Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática,
2016

Rogério Sandro Abreu Afonso

Estratégias de Planeamento Multi-Período em Redes de Trasporte Óticas

Strategies of Multi-Period Planning in Optical Networks

" Deus quer, o homem sonha,
a obra nasce "

— Fernando Pessoa

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Strategies of Multi-Period Planning in Optical Networks

Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor Armando Humberto Moreira Nolasco Pinto, Professor Associado do Departamento de Eletrónica, Telecomunicaçoes e Informática da Universidade de Aveiro, coorientação empresarial do Doutor Rui Manuel Dias Morais, Doutor em Engenharia Eletrotécnica pela Universidade de Aveiro e coordenador de atividades de investigação em otimização de redes na Coriant Portugal.

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agradecimentos / acknowledgements

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Resumo

Os operadores de telecomunicações, encaram um grande desafio que é o aumento de tráfego de internet, este desafio acarreta a necessidade de encontrar soluções para o planeamento escalável dos elementos que compõe a rede de transporte ótica. Posto isto nesta tese são estudados mecanismos de otimização em redes de transporte óticas, direcionados para o dimensionamento dos nós ao longo de vários períodos. São desenvolvidos, em Matlab, dois algoritmos baseados em modelos distintos (ILP e heurística), com o objetivo de fornecer a solução ótima e quase-ótima no que toca ao número de módulos linha e módulos cliente essencias na aferição do custo de investimento (CapEx) e custo de operação (OpEx) em redes de transporte óticas. Além disso é incorporado aos algoritmos um aumento progressivo de tráfego na rede ao longo de vários períodos de tempo. No final é comparada a eficiência da performace dos dois algoritmos aplicando-os a uma rede de transporte ótica realista.

Abstract

Telecommunication operators face a major challenge of increasing internet traffic, this challenge entails the need to find solutions for scalable planning of the elements which compose the optical network. In this thesis there are studies about optimization mechanisms in optical transport networks, targeting node dimensioning of different optical networks over several periods. Two algorithms are developed in Matlab, based on distinct models (ILP and heuristics), with the objective of providing the optimum solution concerning the number of line and client modules, which are essential to assesse the capital expenditures (CapEx) and operation expenditures (OpEx) in optical networks. Moreover is incorporated into the algorithms a progressive increase of network traffic over several periods of time. At the end the performance of the two algorithms is compared by applying them to a realistic transport network.

Contents

List of acronyms

CapEx	capital expenditures
ESM	electrical switch module
EXC	electrical cross connect
IETF	Internet engineering task force
ILP	Integer linear programming
IP	Internet protocol
ITU-T	international telecommunication union - telecommunication standardization sector
LR	long-reach
MPLS-TP	multi protocol label switching - transport profile
OAM	operation, administration and management
ODU	optical data unit
OEO	optical-electrical-optical
OpEx	operational expenditures
OTN	optical transport network
OTU	optical transport unit
ROADM	reconfigurable optical add/drop multiplexer
SDH/SONET	synchronous digital hierarchy/synchronous optical networking
SR	short-reach
TDM	time division multiplexing
WDM	wavelength division multiplexing

List of symbols

(o, d)	demand between the nodes o and d
ϵ	grooming configuration
a	module
A_C	set of modules
c	bit rate of the client signal
C	set of client bit rates
d	node that is destination of a demand
$D_c(o)$	number of client demands with bit rate c in node o
l	bit rate of the line signal
L	set of line bit rates
$M_c(o)$	number of client modules with bit rate c in node o
$M_c(o, a)$	variable indicating whether the module a with bit rate c is used in node o or not
$M_l(o, a)$	variable indicating whether the module a with bit rate l is used in node o or not
N	number of nodes
$N(o)$	number of destination nodes of node o

o	node that is origin of a demand
$O_c(o, d, a)$	number of ports with bit rate c for the demands between the nodes o and d in module a
$\overline{O}_c(o, d, a)$	number of ports with bit rate c for the demands between the nodes o and d in module a already being used
$O_l(o, d)$	number of ports with bit rate l for the demands between the nodes o and d
$O_l(o, d, a)$	number of ports with bit rate l for the demands between the nodes o and d in module a
$\overline{O}_l(o, d, a)$	number of ports with bit rate l for the demands between the nodes o and d in module a already being used
P_c	number of ports of the client module accepting signals with bit rate c
P_l	number of ports of the line module with bit rate l
$t_c(o, d)$	number of client signals with bit rate c between the nodes o and d
$Tsv_c^{nbe}(o)$	number of short-reach transceivers with bit rate c in the node o for non-blocking EXC architectures
$Tsv_l^{nbe}(o)$	number of long-reach transceivers with bit rate l in the node o for non-blocking EXCs architectures
V	set of nodes

List of Figures

List of Tables

Chapter 1

Internet has become an essential service in people's lives worldwide. Its growth dragged millions of users, generated a new way to make business and even diversify the way people communicate. With the overwhelming indicators that this service could be very lucrative, network operators compete in order to provide the best quality service to their clients. As a result of that vigorous competition, networks operators are always looking for new technologies and strategies that can help them provide larger bandwidths, higher transmission bitrates and faster processing. On the other hand, operators have the challenge of keep their investments (CapEx) and operation costs (OpEx) of the network, at an efficient level [1]. Thus, has to be a compromise between quality of service and all the costs surrounding the network. In order to achieve that commitment becomes imperative an optimized network planning and dimensioning. The CapEx is related to the costs with the setup of the infrastructure this includes network elements such as modules, switches, fibers. The OpEx is related to the costs to keep the network operating this includes maintenance, power consumption, rents (such as buildings, equipment or fibers), repairment, ongoing network planning among others.[2]

Wavelength division multiplexing (WDM) is a powerful and reliable technology and it is able to establish optical lightpaths to carry the traffic between the network nodes. Although the capacity of each wavelength channel (in a single fiber) can be up to 100Gbps or more, many user clients don't request all the bandwidth of a wavelength channel. In order to achieve a more efficient utilization of the wavelength resource, traffic grooming is used [3]. In a way that multiple low-rate traffic flows can be combined into a high-capacity wavelength channel as long as the total bandwidth required by these flows does not exceed the capacity of the channel. Multilayer networks enable the interworking between electronic and optical technologies, allowing a more efficient groom, switch and transport of the traffic. Moreover, flexible networks enable operators to setup connections and reconfigure established connections by remote action, thus making transport networks more responsive to the traffic changes.

Due the gradual growth of traffic usually the network deployment process span over multiple periods along a time horizon. During the network operation time, changes in the equipment costs, technology available, and traffic may occur. These potential changes influence the performance of the implemented architectures [4]. Thus, the development of optimization methods suitable for multi-period planning is mandatory in the deployment of multilayer optical transport networks. In a multi-period planning, the operation time horizon of the network is taken into consideration. The network is dimensioned to support the client traffic requests up to the end of the planning horizon. At each period, new client services are preferably installed in already deployed resources. This thesis will present the optimal solution using two different dimensioning tools in a multi-period scenario.

This chapter comprises four sections. In Section 1.1 is described the evolution of protocols used in optical networks, as well as the traffic units quantification. In Section 1.2 are explained the reasons that motivated this thesis, touching on the academic reasons as well as the business reasons. The five major objectives are very explicit in the Section 1.3 and finally the Section 1.4 describes how the whole document is structured.

1.1 Optical Transport Networks

The transport protocols have evolved, for many years operators used predominantly the SDH protocol, but nowadays the OTN (Optical Transport Network) become the main choice of operators. Originally, SDH fiber used only one wavelength. With the evolution of the optical technology has become more economical transmission of multiple signals over fiber SDH using WDM (Wavelength Division Multiplexing) than increasing the flow of a SDH signal. The WDM technology promised to transmit other types of signals in their original format without mapping in SDH signals. OTN introduces a better mechanism in error correction (FEC - Forward Error Corretion) and it includes a header that allow use OAM in WDM networks. In sum, it reduces the complexity of networks and optimize them for a more efficiency, allowing carrying aggregated client traffic with high speed in access networks [6]. One drawback of circuit switching is that it is a technology with constant bit rate. As the network is becoming more packet dominated (e.g., layer-2 Ethernet, layer-3 IP), technologies with constant bit rate can introduce inefficiencies in bandwidth utilization [6]. For instance, because circuit switching uses a dedicated path communication, while the circuit is active, the channel is always occupied even when there is no information to be exchanged.

OTN is a circuit switch technology defined in ITU-T Standard G.709 and provides an unified transport platform that supports various types of client services. The client traffic is encapsulated into optical data units (ODU), regardless of the original protocol. The ODU is the basic payload that is electronically switched and groomed. OTN is a technology with constant bit rate, and the standard G.709 defines five different bit rate signs to client traffic: 1.25 Gbit/s, 2.5 Gbit/s, 10 Gbit/s, 40 Gbit/s and 100 Gbit/s. These signals are known containers for ODUk with k = 0, 1, 2, 3, 4, respectively [5]. There are three specifications: ODU2e, ODU3e and ODUflex. The ODU2e and ODU3e containers have been introduced as an extension to optimize the transport of signals of 10 Gb and 40 Gb Ethernet [5]. ODUflex have any bit rate above ODU0, because it has a flexible size, carries any client signal and occupies minimal time window.

$ODUk$	$ODUnominalrate(Gbits/s)$
$ODU0$	1.24416
$ODU1$	2.49877
$ODU2$	10.0372
$ODU2e$	10.3995
$ODU3$	40.3192
$ODU3e$	41.7859
$ODU4$	104.794

Table 1.1: Optical data units

The ITU-T recommendation G.709 specifies that it is possible to mix various lower bit rate signals, with different bit rates, into a single higher bit rate signal. For line bit rates, there are: 2.5 Gbit/s, 10 Gbit/s, 40 Gbit/s and 100 Gbit/s, referred to as OTUk with k = 1, 2, 3, 4, respectively, and are presented in the following table.

$OTUk$	$OTUnominalrate(Gbits/s)$
$OTU1$	2.66605
$OTU2$	10.7092
$OTU3$	43.0184
$OTU4$	111.809

Table 1.2: Optical transport units

OTN grooming congurations. The presented values are the maximum number of lower bit rate signals that can be groomed into the next higher bit rate signal.

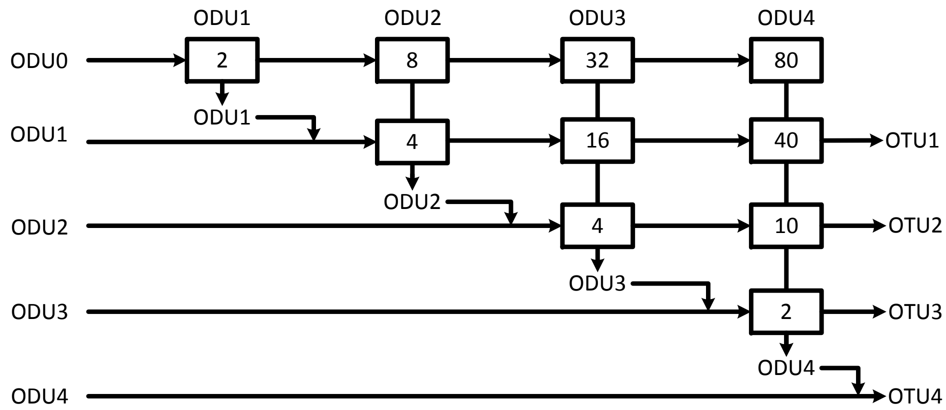

Figure 1.1: OTN grooming congurations. Various lower bit rate signals, with dierent bit rates can be groomed into a single higher bit rate signal [4]

1.2 Motivation

The amount of traffic has increased very substantially so operators have to make adjustments in their already established networks in order to keep providing a good quality of service to their clients. This process, entails big investments in new equipment for the network as well as in its operation. So the operators are very interested in reduce the cost per transported bit as much as possible without compromise the quality of service. In this context the network operator want to scale the network for operation in multiple periods, in which to carry traffic varies (and increases) from period to period. In these circumstances, different strategies can be used to account (or not) interdependence between periods. This thesis aims to address the impact of different strategies multi-period planning have on the efficiency of resource utilization and CapEx.

