Universidade de Aveiro Departamento de
Eletrónica, Telecomunicações e Informática,
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Transporte de Pacotes em Redes Óticas

Optical Packet Transport Networks

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Dissertação 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 Prof. Doutor Armando Humberto Moreira Nolasco Pinto, Professor do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e coorientação científica do Doutor Rui Manuel Dias Morais, Engenheiro na empresa Coriant Portugal, SA.

A todos os que acreditaram e apoiaram

"If I have seen further it was by standing on the shoulders of giants."

Isaac Newton

o júri / the jury

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agradecimentos / acknowledgements

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palavras-chave

Comutação de pacotes, comutação de circuitos, camada ótica, camada elétrica, agregação, CAPEX, OPEX, programação linear de inteiros, arquitetura de nós.

resumo

Nesta dissertação é efetuado um estudo sobre comutação de pacotes e circuitos em redes de transporte óticas, considerando especificidades da arquitetura dos nós, funcionalidades e limitações. É apresentado um modelo de otimização para dimensionamento dos nós, considerando requisitos de tráfego da rede e custos associados, utilizando ferramentas de programação linear inteira (PLI).

Analisando o sinal de cliente, antes de este entrar no domínio ótico, apresentando os principais protocolos, procedimentos e contentores para transporte de dados. No domínio ótico, diversas configurações de agregação são analisadas, considerando o bit rate dos sinais.

Após análise da arquitetura dos nós e modos de transporte, desenvolve-se um modelo matemático capaz de minimizar os custos associados aos nós da rede, para as arquiteturas consideradas.

Os resultados dos diferentes cenários de simulação, com crescimento constante do tráfego são discutidos, finalizando o documento com as principais conclusões obtidas através de análise técnico-económica.

keywords Packet switching, circuit switching, optical layer, electrical layer, grooming, CAPEX, OPEX, integer linear programming, node architecture.

abstract In this dissertation is performed a study of packet and circuit switch on optical transport networks, considering network nodes architecture specifications, functionalities and limitations. It is presented an optimization model for nodes dimensioning, considering network traffic requirements and associated costs, using integer linear programming (ILP) tools.

To start, an analysis of the client signal is done, before it enters the optical domain, presenting the main protocols, procedures and transport containers for data. When in optical domain, various grooming configurations, considering client signals bit rate are analysed.

Considering the node's architecture and transport modes, mathematical models capable to minimize the costs associated with the network nodes are developed for each considered architecture.

Results for different simulation scenarios, continuously increasing network traffic are presented and discussed. This document is finalized with the main conclusions driven by techno-economic analysis.

Contents

List of Acronyms

3R	Reshaping, Retiming and Regeneration
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BMP	Bit-synchronous Mapping Procedure
BWR	Bandwidth Resize
CAPEX	Capital Expenditure
CCITT	International Telegraph and Telephone Consultative Committee
CDC	Colorless, directionless and contentionless
DXC	Digital Cross-Connect
ECS	Electrical Circuit Switch
ECSM	Electrical Circuit Switching Module
EPS	Electrical Packet Switch
EPSM	Electrical Packet Switching Module
ESM	Electrical Switching Module
EPS	Electrical Packet Switcher
EXC	Electrical Cross-Connect
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
GbE	Gigabit Ethernet

GFP	Generic Framing Procedure
GFP-F	Generic Framing Procedure Frame Mapped
GFP-T	Generic Framing Procedure Transparent Mapped
GMP	Generic Mapping Procedure
GMPLS	Generalized Multi-Protocol Label Switch
HAO	Hitless Adjustment of ODU
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
ILP	Integer Linear Programming
IP	Internet Protocol
IP/MPLS	Internet Protocol / Multi-Protocol Label Switch
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LCR	Link Capacity Resize
LSP	Label Switch Paths
LSR	Label Switch Router
MAC	Media Access Control
MPLS	Multi-Protocol Label Switch
MPLS-TP	Multi-Protocol Label Switch Transport Profile
OADM	Optical Add/Drop Multiplexer
OAM	Operations, Administration and Management
OCS	Optical Circuit Switch
ODU	Optical Data Unit
ODUflex (CBR)	ODUflex Constant Bit Rate

ODUflex (GFP)	ODUflex Generic Framing Procedure
OEO	Optical-Electrical-Optical
OLA	Optical Line Amplifier
OLT	Optical Line Terminator
OPEX	Operational Expenditure
OSI	Open Systems Interconnection
OXC	Optical Cross-Connect
OTN	Optical Transport Network
OTU	Optical Transport Unit
OPU	Optical Payload Unit
OXC	Optical Cross Connect
QoE	Quality of Experience
QoS	Quality of Service
RCOH	Resize Control Overhead
ROADM	Reconfigurable Optical Add/Drop Multiplexer
SCU	Single Cost Unit
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Network
TDM	Time Division Multiplexing
TS	Tributary Slot
WDM	Wavelength Division Multiplexing
WSC	Wavelength Splitter or Coupler
WSS	Wavelength Selective Switch

List of Symbols

$\sigma(i)$	nodal degree of node (i).
$(o,\ d)$	demand between node o and d.
$\sigma^{max}(i)$	maximum nodal degree of node (i).
$A(i)$	number of add/drop structures in node i.
C	set of circuit traffic bit rates.
c	bit rate of circuit traffic signals.
d	node that is destination of demand.
E_c	set of node pairs requesting at least one optical channel.
E_p	set of physical links.
G	graph.
i	start node of a physical link.
$\{i,\ j\}$	physical link between nodes i and i.
k	ODU index.
L	set of line bit rates.
l	bit rate of line signal.
$L^{es}(o,\ d)$	number of wavelengths used between nodes o and d for electrical switching architectures.
M	set of OTU indexes.
m	OTU index.

$M_c^{cs}(o)$	number of output modules with bit rate c in node o for circuit switching.
$M_c^{ps}(o)$	number of output modules with bit rate c in node o for packet switching.
$M_{ctr}^{CDC}(i)$	number of control modules in node i for the colorless, directionless and contentionless ROADM.
$M_l(o)$	number of output modules with bit rate l in node o for circuit switching.
$M_{mwss}^{ads}(i)$	number of $\mathrm{P}_i \times \mathrm{P}_o$ WSSs required in the add/drop structure of node i.
N	number of nodes.
o	node that is origin of a demand.
$O_c^{ps}(o,d)$	number of ports with bit rate c for the demands between nodes o and d.
$O_l(o,d)$	number of line ports with bit rate l for the demands between nodes o and d.
$[P]$	matrix with packet traffic request, for all node pairs.
$p(o,d)$	packet traffic between nodes o and d.
$P_{ads}^{CDC}(i)$	number of add drop ports in the add/drop structure for node i in colorless, directionless and contentionless ROADMs.
P_c^{cs}	number of output ports accepting signals with bit rate c for circuit switching.
P_c^{ps}	number of output ports accepting signals with bit rate c for packet switching.
P_l	number of output ports (line ports) accepting signals with bit rate l for circuit switching.
S_c^{ps}	number of slots occupied by the packet traffic modules with bit rate c.
S_{mwss}^{ads}	number of slots occupied by the P_i P_o WSS module in the add/drop structure.

$S_{tot}^{CDC}(i)$	number of slots in node i for the colorless, directionless and contentionless ROADM.
$S_{tot}^{cs}(o)$	number of slots in node o for electrical circuit switching.
$S_{tot}^{ep}(o)$	number of slots in node o for electrical packet switching.
$t(d,k)$	circuit traffic of transmission unit ODUk, destined to node d.
$[T_o]$	matrix with circuit traffic request, for all destiny nodes.
$Tlv_l^{cs}(o)$	number of long-reach transceivers with bit rate l in node o for circuit switching.
$Tsv_c^{cs}(o)$	number of short-reach transceivers with bit rate c in node o for circuit switching.
$Tsv_c^{ep}(o)$	number of short-reach transceivers with bit rate c in node o for packet switching.
$U(i,j)$	number of transmission systems installed in the link between nodes i and j.
V	set of nodes.

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Chapter 1

Introduction

Telecommunications play a major role in nowadays life, connecting not only individuals, but also cultures, societies and economies. The etymology of telecommunications is Greek, where *tele* meant "over distance" and *communicara* meant "ability to share", the telecommunication is the act of share information over distance [1].

During time, telecommunications have evolved, since the smoke signals with all the inefficiencies associated to such a basic and limited message encoding and unpredictability of transmission mean as the air. The telegraph, with a well defined and dedicated wire for signal transmission and a more comprehensive coding enabled communications at useful distances, with reliable quality, easing economical transactions [2, 3]. Soon, the telephone and radio filled the gap in individual and corporate needs for information share, each making use of different transmission means, the wire and the air. Information could now travel distances in form of sound waves, but that was not enough as humans have visual needs and so the television arrived, modifying the way people assessed information [4].

In first half of 20th century computers appeared, which allied with data transmission and information theory, studied and discussed at the time, changed the way information was accessed, allowing also its processing. Promptly were identified many possibilities allied with the creation of computer networks, either closed intra-institutional or open access, to serve organizations or individuals demands. The crescendo, maturation and popularization of computers and computer networks usage brought many modifications in entertainment, health care and education among other aspects of social life, with telecommunication operators moving efforts to provide better Quality of Service (QoS) and Quality of Experience (QoE) to users while, at least, maintaining incomes [1, 5].

When in second half of 20th century Corning developed the first optical fibre with usable attenuation, also compact lasers were introduced, allowing transmission of light in optical fibre, was given major step to first generation optical networks [6]. At this point, optical fibre was used as a replacement for copper cables, offering bigger capacity and better performance (lower Bit Error Rate (BER)). The leading communication protocols used to transmit signals, at the time, were Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH). With no major differences between SONET and SDH, the first was developed and mainly present in North America, while the second had its impact in Europe and Asia. Using Time Division Multiplexing (TDM) and circuit switching it allow data transference at high transmission rates using multiple channels in one optical fibre. A clock reference, present at both ends of a connection, for signal multiplexing and demultiplexing, enables signals extraction or insertion without fully demultiplexing or multiplexing a frame, respectively. In this protocols, each message needs to be transmitted sequentially, occupying the transmission mean for the entire required time [7]. The second generation of optical networks, took advantage on incorporation of intelligent functions in optical part of the network, as routing and switching. The main difference between the two generations is that in the first, at every network node, data should be converted from optical to electrical domain to perform intelligent functions and converted back to optical before proceed transmission [8]. In second generation, using Wavelength Division Multiplexing (WDM) and optical circuit switching in optical domain, data intended for a node was not mandatory to be handled in intermediate nodes and WDM provided a large number of channels over a single physical mean, by transmitting at different frequencies[1] and avoiding proliferation of cables every time more capacity was desired, which was the previous solution. An example of a wavelength routing network is presented in Figure 1.1, with key elements.

Standardized after 2009 by ITU-T Recomendation G.709/Y.1331 (02-12) [9], the Optical Transport Network (OTN) defines a set of optical network elements connected by optical fibre links, providing support for WDM and client signals transport over optical channels. The different client signals can be groomed in higher bit rate signals to enable an efficient transport using optical circuit switching. Optical networks, with the necessary evolution over its diverse equipments and topological solutions represent the current state of art in wired telecommunication networks, with major market operators already having a fully operational backbone network running over optical fibre and gradually providing metro and access services over the same transmission mean.

Parallel with the evolution in optical networks, the proliferation of internet, world wide web and machine-to-machine connections, among other services, led to modifications in accessed contents towards predominance in packet traffic, characterized by variable sized data bursts with no end-to-end connection necessity, contrasting with

[1] Frequency and wavelength are directly associated mathematically

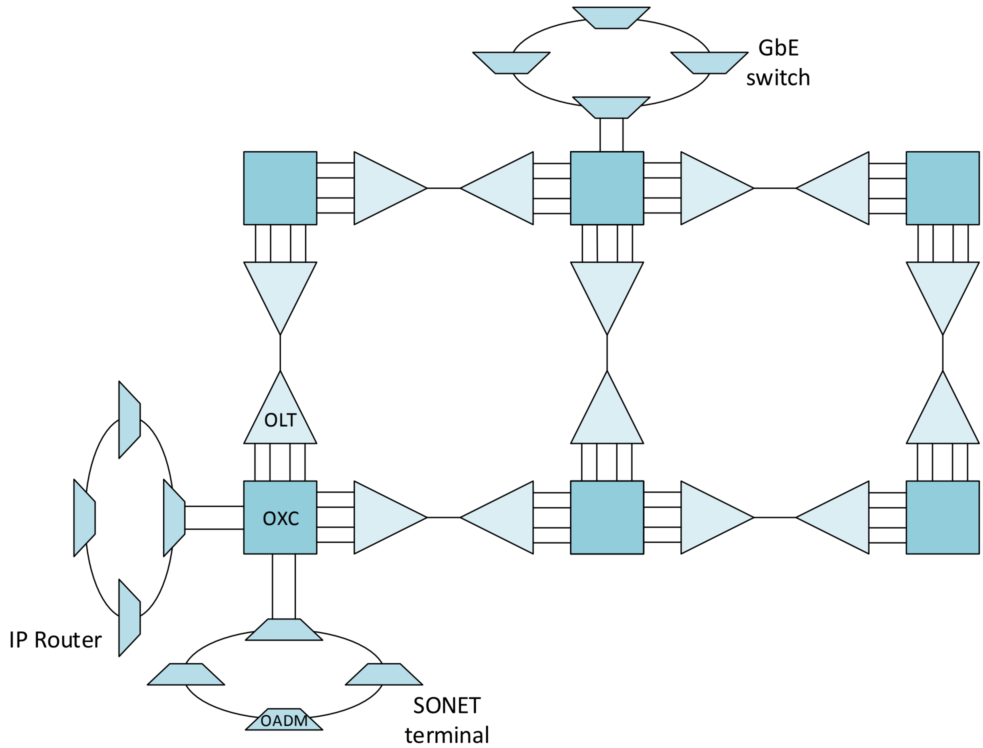
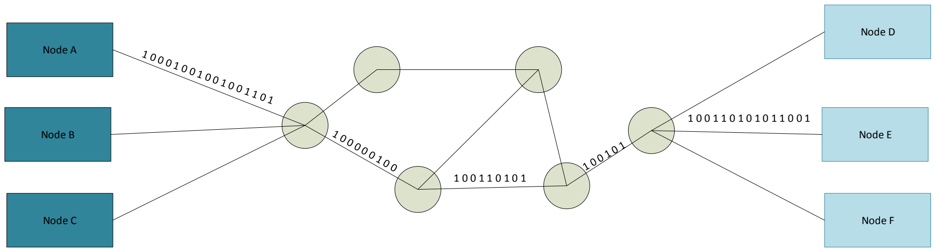


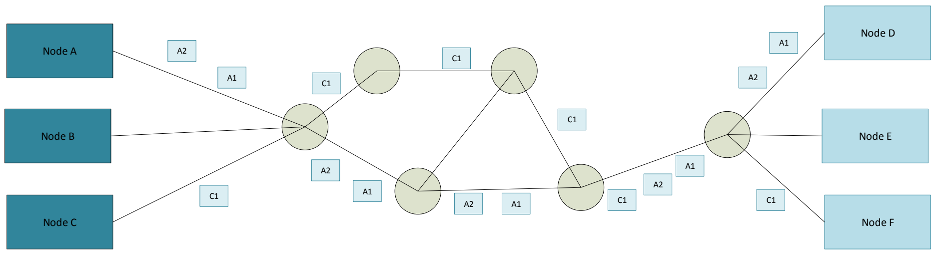
Figure 1.1: WDM wavelength-routing network with OADMs, OXCs, OLTs and IP router, SONET and SDH terminal and GbE switch as network lightpaths users [8].

fixed connections, many times implying bandwidth wastage [10]. The doubt raised if it still makes sense to use circuit switching in predominantly packet oriented networks as data networks, the solution passed by the development of a switching type without fixed number of digital channels nor fixed bit rate, in this way different sized packets could be multiplexed together to fit instantaneous traffic requests [11]. This alternative to TDM and Frequency Division Multiplexing (FDM) is called statistical multiplexing and dynamically allocates bandwidth, providing enhancements in bandwidth utilization. Packet switching moves data across the network in separate, small blocks, based in destination addresses and reassembles the entire message in sequence, when received. Circuit switching requires a dedicated point-to-point connection for the entire duration of message transmission [12], a difference illustrated in Figure 1.2, with remaining relevant differences detailed in Table 1.1. Worth to notice the relation between cost efficiency, complexity and bandwidth wastage, clearly indicating that despite the bigger complexity in packet switch, this disadvantage is frequently surpassed by a better bandwidth usage, which reflects in cost efficiency.

To analyse the cost efficiency two aspects have to be evaluated, the Capital Expen-



(a) Circuit Switch Network example. For nodes B and C to establish a connection, physical line has to be free, in this case, requests for connections are denied, because node A is already using the physical link to connect with node E.



(b) Packet Switch Network example. Nodes A and C share bandwidth for connection with Nodes D and E.

Figure 1.2: Example of two network switch solutions: (a) Circuit switch network. (b) Packet switch network.

Table 1.1: Packet and circuit switching characteristics: restrictions imposed, bandwidth consequences, packet transmission and reception features and implications in network [13].

	Packet Switching	Circuit Switching
Dedicated Path	No	Yes
Bandwidth available	Dynamic	Fixed
Bandwidth wastage	No	Yes
Each packet follows same path	No	Yes
Packets arrive in order	No	Yes
Delay	Low	High
Reliability	High	Low
Deal with failures	Reroute	Rebuilt
Transparency	Yes	No
Complexity	Low	High
Cost efficiency	Low	High

diture (CAPEX) and Operational Expenditure (OPEX). The first referring to costs acquiring materials, installation and every other one-time payment expense. OPEX refers to costs in rentals, either for materials or space, maintenance or other regular interventions, essentially any expense predicted to be spread along expected operation time. All this aspects are key elements when designing networks, affecting the way network are built and consequently used equipments, since different equipments allow different switching operations and a priori knowledge of the network traffic is necessary for a successful network deployment. One of the network elements greatly affected by the switching technique is the network node, responsible for a major piece of expenditure, either CAPEX and OPEX, as acquisition is necessary, as well as power supply. A network design can dictate the survivability of the same and lead market operators into paths of prosperity or decay.

1.1 Motivation and objectives

Telecommunication networks are very complex entities and a very detailed set of variables have to be considered to achieve optimal solutions, considering network identity and evolution. The solutions to compute such predictions often rely on statistical, heuristic or Integer Linear Programming (ILP) methods. The first, fast to simulate and suitable for preliminary stages, can produce erroneous results driven by changes in assumptions. The second, also fast and scalable, have suitability problems for large instance problems, accompanied by hardness over new constraints implementation and does not guarantee an optimal solution in all situations. The ILP method offers optimal solution in every situation, but computational resources can obstruct scalability. The differences over the used methods can be used in advantage of the designer to overvalue products, resulting in one false optimal solution that does not fit the network requirements, fits only the selling objectives.

This dissertation, with the impartiality of academic environment, overcomes the lack of a generic solution, vendor-independent and not result-oriented, with defined objectives:

- Acquire knowledge of the main protocols used to map packet client signals into optical channels, suitable to be carried in circuit switched optical transport networks.
- Understand the network nodes architecture, functions and functionalities depending on the transport modes.
- Develop a mathematical model capable to minimize costs associated with network nodes dimensioning.
- Analyse different architectures for optical nodes.

1.2 Documents structure

This dissertation is composed by six chapters in its route to study packet client signals modifications since network entrance, until drop in destination node, accounting for the expenses it is associated within the network nodes.

In Chapter 2, an explanation of the OSI layered model hierarchy levels is presented and protocol stack to study is identified. The signal mapping from Internet Protocol (IP) to OTN is accompanied and an insight on the packets and frame modifications is given, covering the append of headers and error correction mechanisms, as well as changes driven by intermediate procedures. The enabler protocols for optical add/drop multiplexing once the signal enter the optical domain are traversed and the available grooming configurations are depicted.

The available transport modes, currently deployed are introduced in Chapter 3, to give an insight on network node functions to perform for each. The electrical and optical layers equipments of network nodes are studied after, with particular attention in Electrical Packet Switcher (EPS) and Electrical Circuit Switch (ECS) devices, in electrical layer, and the way both can interoperate. In optical layer, fixed frequency and fixed direction Reconfigurable Optical Add/Drop Multiplexers (ROADMs) are explained, to further comprehension of colorless, directionless and contentionless ROADMs.

Mathematical models, to optimize the nodes with the referred architectures, is the object study of Chapter 4, where more detail is presented to complete the knowledge over leading solutions operation, advantages and limitations and a deeper understand over nodes composition and expenses. The models are based in ILP and objective functions are determined and explained, along with related constraints.

In Chapter 5, simulation results obtained using the mathematical models of previous chapter are presented, comparing the associated costs for the different node architectures, considering CAPEX and OPEX for electrical and optical layers solutions. Conclusions over the simulation results are also presented.

