Master of Communication Systems

Techno-economic analysis of Open Optical Line Systems

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Abstract

Technology innovations and capacity upgrades in optical networks have influenced the optical transmission. As a result, network operators are considering separating hardware and software components in order to achieve efficiency and promising savings during network operation and network lifecycle. This leads to resolving the vendor lock-in and opening up the optical networks architectures such that different kinds of disaggregation models can be supported in the DWDM transport layer.

In this master thesis, a techno-economic analysis which compares the economical differences between an integrated and disaggregated optical network has been conducted. For the analysis, an actual test case scenario of a European interregional network has been utilized. The line system and transponders components, price lists and features are based on actual vendor components in today’s optical transport networks.

According to the results, it has been concluded that all total cost investments required for an integrated or disaggregated approach of DWDM system are traffic dependent. Moreover, capital expenses of open architecture are influenced by business model policy in price reduction due to multiple vendors’ competition on transponders. Calculations demonstrated that a disaggregated approach can introduce considerable total cost savings about 21% less total investments that include 25% less costs for capital expenses and 3% higher cost for operational expenses on an average traffic volume of European network. Finally, by increasing 5-10 times the traffic volume of European network it has been noticed that disaggregated system reduced total cost by 39% and 43% respectively.

Keywords

Capital expense (CAPEX), operational expenses (OPEX), optical networks, dense wavelength-division multiplexing (DWDM), disaggregated DWDM, integrated DWDM, traffic volume, transponders, line system
Abstract

Tekniska innovationer och trafiktillväxt påverkar utvecklingen av optisk transmission. En konsekvens av detta är att nätoperatörer undersöker möjligheterna att separera hårdvara och mjukvarukomponenter för öka effektiviteten och sänka kostnader för drift. Detta minskar inläsning till enskilda leverantörer och öppnar upp dom optiska näten för att byggas med olika typer av disaggregering i DWDM transporten.


Beräkningarna visar att disaggregerade system kan sänka kostnaderna med 21%, i dessa siffror ingår 25% lägre kostnad för investeringar och 3% högre driftkostnader. Slutfinal, genom att öka trafikvolymen med 5 respektive 10 ggr från den ursprungliga trafik matrisen så kan de totala kostnaderna sänkas med 39% och 43%.

Nyckelord
Capital Expense (CAPEX), driftskostnader (OPEX), optiska nätverk, tät våglängds delnings multiplexer (DWDM), disaggregerad DWDM, integrerad DWDM, trafikvolym, transpondrar, linjesystem
# Table of Contents

Chapter 1 ...................................................................................................................... 5  
Introduction ................................................................................................................ 5  
  1.1  Background ........................................................................................................ 5  
  1.2  Problem definition ............................................................................................. 6  
  1.3  Purpose ............................................................................................................... 7  
  1.4  Goal ................................................................................................................... 7  
    1.4.1  Benefits, ethics and sustainability ............................................................... 7  
  1.5  Methodology / Methods .................................................................................... 8  
  1.6  Delimitations (Avgränsningar, swe) ................................................................. 9  
  1.7  Outline (Disposition) ........................................................................................ 9  

Chapter 2 ..................................................................................................................... 11  
Optical Line Systems ................................................................................................ 11  
  2.1  Dense wavelength division multiplexing (DWDM) network components .......... 12  
    2.1.1  Transponders ............................................................................................... 14  
    2.1.2  Optical amplifiers ....................................................................................... 15  
    2.1.3  Reconfigurable optical add-drop multiplexer (ROADM) ......................... 15  
    2.1.4  Network management system (NMS) ......................................................... 18  
    2.1.5  Optical system controller .......................................................................... 19  
    2.1.6  Software defined network (SDN) controller ............................................ 20  
    2.1.7  Planning tool ............................................................................................... 22  
  2.2  Integrated/ Closed Optical Line Systems ......................................................... 23  
  2.3  Disaggregated /Open Optical Line Systems .................................................... 24  
  2.4  Requirement for Open Optical Line Systems ................................................... 25  