It would be extremely difficult to make a fast and scalable planning to a multi-period network by hand, so it is used a network planning tool. In the budgeting stage, a planning tool offering a cost-efficient solution to the network operator has a huge benefit in a competing environment. After, in the operation stage, the planning tool can be used to re-optimize the available resources, making possible additional cost savings to network operators [4]. For example, planning can aim for the network plan taking into account all traffic to be carried on the network life cycle, being determined then the resource utilization per period, or may focus on the planning incremental periods.

Many operators and vendors use their own developed software like Coriant TransNet [7] and 7196 [8], Alcatel-Lucent 1390 [9], Cisco network planning system (WAE) [10], Ericsson optical networks planner [11]. However, these tools are not publicly available to perform comparative studies of the obtained solutions due to business reasons.

1.3 Objectives

This thesis intended to achieve five main objectives:

1. Develop an open source code for multi-period dimensioning;

2. Develop ILP model for multi-period dimensioning;
3. Develop heuristics for multi-period dimensioning;
4. Compare and validate heuristics with ILP for a small network;
5. Apply heuristic method to a realistic network.

1.4 Thesis outline

This thesis is organized in five chapters. Chapter 2 shows the architectures of the components of the optical network, such as links and nodes. Thereafter it is approached some of the the operations performed in the node such as the grooming and also how the traffic is routed inside the node by the multiplexing architecture based in electrical cross connects (EXC). Also there is a detailed description of the various multi-period planning approaches and the case study of the thesis is explained. The Chapter 3 begins to show an example of a simple ILP problem and then the ILP model applied to the a reference network is presented. The Chapter 4 shows the pseudo algorithm applied as well as the results for the reference network. In the Chapter 5 are presented the results of both models (ILP and heuristic), the parameters CapEx and power consumption for a realistic network are also presented. At the end in Chapter 6 are described the final conclusions as well as the future directions to this thesis.

Chapter 2

Network Architecture

Optical transport networks comprise a set of nodes, connected by optical fiber links, and have the function of providing transport, routing and security of data to the client signals. The low-speed client signals need to be efficiently groomed into high-speed optical channels in order to optimize the available resources. The grooming is realized by electronic devices, so this operation imposes a conversion of the optical signals to electrical, perform the grooming operation, and then convert the electrical signals back to the optical domain so they can be transmitted in the optical links. However optical-electrical-optical (OEO) conversions and electronic processing are costly operations, they add more flexibility to the grooming operation. Currently, multi-layer nodes can be implemented using a variety of architectures with dierent levels of exibility [12]. In this thesis we choose to use the node architecture based on electrical cross connects (EXCs) because of the flexibility that this architecture has to offer in terms of grooming performance. In this chapter the multi-period planning and several approaches are discussed.

In sum the chapter is organized in five sections. The links architecture and transmission system are present in Section 2.1. Section 2.2 is devoted to the nodes architecture, and Section 2.3 to their respective grooming schemes and multiplexing architecture. In Section 2.3.1 are presented several approaches in multi-period plannig. At the end in the Section 2.5 is explained the case study of the thesis as well as the parameters and the traffic patterns used in both models.

2.1 Links

Links can be composed by one or more transmission systems. The transmission system starts and ends in the node and has the function of transport a WDM signal between directly connected nodes. We the transmission optical systems are formed by the OLT, the stages of regeneration and the fiber optics. The architecture of the optical network transmission system transport is shown in Figure.

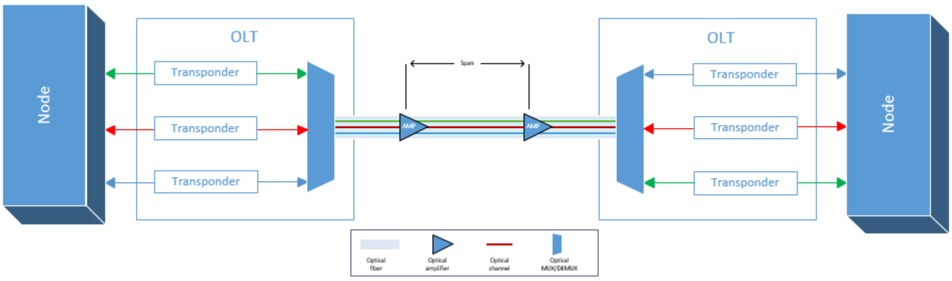

Figure 2.1: Transmission system

The transmission system shown in Figure is a bidirectional system, it is composed by a node, structure showed in the Figure (node), that is connected to its terminal, the OLT. The OLT (Optical Line Terminal) comprise an optical MUX / DEMUX, optical fibers and finally transponders. MUX is a device that allows to insert several optical signs centered at different wavelengths in a single fiber, typically lengths Wave ITU-T grid (ITU-T - International Telecommunication Union Telecommunication Standardization Section) [13, 14]. At the opposite end of the fiber, the DEMUX performs the function reverse, separating the different wavelengths. The transponders are modules composed of two interfaces, a short interface distance and a long distance interface. The transponders perform the mapping of the input signal at a given wavelength and place a header and an error corrector code. They also have monitoring functions, error checking and generation of an optical signal. The transponders still have the ability to regenerate the optical signal from the network. Regeneration is done by converting the input optical signal into an electrical signal, causing the data recovery and converting this electrical signal back to an optical signal. Each optical channel requires two transponders, one at each end of the optical fiber. One of the limiting effect in optical transmission is fiber attenuation. In order to coupe with fiber attenuation the optical signal has to be amplified otherwise it became too weak for a good detection. To do so, optical amplifiers are incorporated along the optical fiber. The separation between consecutive amplication stages is called the span. Typically, an amplier acts over the complete spectral range at once (e.g., the conventional band, i.e. the C-band, from 1531 nm to 1570 nm [15]), so all the wavelengths are amplied at the same time. Moreover, optical ampliers are transparent to protocol, modulation and bit rate thus, they can be changed without replacing the amplier.

Transmission systems are installed within conduits [26] because conduit provides a protection for the transmission system. Conduits can be buried on the ground or submersed in the water, and usually follow major railways, roads, rivers, or oceans [16]. Typically, in line optical amplifiers are modules installed into small cabinets located along the conduit.

2.2 Nodes

The structure of a node can be viewed as a hierarchy where multiple devices are connect to a larger size equipment. A node is composed by a rack, is the structure that support all the components. A rack has room for put together a number of shelves, each shelf has a limited number of space units, called slots. The slots are empty spaces that allow to connect the different modules (also named card or blade) depending on the architecture of the node used. A module is the device where encapsulation, grooming and wavelength assignment take place, to do so it is equipped with components like electronic processors and lasers that allow to perform those operations [17]. Each type of module can occupy one or more slots in the shelf. Moreover, some predetermined slots are reserved for the control modules that are required for operation, administration and management (OAM) of the system. Usually modules have connections through the front panel and the backplane switch. These modules can directly communicate with each other through the backplane. However, modules connected to different switch backplanes generally cannot communicate with each other except when there is an external link (such as a short-reach fiber link) connecting them [18, 19]. Figure 2.2 presents the schematic of a rack that can support up to three shelves, a power and a cooling system. The shelf in the middle has 12 slots and it is equipped with three modules. One module with four ports occupying one slot, another module with sixteen ports occupying two slots and the control module.

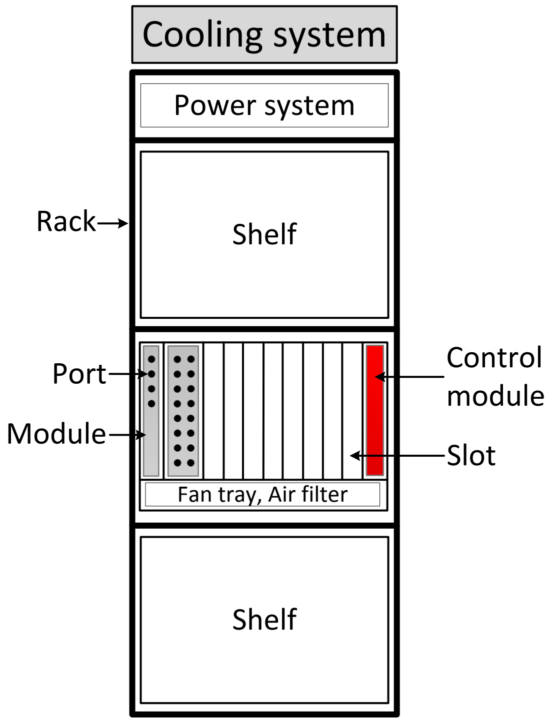

Figure 2.2: Node architecture [4]

In the front panel there are ports, connect by optical fibers, whereas backplane communication uses electrical pin connectors [18, 19]. Ports are equipped with transceivers that make possible the interface between two different modules through optical fibers. A transceiver implements the physical media adaptation functions to transmit and receive the optical signals over the defined reach, thanks to that further in this work we always assume bidirectional connections [17]. There are two types of transceivers, short-reach and long-reach, that can be used depending on the travel distance. Usually, short-reach transceivers are gray, i.e. are wavelength independent and long-reach transceivers are colored, i.e. are wavelength dependent.

2.3 Grooming

Now that it was explained the structure of nodes and links, in this section it is expressed the operations that take place in the node. Each node can perform six main functions: encapsulation; electrical switching; deterministic or statistical multiplexing (grooming); wavelength assignment; optical switching; and optical multiplexing. The client signals, regardless of the native protocol, are received by the node and encapsulated using a standard/protocol that meets transport networks requirements (Optical Transport Network (OTN) nowadays). The encapsulation process attaches controlling information to the client signal. The encapsulated client signals can then be electrically switched, groomed, routed, and forwarded toward their final destination, allowing the rearrangement and interconnection of lower data rate signals to, or between, higher bit rate signals. Traffic grooming was originally introduced for wavelength-division-multiplexing (WDM) rings, where multiple low-rate SDH/SONET circuit connections (such as OC-1, OC-3, etc.) are aggregated onto a high-rate wavelength channel, such as, OC-48 (2.5 Gbps), OC-192 (10 Gbps), or OC-768 (40 Gbps). Then the techniques for traffic grooming were extended to mesh topologies, which are widely deployed in todays backbone networks. The objective of grooming is usually either to maximize network throughput or to minimize network cost in terms of optical transponders, electronic processing, or power consumption [20, 21].

The first generation of traffic grooming is realized by Layer-1 time-division-multiplexing (TDM) circuit switching (for example SDH/SONET, now optical transport network (OTN) is the most common used protocol). As the network is becoming more packet dominated (for example Layer-2 Ethernet, Layer-3 IP), the concept of grooming is evolving to aggregating multiple low-rate traffic flows (either packet or circuit flows) onto a high-rate wavelength channel. So, the function of grooming can also be realized by packet switching (IP/MPLS or Ethernet). Note that there is an important difference, in models used to optimally design optical networks for grooming packet and circuit traffic flows: packet flows are usually splittable into finer flow granularities (as fine as a packet), while circuit flows are usually not. Essence of Current Grooming Paradigm Current grooming approaches based on Layer-1, Layer-2, and Layer-3 switching are realized by electronics. In general, grooming involves multi-layer node architectures, where an electrical layer (Layer 1, 2, or 3) and an optical layer (Layer 0) collaborate to support grooming. The traffic-grooming problem can beivided into two sub-problems: 1) electrical-layer traffic routing over a virtual topology formed by a set of virtual links lightpaths); 2) optical-layer routing and wavelength assignment (RWA) or routing and spectrum assignment (RSA) to establish the virtual links.

Traffic grooming can increase the utilization of optical-layer resources such as transponders and wavelengths, thereby reducing network cost to satisfy a certain amount of traffic. There is a tradeoff between network cost (transponder cost) and spectrum utilization: in an opaque network, where optical-electrical-optical (OEO) conversion and grooming are applied to traffic flows at every intermediate network node, optical spectrum is most efficiently utilized. But network cost could be high since excessive OEO conversions and electronic processing are used; on the other hand, if network is optimized for transponder cost, spectrum utilization has to be sacrificed. So, network operators should design and operate their networks according to their specific situations. Also, from the view of quality of service (QoS), traffic grooming can increase end-to-end latency for individual traffic flows because of indirect routing and intermediate electronic processing [22].