In Chapter 6, an overall description of the realized work takes place and future work possibilities are identified.

1.3 Contributions

This dissertation presents a study on packet signals transportation over optical network and the protocols used to enable transportation of packet traffic over a predominantly circuit switched network. Node architectures capable to perform each switching type are introduced, along with transport modes and optimization models for nodes dimensioning are explained, with simulation results analysed in the end. In the author's opinion, the main contributions of this work are the following:

- Analysis of a protocol stack able to map client signals from network layer, through data link layer, until physical layer and detailing the main protocols and procedures used in the process.
- Development of ILP models that enable network nodes optimization and appliance.
- Identification of scenarios propitious to deployment of specific node architectures.

Chapter 2

Mapping IP Signals

The design of a network is a complex task, connecting a variety of services in a common infrastructure. To simplify the view behind networks, a layered architecture was proposed, early in 1980's decade, derived from a joint effort of two organisations: International Organization for Standardization (ISO) and International Telegraph and Telephone Consultative Committee (CCITT). This standard model is called The Basic Reference Model for Open Systems Interconnection, also known as Open Systems Interconnection (OSI) [14]. In this model, layers are stacked vertically, meaning each layer has a specific function and directly connects to the ones above and below, in cases it exists. Each layer provides certain services to the layer stacked above, and expects the layer below to deliver certain services. In a network element, data flows between layers and every layer multiplexes higher level connections [8, 14, 15].

The classical layered hierarchy, OSI model is presented in Figure 2.1, where the different layers can be identified and the layers object of study are highlighted. The

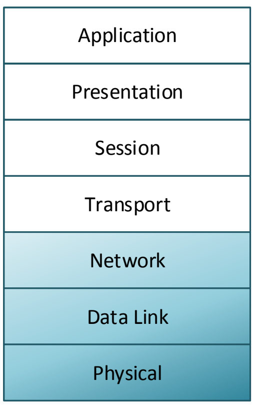


Figure 2.1: Classical OSI model layered hierarchy. Layers one, two and three highlighted, respectively physical, data link and network layers, the focus of this chapter.

physical layer, being the lower one, has the function to provide the layer above it with a channel, with a certain amount of bandwidth [8, 15]. This layer defines the interface for different types of communication channels, for instance optical, wireless, coaxial or twisted-pair cable, our study interest is in the optical one [8, 15]. The *data link layer*, responsible for framing, multiplexing and demultiplexing data is the layer above physical [8, 15]. Typically, data is broken into frames, before transmission, to ensure reliable delivery of data across links, this layer provides a clear delineation between frames and enables detection of link errors through additional overhead [8]. Above data link layer, is located the *network layer*, providing the mechanisms to routing traffic between different networks (internetworking) [8, 15]. The main difference between virtual circuits and datagrams is the notion of connection, existent in virtual circuits, but not in datagrams [8]. This layer is also responsible for the end-to-end routing and transport the message from source to destination [8, 15]. Above network layer are transport, session, presentation and application layers. These are out of our study scope, with specific information available on proper literature [8, 14, 15].

In the following sections the chosen protocol stack, see Figure 2.2, is explained. Starting with IP [16] frame structure and its evolution to Internet Protocol / Multi-Protocol Label Switch (IP/MPLS) [17]. The Multi-Protocol Label Switch Transport Profile (MPLS-TP) is also referred. The final frame to be examined, before OTN, is Gigabit Ethernet [18], after which an overview on Generic Framing Procedure [19] is presented. Concluded the protocol stack, an explanation of the used grooming technique is carried out. This chapter ends with a brief summary clarifying the overall process of packets mapping into OTN and further grooming with other signals [9].

2.1 Mapping signals into OTU

Internet represents major part of telecommunication network accesses for packet transmission between source and destination points. IP provides an efficient method to route the transmitted packets, considering the points addresses performing statistical multiplexing on the various packet streams, along with basic restoration mechanisms [8, 16]. Due to its importance, IP has been upgraded to answer arising challenges and allow synergy with uprising technologies while maintaining the existing compromises, therefore an enhancement with Multi-Protocol Label Switch (MPLS) to provide virtual circuits services was natural, as it quickened the packets forwarding and the IP/MPLS appeared [21].

MPLS is a technique that takes advantage of Label Switch Paths (LSP) to perform packets routing [22, 23]. Every packet is encapsulated with an MPLS header and when

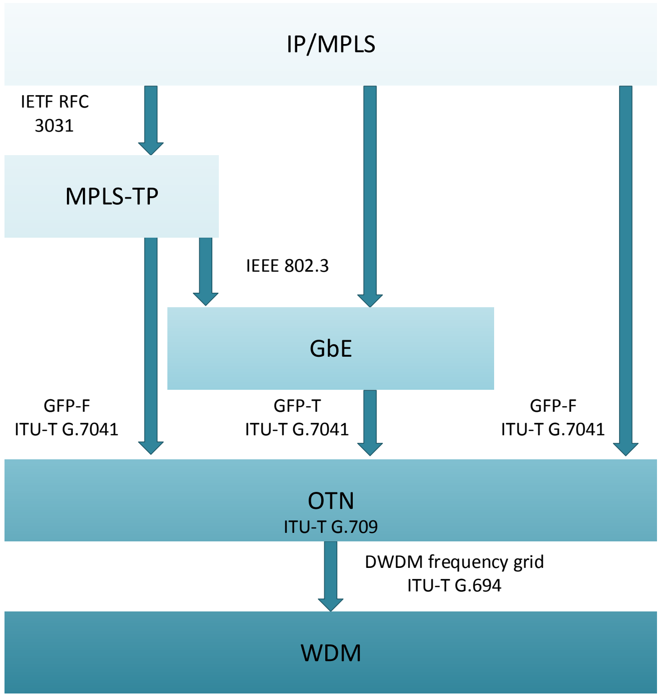


Figure 2.2: Protocol stack selected in this document to implement IP/MPLS over WDM, with the different recommendations identified [17, 19, 18, 9, 20].

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the packet arrives to a new router, the header is copied to a separate forwarding table and routes the packet based on that table match [22, 23]. Time is saved because MPLS tables have less entries than IP routing tables and because an LSP is predetermined for each connection, instead of what happens in IP, where paths are variable [22]. As stated by CISCO in an MPLS overview (2007) [24]:

> ”...MPLS is a high-performance packet forwarding technology that integrates the performance and traffic management capabilities of data link layer (Layer 2) switching with the scalability, flexibility, and performance of network-layer (Layer 3) routing. It enables service providers to meet challenges brought about by explosive growth and provides the opportunity for differentiated services without necessitating the sacrifice of existing infrastructure.
>
> The MPLS architecture is remarkable for its flexibility:
>
> - Data can be transferred over any combination of Layer 2 technologies
> - Support is offered for all Layer 3 protocols
> - Scaling is possible well beyond anything offered in todays networks.
>
> Specifically, MPLS can efficiently enable the delivery of IP services over

an ATM[1] switched network. It supports the creation of different routes between a source and a destination on a purely router-based Internet backbone. Service providers who use MPLS can save money and increase revenue and productivity."

The potentialities of MPLS application in IP enhancement were to big to be ignored and it conquered its own space, in a manner that further studies over possible utilization were carried out, opening space for different types of MPLS protocol variants, such as Generalized Multi-Protocol Label Switch (GMPLS) and MPLS-TP, with the latest worthy of study for application in optical networks [25, 26].

MPLS-TP appears as a possible solution for packet-based data transmission with emphasis in operation and maintenance capabilities . Similar to previous MPLS, differs from it in the way it is connection oriented with pre-configured bidirectional paths [27]. Current trends point to a growth in packet based traffic in networks and emerging protocols need to assist actual and former technologies while forecast user tendencies able to change paradigms, MPLS-TP offers that with the possibility to work over Gigabit Ethernet (GbE), a growing layer 2 solution [25, 26, 28].

The GbE, natural successor of Ethernet and fast Ethernet is available at different rates, from 1 Gbps to hundreds of Gbps. Encapsulation of various types of signals into GbE signals must be allowed through use of reliable techniques, where GFP is identified as a fully deployed procedure, to transform a variable rate signal into a fixed bit rate signal. The signal with fixed bit rate can then be enclosed into GbE, with a known bit rate of 1, 10, 40 and 100 Gbps for current commercial networks. The choice over GbE lays on its dominance over the other layer 2 technologies and the fact that it is fully implemented with proved robustness [8, 18, 29].

The newly generated signals to be transported over the OTN, should first be mapped to a fixed rate container capable to create Optical Data Unit (ODU) signals of different orders. ODUflex was created specifically for the purpose, being able to build all order ODUs through scalability [30]. ODUflex has a constant bit rate of 1.25 Gbps, creating ODUs of orders 0 to 4, with bit rates of 1.25, 2.5, 10, 40 and 100 Gbps, respectively [9]. The bit rates of GbE signals and ODU containers do not have a direct match, introducing the need to complete container occupation. In must cases, GbE has slightly lower bit rate than ODU, creating the opportunity for robustness and DC balance increase while completing the container size, using different encoding relations, from 8B/10B to 1024B/1027B [31]. The encoding characteristics are quite vast, with different patents for line codes, reason why no deeper elucidation is carried

[1]Asynchronous Transfer Mode (ATM) is a layer 2, high speed network architecture, oriented for packet switching.

in this subject, although available in proper literature [32, 33].

For a better comprehension of the signal modifications since packet transmission until the final shape, an insight over the abovementioned protocols and frame constitution is compiled. The set of procedures converge in an Optical Transport Unit (OTU) container. All take place in electrical domain and intend to enhance granularity in final container occupation and signal Operations, Administration and Management (OAM) [34].

2.1.1 IP

The recognized dominant network layer protocol for connection between computers, IP is described in Internet Engineering Task Force (IETF) standard RFC 791 [35] and has a relatively simple frame composition, when compared to lower level frames, sufficient to grant point-to-point connection identification with basic security methods. Figure 2.3 shows the frame construction with the reserved space for each field in an IPv4 frame, where the header of 32 bits $\times$ 20 bytes is explained [36].

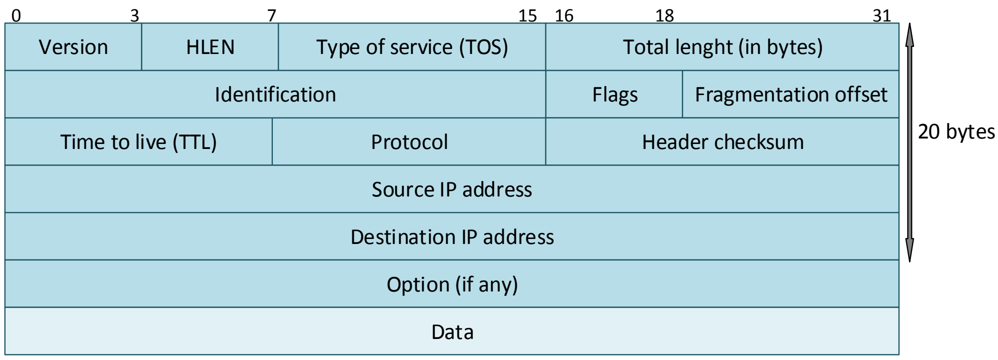


Figure 2.3: IP frame structure with respective fields identification for(IPv4) [36].

- **Version-** Identifies the IP version. For IPv6 this field occupies 6 bits;
- **HLEN-** Header length informs on how many 32-bit words compose the header;
- **TOS-** Type of service has a 3 bits set on the left, the precedence bits (ignored as of today), the 4 bits next represent the type of service with bits for delay minimization, throughput and reliability maximization and cost minimization. The last bit is left unused;

- **Total Length-** Expressed in bytes, notifies over the IP datagrams length. With the necessary calculations, the maximum size for the datagram obtained is 65535 bytes;
- **Identification-** Identifies fragments of IP datagrams;
- **Flags-** Set of three bits with the first one left unused. The second is for fragmentation allowance and the third for extra fragmentation information;
- **Fragmentation offset-** Contains the offset of fragmented datagrams;
- **TTL-** Time to live represents the number of hops the datagram can go through before being discarded. This field starts with the maximum number allowed and is decremented in every hop, until reaches zero and the datagram is discarded;
- **Protocol-** Used in transport layer;
- **Header checksum-** Calculated using an algorithm covering all the fields in header. Used to verify correct transmission of the frame, through result comparison in source and destination,
- **Source IP address** and **Destiny IP address-** Identification of frame sender and receiver;
- **Option-** Notifies the options that are enabled in a particular datagram;
- **Data-** Information to be sent across addresses.

2.1.2 IP/MPLS

MPLS is not assumed as a layer 2 or 3 technique, it is inbetween data link and network layers, standerdized by Internet Engineering Task Force (IETF) in standard RFC 3031 [17], provides an LSP between network nodes, it consists only in the insertion of a label in contrast with the remaining protocols that introduce headers. This label has smaller dimension, because the forwarding table respecting MPLS has reduced dimension, when compared to IP routing tables. The placement of the label is illustrated in Figure 2.4 and the various variants of MPLS can stack in the space between layers two and three, as would be the case when using IP/MPLS and MPLS-TP simultaneously.

The operation of an MPLS network is understood better with visual aid, purpose served by Figure 2.5. An IP packet enters the network through a router that implements label switching, Label Switch Router (LSR), and introduces a label associated with the LSP according to the forwarding table. The packet containing the label is then

Figure 2.4: MPLS label placement in a frame, between layers 2 and 3 headers. Multiple labels can be stacked.

switched over the network to next LSR where the label is extracted and used as index for that router's forwarding table and accordingly, a new label is introduced to forward the packet over a specified link. This process keeps going until the last router in the network is traversed by the packet. In the last node, the label is removed and no other is introduced [37].

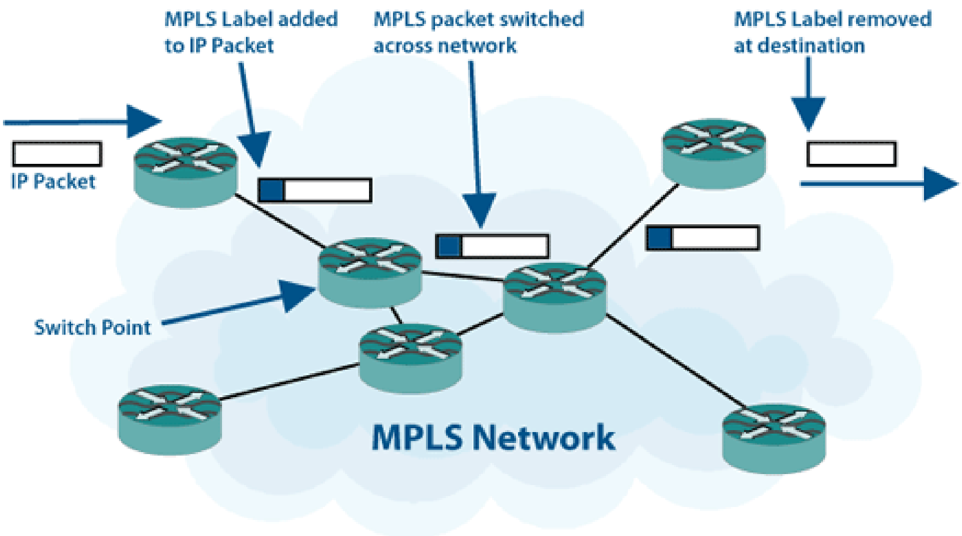


Figure 2.5: Multi-Protocol Label Switch network example. In this example is visible the label placement and removal and the packets forwarding process [38].

2.1.3 GbE

Defined in Institute of Electrical and Electronics Engineers (IEEE) by standard 802.3 [18], Gigabit Ethernet is a leader layer 2 protocol to support a multiple number of bit rates in client signals keeping frame constant, or at least with minimal variations. For GbE to maintain the minimum and maximum sizes of Ethernet, it implies a reduction in the allowed cable size, to useless dimensions. The solution was to add, or extend where existent, a carrier event, when the frame is shorter than a required minimum value - 512 bytes. The frame is padded with special symbols that can not occur in the payload. This process is called *Carrier Extension*[29].

The modifications in GbE rates is based in transference speed and containers size, not on the modification of the frame. In Figure 2.6 the frame structure is illustrated, with the different blocks that compose it, along with a brief explanation on the respective functions.

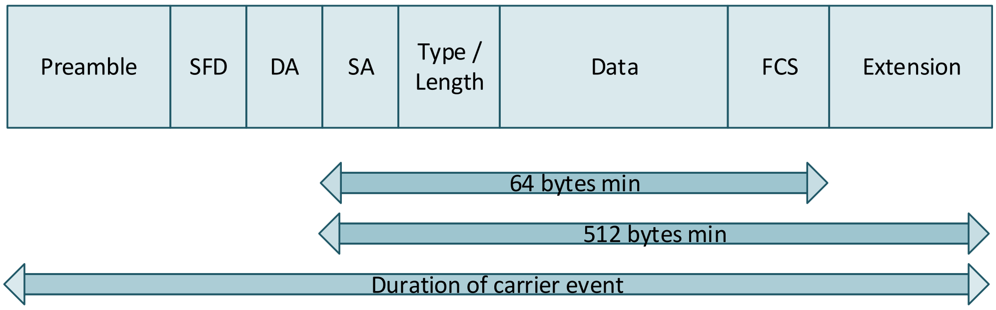


Figure 2.6: GbE frame with Carrier Extension process and building blocks identification [29].

- **Preamble-** Consists of seven bytes, alternating 1's and 0's in type "1010101", allowing receiver clock synchronization;
- **SFDA-** The Start Frame Delimiter, a single byte used to indicate the frame start;
- **DA-** Destination Address, indicates the address of the intended frame recipient;
- **SA-** Source Address, is the address of the transmitter;
- **Type / Length-** Indicates the data length in the Ethernet frame, which can vary from 0 to 1500 bytes;
- **Data-** Information to be sent in the frame;
- **FCS** Frame Check Sequence, refers to an extra error detection code;
- **Extension-** Responsible to adjust the frame size.

2.1.4 GFP

For GbE to start being predominant also in metro and backbone networks, providers needed to make a good use of its flexibility and cost efficiency, using it to transport not only framed, but also packet based traffic. GFP, defined by International Telecommunication Union (ITU) recommendation G.7041/Y.1303 [19], works as a rate-adapting bridge, able to encapsulate frame or packet-based protocols to GbE and OTN, while enables packet streams error correction and channel identification for port multiplexing. Supporting point-to-point and ring applications, this mechanism avoids payload specific frame expansion, saving bandwidth by eliminating bit stuffing necessity [19, 39, 40].

Two mapping modes are currently defined for GFP, the Generic Framing Procedure Frame Mapped (GFP-F) and Generic Framing Procedure Transparent Mapped (GFP-T). GFP-F maps an entire original frame into one GFP frame, example is a GbE frame mapping [19, 39]. GFP-T is specific for block-code client signals that require low transmission latency. It de-maps the original signal and then maps it into GFP frames, the main advantage of this process is it avoids buffering an entire frame before map it into the GFP frame. The resultant GFP frame is presented in Figure 2.7.

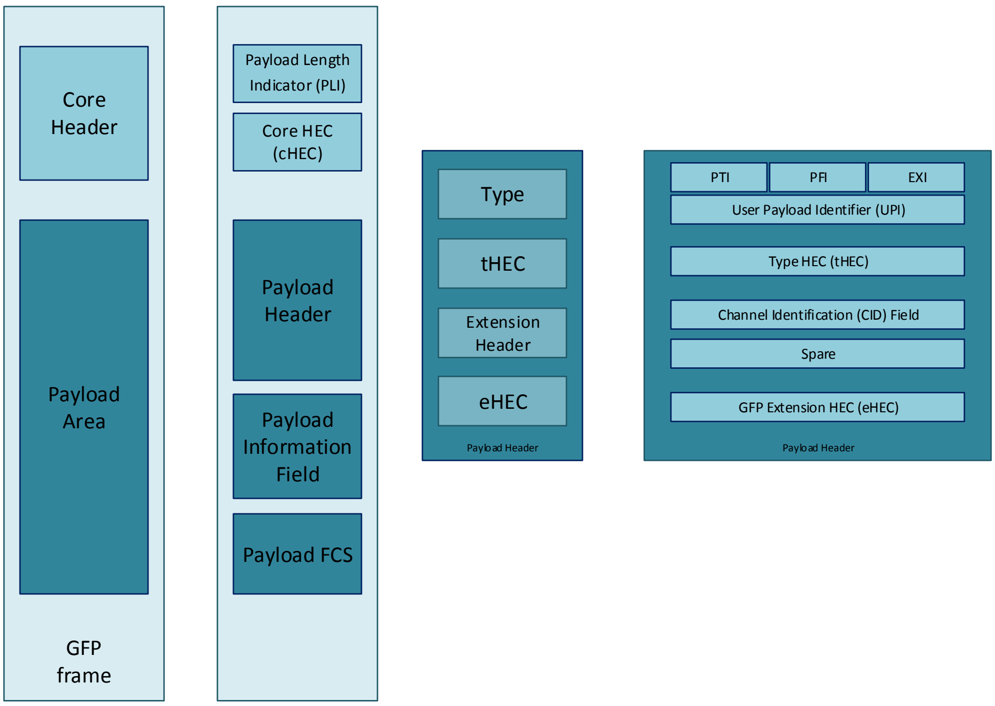


Figure 2.7: GFP frame structure and blocks identification [40].