Chapter 3 ..................................................................................................................... 28  
Evaluation Methodology ............................................................................................ 28  
  3.1  Techno-economic evaluation framework .......................................................... 28  
    3.1.1  Dense wavelength division multiplexing (DWDM) network model .......... 29  
    3.1.2  Market model ............................................................................................... 33  
    3.1.3  Network dimensioning ............................................................................... 33  
    3.1.4  Business cost model ................................................................................... 35  
    3.1.5  Total cost of ownership (TCO) model ....................................................... 38
Chapter 4........................................................................................................................................... 47
Evaluation results ................................................................................................................................. 47
  4.1 Techno-economic evaluation results .............................................................................................. 48
  4.2 Total cost investments .................................................................................................................... 50
  4.3 Capital expenses versus operational expenses .............................................................................. 52
  4.4 Sensitive total cost analysis ........................................................................................................... 57
  4.5 Network performance and cost efficiency ...................................................................................... 62
Chapter 5............................................................................................................................................... 64
Conclusion and future work .................................................................................................................. 64
References............................................................................................................................................. 68
Appendix A........................................................................................................................................... 73
Appendix B........................................................................................................................................... 78
Chapter 1

Introduction

Nowadays, the optical transmission is based on vendor’s proprietary technology and this can impact the architecture of optical networks. Since optical network architecture is depending on vendor’s domains these optical networks are referred as closed systems. In closed systems, all the hardware equipment and the control software of each network is offered by the same vendor, and hardware and software are closely coupled. However, the evolution of optical transport networks, in order to adapt to various emerging network applications such as: 4K/8K video, Virtual Reality (VR) /Augmented Reality (AR), cloud computing, 5G and datacenter services has increased the need of providing more open interfaces [1]. By taking advantage of Software Defined Networking (SDN), the optical networks can be opened up and the network functionality is easily accessed and configured under multi-vendor requirements. In open optical systems, the optical line system is disaggregated, so that transponders and embedded interfaces from any vendor could be connected together and build up an optical line system which architecture is based on multiple suppliers. This flexibility requires multi-vendor management which can be achieved by utilizing open interfaces and open APIs. SDN openness and multivendor environment for management are crucial characteristics for building an open optical line systems

1.1 Background

Traditional closed/integrated Dense Wavelength Division Multiplexing (DWDM) systems consist of Transponders and Optical line system which includes various types of multiplexing, amplification and related optical functions. From the above components, including the management and control systems, a single vendor is responsible for offering them. Their highly deployment so far is connected with the fact that end-to-end performance can be assured by one supplier. Also, closed systems deployment can give the lowest operational complexity and risk. This influences the decision of service providers to historically prefer the integration approach [2].
In the disaggregated / open optical line systems (O-OLS) all line systems are provided by a single vendor, while the terminal equipment such as transponders are supplied by multiple vendors. Moreover, transponders controller and the line system controller are provided by any vendor since open APIs and information models are capable of supporting this kind of flexibility [2]. The disaggregation in O-OLS can give the freedom into network operator to select best-in class products for building up openness into the whole system. Openness is also based on the open APIs that SDN functionality can offer [3] but since SDN can also be deployed into closed systems, the difference in the O-OLS systems, is that a global multi-vendor SDN controller is offered. In this multi-vendor approach, the network operator is responsible for network software, including management, control and planning [3].

A comparison between Closed OLS and O-OLS as a follow-up of a techno-economic analysis of their business model is necessary. Based on the results, conclusions will be made in order to decide which model is more beneficial for deployment in today’s telecommunications industries. For this purpose, a Total Cost Ownership (TCO) analysis that is usual performed within five years is suited to determine best vendor’s offers and provide answers on the trade-off between Integrated and Disaggregates OLS. An overview of Capital Expenses (CAPEX) and Operational Expenses (OPEX) can estimate how TCO is affected by introducing openness to the OLS and the average accumulative TCO savings. This can lead to proper assumptions about the economic consequences for deploying a closed or an open model in OLS networks.

1.2 Problem definition

Disaggregation enables innovation by providing efficient scaling. Also, it encourages a building approach to the most functional blocks so that to decrease the initial spend on an open line system. The above key points enable network operators to grow incrementally as traffic increases, in a more efficient way from integrated optical line system. Also, network operators are capable of exploiting third-party coherent optics or external transponders. However, the openness introduces some challenges in optical networks. DWDM optical systems are analog and there are many complexities in planning, configuration and control. An intelligent software management
system for optimization and control is required to easily adjusted to the deployment of disaggregated packet-optical solutions [4].

How advantageous can be the deployment of O-OLS instead of closed OLS for the market based on pricing competition, innovation speed, reach/capacity, operational costs and high availability?

1.3 Purpose

The purpose of the degree project/thesis is to investigate the economical differences between the closed/integrated optical systems of today and open optical line systems. By comparing the Integrated system and the Open Optical line system, two business model should be applied which will take the investment and operational costs into account. Understanding and defining differences in operational costs between the systems is considered to be an important part of the degree project work.