2.3.1 Multiplexing Architecture

This section presents the flexible architecture based on EXCs. EXCs are equipments that allow circuit switching or packet switching of client signals through backplane communication. EXCs comprise client modules to receive the client signals and to perform encapsulation, electrical switching modules, and line modules to perform grooming and wavelength assignment. The ports of the client modules are equipped with short-reach transceivers whereas the ports of the line modules are equipped with long-reach transceivers. Usually, the modules port density depends on the port bit rate and slot capacity of the equipment. In general, EXCs can perform non blocking switching. Thus, client signals can be connected to any module that is configured to accept them as the EXC can be remotely controlled through the electrical switch module (ESM). The ESM is then responsible to switch the client signals via backplane to the line modules or between line modules.

An example of a general EXC is presented in Fig. 2.3. Each solid close box represents a required module. Gray circles are client ports and color circles represent line ports. Additionally, gray arrows depict client signals and color arrows depict line signals. Solid lines represent connections via fibers and dashed lines represent connections via backplane and controlled by the ESM module. It can be observed three types of client modules that can accept three different client bit rates (one module for each bit rate), three line modules, and one ESM. Independently of the wavelength in which the client signal will be transported, it can be connected to any module that is able to accept it. The ESM module receives the signals from the different client modules and switch them into the line modules and between line modules.

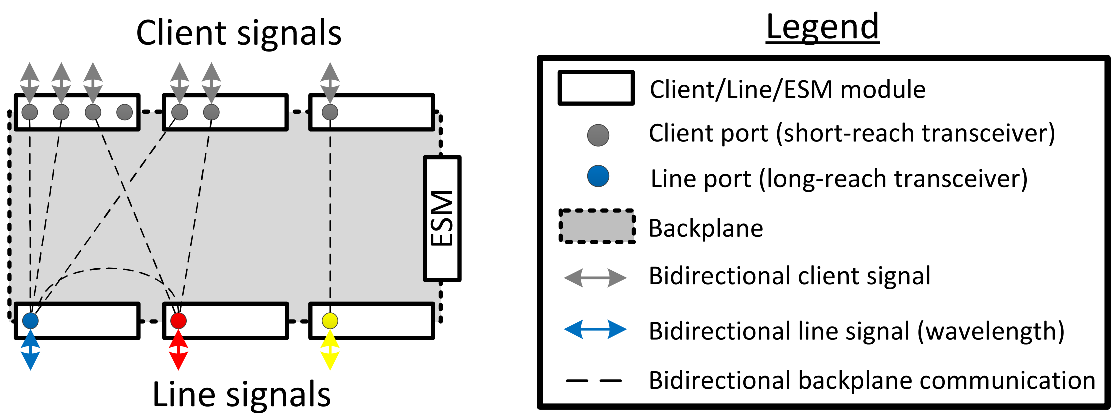

Figure 2.3: Electrical cross connect example. The flexible architecture requires a shelf enabling backplane switching, one type of client module per client service, line modules and an electrical switch module (ESM). The figure presents three types of client modules, three line modules, and one ESM. [4]

When discussing in which layer the electrical switching should be performed, three principal node architectures can be distinguished: parallel, layered and hybrid. In the parallel architecture (see Fig. 2.4(a)), independent ODU and MPLS switches exist for the circuit and packet traffic, respectively. Note that the use of either only ODU or only MPLS switch is also an alternative. As in this option the switches are independent devices, the same wavelength cannot be shared for circuit and packet traffic. Thereby creating possible network inefficiencies. In the layered architecture (see Fig. 2.4(b)), the packet traffic is not directly encapsulated onto a wavelength but passes through the ODU switch first. Packet traffic is encapsulated into ODUs that are then switched and groomed along with circuit traffic in the ODU switch. This solution offers an alternative approach for better bandwidth exploitation as it allows the coexistence of circuit and packet traffic within the same wavelength. However, at the cost of doubling the number of equipments. In the hybrid architecture (see Fig. 2.4(c)), an integrated switch matrix is used for processing both the circuit and the packet traffic. This can lead to cost savings, as the common parts (e.g., power supply, OAM communication, racks, fans) are shared, and the communication devices between layers (e.g., short-reach transceivers) reduced. Moreover, circuit and packet traffic can share the same wavelength.

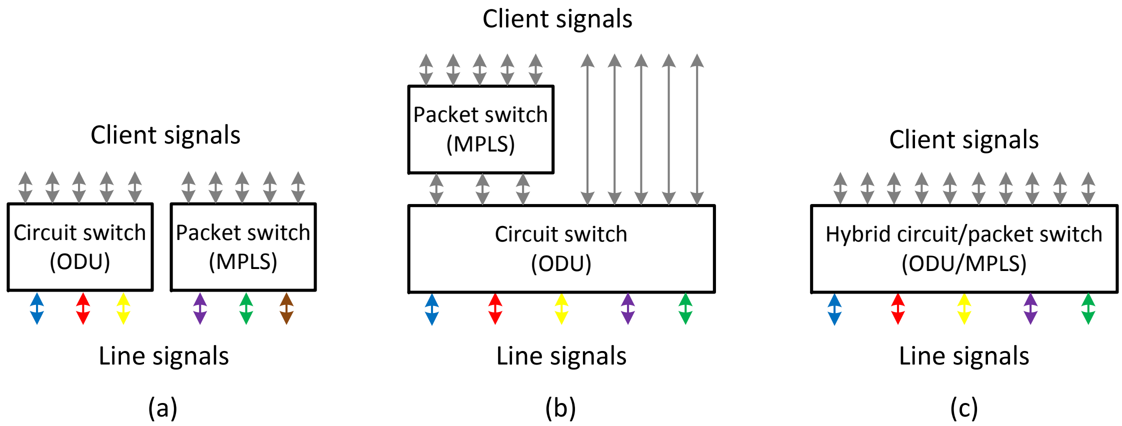

Figure 2.4: Flexible node architectures: (a) parallel, (b) layered, (c) hybrid. In parallel nodes separate ODU and MPLS switches exist for the circuit and packet traffic. The layered nodes do not encapsulate the packet traffic directly onto a wavelength but always passes through the ODU switch first. In the hybrid nodes, the switch matrix is used for processing both the circuit and the packet traffic. Regardless the node deployed, the line signal is an OTU [4].

2.4 Multi-period planning

The gradual growth of traffic is one of the main challenges that the operators have to cope, so there is a critical importance to make adjustments in the network in several periods of time. Such adjustments can be a simple reformulation of the traffic aggregation in the nodes or even an increment of components in the network. In order to make such changes in the network with the objective of minimize the costs, there is imperative to take into consideration many parameters that during the operation can change over time. For example, equipment costs decrease, technology develops further and uncertainty demand requests are factors that directly influence the performance of the network.

In the multi-period planning, the network is dimensioned to support the client traffic requests up to the end of the planning horizon [21]. The client traffic in transport networks is a very unstable factor, so depending on the amount of forecasted traffic information there are several multi-period planning approaches that can be employed [22]. This thesis only focus on the incremental planning approach where dimensioning is performed successively and separately for each period, one at a time, without having any knowledge about the traffic of future periods.

2.4.1 Multi-Period planning approaches

In the following we introduce the most commonly used multi-period planning approaches. These approaches are distinguished by the amount of forecasted information that each one requires.

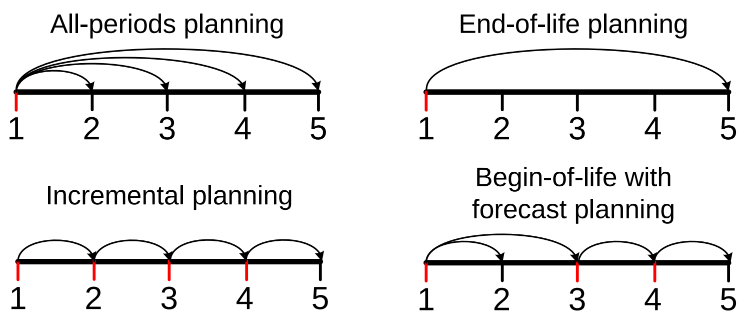

Figure 2.5: Different multi-period planning approaches[4]

2.4.2 Incremental Planning

In Incremental planning the network planner has only knowledge of the recent periods demand and the results of former periods calculations. The network solution is then calculated step by step for each time period separately. Although the solution is optimal for each time period itself, optimality of the overall solution is not guaranteed [23].

2.4.3 All-Periods Planning

The All-Periods approach calculates network costs for all time periods in one optimization step. Therefore, demand forecasts for each time period as well as the cost development per time period are input to this approach. As long as this forecast knowledge is correct, the approach leads to an optimal overall solution. As such, All-Periods planning can provide a lower bound for network costs which is useful when comparing approaches [23].

2.4.4 End-of-Life Planning

This approach plans the network for a certain period in the future, the presumed end of life (EoL) of the network. Therefore, the cumulative demand forecast for this last period is given as an input to the planning. After calculating the EoL plan, the network is planned incrementally, always on the condition that this EoL plan is met. So the network converges toward the EoL solution. This approach leads to an optimal overall solution for the last period, however, optimality may be missed if the forecast knowledge of the EoL period is incorrect. Furthermore, the development of equipment costs over the considered time horizon cannot be taken into account [23].

2.4.5 Begin-of-Life with Forecast Planning

The Begin-of-life (BoL) with forecast approach is a combination of the All-Periods approach and the Incremental approach. Its usage is recommended if the network planner has forecast knowledge of the rst years but not for all considered periods of time. This is often a more realistic situation than pure All-Periods planning, as demand forecasts are more accurate for short term future. For this approach the periods with demand forecasts are calculated with the All-Periods planning whereas following time periods are planned incrementally [23].

2.5 Case study

Techno-economic studies are decisive to identify the most profitable deployment solution and assess the influence of the various cost contributions. The chapter shows an analysis to the CapEx and power consumption, in order to evaluate the relative influence of the modules in the total network cost. It is analyzed three networks with progressive number of nodes, using different traffic loads and traffic patterns. It is considered four client bit rates (1.25 Gbit/s, 2.5 Gbit/s, 10 Gbit/s, and 40 Gbit/s) and a single line bit rate of 100 Gbit/s, defining $C = \{c : c \in \{1.25, 2.5, 10, 40\}\}$ and $L = \{l : l \in \{100\}\}$. The type of available modules, the number of ports, the number of required slots, the power consumption in Watts (kW), and the price in Euros are presented in Table 2.1

Table 2.1: Client traffic patterns.

Pattern Id	**1.25 Gbit/s**	**2.5 Gbit/s**	**10 Gbit/s**	**40 Gbit/s**
1	50%	30%	20%	0%
2	10%	60%	20%	10%
3	5%	15%	55%	25%
4	0%	15%	20%	65%

As aforementioned, we analyze one network node using different traffic loads, traffic patterns and number of destination nodes. The number of destination nodes is the number of other nodes to/from which the node has at least a demand.

Table 2.2: Modules specifications for the electrical cross connect modules.

Module type	**Ports**	**Power consumption (W)**	**Price (Euros)**
Electrical cross connect modules			
1.25 Gbit/s	32	224	3000
2.5 Gbit/s	24	360	3500
10 Gbit/s	10	340	4500
40 Gbit/s	2	320	5000
100 Gbit/s	1	360	10000
Control	-	900	7000
ESM	-	300	2000

The traffic is distributed over the four client bit rates, defining a traffic pattern, the initial total traffic is 200 Gbit/s, and increases 10% in each of the 30 periods considered, thus being of 3.4 Tbit/s in the last period. Moreover, to evaluate the dependence of the node architecture with the traffic pattern we consider the four traffic patterns presented in Table 2.1. The impact of the node architecture and traffic pattern in the number of line interfaces, CapEx, power consumption over multiple periods is assessed. The CapEx and the power consumption is calculated based on the number of client and line modules. In Section 5 the results of both approaches (ILP and heuristic) applied to realistic network are presented.

