calculated as:

$$A_{l^v} = A_{l^v}^W + (1 - A_{l^v}^W) \times A_{l^v}^B \tag{5.27}$$

where $A_{l^v}^W$ is the availability of the primary (working) virtual link l^v and $A_{l^v}^B$ is the availability of the backup virtual link. The expressions for $A_{l^v}^W$ and $A_{l^v}^B$ are given by:

$$A_{l^v}^W = \prod_{\forall l \in R_{l^v}^W} p_l \tag{5.28}$$

$$A_{l^v}^B = \prod_{\forall l \in (\bigcup_{i \in X_{l^v}} R_i^W) \bigcup R_{l^v}^B} p_l \tag{5.29}$$

where:

- $R_{l^v}^W$ is the set of physical links belonging to the route that implements the virtual link l^v
- p_l is the probability of physical link l being in operative state. This is input data, computed using Eq. (4.1), from Section 4.1.
- X_{l^v} is the set of virtual links with lower priority than l^v and that could share backup wavelengths
- $R_{l^v}^B$ is the set of physical links belonging to the backup route of virtual link l^v

Then, the expression for shared availability of link virtual l^v is constructed joining the equations (5.27), (5.28) and (5.29) as follows:

$$A_{l^v}(X_{l^v}) = A_{l^v}^W + (1 - A_{l^v}^W) \times \prod_{\forall l \in (\bigcup_{i \in X_{l^v}} R_i^W) \bigcup R_{l^v}^B} p_l \tag{5.30}$$

Noting that the physical implementation of a virtual link corresponds to a point-to-point connection, Eq. (5.30) is equivalent to Eq. (4.7). Thus, following the same reasoning used Chapter 4, Section 4.3-4.4, the following ILP model can be stated:

Sets and indexes

- L: set of network physical links.
- L^V: set of all virtual links established over the physical network.

- $L_l^{V,B}$: set of all virtual links whose backup routes use the physical link l.
- $R_{l^v}^W$: set of links conforming the working route of virtual link l^v.
- $R_{l^v}^B$: set of links conforming the backup route of virtual link l^v.
- $X_{l^v}^{All}$: set of virtual links that could share backup wavelengths with virtual link l^v.
- l: index used to traverse the sets of physical links L, $R_{l^v}^W$ and $R_{l^v}^B$.
- i: index used to traverse the sets of virtual links L^V and $L_l^{V,B}$.
- j: index used to traverse the sets of virtual links L^V, $L_l^{V,B}$ and $X_{l^v}^{All}$.
- k: index used to traverse the sets of virtual links L^V and $L_l^{V,B}$.

Parameters

- p_l: availability of physical link l.
- $A_{l^v}^{Target}$: target availability value for virtual link l^v.
- $A_{l^v}^W$: availability of the working lightpath used to establish virtual link l^v.

Decision variables

- $x_{i,j}$: binary variable that is equal to zero if connection $j \in X_i$ (i.e. virtual link j shares backup wavelengths with virtual link i and has higher priority than virtual link i).
- $y_{l,i,j}$: binary variable that takes value 1 when the backup lightpath of virtual link i shares a wavelength on link l with a higher-priority connection j.
- $z_{i,l}$: binary variable equal to 1 if $l \in (\bigcup_{j \in X_i} R_j^W) \bigcup R_i^B$.

Minimize

$$\sum_{l \in L} \sum_{i \in L_l^{V,B}} y_{l,i,i} \tag{5.31}$$

Subject to

$$\sum_{l \in L} z_{i,l} \times \log(p_l) \geq \log\left(\frac{A_i^{Target} - A_i^W}{1 - A_i^W}\right), \forall i \in L^V \tag{5.32}$$

$$z_{i,l} = 1 \qquad , \forall i \in L^V, \forall l \in R_i^B \tag{5.33}$$

$$z_{i,l} \geq x_{i,j} \qquad , \forall i \in L^V, \forall j \in X_i^{All} \;, \forall l \in R_j^W : i > j \tag{5.34}$$

$$x_{i,j} = 0 \qquad , \forall i, j \in L^V : j \notin X_i^{All} \; i > j \tag{5.35}$$

$$y_{l,c,i} \leq x_{c,i} \qquad , \forall l \in L, \forall l, i \in L_l^{V,B} : i > j \tag{5.36}$$

$$\sum_{j \in L_l^{V,B} : i \geq j} y_{l,i,j} = 1 \qquad , \forall l \in L, \forall i \in L_l^{V,B} \tag{5.37}$$

$$y_{l,i,j} \leq y_{l,j,j} \qquad , \forall l \in L, \forall i, j \in L_l^{V,B} : i > j \tag{5.38}$$