1.4 Goal

The goal of the degree project is to analyze the optical reference network of a country and make this analysis applicable for any other countries that are also considering to open up the traditional Integrated Optical line system to a Disaggregated Optical line system. Based on a complete cost analysis for selected case scenarios a thorough opinion would be performed for the business viability of open optical line systems. As a result, operators like Telia Company that has been requested the openness of Optical Line Systems would investigate and consider the advantages and disadvantages of O-OLS deployment.

1.4.1 Benefits, ethics and sustainability

This degree project will give an insight on Telecommunication industries that are considering the disaggregated approach of Dense Wavelength-Division Multiplexing (DWDM)- Optical Line Systems. The business model comparison of Integrated and Disaggregated Optical Line Systems will address the constraints that are associated with Integrated and Disaggregated Systems. Disaggregated systems can provide a quick adoption to the latest
technologies. This is what operators need to consider so that they will easily manage and reduce network OPEX.

Sustainability is always considered for both Integrated and Disaggregated Optical line systems so that will reduce the ongoing energy consumption of fibers deployment. Especially for open Optical line systems, the purpose of reducing TCO will be considered as the case of optimizing infrastructure design for sustainability [5].

1.5 Methodology / Methods

There is a variety of methods that can be used for a degree project. Based on the content research methodology can be divided into two main categories.

Qualitative research methodology is a multimethod for giving an interpretive, naturalistic approach to its subject matter. This is based on the fact that qualitative researchers study things in their natural settings. The purpose of qualitative research is to understand the social reality of individuals and groups. For this purpose, several methods for collecting empirical materials, ranging from the interview to direct observation, to the analysis of artifacts, documents, to the use of visual materials or personal experience [6].

Quantitative research methodology gathers data in a numerical form which can be put into categories, or in rank order or measured in units of measurement. This type of data can be utilized for the construction of graphs and tables of raw data. The purpose of quantitative research is to establish general laws of behavior and phenomenon or contexts. It can be usually used to test a theory and support or reject it [6].

In this degree project, the quantitative research methodology is more suitable for conducting a research on open optical line systems. The exact type of methodology that can be used for assessment and collect data is based on a comprehensive techno-economic analysis. Due to the fact that the typical life cycle of optical line system consists of planning, initial installation, operational phases and teardown, techno-economic analysis can be useful to get an estimation of the required investment cost and business viability of the whole project. For the case of closed and open Optical line systems two different business models would be defined in order to compare the available
technologies. This will help the operators to narrow down the technological options and choose the most cost efficient technology which is supported even on a single vendor or on multiple-vendors [7].

1.6 Delimitations (Avgränsningar, swe)

The degree project is going to perform a TCO Analysis for both Closed and Open Optical Line Systems by taking into consideration the interregional optical network of a European country. The case of openness that would be examined for the European network would have the following characteristics.

Transponders would be given by multiple vendors, line system would be offered by one single vendor, planning tool and system integration would be deployed by different vendors as well. These characteristics will limit the analysis of operational and capital expenses and the cost would be affected accordingly based on vendor competition for the open case and vendor's monopoly on closed case [8].

Fault localization and network security need to be highlighted on the Disaggregated systems due to problems that can arise. For a fault location, a multi-vendor collaboration between all parties is necessary. Due to high openness, network uncertainty seems to be high. This is because no single party understands its responsibility in fault management for the whole network and fault demarcation is quite hard if it is not managed by the operators [1].

For Network security, a fully open network can lead to transparency and it can be easily exploited thus be vulnerable to attacks. This high risk of network attacks, is affecting network components such as: site location, optical amplifier deployment and fiber layout [1]. Although it is very important to understand the network security issues of open line system approach, these issues are not part of this master thesis and they will not be addressed.

1.7 Outline (Disposition)

In Chapter 2, the architecture of optical line system is described thoroughly in order to be very well understood the importance of each separate component for optical line system network operation. Moreover, the two
different models that are going to be compared are presented thus focusing on the requirements that an open optical line system should cover regarding Telia operator views.

In Chapter 3, the techno-economic evaluation framework that will be utilized for performing the techno-economic analysis is shown. As a result, all the necessary models such as: network, market, business and total cost model are demonstrated. A complete analysis on their input parameters including functions and equations for calculations, is carried out.

In Chapter 4, the evaluations result of the comparison cost analysis between the two proposed optical line architectures are displayed. The evaluation includes an overall view of total cost investments, capital expenses versus operational expenses and a sensitive total cost analysis. Finally, conclusions about network performance and cost efficiency are presented.