Chapter 3

ILP Model

The study of problems in which it is intended to minimize or maximize a cost function subject to a set of constraints is called optimization. In the cases that the solutions set is finite it is called combinatorial optimization. The solutions set being finite do not help in the majority of the problems since the number of possible solutions could be so huge that is impossible to evaluate all of them in short time.

This chapter comprise three sections. Section 3.1 shows an example of a combinatorial optimization problem in order to introduce the usage of ILP model to a basic problem. In Section 3.2 is presented the ILP model used for optimization of line modules only without multi-period planning, this model is helpful to understand the next one. In Section 3.3 is showed in detail the whole ILP model used already with the multi-period planning incorporated. For this thesis it was choosen the incremental planning approach because it allows the algorithm to perform step by step, which facilitates the process of implementation. At last in Section 3.4 are presented results of the ILP model applied to a reference network.

3.1 Combinatorial optimization problem

Combinatorial optimization problems can be divided into: P - set of problems for which exist a polynomial time algorithm that determines the optimal solution; NP - set of problems for which does not exist a polynomial time algorithm that determines the optimal solution. The knapsack problem consists on selecting a set of items, each one with a determined mass and value, in order to maximize the sum of the values that can be put in the knapsack without exceeding its maximum capacity.

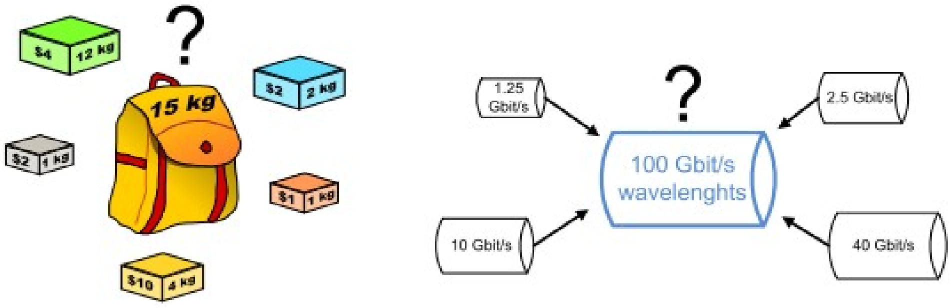

Figure 3.1: Knapsack example

In transport networks it is intended to groom low order client signals into high order optical channels, without exceeding the bandwidth of the optical channel. The knapsack problem is a NP problem.

In an optimization problem we have an objective function that is intended to be minimize/maximize when subject to a set of constraints. The objective function is related to the set of constraints by the decision variables. Any decision variables values that satisfy the set of constraints are called admissible solution. The problem optimal solution will be the values of an admissible solution(s) that obtains the higher (or lower) objective function value. The main goal is then to determine the non-negative values of the decision variables x1,x2,...,xN , such that all the linear equations (inequations) are satisfied and the value of the objective function is maximized (minimized).

$$minimize(maximixe)z = (c_1x_1 + c_2x_2 + ... + c_Nx_N \tag{3.1}$$

subject to

$$a_11x_1 + a_12x_2 + ... + a_1Nx_N <= b_1 \tag{3.2}$$

$$a_21x_1 + a_22x_2 + ... + a_2Nx_N >= b_2 \tag{3.3}$$

$$a_M1x_1 + a_M2x_2 + ... + a_MNx_N = b_M \tag{3.4}$$

$$x_1, x_2, ..., x_N >= 0 \tag{3.5}$$

The equation 3.1 is the objective function whereas the equations 3.2, 3.3, 3.4, and 3.5 are the constraints.

3.2 Electrical cross connects based architectures

The EXC-based architecture, presented in Fig. 2.3, requires client modules for each c type of traffic, line modules, and an ESM per shelf. It is very important to note that this architecture allows any demand to be plugged into any client port of any client module, regardless of the destination node. This is possible thanks to the common backplane shared between the modules of the node. In sum all possible grooming configurations are allowed. In the following the models for non-blocking EXC architectures is presented [4].

The client signals are received by client modules equipped with short-reach transceivers. The total number of short-reach transceivers with bit rate c required in the node o for non-blocking EXCs architectures, $Tsv_c^{nbe}(o)$, is given by

$$Tsv_c^{nbe}(o) = \sum_{d \in V} t_c(o,d), \quad \forall\ c \in C, \forall\ o \in V. \tag{3.6}$$

Client modules can have one or more ports. Thus, the number of client modules accepting signals with bit rate c, required in the node o, $M_c(o)$, is given by

$$M_c(o) = \left\lceil \frac{\sum_{d \in V} t_c(o,d)}{P_c} \right\rceil, \quad \forall\ c \in C, \forall\ o \in V, \tag{3.7}$$

where P_c is the number of ports of the client module accepting signals with bit rate c.

The client signals are groomed to form line signals. The ILP to minimize the number of line modules with bit rate l in node o, $M_l(o)$, used in non-blocking EXC architectures is as follows,

$$\mathit{minimize} \quad \sum_{l \in L} \sum_{o \in V} M_l(o) \tag{3.8}$$

$$\mathit{subject\ to}$$

$$\sum_{c \in C} c t_c(o,d) \le \sum_{l \in L} l O_l(o,d), \quad \forall (o,d) \in E_c \tag{3.9}$$

$$M_l(o) \ge \frac{\sum_{d \in V} O_l(o,d)}{P_l}, \quad \forall l \in L, \forall o \in V \tag{3.10}$$

$$O_l(o,d) \in \mathbb{N}_0, \quad \forall l \in L, \forall (o,d) \in E_c \tag{3.11}$$

$$M_l(o) \in \mathbb{N}_0, \quad \forall l \in L, \forall o \in V \tag{3.12}$$

Objective (3.8) is the generic cost function and intends to minimize the number of line modules in the network. Constraints (3.9) ensures that the bandwidth provided by all the line signals between the nodes o and d, $O_l(o,d)$, is higher or equal than the bandwidth requested by all client signals between the same node pairs. Constraint (3.10) ensures that the number of line modules with bit rate l is higher or equal to the relation between the number of required line signals with bit rate l for all destination nodes, and the number of output ports that the line module can support P_l. Finally, constraints (3.11) and (3.12) define the variables $O_l(o,d)$ and $M_l(o)$ as non negative integer variables. Line modules ports are equipped with long-reach transceivers. The number of long-reach transceivers with bit rate l in the node o, $Tsv_l^{nbe}(o)$, is given by

$$Tsv_l^{nbe}(o) = \sum_{d \in V} O_l(o,d), \quad \forall l \in L, \forall\ o \in V. \tag{3.13}$$

In this type of architecture, only one control module, and one ESM, is required in node o for non-blocking EXC architecture.

$$M_{sf}^{nbe}(o) = M_{ctr}^{nbe}(o) = M_{esm}^{nbe}(o) = 1, \quad \forall o \in V. \tag{3.14}$$

3.3 Non-blocking electrical cross connect

The non-blocking EXC architecture do not have any constraint in the interconnection between modules, this feature facilitates the formulation of the model. Four variables are required, the variables $O_c(o,d,a)$ and $O_l(o,d,a)$ are the number of ports with bit rate c (and l respectively) required for the demands between the nodes o and d located in module a. Each module can have one or more ports. The variables $M_c(o,a)$ and $M_l(o,a)$ are binary variables defining if the module a with bit rate c (and l respectively) is used in node o or not. Moreover, the number of ports already in use in previous periods is an input of the model. We will denote by $\overline{O}_c(o,d,a)$ and $\overline{O}_l(o,d,a)$ the number of ports with bit rate c (and l respectively) already being used by the demands between the nodes o and d located in module a. In the first period $\overline{O}_c(o,d,a)$ and $\overline{O}_l(o,d,a)$ are zero. The ILP model calculates the cumulative number of client and line modules and is as follows

$$minimize \quad \sum_{o\in V}\sum_{a\in A_C}\left(\sum_{c\in C} M_c(o,a) + \sum_{l\in L} M_l(o,a)\right) \tag{3.15}$$

$$subject\ to$$

$$t_c(o,d) \leq \sum_{a\in A_C} O_c(o,d,a), \qquad \forall (o,d)\in E_c, \forall c\in C \tag{3.16}$$

$$c\sum_{c\in C}\sum_{a\in A_C}\left(\overline{O}_c(o,d,a) + O_c(o,d,a)\right) \leq l\sum_{l\in L}\sum_{a\in A_C}\left(\overline{O}_l(o,d,a) + O_l(o,d,a)\right), \qquad \forall (o,d)\in E_c \tag{3.17}$$

$$M_c(o,a) \geq \frac{\sum_{d\in V}\left(\overline{O}_c(o,d,a) + O_c(o,d,a)\right)}{P_c}, \qquad \forall c\in C, \forall o\in V, \forall a\in A_C \tag{3.18}$$

$$M_l(o,a) \geq \frac{\sum_{d\in V}\left(\overline{O}_l(o,d,a) + O_l(o,d,a)\right)}{P_l}, \qquad \forall l\in L, \forall o\in V, \forall a\in A_C \tag{3.19}$$

$$O_c(o,d,a) \in \mathbb{N}_0, \qquad \forall c\in C, \forall (o,d)\in E_c, \forall a\in A_C \tag{3.20}$$

$$O_l(o,d,a) \in \mathbb{N}_0, \qquad \forall l\in L, \forall (o,d)\in E_c, \forall a\in A_C \tag{3.21}$$

$$M_c(o,a) \in \{0,1\}, \qquad \forall c\in C, \forall o\in V, \forall a\in A_C \tag{3.22}$$

$$M_l(o,a) \in \{0,1\}, \qquad \forall l\in L, \forall o\in V, \forall a\in A_C \tag{3.23}$$

The objective function (3.15) aims to minimize the total number of client and line modules of the network. First constraint (3.16) ensures that the $t_c(o,d)$ client signals between the nodes o and d with bit rate c have a client port in one of the modules a, $O_c(o,d,a)$. Constraint (3.17) guarantee that the total bandwidth required for all client signals, in all periods, $\overline{O}_c(o,d,a) + O_c(o,d,a)$, is smaller or equal than the total bandwidth provided by all line ports, $\overline{O}_l(o,d,a) + O_l(o,d,a)$. Constraints (3.18) establish if the client module a with bit rate c in node o, $M_c(o,a)$, is used or not. Important to note that each module with bit rate c has P_c available ports. Constraint (3.19) resembles the previous constraint (3.18) however regarding line modules with bit rate l, $M_l(o,a)$, and assuming that the line module with bit rate l has P_l ports. Finally, constraints (3.20) and (3.21) specify the variables $O_c(o,d,a)$ and $O_l(o,d,a)$ as non negative integer variables, and constraints (3.22) and (3.23) define the variables $M_c(o,a)$ and $M_l(o,a)$ as binary.

Client and line ports are equipped with short-reach and long-reach transceivers, respectively. The number of short reach transceivers in node o with bit rate c for non-blocking EXC architectures, $Tsv_c^{nbe}(o)$ is calculated as

$$Tsv_c^{nbe}(o) = \sum_{d \in V} \sum_{a \in A_C} \left(\overline{O}_c(o,d,a) + O_c(o,d,a) \right), \quad \forall c \in C, \forall o \in V, \tag{3.24}$$

and the number of long reach transceivers in node o with bit rate l for non-blocking EXC architectures, $Tsv_l^{nbe}(o)$ as

$$Tsv_l^{nbe}(o) = \sum_{d \in V} \sum_{a \in A_C} \left(\overline{O}_l(o,d,a) + O_l(o,d,a) \right), \quad \forall l \in L, \forall o \in V. \tag{3.25}$$

Note that, in this type of architecture only one control module, and one ESM is required.