$$y_{l,i,k} + y_{l,j,k} \leq 1 + x_{i,j} \qquad , \forall l \in L, \forall k, i, j \in L_l^{V,B} : j < i \land k < i \land k < j \tag{5.39}$$

$$x_{i,j} \in \{0, 1\} \qquad , \forall i, j \in L^V : i > j \tag{5.40}$$

$$y_{l,i,j} \in \{0, 1\} \qquad , \forall l \in L, \forall i, j \in L_l^{V,B} : i > j \tag{5.41}$$

$$z_{i,l} \in \{0, 1\} \qquad , \forall l \in L, i \in L_l^{V,B} \tag{5.42}$$

5.5 Numerical results

Both ILP models were solved in a Intel Core (TM) i5-4200U, 8GB RAM considering the NSFNet topology (shown in Figure 5.1)as physical substrate. NSFNet is made of 14 nodes and 42 unidirectional links.

The set V of virtual networks was made of 30 ring topologies, ranging from 4 to 8 nodes. Each virtual topology from the set V was generated as follows. A uniform random variable was used to determine the number of nodes. Next, the set of physical nodes where the virtual nodes must be mapped was determined using a uniform random variable in the range [0,13] (without replacement). They had to be connected forming a ring, using bidirectional links (one in each direction of each node pair). Table 5.1 shows the information related to each virtual network. The first column identifies the virtual network, the second and third list the number of virtual nodes and links whilst the last column list the physical nodes where the virtual nodes must be mapped in a ring topology (thus, the last node in the list must be connected to the first node of the list).

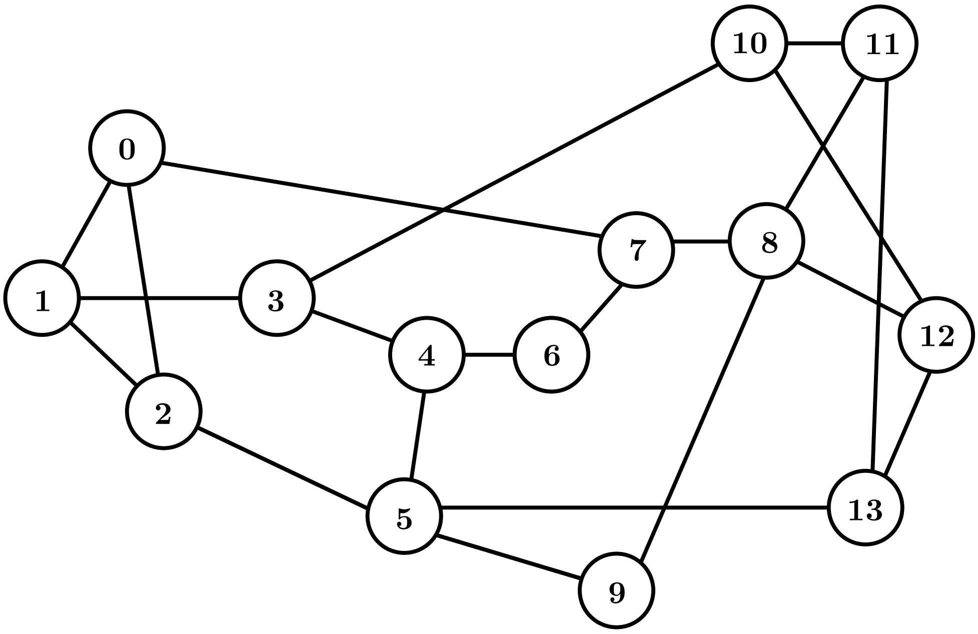


Figure 5.1: NSFNet, 14 nodes and 42 undirected links

Table 5.1: Set V of virtual networks randomly generated.

Virtual Network ID	Number of virtual nodes	Number of virtual links	Physical nodes mapping
0	4	8	(12,8,10,7)
1	8	16	(2,12,0,3,9,4,11,8)
2	8	16	(12,7,9,4,8,10,11,6)
3	5	10	(8,6,2,12,5)
4	8	16	(5,10,7,1,12,9,0,6)
5	6	12	(7,9,8,11,4,10)
6	7	14	(9,4,10,11,3,12,8)
7	8	16	(0,6,10,12,8,1,3,2)
8	5	10	(9,10,3,12,0)
9	8	16	(0,7,1,8,9,11,5,3)
10	4	8	(7,8,11,6)
11	4	8	(3,5,0,2)
12	7	14	(0,4,5,11,12,8,2)
13	6	12	(11,3,7,5,9,12)
14	5	10	(2,9,6,3,7)
15	7	14	(7,0,11,5,9,6,8)
16	4	8	(3,7,0,9)
17	4	8	(2,7,10,3)
18	4	8	(12,3,4,5)
19	4	8	(7,2,10,1)
20	6	12	(3,8,11,10,7,1)
21	6	12	(4,0,9,8,3,12)
22	8	16	(10,3,7,2,9,12,1,8)
23	4	8	(1,5,7,12)
24	5	10	(3,6,11,8,1)
25	5	10	(8,1,10,12,0)
26	8	16	(1,7,5,4,0,11,8,9)
27	4	8	(12,9,5,4)
28	4	8	(8,2,7,10)
29	6	12	(12,1,5,8,4,2)