In Chapter 5, the conclusion and future work associated with techno economic analysis between integrated and disaggregated approach of optical line systems are demonstrated. Emphasis is given on business viability of open optical line systems, the constraints related with level of disaggregation of the system and open optical line system sustainability.
Chapter 2
Optical Line Systems

In this chapter, DWDM/Optical line Systems are going to be represented. The emphasis will be given on optical line system components’. Also, the integration of terminal and line systems will be seen.

The fast growth of users and services provided for the telecommunication companies have forwarded a widespread installation of DWDM technology in the last years. DWDM were firstly implemented for long haul applications. This has a considerable effect in reducing the installation costs of new fibers and equipment. DWDM intercontinental submarine systems were used later as a sequence of deployment. In the metropolitan areas DWDM networks seem to cover great space of spectrum and they offer a minor cost [9].

Due to the variety of functions and system complexity in a DWDM network, maintenance needs to be taken into consideration and be done properly. Also, the DWDM channels need to be monitored concerning its optic power, signal-to-noise ratio and spectral shifting, in order to guarantee the end-to-end service [9].

DWDM systems from both technical and economic perspective can offer potentially unlimited transmission capacity which is one of the most positive sides of DWDM technology. The demands of the network might change due to end user behavior of increasing the traffic growth. As a result, the network is being upgraded continuously to provide the required capacity to the customers. Because of these demands, it is needed to update the equipment or increasing the number of wavelengths on the fiber without expensive upgrades. Capacity can be obtained for the cost of the equipment, and existing fiber plant investment is maintained [10].

Increasing the bit rate of existing optical carriers and increasing the number of optical carriers either by reducing or maintaining the spectral separation between them in one or multiple fibers can give great results. A combination of the aforementioned beneficial methods can expand the network capacity [11].
Typically, optical line systems are closed systems in which their components are offered by the same vendor and software and hardware are closely coupled. However, the latest demands of technology can provide openness on the transmission system and this means that physical layer and control layer will be provided by multiple vendors [1].

The level of integration and disaggregation that is going to be analyzed is shown in Figure 2.1. The terminal system which includes transponders, the optical line system which includes, amplifiers, ROADMs, etc. can be produced from a single vendor in the case of integrated system. In contrast, on the disaggregated system the optical line system is offered by one vendor and the transponders are left on the scope of multiple vendors to provide them [12].

On the following sections a complete analysis and description of a DWDM system including the different DWDM components used in today’s market, is done. Also, the different architectures of open and closed DWDM/Optical line systems are presented.

![Figure 2.1 optical line systems](image)

2.1 Dense wavelength division multiplexing (DWDM) network components
DWDM systems are capable of using optical devices to combine the output of several optical transmissions, figure 2.2 [42]. During the transmission process in DWDM, multiple data signals are using different wavelengths of light through a single fiber. Incoming optical signals are assigned to specific frequencies within a designated frequency band. DWDM is a cost-effective way of increasing capacity without replacing fiber [42].

![Figure 2.2 Dense wavelength division multiplexing](image)

Figure 2.2 Dense wavelength division multiplexing [42]

DWDM network setup requires various network components to make the system work. Providing optimal optical power is the major constraint for the network. A typical DWDM system consists of terminal side (transponders), line side (line system) and management components as it is shown on figure 2.3 below.

![Figure 2.3 DWDM system](image)

Figure 2.3 DWDM system
At the following subsections the typical DWDM components that are required for the deployment of a DWDM network are depicted.

2.1.1 Transponders

Client specific devices from same or different wavelength, are coming into the DWDM system. In order to tune the incoming signal as prerequisite of optical line system that supports operation in C-Band\(^1\) transponders are required. Tuning of incoming signals is performed by first converting the optical signal into electrical and then regenerated to optical signal with a λ wavelength. A transponder box is in charge of the Optical - Electrical-Optical (O-E-O) conversion of wavelengths of light. During O-E-O operation the transponder converts the client optical signal back to an electrical signal and then performs either 2R( reamplify, reshape) or 3R( reamplify, reshape and retime) functions [13]. This electrical signal is then used to drive the WDM laser. Each transponder within the DWDM system converts its client’s signal to a slightly different wavelength. The wavelengths from all the transponders in the system are then optically multiplexed. In the receive direction of DWDM system, a reverse process is performed. During transponder operation individual wavelengths are filtered and sent to individual transponders [10]. In figure 2.4 is shown the functions that a typical DWDM transponder uses.