At this stage, $\overline{O}_c(o,d,a)$ and $\overline{O}_l(o,d,a)$ are updated to use in the next period. Regarding $\overline{O}_c(o,d,a)$ is updated by

$$\overline{O}_c(o,d,a) = \overline{O}_c(o,d,a) + O_c(o,d,a), \quad \forall c \in C, \forall (o,d) \in E_c, \forall a \in A_C. \tag{3.26}$$

The variable $\overline{O}_l(o,d,a)$ is updated in a similar way than $\overline{O}_c(o,d,a)$, thus guaranteeing that the previous grooming configurations are maintained. Thus, $\overline{O}_l(o,d,a)$ is updated as

$$\overline{O}_l(o,d,a) = \overline{O}_l(o,d,a) + O_l(o,d,a), \quad \forall l \in L, \forall (o,d) \in E_c, \forall a \in A_C. \tag{3.27}$$

3.4 Reference network

The reference network presented is purely an example, both models work regardless the topology of the network, because the optimization is performed for each node, for that the most important data to take way of the reference network is the number of nodes, in this case is six as is showed in the 3.2.

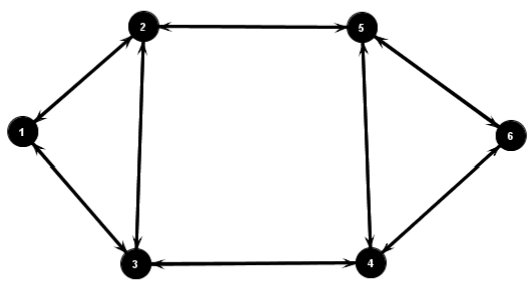

Figure 3.2: Six node network

This network is used to test the ILP model. We assume that the ILP model gives the optimal solution possible, because the solver tests every solution possible, and saves the best one. Thus, in order to validate the heuristic model is used the reference network in Section 4.1, comparing it to the results of the ILP model, applied to the reference network.

3.4.1 Line modules

In following is showed the cumulative number of line modules, produced by the ILP model presented in Section 3.3 and applied to the reference network showed in the previous Section.

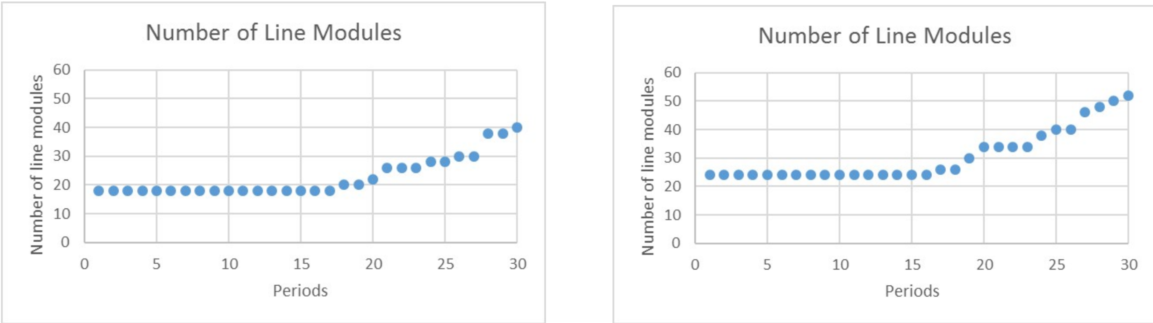

Figure 3.3: Total number of line modules for pattern 1 and pattern 2 obtained by ILP model.

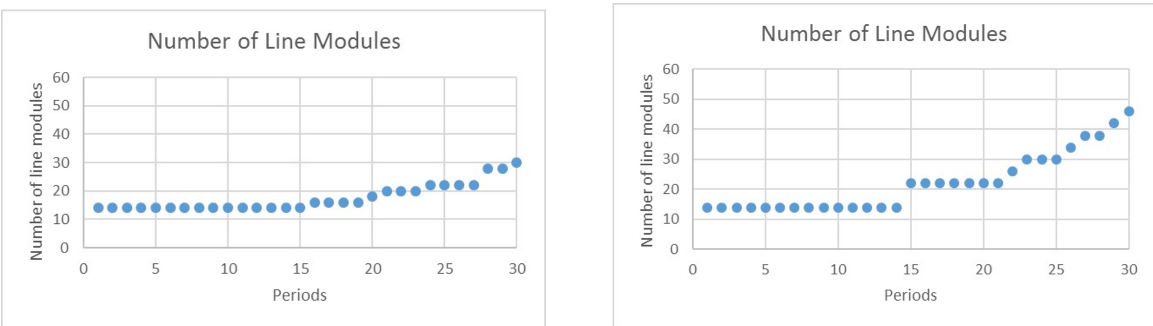

Figure 3.4: Total number of line modules for pattern 3 and pattern 4 obtained by ILP model.

We can see one common tendency in all figures, that is in the first periods the number of line modules tend to be constant, that happens because the increase of traffic (more 10% each period) at the beginning is not enough to overflow the capacity of the initial line modules. For the Figure 3.3 we can see that change right about the 20th period, whereas in the Figure 3.4 it happens in 15th period. This disparity occur because, for pattern 1 and 2 the small granularity (lower client bitrate) of traffic compose the majority, it takes more time to reach the point of need more line modules. For the pattern 3 and 4, we see a tendency to have less line modules at the beginning, because the traffic is distributed in majority to higher client bitrate, in other words the client traffic is more concentrated for the similar amount of demands. After several periods can see a more significant increase in the number of line modules, and it happens due to the faster scalability of traffic in the last periods. This is more evident in Figure 3.4 (pattern 4), also that is why we see a bigger gap between the cumulative number of line modules for adjacent periods.

3.4.2 CapEx analysis

In following is showed the cumulative capital expenditures (thousand of Euros), calculated based on the number of client and line modules provided by the ILP model. Also are used the monetary values presented in Table 2.2.

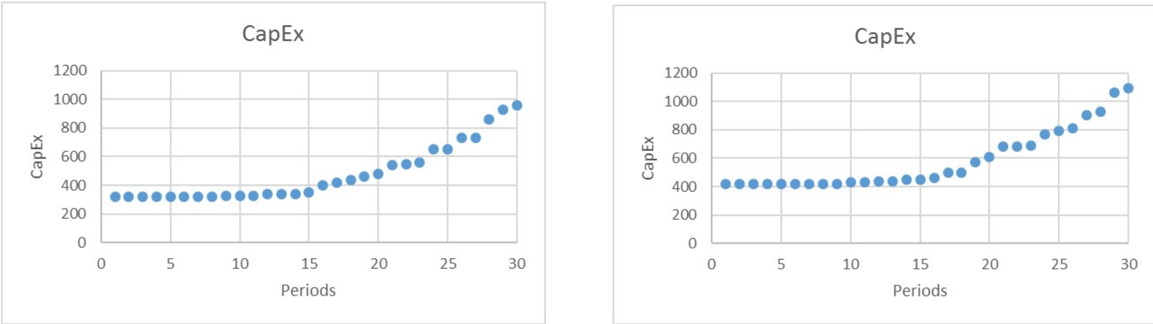

Figure 3.5: CapEx (thousand of Euros) for pattern 1 and pattern 2 obtained by ILP model.

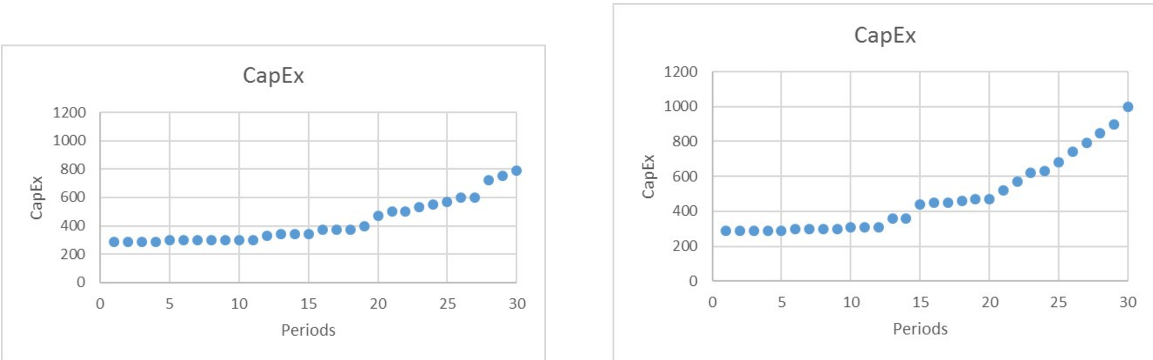

Figure 3.6: CapEx (thousand of Euros) for pattern 3 and pattern 4 obtained by ILP model.

All CapEx results are a direct reflex of the line modules results added the cost of client modules. For that reason and allied to the fact that line modules play a significant role in capital expenditures calculation because line modules are expressively more expensive then client modules (see Table 2.2), so we can see the same kind of tendencies presented in the results of Section 3.4.1. In this thesis the CapEx results gain more importance once compared to the CapEx results of the heuristic approach.

3.4.3 Power consumption

In following is showed the power consumption (kW), based on the number of client and line modules provided by the ILP model applied to the reference network. For this thesis the results of power consumption are the results representative of the operation expenditures (OpEx). Also are used the power consumption references presented in Table 2.2.

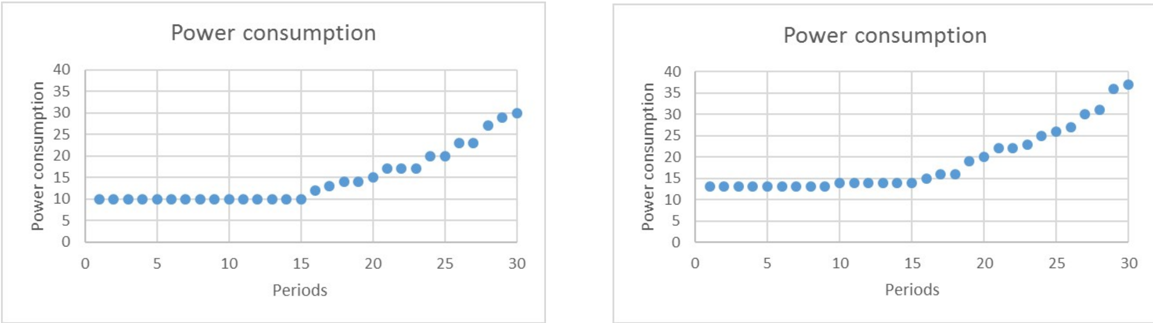

Figure 3.7: Power consumption (kW) for pattern 1 and pattern 2 obtained by ILP model.

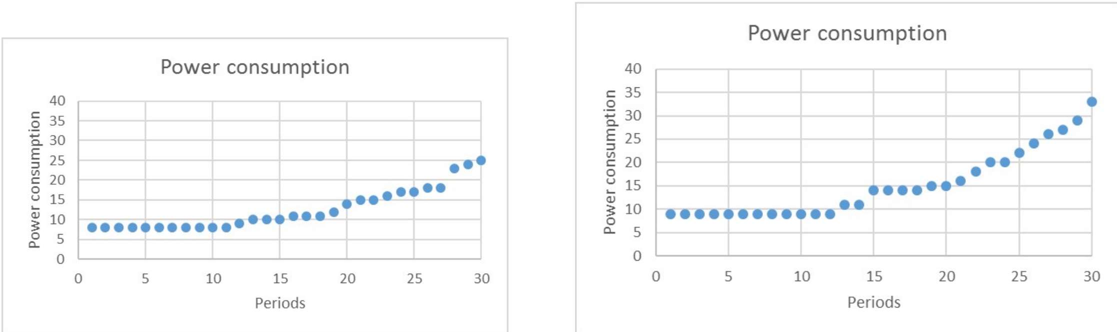

Figure 3.8: Power consumption (kW) for pattern 3 and pattern 4 obtained by ILP model.

All the types of modules have similar power consumption (see Table 2.2). Even so we can see in Figure 3.8 (for pattern 3 and 4) a slight less power consumption comparing to the Figure 3.7 (for pattern 1 and 2) due to the less line modules.

Chapter 4

Heuristics

Due to the scalability problem of the ILP model, there must be another mechanism in order to achieve the the best solution possible for a realistic network. There is why in this thesis it was developed a heuristic approach to the given problem. In the Section 4.1.1 of this chapter is presented the total number of line modules calculated by the heuristic algorithm over various periods. In the Section 4.1.2 is presented the capital expenditures calculated in thousand of Euros. In the Section 4.1.3 is presented the power consumption of in kW. Both models were tested for the patterns of traffic showed in Table 2.1. The scheme of the heuristic algorithm is shown next.