- **Core Header-** Used to describe GFP frame, disregarding the content of higher layer Protocol Data Units (PDUs);

- **cHEC-** Contains CRC error control code for Core Header contents protection;
- **Payload Header-** Supports data link management procedures specific to client signal;
- **Type-** Identification of format and presence of Extension Header and Payload FCS. Distinguishes between GFP frame types and services in multi-service environment;
- **Payload Type-** GFP client type identification;
- **Payloafd FCS-** Informs about the presence of Payload FCS field;
- **Extension Header Identifier-** Identifies the GFP Extension Header;
- **User Payload Identifier-** Conveys the type of payload carried in GFP Payload Information field;
- **tHEC-** Protects Type field integrity;
- **Channel Identification (CID)-** Identifies the communication channel at GFP terminal point;
- **GFP Extension Header-** Supports technology specific headers;
- **Extension HEC-** Protects Extension Header contents integrity;
- **Payload Information-** Contains the framed PDU in GFP-F and a group of client characters in GFP-T;
- **Payload FCS (pFCS)-** Protect the GFP payload contents.

2.1.5 ODUflex

When OTN first appeared, the smallest container was ODU1, with a bit rate of approximately 2.5 Gbps, allowing GbE to be directly mapped using GFP-T [30]. This method, although valid, introduced a waste of half the ODU1 bandwidth when carrying one 1 GbE signal and supervision/management loss when carrying two signals of 1 GbE (Figure 2.8) [30, 31]. Allied with convergence on packet and TDM networks, appeared the need to standardize a new container to efficiently carry 1 GbE signals across the OTN. In this context ODU0 solved the problem, with a container half the size of ODU1, able to transparently map 1 GbE client signals and effectively doubling capacity (Figure 2.9) [30, 31].

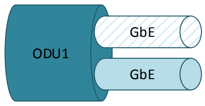


Figure 2.8: Two 1 GbE client signals mapped directly into ODU1 container [31].

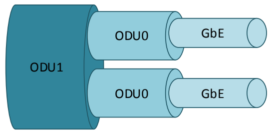


Figure 2.9: Two 1 GbE client signals mapped to ODU1 through ODU0 [31].

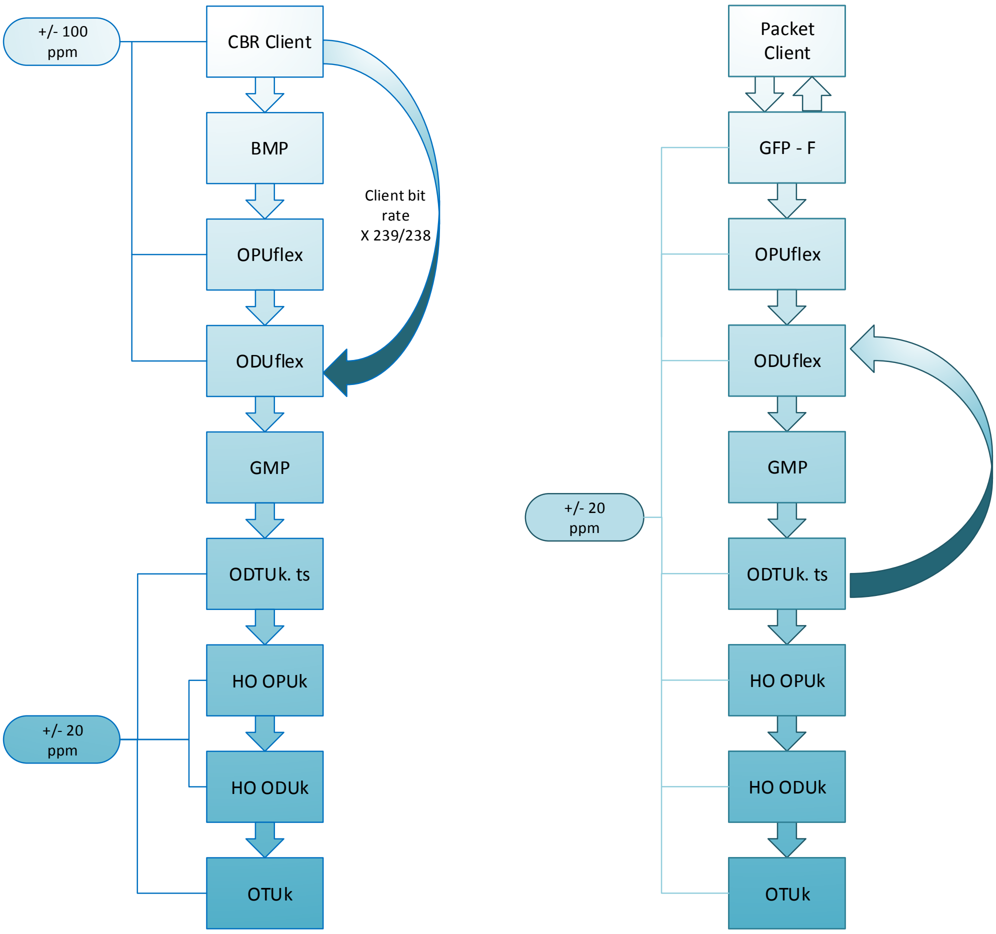
ODU0 was an efficient solution for GbE clients and at same time, a proof on how unpredictable the rate for future clients would be. By the time, other clients demand the same attention given to GbE, e.g. fibre channel and video distribution. To accommodate current and future clients, ODUflex was defined, as container capable to fit any client signal rate, occupying the minimum number of time slots in higher order ODUs [30]. To support constant and variable bit rate signals, were defined in ITU recommendation G.709/Y1331 [9] two ODUflex types, ODUflex Constant Bit Rate (ODUflex (CBR)) and ODUflex Generic Framing Procedure (ODUflex (GFP)), respectively, with different signal mapping procedures, as shown in Figure 2.10 [34].

ODUflex (CBR)

When the signal to map in ODUflex has constant bit rate, it is mapped using Bit-synchronous Mapping Procedure (BMP) , without juxtaposition necessity, as the client clock is used to synchronize the ODUflex signal. This signal occupies the same tributary slots, duo to constancy in time. After mapped into ODUflex (CBR), this kind of signal is also mapped using Generic Mapping Procedure (GMP). Only client signals greater than 2.488 Gbps are mapped into ODUflex (CBR) using BMP. When the client signal is below 1.244 Gbps, it is mapped into ODU0 using GMP. Client signals between 1.244 and 2.488 Gbps are mapped into ODU1 using GMP. This allows ODUflex to be any rate greater than ODU1 [30, 41].

ODUflex (GFP)

When the signal to map in ODUflex has variable rate, the mapping is done in ODUflex (GFP) using a local clock to generate the signal. The client signals are



(a) ODUflex (CBR) mapping diagram. (b) ODUflex (GFP) mapping diagram.

Figure 2.10: ODUflex signal mapping diagram for ODUflex (CBR) and ODUflex (GFP) [34].

encapsulated into ODUflex (GFP) through GFP-F and any bit rate client signals can be encapsulated [30, 41].

2.1.6 OTU

The data encapsulated through GFP can now be mapped into ODUflex containers, that by turn, contains the Optical Payload Unit (OPU). When the OPU is generated a header is added, carrying the Resize Control Overhead (RCOH), formed by Link Capacity Resize (LCR) and Bandwidth Resize (BWR), among other fields, further used in Hitless Adjustment of ODU (HAO) to add or drop Tributary Slots (TSs) along the end-to-end path, process studied in next section. When, after, ODU is generated, another header is introduced, to provide end-to-end and Tandem Connection supervision. The ODU frame is used to generate the OTU, the frame that will be carried over the transport network. In this frame generation, a final overhead is added as well as Forward Error Correction (FEC). The OTU overhead will provide Operations, Administration and Management capabilities. A representative illustration of the process is presented in Figure 2.11 and the final frame aspect in Figure 2.12.

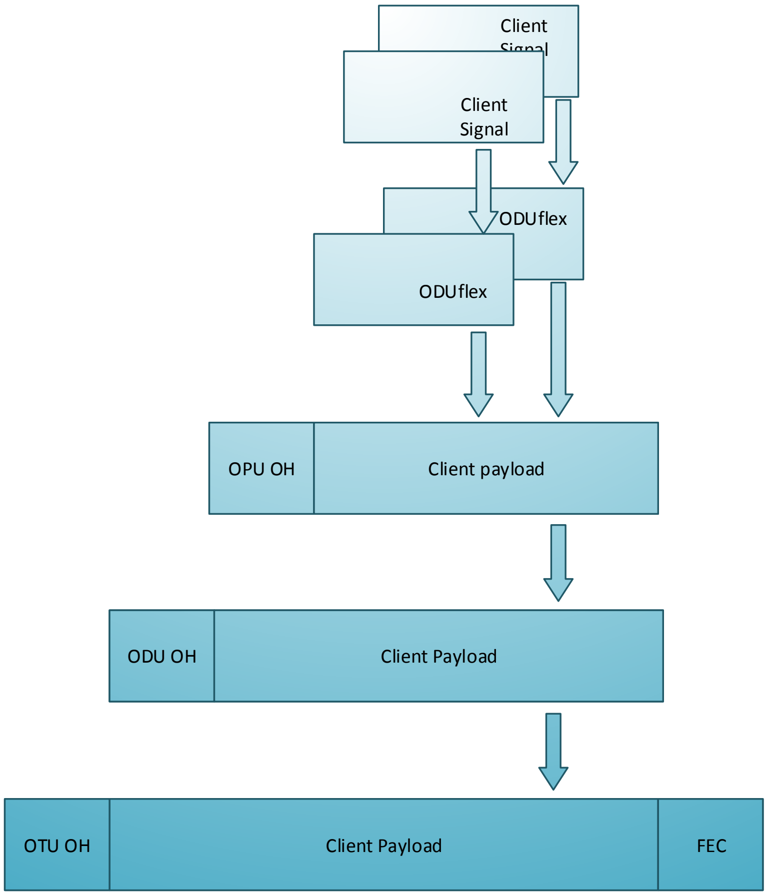


Figure 2.11: OTU frame mapping process diagram, considering multiple client signals mapped into multiple ODUflex containers and groomed in a single OPU.

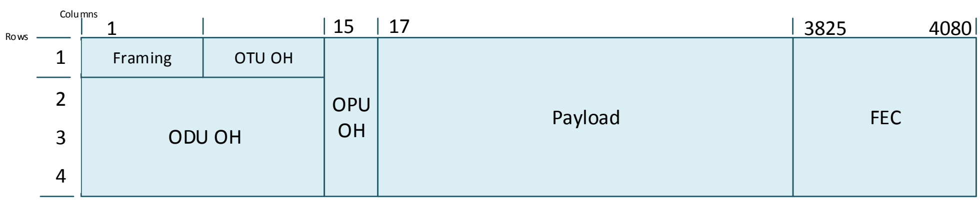


Figure 2.12: OTU frame structure, with processed headers, framing and error correction mechanism fields.

2.2 Grooming OTU signals

To support increase and decrease in ODUflex client data rate across the entire end-to-end path, over a group of Tributary Slots (TSs), the chosen mechanism is HAO, defined in ITU recommendation G.7044/Y.1347 (10/11) [42]. All the tributary slots that carry the client signal follow the same path from source to sink, therefore no need to compensate individual TSs having different time delays[42]. To accomplish hitless bandwidth adjustment for ODUflex signals in a connection, all nodes must support HAO protocol, or the connection will need to tear down and be rebuilt. To prevent buffer overflow or underflow, the bit rate adjustment occurs simultaneously among all the nodes in the connection [42]. A resizeable ODUflex signal occupies the same number of tributary slots at every link in the server. In cases of bandwidth adjustment, the same number of tributary slots on each link traversed by the resized ODUflex signal must be involved. The HAO application supports bandwidth increase or decrease from a current n_1 to a different n_2 range, if the link in the server permits. The available ranges are covered in Figure 2.13.

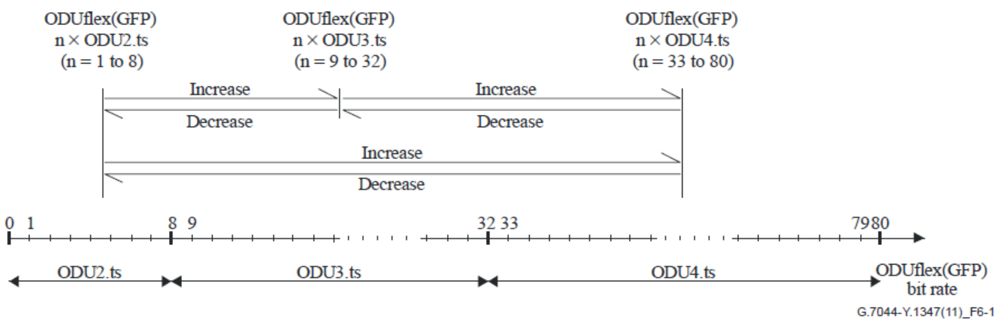


Figure 2.13: Recommended ODUflex(GFP) bit rate in HAO capability [42].

The synchronization of the changes in capacity shall be achieved by RCOH. The RCOH is carried in the higher order OPU (HO OPUk) tributary slot overhead and in the OPUk overhead, as shown in Figure 2.14. These RCOH bytes are located in column 15, rows 1,2 and 3. The HO OPUk RCOH is carried in the tributary slot which is to be added or dropped. If multiple tributary slots are involved in one operation, the protocol is carried in all of these tributary slots RCOH, being the identical RCOHs transmitted equally. The RCOH, as documented in [42] is divided in two parts, the LCR and the BWR, each with proper protocol and functions.

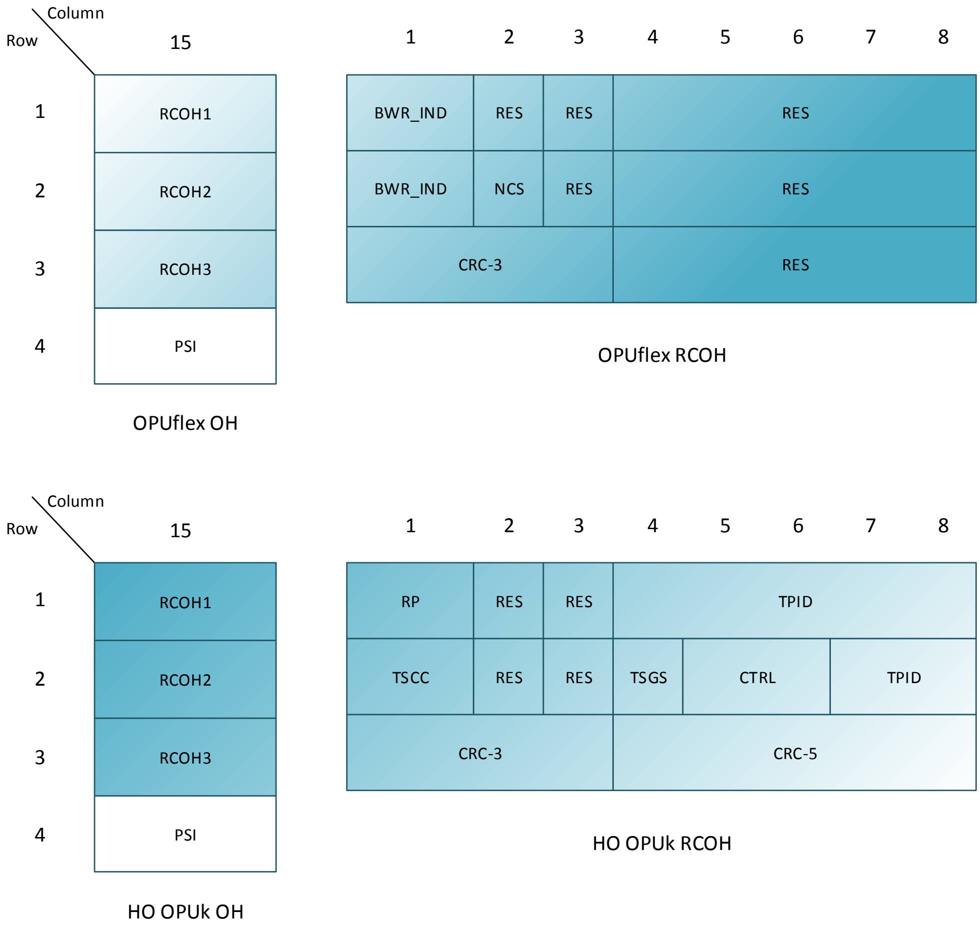


Figure 2.14: RCOH format [42].

2.2.1 LCR-Link Connection Resize

Responsible to adjust the tributary slots assignment to ODUflex, contains:

- **CTRL-** Used to provide the operation indication of the individual tributary slot that belongs to a specified ODUflex connection, agreeing with the Table 2.1;
- **TPID-** Tributary Port ID, used to identify tributary slot port ID, carries the the tributary port number to which the tributary slot is to be added or dropped. Has a 7 bits dimension, allowing identification of 128 addresses, of which only 80 are currently used. To know the refering address, the value 1 should be added after binary to decimal conversion;
- **TSGS-** Tributary Slot Group Status, used for link aknowledgement indication. Is genarated by the HO OPU to inform a match between the tributary slots

indicated in the receiver CTRL and TPID, in both cases, increase or decrease on bandwidth.

Table 2.1: CTRL field functions

Value	Command	Remarks
00	IDLE	Indication that the node has completed LCR and there is no new LCRoperation. IDLE may also be transmitted for a short time at operation start before transmission of the ADD/REMOVE command.
01	ADD	Indication that the tributary slot is to be added to the ODUflex connection
10	REMOVE	Indication that the tributary slot is to be removed to the ODUflex connection
11	NORM	Indication that LCR will be started at the next resize multiframe boundary when sending out NORM command after ADD or REMOVE command at the resize multiframe boundary

Each link connection in the ODUflex trail has its own LCR protocol, like the one shown in Figure 2.15

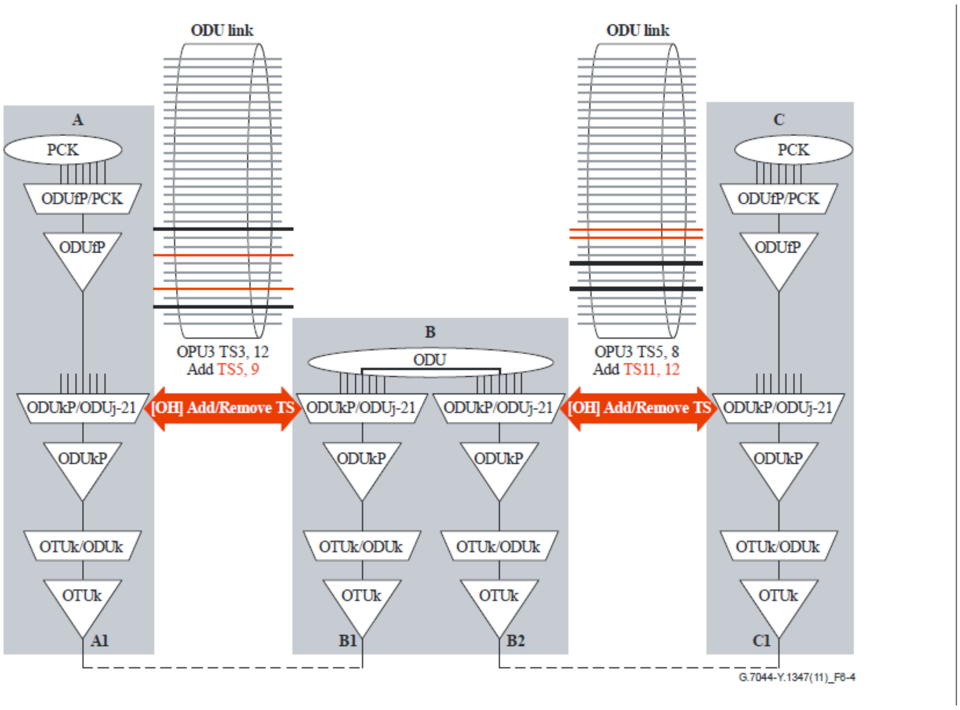


Figure 2.15: LCR protocol [42].