![Figure 2.4 Transponder functions](https://en.wikipedia.org/wiki/C_band_(infrared))

In today’s market many transponders are designed as protocol and rate-transparent fiber media converters that support transceiver module slots with data rates up to 11.32 Gbps. Moreover, transponders are applicable with different fiber types that support conversion of multi-mode fiber to single-mode fiber, and dual fiber to single-fiber [14].

2.1.1.1 Transponders products in today’s market

\(^1\) In infrared optical communications, C-band refers to the wavelength range 1530–1565 nm, which corresponds to the amplification range of erbium doped fiber amplifiers (EDFAs).
Based on multiple vendors’ products, today’s market is composed of a range of DWDM transponders for building modular, cost-effective optical transport networks for long haul, metro, regional, interregional and data center applications.

Examples of transponder products built by different vendors show how a vendor can implement and offer transponder solutions. The below listed products on Appendix A are covering the typical requirements of the optical network. However, this does not necessarily mean that the deployment of the transponders can be restricted into these categories for building a DWDM network that has a good performance.

2.1.2 Optical amplifiers

Optical amplifiers (OA) are used for boosting the amplitude or adding gain to optical signals that are passing through the fiber. Their main characteristic is to stimulate directly the photons of the signal with extra energy. In the optical networks there are two main categories of amplifiers the Erbium Doped Fiber Amplifier (EDFA) and the Raman amplifier [13].

EDFA is the most commonly used type of amplifiers in optical fibers. It is functionality is based on amplifying signals across a wide range of wavelengths. This type of amplifier can be efficient in the wavelength range of 1530 to 1565 nm, and gain can be extended up to 30 dB which means that it can support 1000 photons out per photon in. In order to meet the requirements of today’s optical networks, EDFAs are designed to meet the need for C-Band testing of active and passive components. They provide high power, high reliability, and superior optical performance. All these pros made EDFA latest modules technologies to fit in today’s highly dynamic networks and cost sensitive market [13, 16].

Raman amplifier is based on Raman gain. Ram main characteristic is to use the effect of Raman scattering. Based on that, light with high power and a corresponding wavelength is pumped into the fiber and then amplification will be performed if the incoming wavelength is covering the Raman gain spectrum [17].

2.1.3 Reconfigurable optical add-drop multiplexer (ROADM)

ROADMs one of the most valuable components of the DWDM network. It is a form of optical add-drop multiplexer that allows individual or multiple
wavelengths which carry data information to be added or dropped respectively on an incoming fiber link. ROADM is filtering the signal of specific DWDM channels to electric signal and back again to optical signal on all DWDM channels. A wavelength selective switching module (WSS) is utilized for performing switching operation of traffic a wavelength-division multiplexing. In ROADM, the number of network connections terminating or originating from the node is referred as degree of the node. Every ROADM card has add/drop ports that can be interconnected for pass through traffic from one direction to another or connected to a local add/drop [13].

ROADM cards can be colorless, directionless and contentionless. The advantage of providing a directionless ROADM card is crucial for dynamically add/drop a channel in of the directions (degrees). Directionless ROADM broadcast the signal from the mux-demux unit in all directions and this make possible for degree ROADM can be provisioned to select channels through the network [13].

For a ROADM node that contains N degree, it is based on vendors’ specifics if the suggested functionality will be implemented on one or N number of ROADM cards which provide direction-less functionality [13]. For instance, it can be one card per ROADM direction or it can be one per ROADM direction and traffic direction.

### 2.1.3.1 ROADM types used in today's market

Based on Fujitsu's white paper report, in classic ROADM, the mux/demux is a passive device that is deployed with Arrayed Waveguide (AWG) technology, actually a prism is separating is each wavelength into individual input and output ports [18].

ROADM’s classic architecture gives the opportunity for adding or dropping by simplifying planning, achieving better bandwidth utilization and offering reliable network engineering. However, they are limited by fixed wavelength assignments to specific ports, fixed direction assignments for multiplexers and partitioned add/drop structures due to wavelength-contention conflicts [51]. As a result, in today's optical network architecture classic ROADM have been replaced by Colorless Directionless (CD) and Colorless Directionless Contentionless (CDC) ROADM [18].
CD/C ROADMs allow wavelength reassignment such that manual intervention is not required but there is a tradeoff between higher node complexity and costs. Both CD and CDC architectures utilize a common optical core, support flexible grid channel spacing but drop side of ROADM is implemented in a different way. Compared to classic ROADM, CD and CDC are using route and select architecture based on WSS modules as it shown in Figure 2.15. Moreover, the fixed port AWG has been replaced by the flexible drop-side architectures that give the opportunity to any transponder or muxponder to be assigned to any wavelength and can be sent to any WDM degree [18].