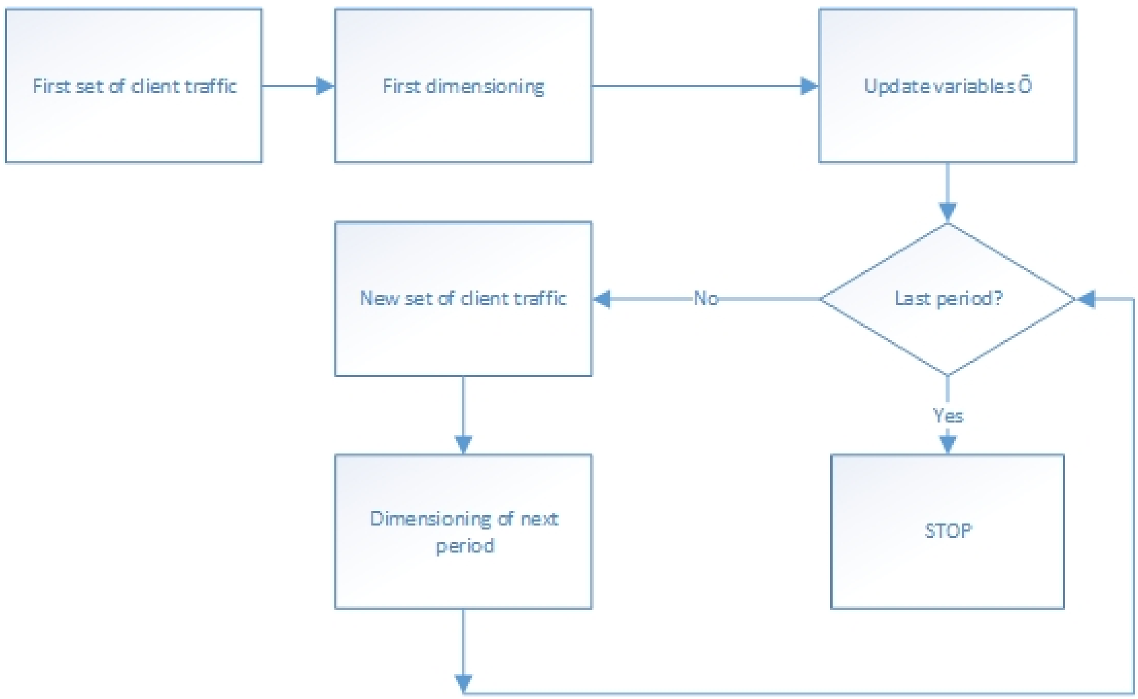

Figure 4.1: Pseudo algorithm of heuristic approach

The heuristic model is designed to read all demands of each client bitrate and switch them all together into the same line module. When the capacity of the line module is fully reached, the algorithm increments another line module for that demand. Moreover the algorithm do this task for every period.

4.1 Reference network

The reference network presented is purely an example, both models work regardless the topology of the network, because the optimization is performed for each node, for that the most important data to take way of the reference network is the number of nodes, in this case is six as is showed in the Figure 3.2.

This network is used to validate the heuristic model. We assume that the ILP model gives the optimal solution possible. Thus, the validation of the heuristic model, it is done by comparing the results to the ILP model results, applied to the reference network.

4.1.1 Line modules

In following is showed the cumulative number of line modules, produced by the heuristic model presented in Section 4 and applied to the reference network showed in the previous Section.

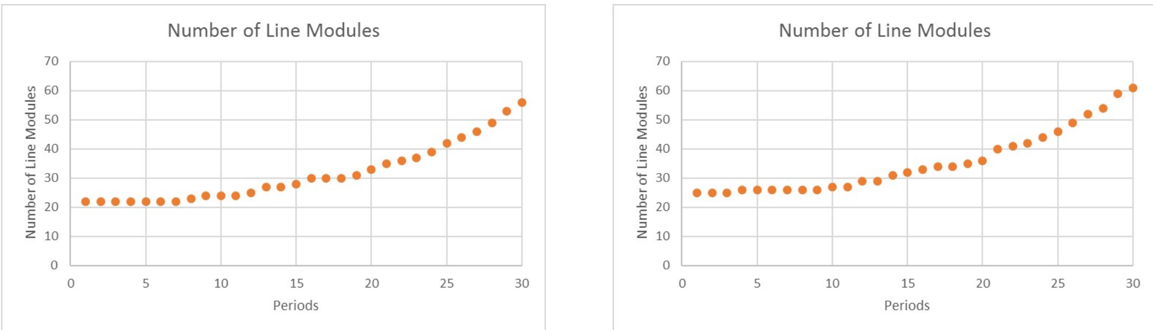

Figure 4.2: Total number of line modules for pattern 1 and pattern 2 obtained by heuristic model.

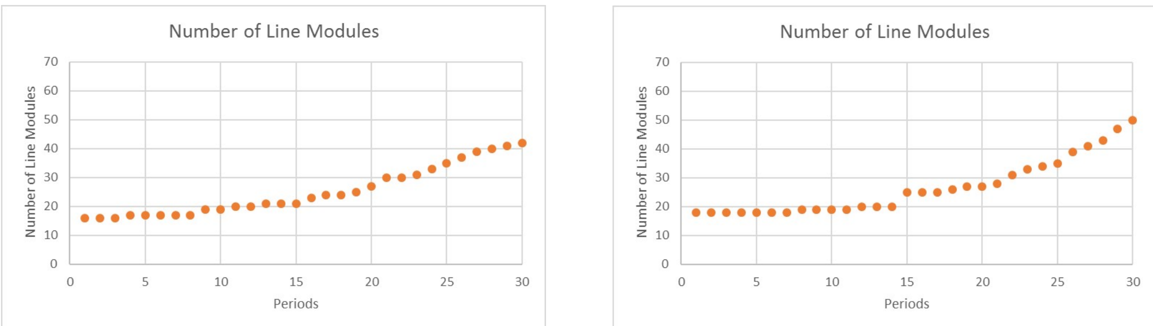

Figure 4.3: Total number of line modules for pattern 3 and pattern 4 obtained

We can see in Figure 4.2 the results for the pattern 1 comparatively to the ILP results in Figure 3.3 are the ones with the bigger gap (in comparison with the other patterns), this is explained by the fact that the majority of the client traffic is composed by 1.25 Gbit/s, so the switching process becomes more flexible, given that is easier to rearrange lower bitrate traffic oppose to high bitrate traffic.

Due to the fact that the heuristic solution aggregates all different client bitrates with the same demand, the results emerge almost as a linear. This is a direct reflex of the linear increase of client traffic (more 10% each period), so the number of line modules increases in a similar way as the traffic does. As expected we can see in general the heuristic solution is not as good as the ILP solution.

4.1.2 CapEx analysis

In following is showed the cumulative capital expenditures (thousand of Euros), calculated based on the number of client and line modules provided by the heuristic model applied to the reference network. Also are used the monetary values presented in Table 2.2.

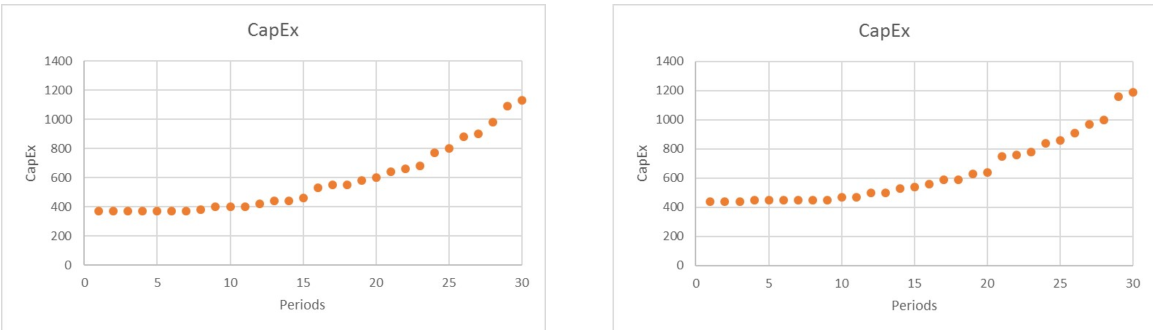

Figure 4.4: CapEx (thousand of Euros) for pattern 1 and pattern 2 obtained by heuristic model.

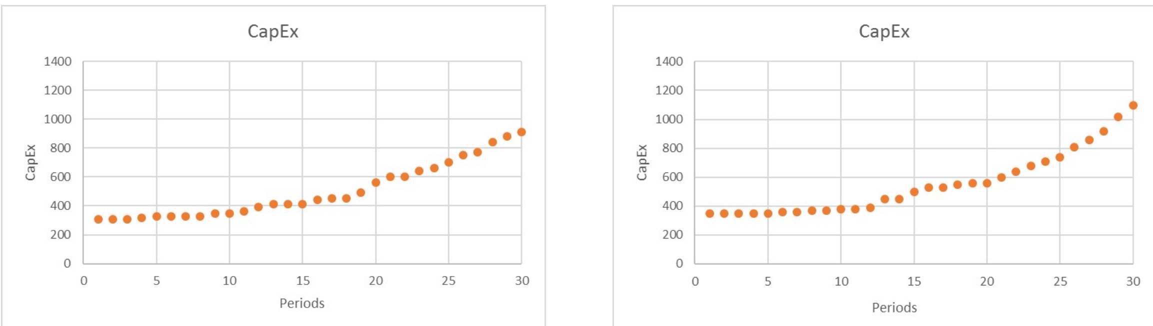

Figure 4.5: CapEx (thousand of Euros) for pattern 3 and pattern 4 obtained by heuristic model.

We can see that the capital expenditures provided by the heuristic model are slightly higher comparative to the ILP results presented in Section 3.4.2. Thus, this results are expected given the significant influence of number of line modules in the capital expenditures calculation.

4.1.3 Power consumption

In following is showed the power consumption (kW), based on the number of client and line modules provided by the heuristic model applied to the reference network. For this thesis the results of power consumption are the results representative of the operation expenditures (OpEx). Also are used the power consumption references presented in Table 2.2.

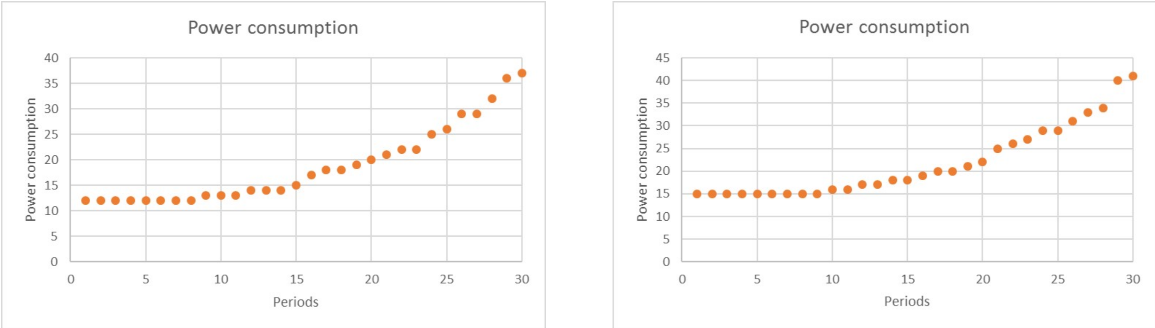

Figure 4.6: Power consumption (kW) for pattern 1 and pattern 2 obtained by heuristic model.

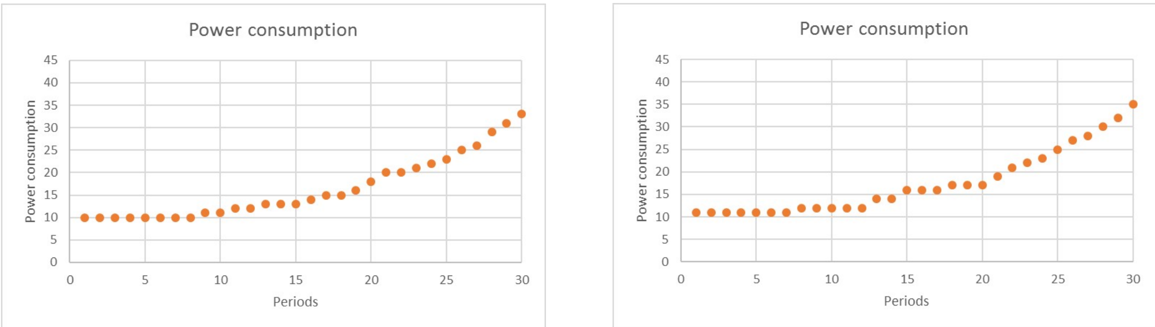

Figure 4.7: Power consumption (kW) for pattern 3 and pattern 4 obtained by heuristic model.