2.2.2 BWR-Bandwidth Resize

Checks for consistent configuration of tributary slots to be added or removed from the ODUflex link connections along the trail and verify the network connectivity of the trail, is composed by:

- **NCS-** Network Connectivity Status, acknowledgement indicator for network connection, used by the sink ODUflex to acknowledge the ODUflex source directly, when the sink receives the correct TSCC value. No intermidiate nodes need to process the signal;

- **TSCC-** Tributary Slot Connectivity Check, checks the connectivity of the link connection and ODUflex connection. Carries information associated with a TS being added or dropped and is propagated hop by hop from source to sink. Initially, his value is set to '0', changing to '1' during the resizing time and reset to '0' after the resizing operation;

- **RP-** Resizing Protocol Indicator is used to indicate if the resizing protocol is carried in the RCOH. For the '1' case, RCOH is carrying resizing protocol. When this bit is set to '0', informs that the resizing process is exited;

- **BWR_IND-** Bandwidth Resize Indicator indicates that the ODUflex source is adjusting the signal's bit rate. Has the '0' value before ODUflex source starts ramping, changing the value to '1' when ODUflex should stop ramping. Is used to trigger the start of the ramp at the downstream nodes, and to signal the rampings end.

As for LCR protocol, a schematic of this protocol is shown in Figure 2.16

2.3 Summary

In this chapter was studied how client signals are mapped for future transport over OTN, the protocols used in this dissertation for OSI layers were explained, finishing with bandwidth and line rate resize, considering ODU levels and bit rates. To start, the IP packet was introduced and identified as major protocol used in network layer. Further, the enhancement of IP packet with MPLS functionalities was addressed, with special interest in IP/MPLS and MPLS-TP, that although similarities have different deployment purposes. The GbE was elected for data link layer protocol, a choice driven by its increasing deployment in current networks. With the aim to allow transportation of the previous signals in OTN, a procedure that allows mapping of signals with and

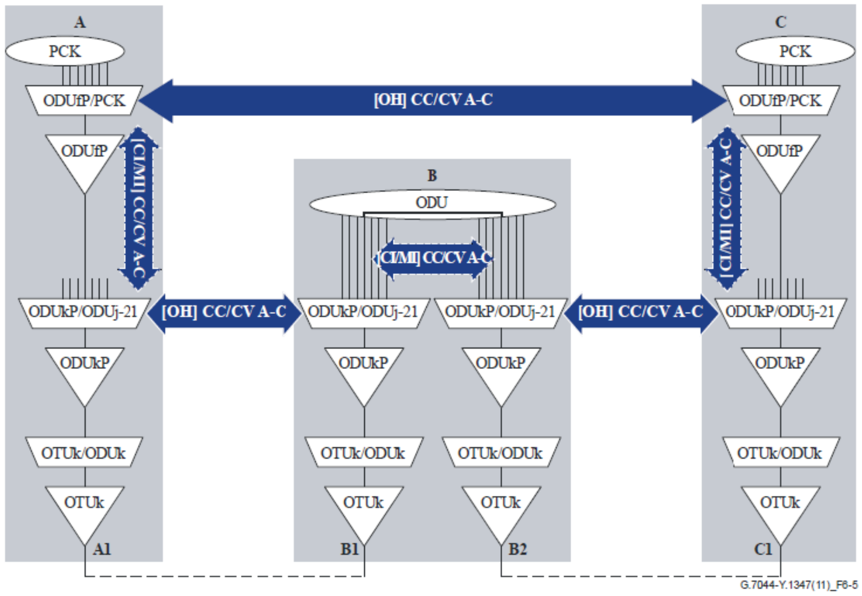


Figure 2.16: BWR protocol [42].

without fixed bit rate was identified in GFP, with the two variants, GFP-T and GFP-F. The signals, now guaranteeing a set of requirements for OTN protocol, are mapped into ODU containers, where special attention is given to ODUflex, used to provide thinner granularity, before the groomed signals are encapsulated into OTUs. To enable grooming process, and the associated protocols, the HAO was studied, with enphasis in LCR and BWR protocols.

For a clearer comprehension, lets consider the Figure 2.17, that succinctly describes the subjects studied in this chapter. The client signals can be entering the network as IP/MPLS, MPLS-TP or GbE signals. In every case, these signals are mapped into ODU containers, that later will originate OTU signals. While GbE signals are directly mapped into ODUs, using GFP-T, IP/MPLS and MPLS-TP signals can be directly mapped into ODUs using GFP-F or originate, before, GbE signals, that will follow the normal course of GbE client signals. For the IP/MPLS client signals, another possibility exists, as these, not only can be mapped into ODU and GbE signals, but also to MPLS-TP signals, proceeding in each case as the other protocol native client signals. The ODU signals, are after groomed together, with the depicted configuration, to achieve better thinner granularity and better bandwidth usage, before the final OTU signals are transported over the network.

For simplicity, let us focus in transporting IP/MPLS client signals, using 10 GbE, after groomed with another 10 GbE and two additional signals of 40 GbE. The IP/MPLS packet is mapped into a 10 GbE signal and encapsulated in a ODU2 container, reserving a 10 Gbps connection. The ODU2 container is after groomed along with one more ODU2 container and two ODU3, requiring a 100 Gbps connection, these four signals, add up to fit an ODU4 container, making the transportation more efficient.

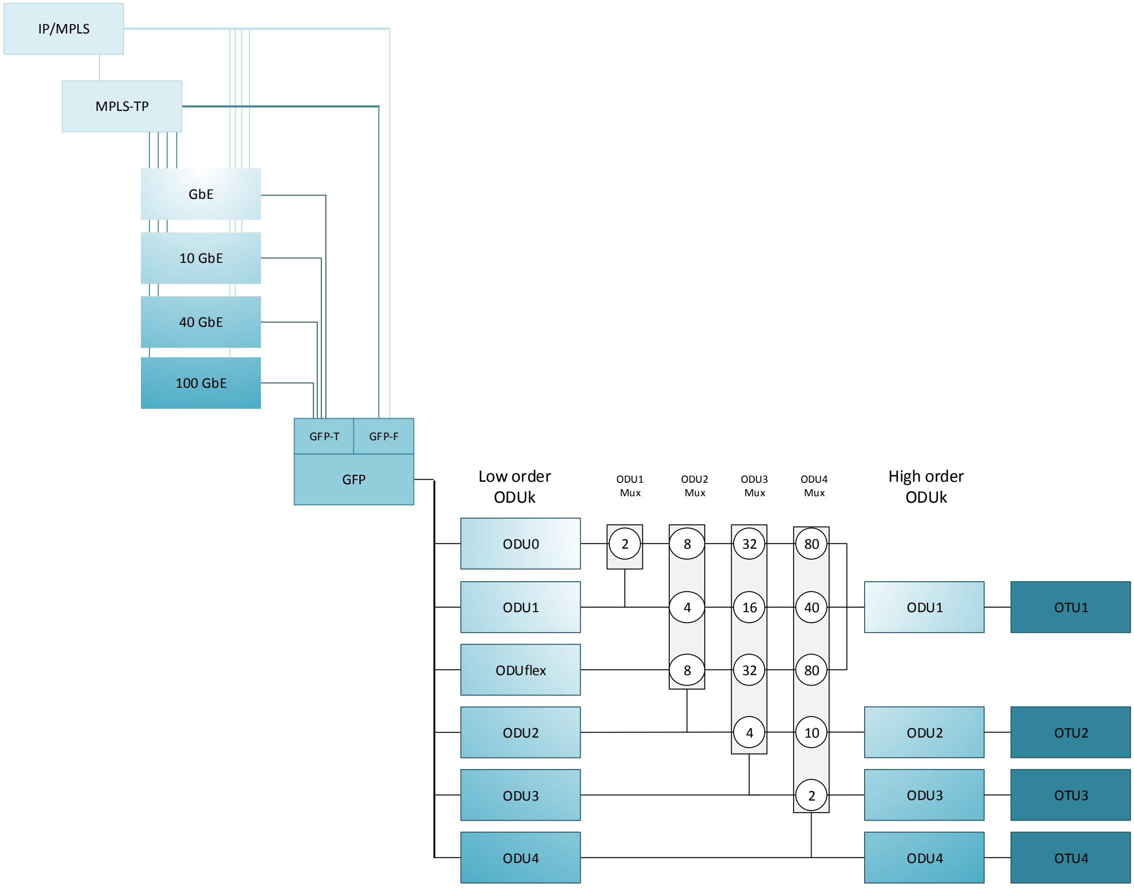


Figure 2.17: Network mapping and grooming overview, including the studied client signals and final containers, along with grooming configuration.

Chapter 3

Network node architecture

In previous chapter were studied the signals to transmit over Optical Transport Network, and the modification it suffers due to different protocols and procedures, to allow packets transportation over an essentially circuit switch network. In Optical Transport Network, a set of network elements is connected through optical fibre, enabling high speed transmission, requiring the elements to provide transport, routing, supervision and survivability to the studied client signals (IP/MPLS, MPLS-TP, GbE and OTN), that represent the client signals to transport. For a better utilization of the network elements and connections, is necessary that low-speed client signals are groomed together, to form higher-speed signals able to be transported in optical domain. The encapsulation and grooming configurations to use throughout this work are the ones documented in Chapter 2.

The client signals to transport over optical networks are, to start, electrical signals with necessity to be handled in electrical devices, where grooming and switching take place before wavelengths are assigned for transportation and further switching is performed in optical devices. Nodes incorporating both types of devices are used in current networks, with Optical-Electrical-Optical (OEO) conversions taking place, leading the expenses related with this elements, motivating the development of solutions that enable some cost savings. In this context transparent and translucent transport modes are seen as upgrades to the previously only existent opaque transport mode. The transport mode(s) used in the network have major impact in the design of electrical and optical devices implemented in each network node, as it dictates the operations to realize in the various nodes, with dependence on either or not OEO is performed. Also, in a network where signals are dealt with in two different domains, is mandatory to bound the specific functions taking place in each and, for the switching operation, taking place on both, clarify the procedures, input and output signals.

This chapter is organized in five sections, with the first one presenting an insight over the transport modes. The second section introduces the physical architecture of a basic network node, with the constituent equipments and connections between modules. In third chapter, the electrical layer functions are described, with focus on electrical packet and circuit switching. A fourth section, where optical switching is explained, along with the equipment that enables it ends the description of network node architecture. This chapter finishes with an overview of the same, in fifth section.

3.1 Transport Modes

In optical networks, the connection between nodes is done using optical fibre, traversed by signals through assigned wavelengths that are optically switched and multiplexed. Before a wavelength is assigned for signal transportation, the signal exists as electrical message, dealt with in electrical equipments that, obeying Optical Transport Network protocol [9], are encapsulated independently of native protocol. Hence, in every node, equipments performing electrical and optical functions have to be present, as shown in Figure 3.1

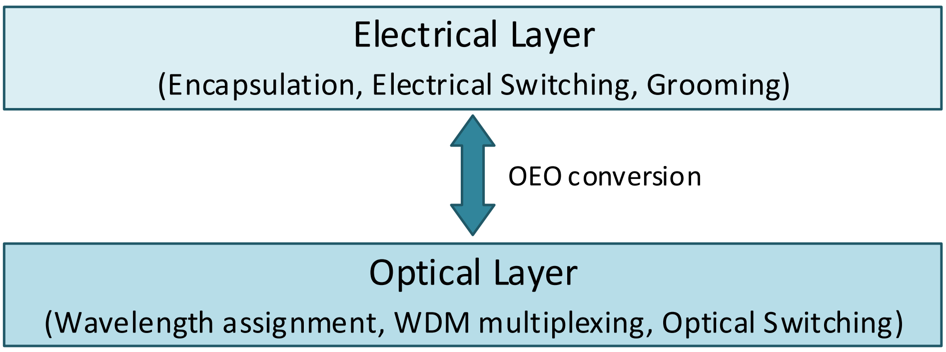


Figure 3.1: Set of functions performed by electrical and optical layers of network node.

For signals to exchange domain, Optical-Electrical-Optical (OEO) conversion has to be realized, with attached expenses, that currently can represent more than half of network node Operational Expenditure. For this reason, a solution had to be developed, to avoid the mandatory OEO conversion realized in every node of the, former only option, opaque networks. Transparent and translucent networks appeared as an enhancement for optical networks, allowing OEO conversion to be held only in end-nodes or some intermediate nodes, respectively. The nodes where OEO is performed, for each transport node, as well as the functions realized by each layer of the network

Table 3.1: Functions performed by each node layer in different nodes, depending on transport mode.

		Electrical Layer	**Optical Layer**
Opaque	End Node	• Encapsulation • Electrical switching • Grooming	• Wavelength assignment • WDM multiplexing
	Intermediate Node	• Encapsulation • Electrical switching • Grooming	• Wavelength assignment • WDM multiplexing
Transparent	End Node	• Encapsulation • Electrical switching • Grooming	• Wavelength assignment • WDM multiplexing
	Intermediate Node		• WDM multiplexing • Optical switching
Translucent	End Node	• Encapsulation • Electrical switching • Grooming	• Wavelength assignment • WDM multiplexing
	Intermediate Node	• Electrical switching* • Grooming*	• Wavelength assignment* • WDM multiplexing • Optical switching

* Perfomed only in intermediate nodes where OEO conversion is realized.

node are presented in Table 3.1. An insight over the transport modes is after given in following subsections.

3.1.1 Opaque transport mode

In opaque transport mode, OEO conversion is realized in every node, with signal regeneration taking place in electrical domain. The set of signals is demultiplexed and individual signals are dropped if end-node has been reached, allowing new signals to be multiplexed with the present ones to continue transport until next node. In optical domain, only WDM multiplexing is performed. On the plus side, this transport mode enables better optical channels capacity usage, as it realizes traffic grooming in every node, granting maximum channel exploitation. Since regeneration is frequent, propagation and accumulation of physical impairments is eliminated. Wavelength utilization is enhanced driven by the lack of necessity to ensure wavelength continuity in intermediate nodes. On down side, the costs associated with OEO conversions are high, both CAPEX and OPEX, as acquisition and power supply for transponders can represent 50 to 70 percent of node expenses [43, 44].

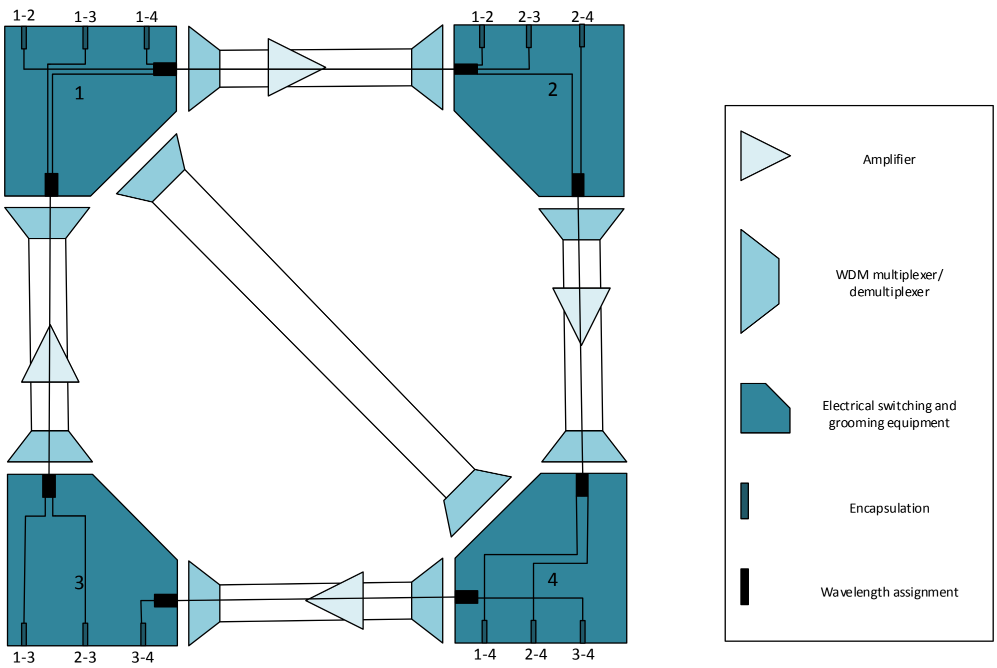


Figure 3.2: Opaque mode operation with a link-by-link grooming scheme [43].

Figure 3.2 illustrates a four nodes network operating in opaque mode. Taking, for example the node 1, can be seen the client signal between nodes one and four is groomed together with client signal between nodes one and two, after in node two, it is groomed together with client signal between nodes two and four. Taking an OEO conversion at every node, this transport mode does electrical switching and grooming, as well as encapsulation. Since wavelength assignment and WDM are the only functions apart from transmission taking place in optical domain, this transport mode only requires modules performing electrical layer functions.

3.1.2 Transparent transport mode

Transparent transport mode, only performs OEO conversion at the end nodes, keeping the signal in optical domain in all intermediate nodes, what forces the signal to traverse longer distances without regeneration, leading to degradation in signal quality but bringing enhancements in network costs by cutting power consumption and equipment acquisition associated with OEO conversions. Because OEO is only realized in end-nodes, wavelengths can only be shared by signals with same source and destination, restricting the wavelength channels utilization, for the same reason, wavelength continuity is a demand [43]. In source nodes, the client signals are assigned with a wavelength for the end-to-end connection. Common with opaque transport mode, in this mode, also switching, grooming and encapsulation are done in electrical domain, but only in a first stage, for signals sharing source and end nodes, after what the signal is switched and routed through the network in optical domain.

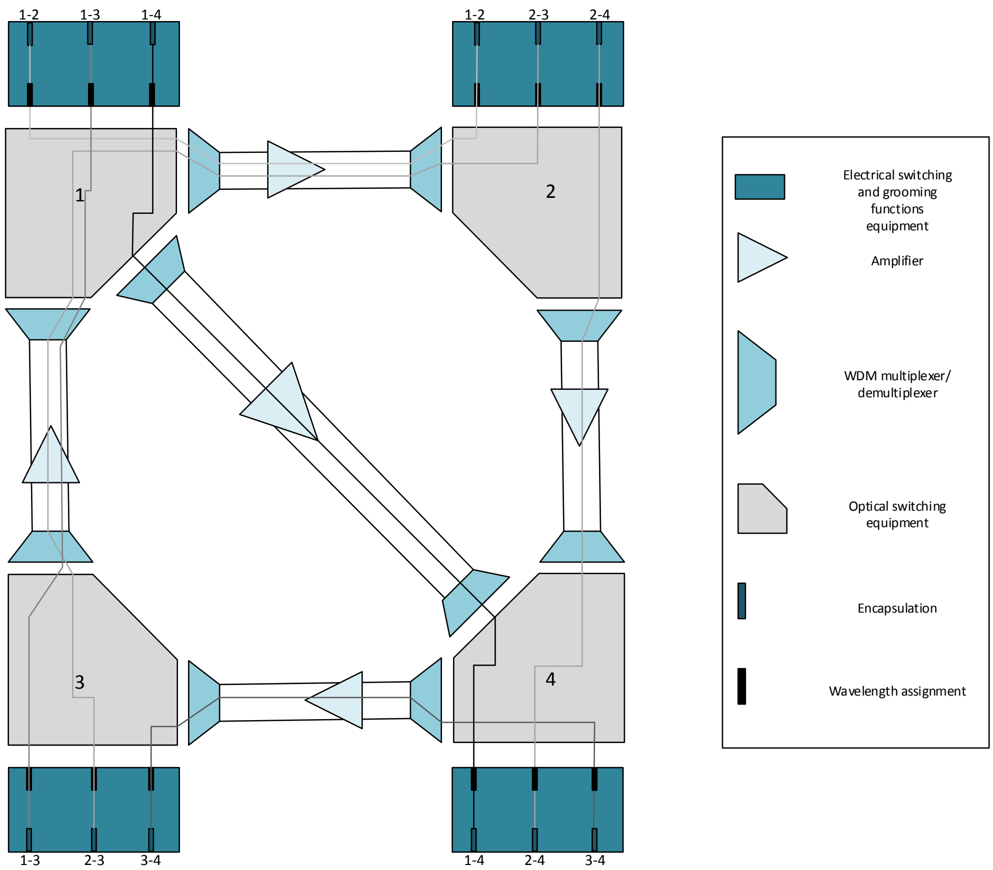


Figure 3.3: Transparent mode of operation with a single-hop grooming scheme [43].

The transparent transport mode operation is illustrated in Figure 3.3, with a four node network. Isolating a single node, e.g. node one, is simple to realize how signals are processed. Client signals arriving in node one, are added in electrical layer and groomed together if source and destination nodes are shared. After, already in optical layer, a dedicated wavelength is assigned for node-to-node connection, that wavelength remains in optical layer for each intermediate node [43]. When signals reach destination, wavelengths are dropped and signals are sent back to electrical layer.

This transport mode, has necessity of modules containing electrical and optical layers. The first, responsible for signal switching and grooming, considering destination nodes, the second incumbent to switch signals throughout the network using different wavelengths for each connection. In this case, an end-to-end connection is reserved for each node pair, with no channel share.