The dimensioning of working wavelengths (that is, the working wavelengths used to establish the working lightpaths of the virtual links) was carried out for 3 different values of maximum blocking: 0.01;0.001;0.0001 for traffic loads ranging from 0.1 to 0.9 (in steps of 0.1). Figure 5.2 shows the total number of working wavelengths as a function of the traffic load (in the figure, QoS_VN stands for Quality of Service for Virtual Networks, measured as the maximum blocking ratio allowed for each virtual network). The horizontal line corresponds to the

890 working wavelengths required in the case that all virtual network are active simultaneously.

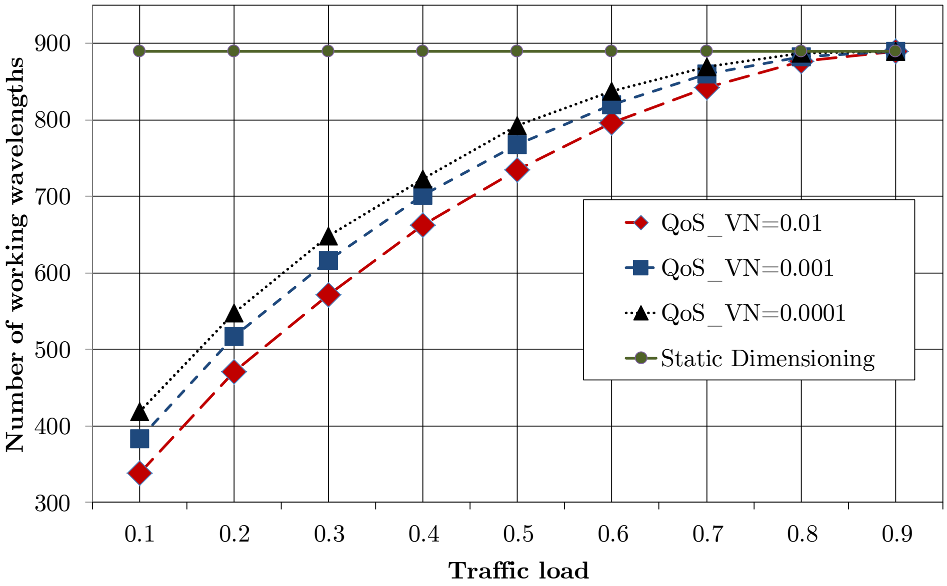


Figure 5.2: Number of wavelengths for traffic load and QoS_VN

As expected, the number of working wavelengths increases with the traffic load and decreases with the maximum acceptable blocking. The maximum value (890) is reached with traffic loads of 0.9, irrespective of the blocking target. In all instances the optimum solution was achieved in a maximum running time of 5[s].

Next, the results of solving the ILP model to dimension the backup wavelengths are presented for availability values of 0.9; 0.99 and 0.999. To verify whether these values could be obtained with shared protection, the availability of the different virtual networks was evaluated assuming dedicated protection for each virtual link. Results are shown in Table 5.2. It can be seen that all virtual networks achieve availabilities higher than 0.999 using dedicated protection and thus, applying shared protection is feasible in this case.

Table 5.2: Maximum availability per virtual network.

Virtual Network ID	Maximum availability	Virtual Network ID	Maximum availability	Virtual Network ID	Maximum availability
0	0.999824	10	0.996698	20	0.999797
1	0.99946	11	0.999942	21	0.999665
2	0.999666	12	0.999729	22	0.999499
3	0.999729	13	0.999726	23	0.999785
4	0.999483	14	0.999796	24	0.99981
5	0.999715	15	0.99969	25	0.999635
6	0.999669	16	0.999782	26	0.999667
7	0.999743	17	0.999825	27	0.997812
8	0.999569	18	0.996015	28	0.999762
9	0.999634	19	0.999723	29	0.999678

Table 5.3 shows the resulting number of backup wavelengths required by the virtual links of all virtual networks. The first column corresponds to the target availability. The second column is subdivided in 3 columns showing the number of virtual links using shared protection, dedicated protection and no protection, respectively. The third column presents the total number of backup wavelengths required to achieve the corresponding level of availability and the final column shows, as a benchmark, the number of backup wavelengths that would have been required if dedicated protection had been used for all virtual links.