Both client and line modules have similar power consumption (see Table 2.2). Even so we can see in Figure 4.6, for pattern 1 and 2, a slight more power consumption comparing to the Figure 4.7, for pattern 4 and 3, due to effect of having more line modules.

Chapter 5

Realistic network

In this chapter it is presented the results of both models applied to a realistic network over 30 periods. The topology of the network it is indifferent for this problem, because the optimization is performed in each node, for that the most important data to take way of the realistic network is the number of nodes, in this case is seventeen as is showed in the 5.1

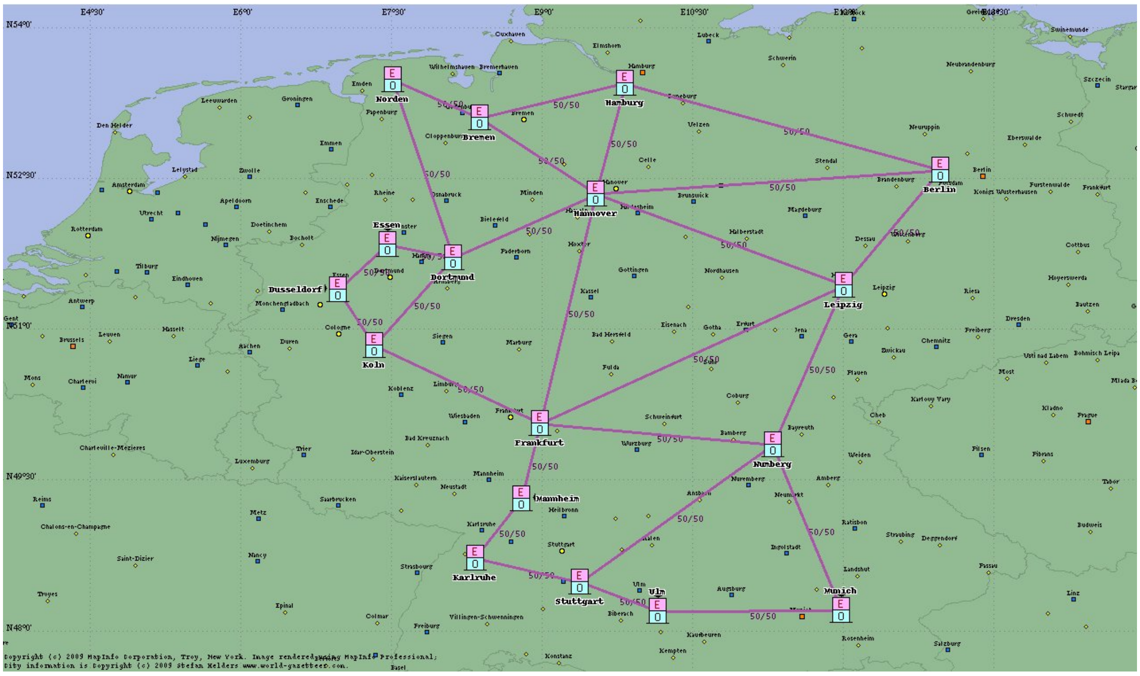

Figure 5.1: Example of a realistic optical network

In the Section 5.1 of this chapter is presented the cumulative number of line modules calculated by the ILP and heuristic algorithms. In the Section 5.2 is presented the capital expenditures calculated in thousand of Euros. In the Section 5.3 is presented the power consumption of in kW. Both models were tested for the patterns of traffic showed in Table 2.1.

5.1 Line modules

In following is showed the cumulative number of line modules, produced by both models, ILP and heuristic, applied to realistic network showed in Section 5.

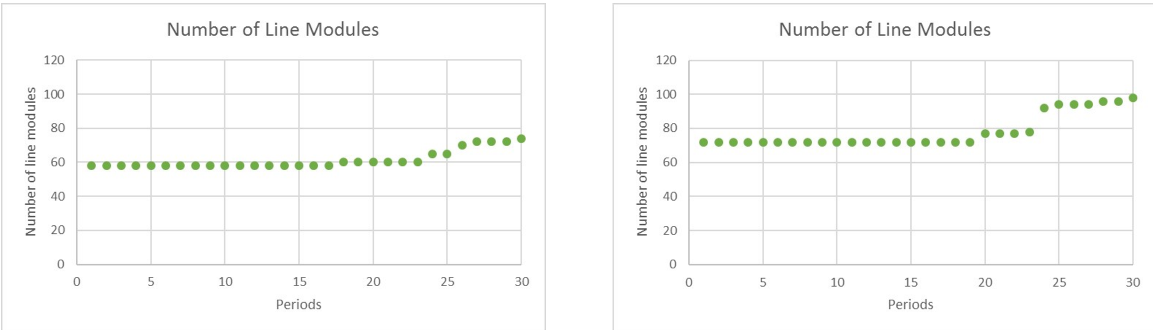

Figure 5.2: Number of line modules for pattern 1 and pattern 2 obtained by ILP model.

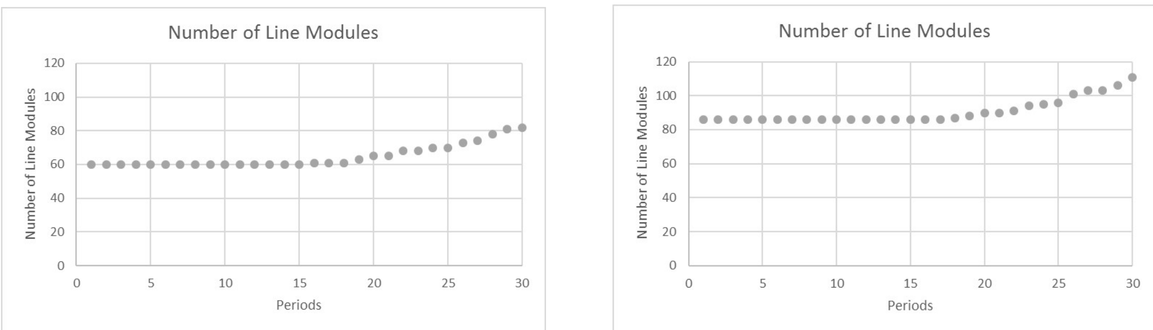

Figure 5.3: Total number of line modules for pattern 1 and pattern 2 obtained by heuristic model.

We can see one common tendency in all figures, that is in the first periods the number of line modules tend to be constant, that happens because the increase of traffic at the beginning is not enough to overflow the capacity of the initial dimensioning of line modules, the same effect seen in the reference network. For the realistic network the scenario is a little bit different because it has more nodes (17 nodes not 6 nodes) but the same amount of initial traffic (200 Gbit/s). Thus are generated more demands and the traffic is more disperse between the different nodes. That is why we see in the Figure 5.2 that the first significant increase of line modules take place at the 18th period.

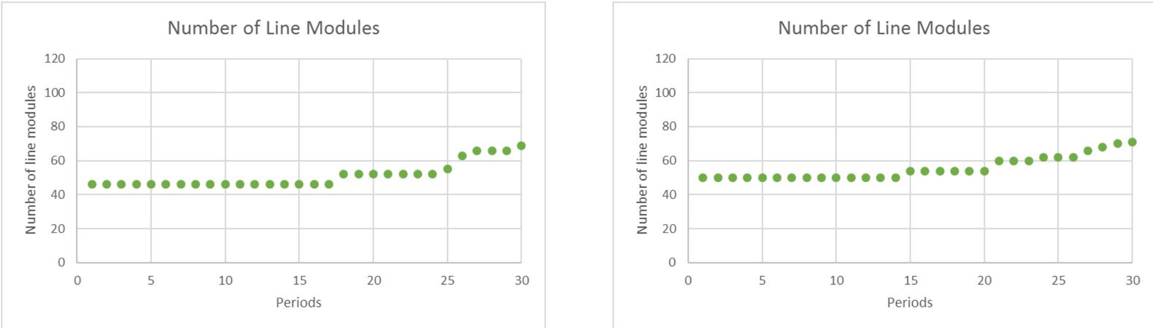

Figure 5.4: Number of line modules for pattern 3 and pattern 4 obtained by ILP model.

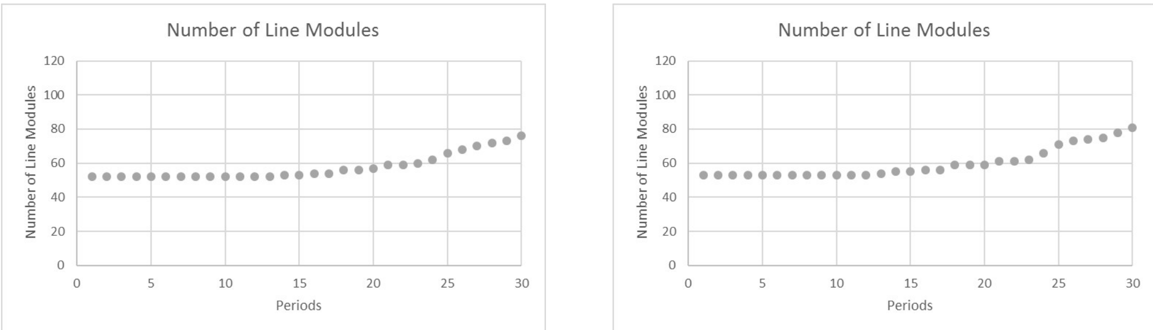

Figure 5.5: Total number of line modules for pattern 3 and pattern 4 obtained by heuristic model.

For the pattern 3 and 4, we see a tendency to have less line modules at the beginning, because the traffic is distributed in majority to higher client bitrate, in other words the client traffic is more concentrated for the similar amount of demands as seen in the reference network as seen in the results of the reference network, in Figure 3.4.

5.2 CapEx analysis

In following is showed the cumulative capital expenditures (thousand of Euros), calculated based on the number of client and line modules provided by the ILP and heuristic model applied to the realistic network. Also are used the monetary values presented in Table 2.2.

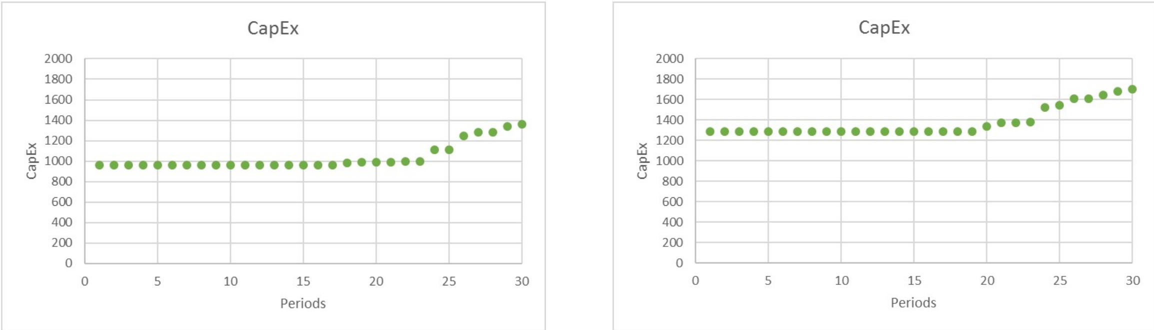

Figure 5.6: CapEx (thousand of Euros) for pattern 1 and pattern 2 obtained by ILP model.