3.1.3 Translucent transport mode

A mix of opaque and transparent transport modes is found in translucent transport mode networks. In these, OEO conversion is performed in specific intermediate nodes, allowing signal regeneration, signal grooming and wavelength assignment, leading to a more efficient wavelength capacity utilization, representing a better overall commitment for the network.

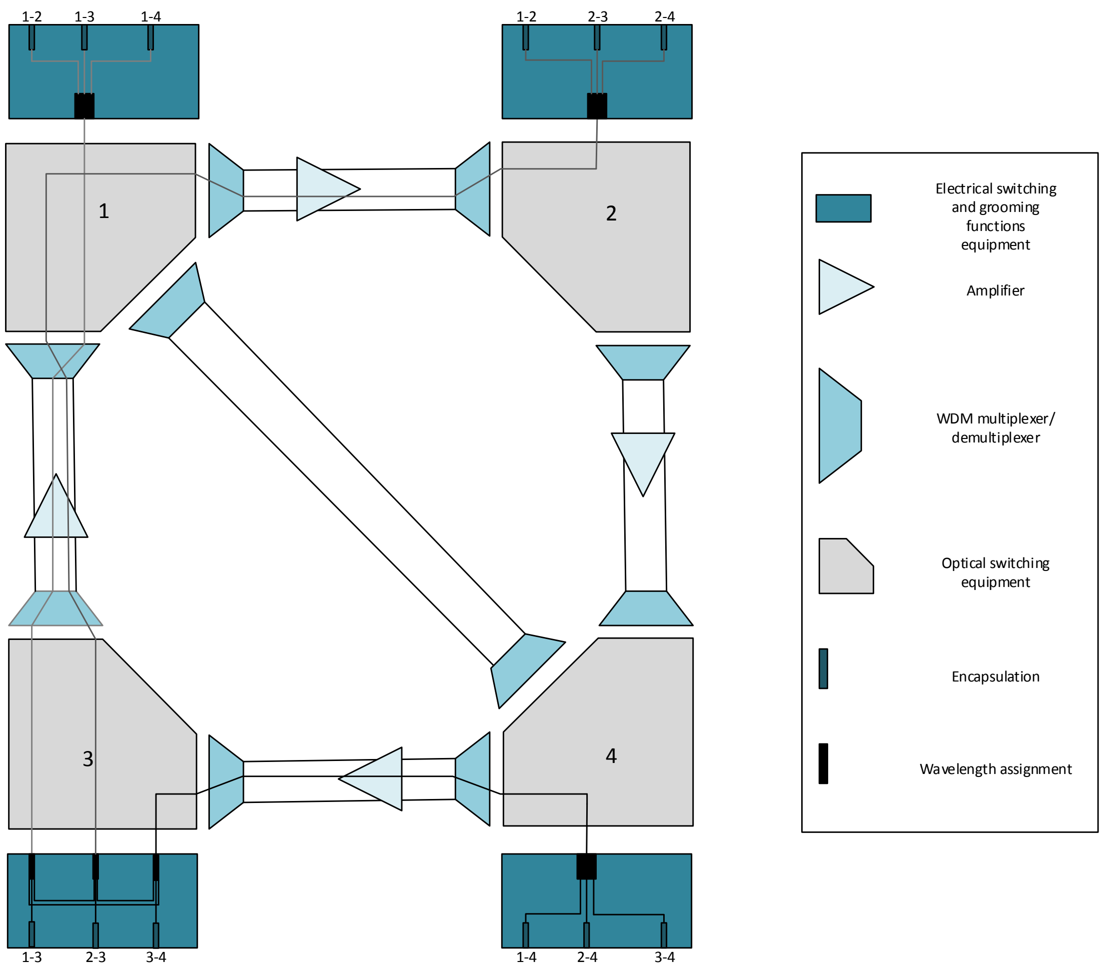


Figure 3.4: Translucent mode of operation with a multi-hop grooming scheme [43].

Figure 3.4 illustrates a translucent network, where node 3 performs OEO conversion functions. Signals entering the node 3 have a specific wavelength channel assigned, depending on destination node. In remaining intermediate nodes, signal does not suffer OEO conversion and is optically switched to next node. To avoid information overload only connections with source or end in node 3 are represented. A signal from node 1 to node 2, enters the network in node 1, where all the signals sharing origin node are groomed together, and are transported to node 3. In node 3, OEO conversion is realized and the signals are groomed with the ones sharing destination node. After, a wavelength is assigned for the set of signals transport until the end node.

In a translucent network, there can be multiple nodes performing OEO conversion. In that cases, the operational mode is similar, if approached as individual blocks capable of scalability. This transport mode is out of the scope of this dissertation and more detail can be found in proper literature.

3.2 Node architectuere

Nowadays networks require nodes capable to efficiently serve increasing requests. The network nodes should, therefore, be customizable systems built by many modules that can be interconnected to enhance the response for growing requirements. As a starting point, let us introduce the physical architecture of a network node, with all the units involved, as illustrated in Figure 3.5, where a basic architecture, able for scalability, is exemplified. The rack, shelves and modules are the three main building blocks in a network node, each of them with well defined functions. The rack provides power to the shelves, while the shelves provide a common infrastructure to the modules [43]. Modules can be electrical or optical devices and both types can be assembled in a same shelf to perform specific functions [43]. Multiple modules can be connected electrically and optically, with electrical connections usually taking place in backplane and optical connections through front panel [43]. These last connections are done using transceivers, that can have short or long reach and implement physical media adaptation functions to transmit and receive optical signals. The points where the connections take place are the ports, which can be of two types: client or line, respectively input and output. The client port does the node interface with client signals, clients with low bit rate that are either entering or exiting the transport network. The line ports receive and emit high bit rate signals that have just been transported and are arriving at a node, or are ready for transmission.

Modules occupy slot spaces in a shelf and some of that slots are reserved for special modules that provide Operations, Administration and Management (OAM) functions.

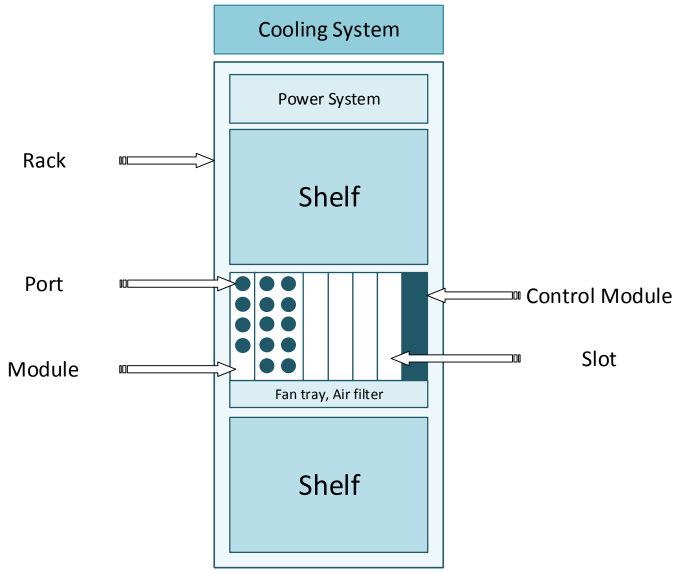


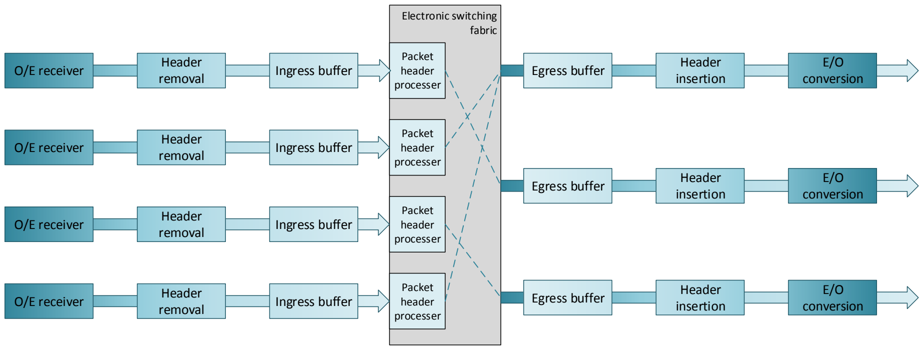
Figure 3.5: Node schematic with port, module, slot, shelf and rack [43].

The shelves are plugged in a rack , that provides mounting mechanisms, along with power supply and cooling system [43]. Also, racks have finite dimensions and can accommodate a limited number of shelves, conditioning the network outgoing, either on acquisition costs, or power consumption expenses. A deep knowledge of the network is crucial, as it influences the number and placement of necessary nodes, to minimize expenses and grant full operability for time to come. As explained, the modules greatly inflate the overall power consumption and acquisition cost of network nodes, requiring a specific design, considering electrical and optical layers.

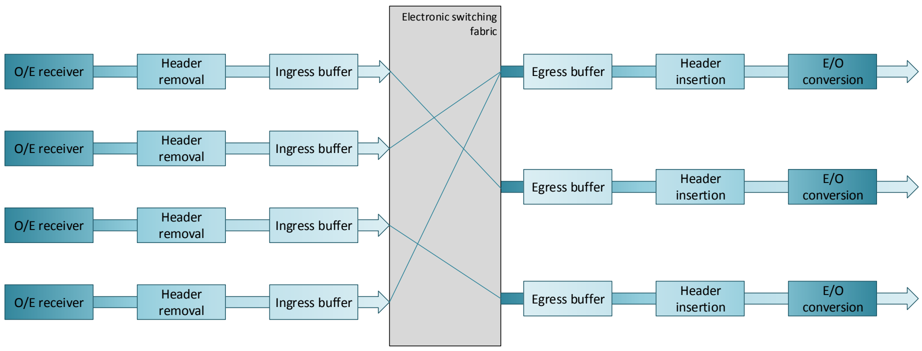
3.3 Electrical layer

The electrical layer of a node is responsible to encapsulate, switch and groom electrical signals, for a better bandwidth usage once these signals are transported in optical domain. It is, although, important not to forget that the electronic signals are mainly packet traffic, before encapsulation in OTN signals, therefore the electrical layer should be able to perform two types of switching: packet and circuit, depending on the module input signals. For the purpose of this work, IP/MPLS, MPLS-TP and GbE signals are considered packet traffic and ODU signals as circuit traffic, with that in mind, Figure 3.6 presents the electrical packet and circuit switching.

The main differences between both are the way switching is done, with no major difference in the way signals are received and transmitted, to and by, the electronic



(a) Electrical packet switching. The dotted line indicates that no fixed connection exists between input and output [45].



(b) Electrical circuit switching. The continuous line indicates a fixed connection between input and output.

Figure 3.6: Electronic switching fabric for packet and circuit switch.

switching fabric. For packet switching are identified packet header processors, responsible for the signals switching considering origin and destination addresses. In circuit switching, since the connections are pre-determined, there is no need to process the signals header, i.e. signals entering a specific port already have an output port assigned. According to the previous difference, and since in packet switching, no pre-determined connections between input and output ports are established, the dotted line in Figure 3.6a represents connections that are not permanent, while the continuous line in Figure 3.6b represents fixed connections. This state in connections being permanent or dynamic plays a major role in signal granularity, due to the fact that in fixed connections, even if no bandwidth is required, the corresponding capacity is allocated, a drawback not present in dynamic connections, that allocate bandwidth capacity depending on requirements for signals transmission, although output ports capacity is permanent. The architecture of nodes to perform packet and circuit switching are addresses in the following subsections, completed by architectures to deploy both of them individually or together.

3.3.1 Electrical packet switching

In a network node meant to realize packet switching in electrical domain, the network node input signal can be IP/MPLS, MPLS-TP and GbE, just to mention the ones used throughout this work. The packet traffic arriving in different input ports travels through a buffer before being processed by an Electrical Packet Switching Module (EPSM) that has the capacity to read the packet destination address, store it until a connection to the desired output port is available and forward it after. In the egress process, another buffer is present, to guarantee a correct grooming of the packet traffic in a circuit traffic signal, in this case an ODU container.

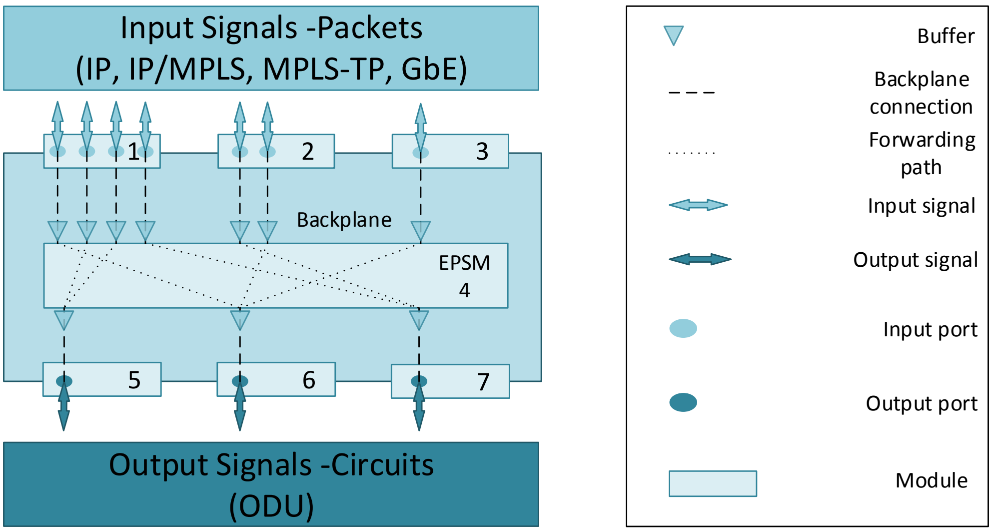


Figure 3.7: Electrical packet switching..

In Figure 3.7 are identified the main blocks of an EPS: the input modules (1, 2 and 3), the output modules (5, 6 and 7) and the Electrical Packet Switching Module (4). The input modules, responsible for signal encapsulation are equipped with short-reach transceivers and the output modules are equipped with long reach transceivers. The connection of both input and output modules with the EPSM is done using backplane communication.

3.3.2 Electrical circuit switching

When paying attention to Optical Transport Network, is noticed the propensity to circuit traffic and switching and for this reason, various individuals and companies defend the necessity to perform circuit switching already in electrical layer. Although some similarities in electrical architecture, the circuit and packet switching have a different operation methods and modules. In circuit switching, as connections are present between input and output ports, the switching module used only has to decide which output ports the incoming signals should be sent to, a function that can be remotely or physically configured.

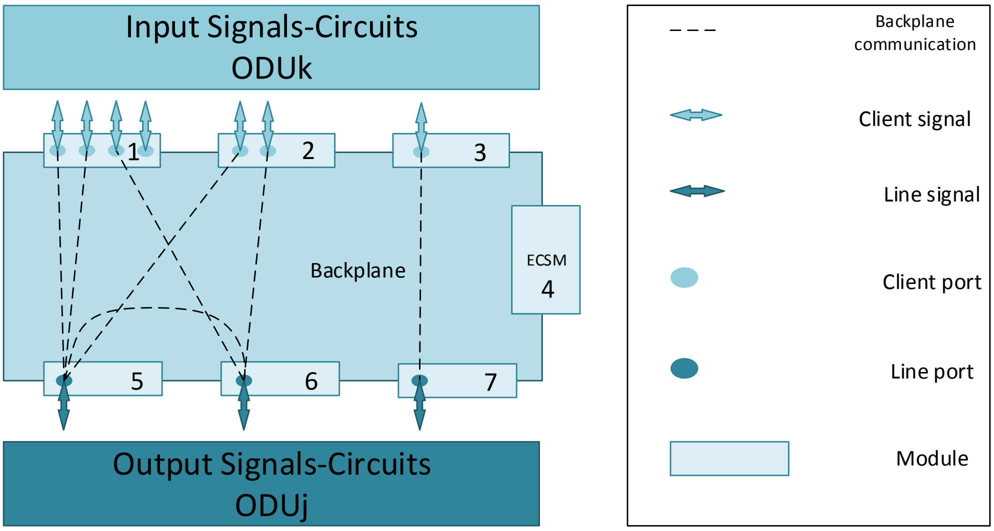


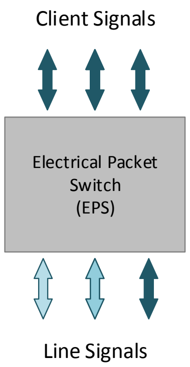
Figure 3.8: Electrical circuit switching..

Figure 3.8 identifies the main blocks of an ECS. The input modules (1, 2 and 3), where signal encapsulation is realized, similar with EPS, also equipped with short-reach transceivers, with different signals entering the node, in this case ODU signals. In the output ports, also equipped with long-reach transceivers, the resulting switching and grooming signals are higher order ODU signals. The first noticed difference is in the Electrical Circuit Switching Module (ECSM) that does not need to perform storing functions, has only to switch the incoming signals to output ports and as the connections are already established, the ECSM only controls the connection taking place through the backplane, with no direct interference over the signals, in sum, only controls the switching, does not perform it and the grooming is a direct consequence of the switching configuration.

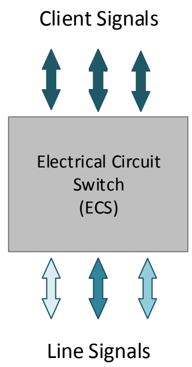
For electrical circuit switching, is also available a simpler architecture, based in muxponders. Muxponder-based architecture implies stricter limitations in switching and grooming configurations, limiting the final signal granularity and for this reason can be considered an outdated solution, despite present in various network nodes.

3.3.3 Electrical switching

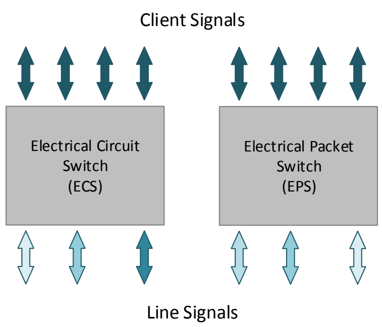
As aforementioned, OTN are mainly used to carry circuit traffic using circuit switching, what poses as a divergence to the current packet traffic increase. The previous EPS and ECS, although completely functional as isolated equipments (Figure 3.9a and Figure 3.9b), can also be assembled together to realize a more robust network node. Two possible solutions are illustrated in Figure 3.9c and Figure 3.9d the first with EPS and ECS built in parallel and the second in a layered architecture.



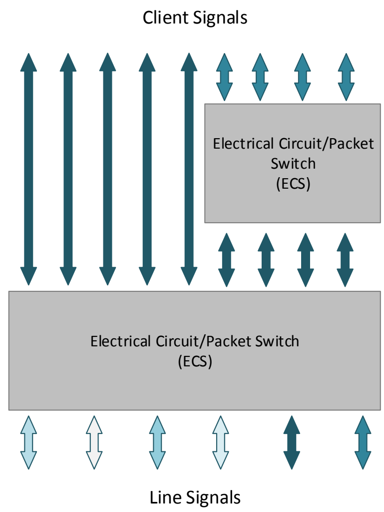
(a) Electrical Packet Switcher (EPS).



(b) Electrical Packet Switcher (EPS).



(c) Parallel architecture



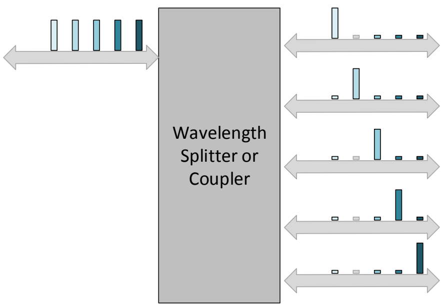
(d) Layered architecture

Figure 3.9: EPS and ECS flexible architectures

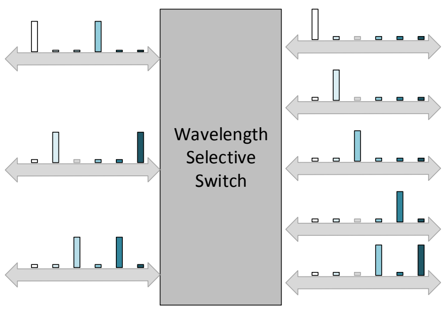
In Figure 3.9c, as depicted, two different switches exists, one for circuit and one for packet traffic switching that albeit being independent devices, able to work isolated, can not use the same wavelengths, i.e. packet and traffic switching resulting signals can not share wavelengths, what implies possible network inefficiencies related with bandwidth exploitation limited by the circuit switching granularity, despite the good bandwidth exploitation introduced by the packet switching. In Figure 3.9d, packet traffic is switched and the resulting circuit traffic signal after enters a circuit switching equipment, while original circuit traffic directly enters the circuit switching device. This way, in the circuit switching equipment, packet and circuit traffic can share wavelengths for transport, leading to a better bandwidth occupation due to a thinner granularity. This solution increases the number of required equipments as, although, using packet and circuit switching equipments, similar to parallel architecture, the circuit switching device has its input and output modules increased, to deal with originally packet traffic.