It can be seen that for low availability values (0.9), all virtual networks achieve the required availability with the working lightpaths alone. That is, protection is not required and then, the number of backup wavelengths is zero. When the availability increases to 0.99, just 3% of the virtual links can operate unprotected. The remaining 334 virtual links require shared protection to be able to achieve the required availability for the virtual network. In this case, the physical network requires being equipped with 608 backup wavelengths. This result was obtained in a running time of 31[s]. With respect to dedicated protection, using shared protection for this level of availability results in a resource saving of 48%, showing that resorting to dedicated protection is not a good choice when low levels of availability are required. If the target availability increases to 0.999, all virtual links can operate under shared protection and the total number of backup wavelengths increases to 623, with a resource saving of 49%. This result was obtained in a running time of 68[s].

These results highlight the fact that dedicated protection should be applied only when high levels of availability are required, as a significant resource saving can be achieved by applying shared protection.

Table 5.3: Solution for the configuration and dimensioning of backup wavelengths.

A_{VN}^T	Number of virtual links			Total number of backup wavelengths	Dedicated Solution
	Shared protection	Dedicated protection	Unprotected		
0.9	0	0	344	0	0
0.99	334	0	10	608	1178
0.999	344	0	0	623	1222

5.6 Conclusions

In this chapter two ILP models for dimensioning and configuration of a network virtualization system were formulated and solved. The system used a WDM network as physical substrate and virtual networks arrived randomly. The first model aimed at minimizing the number of working wavelengths required in the physical substrate such that a maximum blocking probability was guaranteed for the virtual networks. The second ILP model aimed at minimizing the number of backup wavelengths required to ensure a minimum value of availability for all virtual networks.

Results, obtained for a set of 30 different virtual network ring topologies, showed that both models were able to find optimal solutions in reasonable times. Both solutions achieved much lower resource requirements than the worst case solution (static allocation for the first case and dedicated protection for the second case). Future work should focus on evaluating by means of simulation the actual value of blocking and availability achieved by these configurations.

Chapter 6

Concluding this thesis

In this thesis the question of whether network planning problems with non-linear behavior could be solved by using ILP models was addressed. To answer such research question 3 network planning problems were selected because of their applicability to a wide range of similar network planning challenges that might consider limits on the blocking or the minimum availability offered to their clients.

After presenting a compilation of the literature on the network design and planning processes, the thesis focused on three network planning problems with non-linear constrains, namely: dimensioning of dynamic WDM networks subject to a maximum value of blocking rate per connection, dimensioning of backup resources of a WDM network operating under shared path protection subject to guaranteeing a minimum availability value for each connection and dimensioning of a network virtualization system considering limits on blocking and availability of virtual networks. These 3 problems were solved by means of an ILP model.

For the network dimensioning with guarantees of maximum blocking, it was found that the formulation of a solvable ILP model was possible. This was achieved by applying the logarithm function jointly with mixed-zero one models to include the non-linear constraint related to the maximum probability blocking requirement, evaluated by means of the Engset equation.

For the network dimensioning with guarantees of availability under shared path protection, it was found that modeling and solving a ILP was possible. This was achieved by properly estimating an expression for the priority-based availability and the application of the logarithm function, for the cases of a network with and without wavelength conversion.

Whilst the results achieved in this work answered the proposed research question, they also raised a number of few issues representing important topics for future work. They are:

- The broader question of what conditions must present a network planning problem to be able to be solved with the techniques used in this thesis is an open research area.
- The modification of the ILP model used for dimensioning of WDM networks with wavelength conversion to be able to consider networks without this conversion capability would help to understand whether the additional cost associated to implement wavelength conversion is compensated with the lower number of wavelengths required in a wavelength-convertible network.
- In this thesis, fixed routing was assumed. However, in many networks several routes per node pair are considered as a way to adapt to network congestion (adaptative routing) and thus, decreasing blocking. The development of ILP models able to capture the dynamics of adaptative routing to then determine the dimensioning of the network would be helpful to determine the impact of adaptative routing in the network cost.
- Throughout this work, homogeneous traffic load was assumed. However, realistic traffic profiles show that network traffic is highly heterogeneous. Extending the work presented in this thesis to dimension networks under heterogeneous traffic would help solve problems closer to the day-to-day reality of network operators.
- Because of the high cost of protected systems, restoration is used when connections affected by a failure can afford the additional time required to find on real-time the required backup resources. Modeling the availability of restored systems and dimensioning a network operating under restoration would help know whether additional savings could be obtained whilst maintaining the required levels of availability.

- In the last years, elastic optical networks (with elastic allocation of the spectrum instead of fixed allocation as done in WDM networks) have gained importance in the area of optical networking. Developing dimensioning models that include the specific characteristics of such networks would help advance the advantages of such networks in terms of resource savings.

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