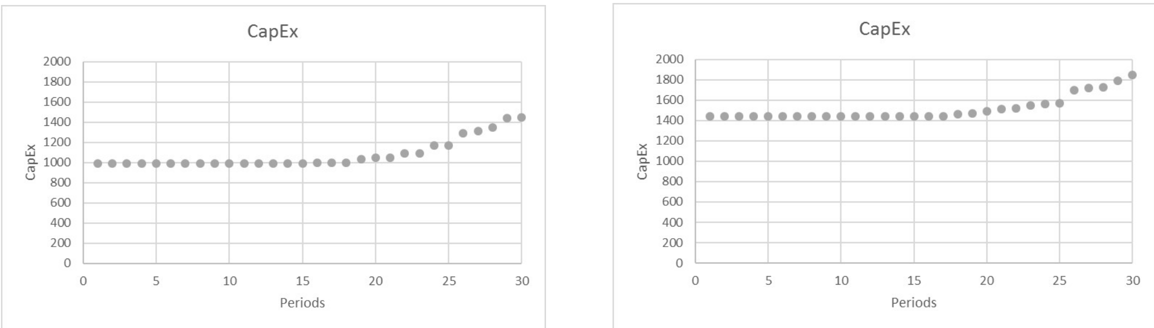

Figure 5.7: CapEx (thousand of Euros) for pattern 1 and pattern 2 obtained by heuristic model.

As we can see by comparing the Figure 5.6 with Figure 5.7 the difference in average between the two models for pattern 1 is €45m, with the CapEx calculated by the ILP model being the minor one. For pattern 2 in average the ILP model provides €138m of savings comparing to the heuristic model.

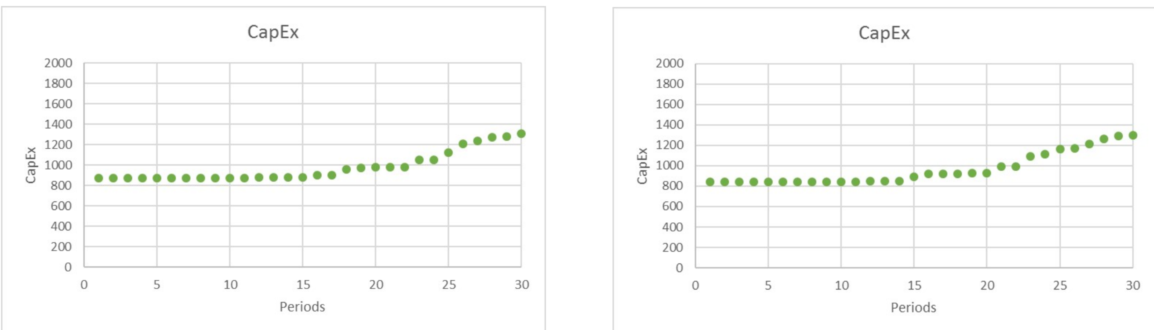

Figure 5.8: CapEx (thousand of Euros) for pattern 3 and pattern 4 obtained by ILP model.

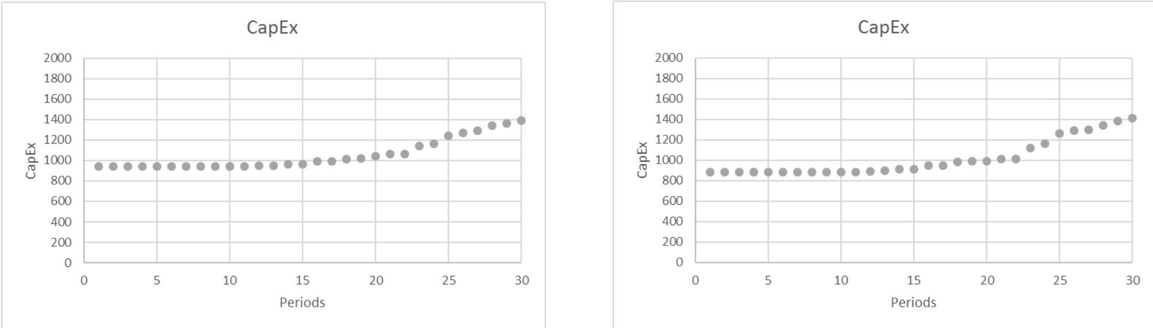

Figure 5.9: CapEx (thousand of Euros) for pattern 3 and pattern 4 obtained by heuristic model.

As we can see by comparing the Figure 5.8 with Figure 5.9 the heuristic model provides a solution more expensive in average of €74m for the pattern 3. For pattern 4 in average the ILP model provides €52m of savings comparing to the heuristic model.

5.3 Power consumption

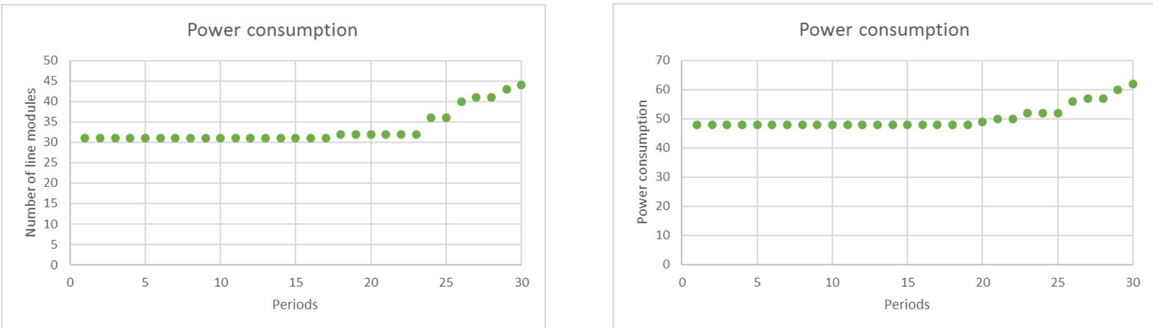

Figure 5.10: Power consumption (kW) for pattern 1 and pattern 2 obtained by ILP model.

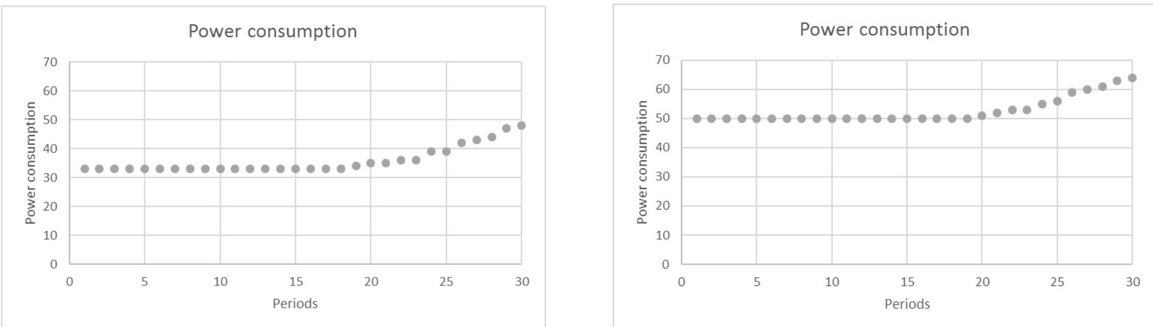

Figure 5.11: Power consumption (kW) for pattern 1 and pattern 2 obtained by heuristic model.

As we can see by comparing the Figure 5.10 with Figure 5.11 the heuristic model provides a solution that consumes more power in average of 2.4 kW for the pattern 1. For pattern 2 in average the ILP model provides 2.2 kW of less power consumption comparing to the heuristic model.

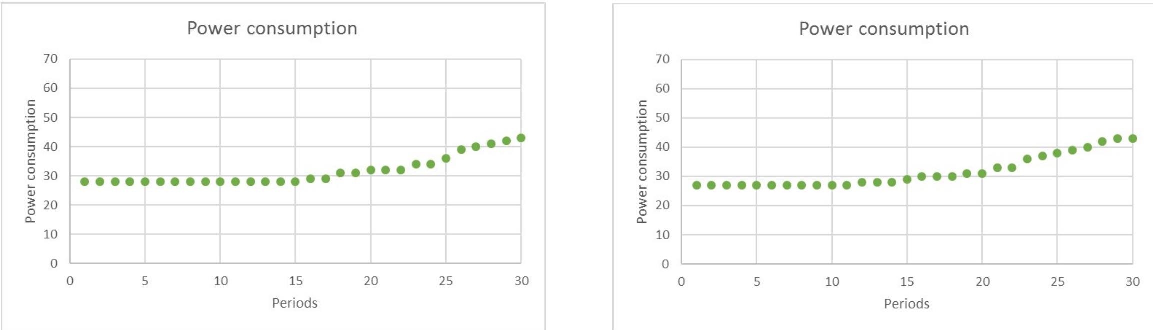

Figure 5.12: Power consumption (kW) for pattern 3 and pattern 4 obtained by ILP model.

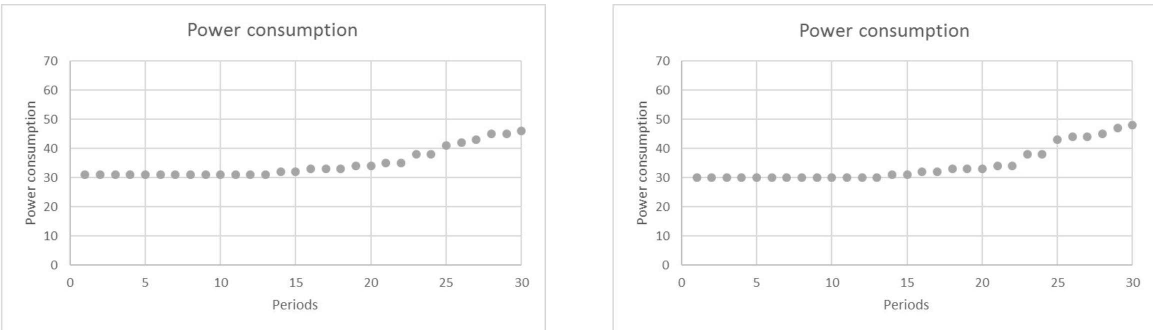

Figure 5.13: Power consumption (kW) for pattern 3 and pattern 4 obtained by heuristic model.

As we can see by comparing the Figure 5.12 with Figure 5.13 the heuristic model provides a solution that consumes more power in average of 3.2 kW for the pattern 3. For pattern 4 in average the ILP model provides 2.8 kW of less power consumption comparing to the heuristic model.

Chapter 6

Conclusions and future directions

6.1 Conclusions

One of the objectives of this thesis was to validate the heuristic model with assistance of the ILP model. This objective was achieved as we can see in the Section 4.1. For instance in Section 4.1.1 we can see that the provided solution applied to the reference network, are in between 75% and 80% as good as the ILP model, so we can consider the heuristic model validated.

For the realistic network we can see in Section 5.1 that the ILP model provides a better solution in terms of cumulative number of line modules. Such results were expected given the fact that the ILP algorithm test every solution and save the best one for each period. The only disadvantage of such algorithm is the time of the execution, each solution for 30 periods it take around 11 hours of processing time, so it is very difficult to implement this algorithm in real time. For the heuristic algorithm we can produce a solution in much less time, in a few minutes, but a not so good solution in comparison to the ILP model.

For the capital expenditures analysis we can see in Section 5.2 that the ILP model produces the most cost savings in comparison to the heuristic model. For the network operators this could be the most important indicator, because the savings could reach the €138m.

The power consumption is a major parameter in terms of OpEx, and it gain a huge importance for the network operators, because it is a cost that extends over time. In Section 5.3 results show us that the ILP model produces better power consumption results, consuming in average up to 3 kW. This is significant because over several years this results mean greats amounts of capital savings for the network operators.

In general the heuristic model can produce good solutions for multi-period planning in a short amount of time, whereas the ILP model produces the most economic solutions but it takes a lot of time. Nowadays the Internet traffic has several patterns variations even during a single day, so for multi-period planning with a short time horizon, the heuristic approach can be a good choice.

6.2 Future directions

For future work:

1. Aplly to the heuristic model, changes of destination nodes in between periods.

2. Take another approaches in terms of multi-period planning, for instance All-Periods, End-of-Life and Begin-of-Life with Forecast planning.

3. Develop the same based algorithms to a different node architecture, for example Partial non-blocking electrical cross connects.

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