3.4 Optical layer

The main operations taking place in the optical layer of the node are the Wavelength Division Multiplexing (WDM) and optical switch. In WDM operation, multiple signals are combined for transmission over a single channel, in this case a single optical fibre, at reception the signals are separated (demultiplexing). The optical switch operation consists in assignment of a connection path (wavelength) for signal to be transported. WDM is performed using a Wavelength Splitter or Coupler (WSC), and the realized function is shown in Figure 3.10a, for optical switch is used a Wavelength Selective Switch (WSS), with operation illustrated in Figure 3.10b.



(a) Wavelength Splitter or Coupler (WSC)



(b) Wavelength Selective Switch (WSS)

Figure 3.10: Common building blocks for nodes optical layer [43].

In Figure 3.10a, looking right to left is easy to see the multiplexing of five separate signals in a single one, containing all the previous. Multiple signals are modulated using a laser beam that assigns each of them a different wavelength, that is after transported over an optical fibre channel. In the reverse way, the demultiplexing of a single signal containing various wavelengths is done, with an optical sensor at the receiver side, that separates the arriving signal into various individual ones. The WSS operation, in Figure 3.10b, has indifferent analysis orientation. Signals at the entrance are routed through ports that grant a path for next destination, in case it is a different node, or drops the signal for electrical layer, if the signal has reached destination. WSC and WSS are the basic blocks composing the optical layer, opening space to a multiplicity of module configurations, depending on the add/drop structure. This add/drop structures, OADM provide a cost-effective form to handle traffic passthrough, deciding at each node what wavelengths are to continue or exit the network, with no need to perform OEO conversion of all wavelengths. Figure 3.11 shortly describes the operation of an OADM in a network node.

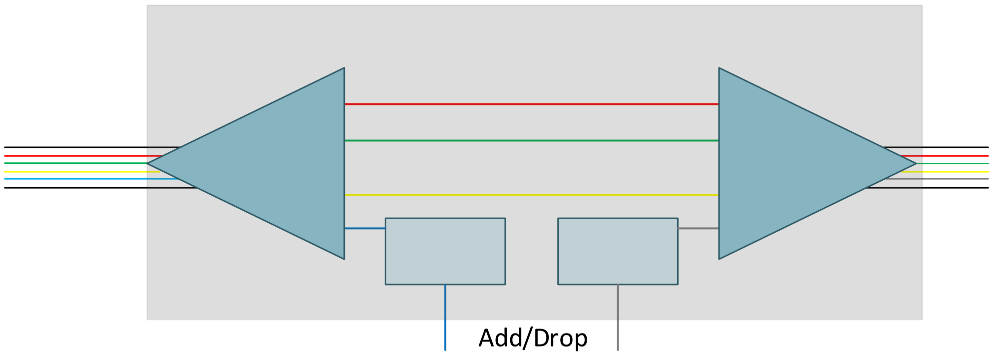


Figure 3.11: Example of optical add/drop multiplexer operation in a network [8].

In the example, the signal modulated with wavelength correspondent to blue is dropped through OADM, and the correspondent to gray a is added. Although in this example the drop of a signal is matched with the add of a new one, that is not necessary, nor is necessary that a signal is drooped for another one to be added, since it is modulated in one available wavelength that is not yet in use.

In the early stages of optical networks, the configuration on signals to add/drop at any node, as well as the paths to forward the signals over were defined at the network deployment and any modification to be made entailed an onsite human intervention. With the spread of optical networks, allied with continuous growth on equipment development and knowledge was possible to perform the reconfiguration of optical switch paths and add/drop structures remotely, the Reconfigurable Optical Add/Drop Multiplexer (ROADM) entered the optical networks equations, allowing operators to escort the network traffic and, based on acquired knowledge, detect behavioral patterns and act accordingly. Let us take a brief look at a normal network, deployed to assist a group of cities, all within a common time zone, is easy to realize the recurrence of low traffic time intervals, where the network can be used to assist other networks, which experience peak interval. Reconfigurability allows the network nodes to efficiently conjugate their low and peak traffic intervals to interoperate with remaining nodes, without daily on-site interventions to modify the optical layer configurations.

ROADMs are built in a similar way to the OADMs, with WSCs and WSSs. Using the same basic blocks, enables a wide combination of add/drop structures, that imposes flexibility restrictions for the node and consequently to the network. Let us assume a basic configuration with four directions for signal to be switched over, three of them with a fixed architecture, and a fourth one free for add/drop architecture choice, as depicted in Figure 3.12, where intuitively, the orientations are named left, right, down and up, and traffic transportation is oriented from up to down, left to right. Wavelengths can be switched over the transmission system, or terminate in the node

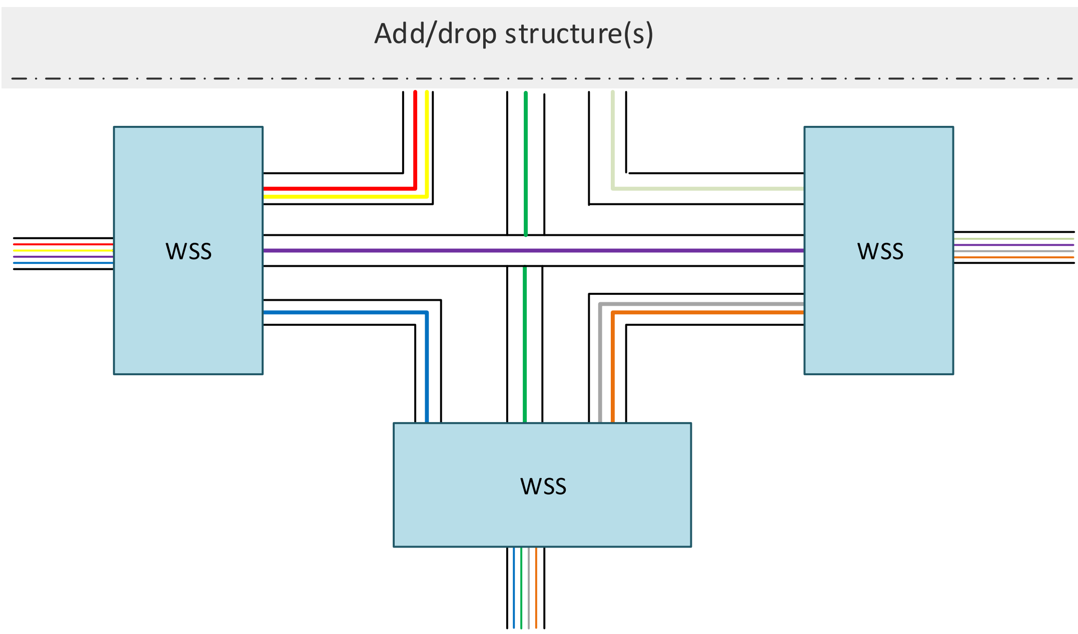


Figure 3.12: Cross connection structure of a ROADM.

Source: Adapted from [43]

and go through the add/drop structure. The red and yellow wavelengths, coming from the left will terminate at the node, also the light grey wavelength coming from the left and green arriving from down will terminate the transmission in the node, through the add/drop structure[1]. The pink, blue, orange and dark gray wavelengths are to continue transmission over the network.

[1]The wavelength can also be entering the network at the add/drop point. To simplify the exem-

The structure presented in Figure 3.12 is called Optical Cross Connect (OXC) and although other structures are available, this will be the elected one for ROADM study. The add/drop structure defines the node flexibility, a set of restrictions the node will present regarding wavelengths acceptance, switching possibilities and the operable contention. We will proceed this study with two different architectures, one with reduced flexibility and other with full flexibility. The fixed frequency and fixed direction ROADM, the first to be addressed, for comparison purpose and familiarity with a restrictive architecture. The second is colorless, directionless and contentionless ROADM. Later in this study, only the last will be considered.

3.4.1 Fixed frequency and fixed direction ROADM

This add/drop structure implementation does not allow any type of flexibility and all reconfiguration presupposes a technician intervention. The ROADM with fixed frequency and direction is exemplified in Figure 3.13. This architecture requires dedicated

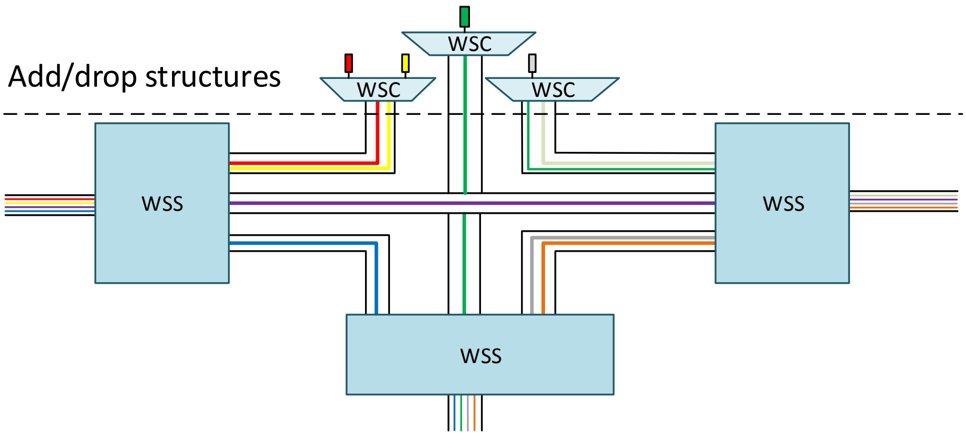


Figure 3.13: Cross connection structure of a ROADM, with fixed frequency and direction architecture [43].

one WSC block per transmission system. The signals have to be sent on fixed wavelength and to one direction. To reconfigure a wavelengths assignment, a transceiver should be placed to the WSC port operating the desired wavelength. Each WSC can only sent and receive signals in a specific direction, moving a wavelength to different direction implies physically moving the transceiver to the WSC desired direcion [43].

plification, is considered the add/drop point as terminator for the wavelengths, with no prejudice for comprehension.

3.4.2 Colorless, directionless and contentionless ROADM

A Colorless, directionless and contentionless ROADM architecture permits full reconfigurability over the three studied aspects. The colorless indicates freedom to remotely modify the wavelengths assigned to each port. The directionless identifies the possibility to redirect the add/drop structure to any channel present in the node. The contentionless informs about the ability to assign any unused wavelength to a transmitter/receiver [2] [43]. An illustration of a colorless, directionless and contentionless ROADM is available in Figure 3.14. Succinctly, describing the add/drop structure, the

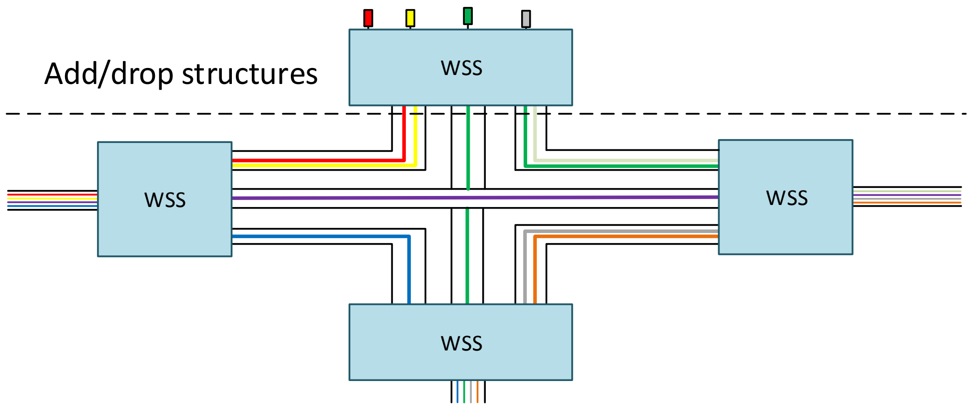


Figure 3.14: Cross connection structure of a ROADM, with colorless, directionless and contentionless architecture. [43]

WSS is responsible to switch any wavelength from an input to output port. The WSS input ports receive the add/drop channels, switching them after through the output ports. As represented by the green signal, as long as the signals travel different paths, they can be connected in a same add/drop structure without blocking.

3.5 Summary

In this chapter were studied the transport modes of operation and architectures to implement in electrical and optical layers of the nodes. A relation between the network node and the signals it processes is the start. It continues by presenting the differences between the different transport modes and respective relation with grooming

[2]Unused in the context refers only to the output port

schemes, for opaque, transparent and translucent modes of operation. The architectures to deploy in each layer are studied. In electrical layer, electrical packet switcher and electrical circuit switcher, for both types of traffic signals. In optical layer, two architectures, with different flexibilities, were depicted. The fixed frequency and fixed direction as an example of a restrictive ROADM and colorless, directionless and contentionless ROADM as opposite, presenting a more flexible architecture.

Chapter 4

Nodes dimensioning

Telecommunication networks are complex and size variable architectures, there is no universal solution that fits majority of scenarios, is therefore mandatory to study the network traffic requests for a correct network projection. One of the principal network elements, claimant for special attention, is the network node, considered the must expensive part of an Optical Transport Network, has the responsibility to aggregate client traffic into wavelengths and switch the wavelengths across transmission systems [43]. Currently, efforts are being carried to increase the capacity provided by wavelengths individually and a somehow contrary effort is done to increase the aggregation granularity. It means, that while the signals to transport over a wavelength are supposed to demand more bandwidth capacity, the client signals that build the transported signal are supposed to decrease or, at least, maintain the individual bandwidth requirements. A solution for this duality passes for multilayer network nodes, capable to perform switch and groom at different rates, increasing with the layer decrease, with layer 3 and layer 2 requiring a lower bit rate switching and thinner grooming than layer 1 [8].

Although the notorious significance of a correct network node design, it is not unusual to neglect restrictions imposed by hardware, being it the rack, shelf and backplane sizes, the availability of modules to deploy, the omission of control modules, among others. A correct and optimized node dimensioning can minimize the total number of required modules, leading to a minimization on the number of racks and shelves, conducting to lower expenses in equipments acquisition, maintenance and power consumption. It is therefore essential to study modules optimization guaranteed to support the network traffic requirements.

In this chapter, organized in four sections, the electrical and optical layer architectures studied in previous chapter are used to build an optimized network node, capable to operate in the also studied transport modes. In the first section, the inputs and assumptions of the dimensioning model for studied architectures are presented. The second section present the optimization model for electrical layer. The optical layer dimensioning model is the focus of third section. This chapter ends with a fourth section that summarizes the work carried over it.

4.1 Dimensioning model

Over the years, since SONET/SDH, dimensioning models considering grooming configurations are part of literature and subject to research. In a bearish thought, is acceptable to think it solely affects the necessary number of ports used to equip the modules. Only when a more realistic and objective study is realized, it is clear to see the influence it brings to the overall networks operation. Hence, it is with better interest that a reduction of the variables set is conducted, by making necessary assumptions that allow to carry a objective work. From the various set of models at disposal, from statistical, heuristic and Integer Linear Programming (ILP), the choice was done over ILP because, although it would lead to another set of assumptions regarding network topology and traffic requirements, it offers an acceptable estimation on the network nodes requirements and prediction of related expenses, while produces an optimal solution for the considered scenarios.

A multilayer network, consisting of N nodes, can succinctly be represented as a graph G=(V, E_c, E_p), with V={1, ..., N} being the set of nodes, E_c= { (o, d) : o, d ∈ V } is the set of nodes exchanging traffic and defining logical topology. The physical links, E_p= { {i, j} : i, j ∈ V }, that defines the physical topology of a network allowing traffic exchange between origin node, o, and destination node, d.

The traffic entering the network at any node is, at first, packet traffic, coming from IP/MPLS, MPLS-TP and GbE routers. Indifferently , the packet traffic to be supported by the network can be represented by a $N \times N$ matrix, *[P]*, consisting of *p(o,d)* elements, depicting the total packet traffic bit rate between the pair of nodes *(o, d)*. As example, *p(2,5)* informs about the total packet traffic bit rate originated in node 2, destined to node 5, intuitively can be concluded that cases when $o = d$ will have no traffic requests. The packet traffic will after be switched and groomed, according with ITU-T recommendation G.709 and form circuit traffic, admitting bit rate c, from the set C= { c: c ∈{1.25, 2.5, 10, 40, 100}}, corresponding to ODUk, being k the index from the set K= { k: k ∈ {0, 1, 2, 3, 4 } }. The result is a 5 × N matrix, $[T_o]$, for each origin node, consisting of *t(d,k)* elements, representing the units of transmission of type k required for traffic transmission to node d. For example, for T_1, *t(2, 3)* informs about the number of ODU3 units required for transmission of the traffic originated in node 1 to node 2.

In electrical layer, to increase bandwidth utilization and wavelengths efficiency, the various *t(d,k)* of different T_o are groomed together, forming higher bit rate signals, henceforth denominated line signals formed by aggregation of ODU signals. The resultant line signals, l, from a set L= { l: l ∈ {2.5, 10, 40, 100 }}, correspond to OTUm, with m being the index form a set M={ m: m ∈ {1, 2, 3, 4 }}, with grooming configuration already illustrated in Figure 2.17, where the ODU signals in the end are directly encapsulated to OTU of the same level. The complete process, as well as data creation is shown in Figure 4.1

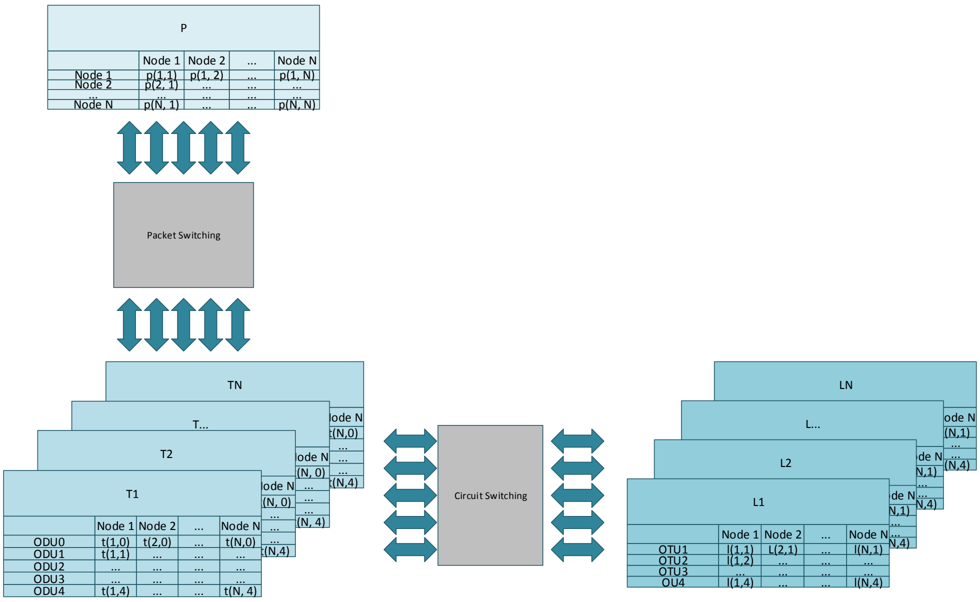


Figure 4.1: Diagram representative of the modifications in client signal processing, performed for each architecture, from EPS and ECS, to optical layer.

The implementation of electrical and optical layers of the node can be done using various equipments, of which, for this work, was chosen Electrical Packet Switcher and Electrical Circuit Switch for electrical layer and fixed frequency, fixed direction ROADMs and colorless, directionless and contentionless ROADMs. These architectures represent the modules to be assembled in the shelves, incorporated in the rack. In Figure 4.2 is an example of a network node, where the rack can accommodate four shelves, occupying one row each, or any combination that does not overpass four rows occupied by the shelves. In this case, the EPS is a module occupying a one raw shelf, as the ROADM, the shelf containing ECS module occupies two rows. From the example, is easy to identify main differences between the used architectures for electrical and optical layers. The electrical layer modules need control module and switching module (Electrical Switching Module (ESM)), the connections between ports and ESM take place using the backplane and for this reason, ports meant to be connected between them need to share a common backplane. In the optical layer, for ROADM, no backplane is required because the connections between ports are performed using optical fibre.

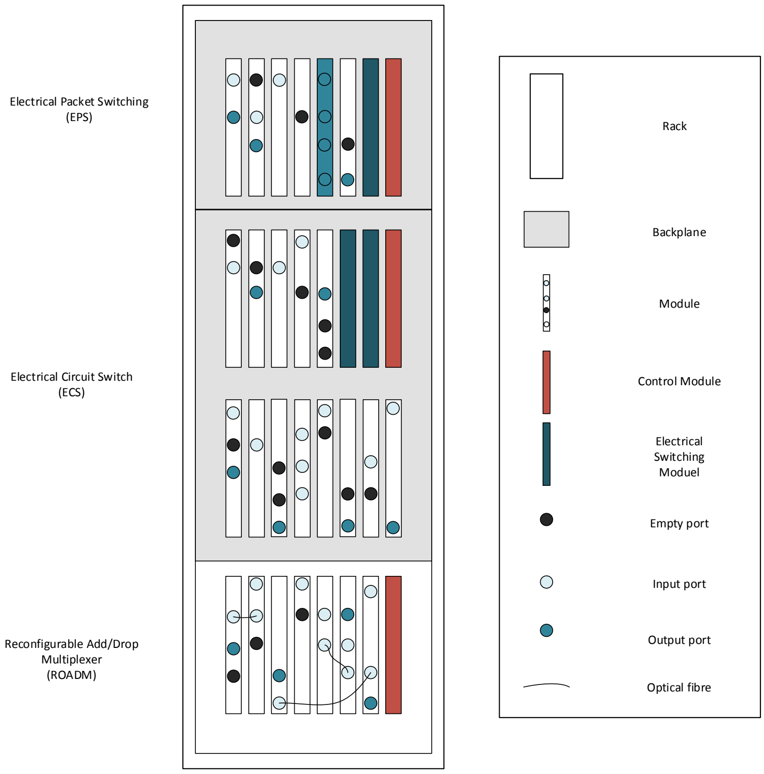


Figure 4.2: Node architecture implementation [43].

4.2 Electrical layer architectures

4.2.1 Electrical packet switching

The optimization model focuses in dimensioning the output modules required after packet traffic switching and grooming. The optimization of output modules $M_c^{ps}(o)$ is achieved through minimization of the required output ports with bit rate c in every node o, with P_c^{ps} being the number of output ports accepted by output module, using the following [43]

$$
\begin{aligned}
& \textit{minimize} \quad \sum_{c\in C}\sum_{o\in V} M_c^{ps}(o); && (4.1)\\
& \textit{subject to} \\
& \quad \sum p(o,d) \leq \sum_{c\in C} cO_c(o,d), \qquad \forall (o,d)\in E_c; && (4.2)\\
& \quad M_c^{ps}(o) \geq \left\lceil \frac{\sum_{d\in V} O_c(o,d)}{P_c^{ps}} \right\rceil, \quad \forall c\in C, \forall (o,d)\in E_c; && (4.3)\\
& \quad O_c^{ps}(o,d) \in \mathbb{N}_0, \qquad \forall c\in C, \forall (o,d)\in E_c; && (4.4)\\
& \quad M_c^{ps}(o) \in \mathbb{N}_0, \qquad \forall c\in C, \forall o\in V. && (4.5)
\end{aligned}
$$

The objective function 4.1 is the generic cost function intended to minimize the number of output modules in every origin node. The constraint 4.2 guarantees the total bandwidth provided by all circuit traffic signals, $O_c^{ps}(o,d)$ is higher or equal to the bandwidth requested by all packet traffic between the same node pairs. Constraint 4.3 ensure the number of output modules with bit rate c is higher or equal to the relation between the value of required traffic for all destination nodes, and the number of output ports supported by the modules.Constraints 4.4 and 4.14 defines O_c^{ps}(o,d) and $M_c^{ps}(o)$ as non negative integer variables [43].

The output modules are equipped with long-reach transceivers. The total number of long-reach transceivers, with bit rate c, in node o, $Tsv_c^{ep}(o)$, can be calculated by [43]:

$$Tsv_c^{ps}(o) = \sum_{d\in V} O_c^{ps}(o,d), \quad \forall c\in C, \forall o\in V. \tag{4.6}$$

The total number of slots needed for electrical packet switching in node o, $S_{tot}^{ep}(o)$, is then [43]:

$$S_{tot}^{ps}(o) = \sum_{c\in C} M_c^{ps}(o) S_c, \quad \forall o\in V. \tag{4.7}$$

With S_c^{ps} representing the number of slots occupied by circuit traffic signals with bit rate c. Also, a control module and an EPSM are needed for each shelf.

4.2.2 Electrical circuit switching

The circuit traffic signals aforementioned are received by input modules of the ECS, equipped with with short-reach transceivers, accepting bit rates c. The total number of short-reach transceivers, with bit rate c in node $o, Tsv_c^{cs}(o)$, is then given by [43]:

$$Tsv_c^{cs}(o) = \sum_{d \in V} t_c(o,d), \quad \forall c \in C, \forall o \in V. \tag{4.8}$$

Since the modules can have multiple ports, the number of modules accepting circuit traffic signals correspondent to transmission unit k, required in the node o, $M_c^{cs}(o)$, is [43]:

$$M_c^{cs}(o) = \left\lceil \frac{\sum_{dinV} t_c(o,d)}{P_c^{cs}} \right\rceil, \quad \forall c \in C, \forall o \in V. \tag{4.9}$$

. being P_c^{cs} the number of output ports accepting signals with bit rate c. The circuit traffic is, after, groomed to form line signals. The ILP used to minimize the number of output modules in electrical layer responsible for circuit switching, therefore line modules, M_l(o) is the following [43]:

$$\textit{minimize} \quad \sum_{l \in L} \sum_{o \in V} M_l(o); \tag{4.10}$$

subject to

$$\sum_{c \in C} c t_c(o,d) \leq \sum_{l \in L} l O_l(o,d), \quad \forall (o,d) \in E_c; \tag{4.11}$$

$$M_l(o) \geq \left\lceil \frac{\sum_{d \in V} O_l(o,d)}{P_l} \right\rceil, \quad \forall l \in L, \forall o \in V; \tag{4.12}$$

$$O_l(o,d) \in \mathbb{N}_0, \quad \forall l \in L, \forall (o,d) \in E_c; \tag{4.13}$$

$$M_l(o) \in \mathbb{N}_0, \quad \forall l \in L, \forall o \in V. \tag{4.14}$$

Similar with the case for EPS, the objective 4.10 is the generic cost function to minimize the number of output/line modules in the network [43]. Constraint 4.11 ensures the bandwidth provided by all line signals between nodes o and d is higher or equal than the bandwidth requested by the circuit traffic signals, between the same pairs of nodes [43]. Constraint 4.12 guarantees 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 available in the module, P_l [43]. Finally, constraints 4.13 and 4.14 define variables $O_l(o,d)$ and $M_l(o)$ as non negative integer values. The differences to EPS dimensioning resides mainly in the input and output signals.

The output modules are equipped with long-reach transceivers, with bit rate l, in the node o, $Tlv_l^{cs}(o)$, is [43]:

$$Tlv_l^{cs}(o) = \sum_{d \in V} O_l(o,d), \quad \forall l \in L, \forall o \in V. \tag{4.15}$$

The number of slots for input and output modules at node o, for circuit switching, $S^{cs}_{tot}(o)$, is achieved by [43]:

$$S^{ps}_{tot}(o) = \sum_{c \in C} M^{cs}_{c} S^{cs}_{c} + \sum_{l \in L} M_l(o) S_l, \quad \forall o \in V. \tag{4.16}$$

Where S^{ps}_{c} is the number of slots occupied by the input modules with bit rate c and S^{ps}_{c} is the number of slots occupied by output modules with bit rate l. Similar with EPS, one control module and one ECSM are needed.

4.3 Optical layer architectures

The optical layer is formed by ROADMs, responsible for multiplexing and switching the multiple wavelength signals traversing the between an origin o and destination d node. The number of wavelengths depends on the electrical layer architecture and, for the considered case, the total number of wavelengths, between nodes o and d, $L^{es}(o, d)$ [43]:

$$L^{es}(o, d) = \sum_{l \in L} O_l(o, d), \quad \forall (o, d) \in E_c. \tag{4.17}$$

The wavelength signals are, after, routed through the physical links$\{i,\ j\}$. The physical topology, E_p and the number of transmission systems installed $U(i,j)$ are inputs for the ROADM dimensioning model, used to calculate the number of transmission systems, defining the nodal degree, $\sigma(i)$ [43]

$$\sigma(i) = \sum_{j \in V} U(i, j), \quad \forall i \in V. \tag{4.18}$$

And the maximum nodal degree admitted for each node, is limited by the number of output potrs in the $1 \times P$ WSS used in the cross connect structure, as well as for the number of required add/drop structures. Hencefore, the maximum nodal degree at node i, $\sigma^{max}(i)$ [43]:

$$\sigma^{max}(i) = P + 1 - A(i), \quad \forall i \in V. \tag{4.19}$$

Being $A(i)$ the number of add/drop structures in node$i$.

In ROADM architectures, one 1 × P WSS module and one pre-amplifier are used for transmission system, making the total number of 1 × P WSS, Mwssi, and pre bosster amplifiers, Mampi, used in the structure calculated by [43] :

$$M_{WSS}(i) = M_{amp}(i) = \sigma(i), \quad \forall i \in V, \tag{4.20}$$

For the specific case of a colorless, directionless and colorless ROADM is required one P_i P_o WSS per add/drop structure, so the total number of add/drop structures of node i, $P_{ads}^{CDC}(i)$ is calculated using [43]:

$$P_{ads}^{CDC}(i) = \sum_{d \in V} L^{es}(o,d), \quad \forall i \in V : i = o. \tag{4.21}$$

To accommodate the $P_{ads}^{CDC}(i)$ channels, one or more add/drop structures can be required. In such cases, cascades of 1 × P WSS are avoided, as it limits the contentionless functionality. The total number of $P_i \times P_o$ WSS required at node i, $M_{mwss}^{ads}(i)$, is equal to the number of add/drop structures and, is [43]

$$A(i) = M_{mwss}^{ads}(i) = \left\lceil \frac{P_{ads}^{CDC}(i)}{P_i} \right\rceil, \quad if P_{ads}^{CDC}(i) \leq P_i \left(P_o - \sigma(i) + 1\right), \forall i \in V. \tag{4.22}$$

The total number of sots required at node i in colorless, directionless and contentionless ROADM, $S_{tot}^{CDC}(i)$, is calculated [43]:

$$S_{tot}^{CDC}(i) = M_{WSS}(i) S_{WSS} + M_{amp}(i) S_{amp} + M_{mwss}(i) S_{mwss}, \quad \forall i \in V. \tag{4.23}$$

With S_{mwss}^{ads}, the number of slots required by the $P_i \times P_o$ WSS module in the add/drop structure. The number of shelves, glsMsfCDCi, and control modules, $M_{ctr}^{CDC}(i)$, required in node i for colorless, directionless and contentionless ROADM is then [43]:

$$M_{sf}^{CDC}(i) = M_{ctr}^{CDC}(i) = \left\lceil \frac{S_{tot}^{CDC}(i)}{S_{sf} - S_{ctr}} \right\rceil, \quad \forall i \in V. \tag{4.24}$$

4.4 Summary

This chapter studies the dimensioning models for electrical and optical layer architectures further considered. Before introduction of the dimensioning models, the set of assumptions is presented, along with traffic modifications suffered along the operations taking place in different architectures. An overall node architecture, capable to perform the required switching and grooming functions is explained after, illustrating the assembly scheme. ILP models for EPS, ECS and colorless, directionless and contentionless ROADM architectures is developed, considering minimization only of output modules that, in turn, minimize the remaining necessary equipments.

Chapter 5

Results

In this chapter, the previous knowledges are assembled to allow dimensioning and optimization of a network node. As stated before, this process is of major importance, as the nodes are responsible not only to perform a variety of functions, but also are the network element with largest associated costs. Usually, the studies regarding network nodes focus on physical and logical topologies, identifying the solution to deploy based on network resilience. In the works where the network nodes are dimensioned and optimized according to expected traffic, usually are considered nodes already receiving circuit traffic, that after realize a result-oriented study regarding the use of optical switching equipments. Also in literature is possible to find studies comparing the different types of Reconfigurable Optical Add/Drop Multiplexers to use, that best match the network requirements. The simulation carried along this work intends to introduce a realistic comparison for a network where the node operate in three different scenarios. The first scenario, where the node performs packet switching, in electrical layer, alone, in an opaque network. In the second scenario, electrical circuit switching functions and equipments are added to the node, for packet and circuit switching in electrical layer, keeping the opaque transport mode. The final scenario, where colorless, directionless and contentionless ROADMs are introduced in the node, changing the transport mode, from opaque to transparent and using Optical Circuit Switch (OCS).

This chapter is organized in six sections, reserving the first to an objective definition of simulation scenario, where logical and physical topologies to use are presented, along with other relevant definitions and assumptions, as is the case of traffic requests for the network and routing table for opaque transport mode. The following three sections present, for each simulation scenario aforementioned, the CAPEX and OPEX results, considering a constant traffic request between network nodes. In the fifth section is studied the response of each simulation scenario for increasing traffic requests. The sixth and last section of this chapter summarizes the conclusions obtained from the different analyses.

5.1 Scenario definition

The logical and physical topologies possible for deployment in a network are vary varied, depending on the number of nodes and required protection, it is, for this reason, impossible to realize a solution capable to cover all the possibilities. In this work, a network as the one illustrated in Figure 5.1 is used, with a total of six nodes, with bidirectional connections as shown. In the chosen network, every node can accept

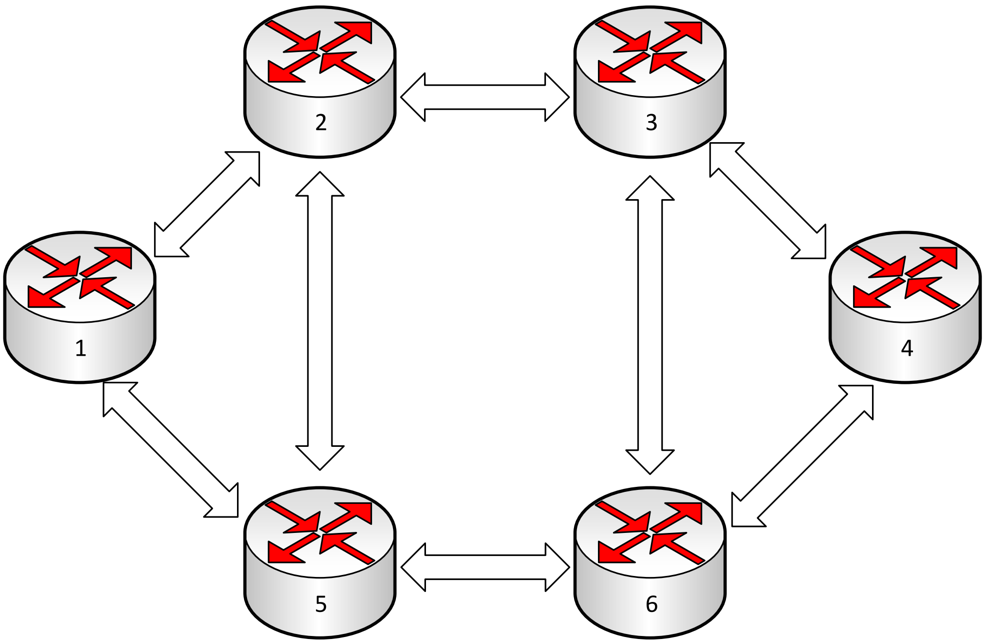


Figure 5.1: Network example used as simulation scenario, with 6 nodes connected.

packet traffic, meaning every node is an origin node, *o*, and the traffic can be destined to any other node, *d*. In opaque transport mode, every node is connected only to adjacent nodes, introducing the necessity for a routing table, able to decide which are the intermediate nodes the traffic has to cross, when the origin and destination nodes are not adjacent. This routing is defined by Table 5.1, where origin, destination and intermediate nodes are explained for each connection demand. The routing table applies only for opaque transport modes, as in transparent transport mode connection exists between any pair of origin and destination nodes.

Given the unpredictable nature of the traffic demands, is very unlikely that any

Table 5.1: Routing table for opaque transport mode

Ingress node	Egress node	Intermediate node
1	2	2
	3	2
	4	2
	5	5
	6	5
2	1	1
	3	3
	4	3
	5	5
	6	5
3	1	2
	2	2
	4	4
	5	6
	6	6
4	1	3
	2	3
	3	3
	5	6
	6	6
5	1	1
	2	2
	3	6
	4	6
	5	6
6	1	5
	2	5
	3	3
	4	4
	5	5

rigid prediction could prove to be accurate. To overpass this difficulty, in this work, no division between the different types of packet traffic request is done. Is considered that the traffic between any pair of nodes, *t(o,d)*, obeys a Gaussian distribution, following equation 5.1, centered in μ and standard deviation σ.

$$t(o,d) = f(x,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad \forall x \in \mathbb{R}, \forall \mu \in \mathbb{R}, \sigma > 0 \tag{5.1}$$

During the different simulation scenarios exists the necessity to normalize the acquisition costs and power consumption for the different equipments used. Table 5.2 presents the outcomes related with the electrical layer switchers, both EPS and ECS, worth notice that for EPS, the power consumption is mainly driven by the output modules, with remaining shelf consumptions neglected. Table 5.3 refers to transceivers and transponders expenses, the transceivers are used for connections between layers in the same network node and transponders to perform the domain OEO conversion. In the absence of accurate information regarding transponders of lower capacity, the minimum value used is the one correspondent to 10 Gbps. For last, Table 5.4 is related with the costs with the ROADM equipments.

Table 5.2: Electrical layer equipments acquisition costs and power consumption [43, 46, 47].

Electrical packet switch			
Interface type		**Acquisition cost (SCU)**	**Power consumption**
48 x 1 Gbps		28,55	10 W/Gb
40 x 10 Gbps		29,5	10 W/Gb
10 x 40 Gbps		31,89	10 W/Gb
4 x 100 Gbps		36	10 W/Gb
Shelf (16 slots)		53,79	
Shelf (32 slots)		295,92	
Shelf (64 slots)		550,64	
Shelf (128 slots)		965,87	
Electrical circuit switch			
Interface type		**Acquisition cost (SCU)**	**Power consumption**
48 x 1 Gbps		3,05	6 W/Gb
48 x 2,5 Gbps		4,5	6 W/Gb
40 x 10 Gbps		6	3,4 W/Gb
10 x 40 Gbps		8,32	3,5 W/Gb
4 x 100 Gbps		14,4	3,6 W/Gb
Shelf	EPSM	3	200 W
(16 slots)	CTRL	8,3	400 W
Shelf	EPSM	3,5	225 W
(32 slots)	CTRL	13	600 W
Shelf	EPSM	6	300 W
(64 slots)	CTRL	31	900 W
Shelf	EPSM	10	500 W
(128 slots)	CTRL	76	1200 W

Table 5.3: Transceivers and transponders acquisition costs and power consumption[43, 46, 47].

Transceivers		
Interface type	**Acquisition cost (SCU)**	**Power consumption (W)**
1.25 Gbps	0,02	1
2,5 Gbps	0,05	1
10 Gbps	0,1	3,5
40 Gbps	0,4	8
100Gbps	1,4	15
Transponders		
Interface type	**Acquisition cost (SCU)**	**Power consumption (W)**
10 Gbps	1	50
40 Gbps	6	100
100 Gbps	15	150

Table 5.4: Optical layer equipments acquisition costs and power consumption [43, 46, 47].

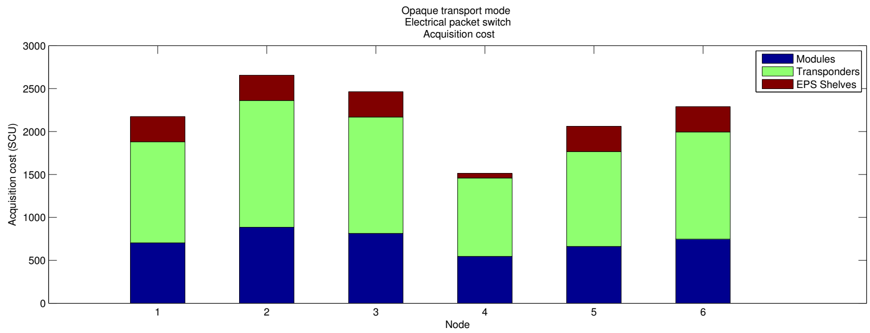
ROADM		
Interface type	**Acquisition cost (SCU)**	**Power consumption (W)**
Pi x Po WSS (9 x 9 ports)	48	55
Control	5,3	300

With the definitions and assumption presented in this section, the simulation of packet and circuit switching in electrical layer and circuit switching in optical layer can be performed, with the belief that the obtained results suit a generality of networks.

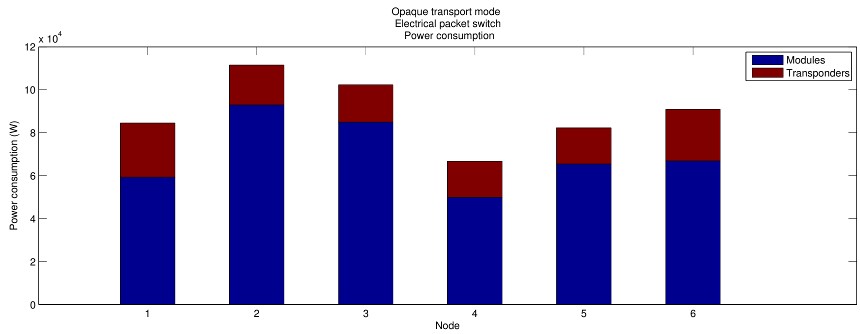
5.2 Opaque transport mode with electrical packet switching

The first simulation scenario refers to a network opearting in opaque transport mode, with the network nodes equipped with EPSs solely. This way, the traffic is received in input modules, neglected in this simulation due to unpredictability in incoming traffic and because is affects the different architectures with equal parameters. The traffic is after switched in the EPS and forwarded to output modules, considering the origin and destiny nodes, as well as intermediate nodes, if needed. In opaque transport mode, the signals need to perform OEO conversion in every node, reason why in this scenario, transponders are used instead of transceivers. The transponders, equip every output port available in the output module, disregarding the port involved being or not in use.

According with equation 5.1, this simulation used μ= 1Tbps and σ= 25%. The obtained results are present in Figure 5.2, where Figure 5.2a represents the acquisition costs with equipment, for each node, and Figure 5.2b informs about the power consumption of the same. As expected, in intermediate nodes, both acquisition costs



(a) Opaque EPS only acquisition costs



(b) Opaque EPS only power consumption

Figure 5.2: Simulation result for opaque transport mode, using only EPS, for 1 Tbps mean traffic between nodes.

and power consumption witness an increase. This effect comes from the fact that more traffic is handles in these nodes, in contrast with nodes with lower nodal degree. Worth notice also that the main drivers for outcomes in network nodes are the modules to implement, confirming the usefulness of the mathematical models, once this equipments are the main focus. For every node, the number of equipments, of different types, can be found in Table 5.5

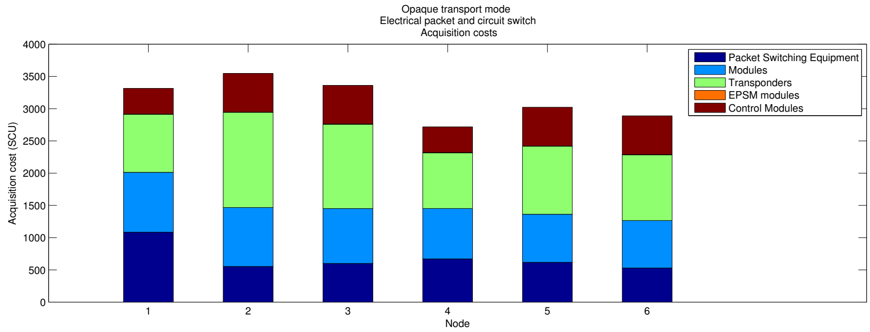
Table 5.5: Equipments used in opaque transport mode, with EPS.

Opaque transport mode							
Electrical packet switch							
		Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
Transponders	10 Gbps	336	96	96	192	144	288
	100 Gbps	56	92	84	48	64	64
Modules	48 x 1	7	2	2	4	3	6
	4 x 100	14	23	21	12	16	16
Shelves	16 slots	0	0	0	1	0	0
	32 slots	1	1	1	0	1	1

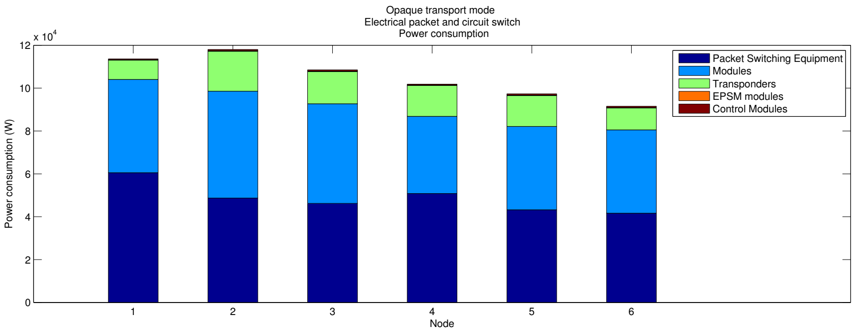
5.3 Opaque transport mode with electrical packet and circuit switching

In this second scenario, the network continues operating in opaque transport mode, but the network nodes are equipped with EPS and ECS architectures. The EPS handles only the traffic correspondent to the specific node, the additional effort of handle the traffic passing through intermediate nodes is performed by the ECS. This way, the traffic entering the network node is switched and groomed first in EPS devices, and further transmitted to the ECS equipment through short-reach transceivers, deployed in equal number in the EPS output and ECS input modules. The traffic is after forwarded to next node where traffic can exit the network, or be groomed with traffic that shares next destination node. For the signals to be transmitted, the output ports of the output modules are equipped with transponders. Again, every output port is equipped with transponders, either or not being used. Since in ECS architecture.

Equation 5.1 is used, again, with the same values, μ= 1 Tbps and σ= 25%. The simulation results, for this scenario are illustrated in Figure 5.3. Figure 5.3a, referring to acquisition costs and Figure 5.3b referring to power consumption, for individual nodes. The first feature noticed is the more flat distribution of the expenses related with the EPS equipments, expectable, since no extra traffic is handled in intermediate nodes, the fluctuation of the same is due only to traffic requests variations. Hence the traffic handle in intermediate nodes is performed by the ECS architecture, there is a justified increment in the expenses related with these equipments. For the traffic requests in this scenario, is possible to verify that the increase in acquisition costs has bigger impact than power consumption. This last characteristic can become a major advantage, as equipment prices for ECS equipments are predicted to drop significantly



(a) Opaque EPS and ECS acquisition costs



(b) Opaque EPS and ECS power consumption

Figure 5.3: Simulation result for opaque transport mode, using EPS and ECS, for 1 Tbps mean traffic between nodes.

over the next years, with efforts being made to increase the capacities available for circuit signals transportation. The equipments used in individual nodes, for architecture, are presented in Table 5.6, for more detail.

5.4 Transparent transport mode using EPS, ECS and OCS

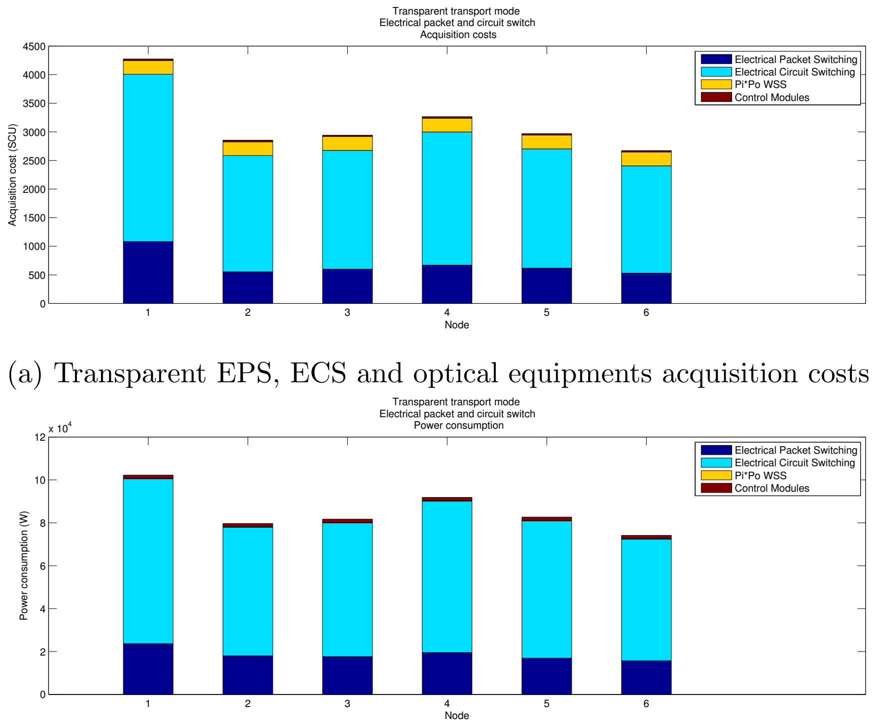
The last simulation scenario respects a network operating in transparent transport mode, with network nodes equipped with EPSs and ECSs in electrical layer and colorless, directionless and contentionless ROADMs in electrical layer. The architectures in electrical layer behave similar with previous scenarios, main difference in the absence of necessity to handle pass through traffic in intermediate nodes. The traffic forwarded in output ports, in optical domain, traverses the network through the ROADMs, where decisions are made, to add, drop or continue the signals transported in wavelengths. The traffic arriving at a node that is not destination passes through it, with no OEO conversion, therefore no processing in electrical architectures.

The traffic generation is kept equal, from previous simulations, with μ= 1 Tbps

Table 5.6: Equipments used in opaque transport mode, with EPS and ECS.

Opaque transport mode							
Electrical packet switch							
		Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
Transceivers	10 Gbps	336	0	144	192	240	96
	100 Gbps	56	48	44	48	40	40
Modules	48 x 1	7	0	3	4	5	2
	4 x 100	14	12	11	12	10	10
Shelves	16 slots	1	1	1	1	1	1
Electrical circuit switch							
		Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
Transponders	10 Gbps	0	6	48	144	96	0
	100 Gbps	60	92	84	48	64	68
Modules	48 x 1	0	2	1	3	2	0
	4 x 100	15	23	21	12	16	17
Shelves	16 slots	1	0	0	1	0	0
	32 slots	0	1	1	0	1	1

and σ= 25%, for equation 5.1. The simulation results are illustrated in Figure 5.4, with acquisition costs present in Figure 5.4a and power consumption in Figure 5.4b, for individual nodes. In this scenario, the fluctuations in EPS and ECS architectures outcomes are due only to original traffic requests between nodes, since no increase in individual nodes expenses arrives from necessity to handle traffic not originated in that node. As can be seen, the optical layer architecture does not represent major outcomes, both in acquisition cost and power consumption, presenting savings in the last feature, when compared with previous scenarios. The equipments used for each node are documented in Table 5.7, for more information. The number of P_1 x P_o WSS devices and control modules for ROADMs refers only to the ones implied by the node in question, is necessary to ensure interconnection between all of them, reason why the total number of ROADMs to deploy in each node is the sum of the equipments imposed by the node and the intermediate nodes that can be traversed by traffic originated in any node.



(a) Transparent EPS, ECS and optical equipments acquisition costs

(b) Transparent EPS, ECS and optical equipments power consumption

Figure 5.4: Simulation result for transparent transport mode, using EPS , ECS and ROADM, for 1 Tbps mean traffic between nodes.

5.5 Scenario comparison for increasing traffic requests

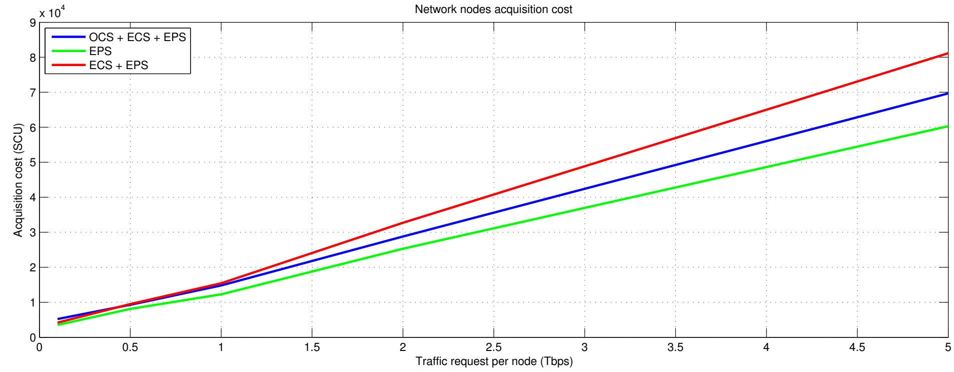
In previous sections were studied different architectures available to deploy in network nodes, along with transport mode and the impact it provokes in acquisition costs and power supply. Although the nodes can be considered the elements responsible for major outgoings, the solution to deploy in a specific network is not mandatory the solution that best matches a network with similar physical and logical topologies, is also a necessity to consider the general traffic requests expected in nodes. With this purpose, this section provides a study of the overall response of the network for different traffic requests, considering the previous scenarios and individual equipment outgoings. The results are shown in figure 5.5.

The simulation result trends indicate that a network operating in transparent transport mode has a better power consumption profile, as can be seen in Figure 5.5b. The architecture presenting the worst performance in this context is the network operating in opaque transport mode, with EPS and ECS, that also presents the worst performance in acquisition costs, illustrated in Figure 5.5a. In turn, networks operating in opaque transport mode, with architecture based in EPS only present the best performance for

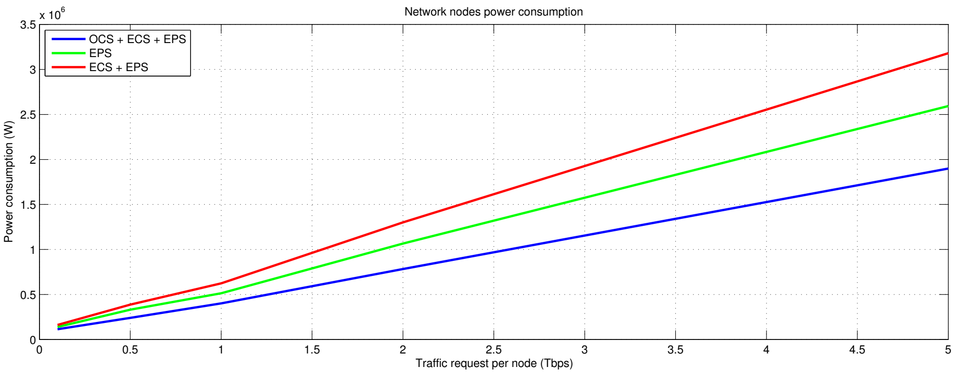
Table 5.7: Equipments used in transparent transport mode, with EPS, ECS and colorless, directionless and contentionless ROADM

Transparent transport mode							
Electrical packet switch							
		Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
Transceivers	10 Gbps	336	0	144	192	240	96
	100 Gbps	56	48	44	48	40	40
Modules	48 x 1	7	0	3	4	5	2
	4 x 100	14	12	11	12	10	10
Shelves	16 slots	0	1	1	1	1	1
	32 slots	1	0	0	0	0	0
Electrical circuit switch							
		Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
Transponders	10 Gbps	0	0	96	144	192	96
	100 Gbps	60	48	44	48	40	40
Modules	48 x 1	0	0	2	3	4	2
	4 x 100	15	12	11	12	10	10
Shelves	16 slots	1	1	1	1	1	1
Reconfigurable add/drop structure colorless, directionless and contentionless							
		Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
P_1 x P_o WSS	9 x9 ports	1	1	2	3	3	2
Control		1	1	1	1	1	1

acquisition costs. Although is not possible to conduct an objective comparison allying both, acquisition costs and power consumption, as power consumption does not have a match with monetary outcomes, is possible to state that the overall best architectures to deploy in a network, are either opaque transport mode with EPSs only, or transparent transport mode with colorless, directionless and contentionless ROADMs. From these, the first is more suitable for operators concerned mainly with acquisition costs, willing to sacrifice future outcomes related with power consumption, with network growth. The second architecture presents a solution for operators, willing to reduce the expenses spread along time, related with power consumption, with an initial effort being made in equipments acquisition. Also, operators established in the markets may



(a) Evolution of acquisition costs for different architectures.



(b) Evolution of power consumption for different architectures.

Figure 5.5: Outgoings evolution for different traffic request, considering the studied architectures.

approach the last solution as an upgrade to currently deployed networks, minimizing the impact of equipments acquisition, while guaranteeing future expenses reduction.

5.6 Summary

In this chapter, different scenarios were simulated, to obtain an insight on network expenses related with different nodes architecture and network transport mode. Networks operating in opaque transport mode, with EPS architecture deployed alone, in a first scenario, and along with ECS architecture were simulated, with main expenses related with acquisition costs and power consumption identified. A network operating in transparent transport mode was also studied, using colorless, directionless and contentionless ROADMs for optical layer architecture. The obtained results for the three cases was discussed, firstly, the response of each architecture to common and permanent traffic request between nodes and after with increasing traffic requests, equal for each architecture, to enable comparison. The network outcomes variation for the different traffic requests was discussed, with implementation suggestions, for different necessities of market operators.

The effort carried in this chapter and the obtained results can constitute a starting point to identify the equipments where enhancements should be done, to reduce the overall network costs. In parallel, the achieved results, can serve as a first estimation on network and network nodes architectures to deploy, further complemented with more detailed set of variables.

Chapter 6

Conclusions and future work

In this dissertation were studied different forms to allow transport of packet traffic in a predominantly circuit switching network as OTN. This document starts by introducing the different possible origins of packet traffic and possible processes it passes through until matching the requirements for transportation. The devices responsible for traffic dispatch in the network are after studied considering the various transport modes. Mathematical modules able to minimize the costs related with the devices are developed and implemented. The implementation of mathematical modules in different simulation scenarios takes place, with interpretation of the results and main conclusions. This documents ends in section 6.2, where suggestions of future work to complement this work are presented.

6.1 Conclusions

This dissertation starts by explaining a protocol stack capable to transport packet traffic signals originated in IP, IP/MPLS or GbE routers and MPLS-TP switches, further mapped into ODU containers, in Chapter 2. For an efficient transport of the, by the time, circuit traffic signals, the ODU containers are groomed together into higher order ODUs, then encapsulated in OTU and transported over the network. The frame modifications and procedures that enable such operation are covered, before explanation of the process used to groom the ODU containers, the HAO. The complete view of the studied signals and respective results is exhibited.

After the signal mapping,in Chapter 3, are studied the network node architectures to deploy, that enable transmission of signals across the network. For the effect, are primarily introduced the transport modes in which a network can operate. For opaque, transparent and translucent transport modes are defined the functions taking place in end nodes and intermediate nodes. According with the functions to perform, the architectures to use are examined, separated by layers. In electrical layer, electrical packet switching equipments are explained, as well as electrical circuit switching. The operation of electrical switching equipments individually or together, in layered and parallel architectures, is addressed, before advancing to optical layer equipments. In optical layer, two the different ROADMs are studied, the one with least flexibility (fixed frequency and fixed direction) and the one with major flexibility (colorless, directionless and contentionless), along with the building blocks.

In Chapter 4, are developed the mathematical models, based in ILP formulations, capable to dimension and optimize the network nodes. The mathematical models are done for electrical packet switching, electrical circuit switching and optical circuit switching. The first one has, as input parameter the total traffic requests originated in that node, for any destination node, and returns the overall number of modules necessary to traffic transmission, with or without next switching equipments. The electrical circuit switching mathematical model receives as inputs the circuit traffic requests originated in previous mathematical model and dimension the equipment to optimize the number of output modules, for circuit traffic transport. This last can proceed to signals transport or forward the traffic requests for the optical layer, where mathematical model exists, considering the colorless, directionless and contentionless ROADM, dimensioned to optimize the number of $P_i \times P_o$ WSS modules needed in each node to perform transmission in transparent transport mode, while the previous ones, operating withou optical layer operate in opaque transport mode.

The mathematical models are, after simulated in three different scenarios, in Chapter 5. In a first instance for comparison purpose, the traffic demands between nodes are kept constant and results are obtained for each node for the different architectures. For electrical packet switching alone, electrical packet and circuit switching in layered architecture, and the previous one with optical circuit switching is performed an analysis of the results, accounting for CAPEX and OPEX, considering acquisition costs and power consumption, for each, respectively. Once the obtained results, for different network nodes, is dissected, an analysis of the overall network response to traffic increase is addressed, with application suggestions for the different architectures, considering different operator priorities and necessities.

6.2 Future work

Apart the satisfaction throughout the realization of this dissertation, some work is not finished, for what is suggested as future work:

- The models developed in this dissertation contemplate only sequential use of

EPS, ECS and ROADM, using colorless, directionless and contentionless flexibility for the last. Hence, as future work, the development of models for other flexibility allowances in optical layer is identified as logical step. The use of different ROADMs can prove to be useful for scenarios not identified throughout this work.

- From the studied transport modes, the models exist only for opaque and transparent operation modes. A detailed study for translucent transport mode, identifying the nodes where OEO conversion brings notorious advantages, and development of models to enable simulation can be a step in right direction. The possibility to deal with traffic in both domains in specific intermediate nodes may modify the requirements for both electrical and optical layers in remaining nodes.

- In this dissertation, the CAPEX and OPEX analysis were done considering only acquisition costs and power consumptions, neglecting the equipments lifetime expectation, acquisition of a variety of miscellaneous materials, human interventions, rentals of space to place the equipments and ducts to pass the cables, just to mention few. A complete work, should overcome these flaws, as well as develop an effort to convert the equipments power consumption into monetary units. This would allow to have a more realistic and failure-proof solution while, at the same time, would allow a merge between CAPEX and OPEX analysis, that enables a more objective identification of optimal solutions.

- The fact that packet traffic demands between nodes is very uncertain was a major difficulty in the first approach to this work. Future works have much to gain if a pattern in packet traffic provenance is identified and quantified. A work like this would make studies like the performed one more robust, by avoiding the possibility to perform groom in high bit rate signals. This is a somehow important advance, in a time when new capacities are being defined for GbE signals, to be deployed in a not faraway future.

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