One limitation that needs to be mentioned for CD ROADM is that they are limited to offer wavelength contention. This means that CD ROADM don’t allow wavelengths of the same frequency to terminate from different WDM directions on the drop side. As a result, careful network planning is necessary to make sure that wavelengths are dropped at a given node are assigned unique frequencies [18].

Figure 2.15 CD ROADM vs CDC ROADM “Fujitsu White paper figure 3” [18]

In order to consider which is the most cost wise ROADM type architecture to implement on an integrated DWDM the following characteristics need to be taken into consideration.

- Number of wavelengths
- Number of degree
- Add/drop ratio
An analysis and cost comparison between classic ROADM, CD ROADM, and CDC ROADM can give estimations of what kind ROADM should be preferred to deploy on a given reference network [20].

Generally, based on Cost comparison paper report of [20] it has been observed that classic colored ROADM architecture offers clear cost superiority. Between CD and CDC ROADM add/drop ratio is a dependable parameter that influences the cost of CD and CDC ROADMs. For example, as the add/drop ratio value increases then CD or CDC ROADM needs to add more high cost WSS modules [20].

2.1.4 Network management system (NMS)

In DWDM networks, Network management system tool is the combination of hardware (server) and software used to monitor and administrate the network. Also, NMS is essential for reassuring a better Quality of Service (QoS). NMS tool will be used for provisioning, performance monitoring, fault identification and possible network recovery [10], [22].

An example of NMS tool that is provided by PacketLight Networks company has the following key characteristics [19]:

- It offers a hierarchical topology view of the devices in the network [19].
- It supports task scheduling for network operation such as: software download, configuration files upload and download [19].
- Collects, presents and saves the performance of monitoring data from all the network elements [19].
- It provides network fault management, network inventory management and service management [19].
- Supports distributed client server network architecture [19].

NMS is capable of accomplishing fast lightpath establishment and includes other network-level issues[pg.~156] [21].

An NMS usually has management protocols. The most common are Simple Network Management Protocol (SNMP), Telecommunication Management Networks (TMN) and common object request broker (CORBA) model [22].

- **SNMP framework**: runs over Internet protocol stack [22].
- **TMN framework**: a common management information protocol, runs over the Open System Interconnection (OSI) protocol stack [22].
- **CORBA model**: gives the opportunity into network elements of different vendors to come with their own management system. Also, it is a software standard that allows interoperability [22].

### 2.1.5 Optical system controller

Although most of optical networks are managed by NMS, right now there are optical networks which are handled by optical domain system specific controllers that are operating on a lower control and management level. Depending on the system strategy and architecture as it is shown on figure 2.16 (closed or open DWDM system), there are two different variations: optical system controller and vendor specific optical system controller. Both of them are utilized due to the slow technical development in the optical technology area. They rely on closed and proprietary APIs to interact with network elements. However, these controllers are offering only limited set of information northbound towards Software defined network (SDN) controller interaction. These optical system controllers are more likely to emerge with medium and short haul network scenarios in which the reach requirements for the optical infrastructure are less demanding [41].

Today, a large number of optical vendors have introduced their own domain specific optical system controllers, but they are still in need of NMS systems to deal with tasks that are related to element configuration and software updates. As a result, optical system controllers are mainly responsible for providing physical management of the network [41].

On the figure 2.16 below it is shown how the two different categories of optical system controller are interacting with other management systems such as NMS, Planning Tool and SDN controller. The two different APIs used for communication with SDN controller differentiate the Packet and Cloud management integration.
Software defined network (SDN) controller

Software-defined Networking (SDN) has dramatically reshaped the way networked systems operate nowadays [40]. By decoupling the forwarding logic from the network elements, an external, programmable entity called SDN controller can enforce network policies in a flexible and reconfigurable way, purely in software. For the optical networks, SDN controller has a crucial role in orchestrating the system. SDN controller can take the responsibility into multiple use cases such as: multi-vendor management, connection management, network monitoring and analysis, connection and topology analysis, utilization analysis and reach planning. In total, SDN controller is extracting functionalities from different vendor’s NMS and offer availability and management through new types of tools and interfaces [41].

On figure 2.17 below it is demonstrated how SDN controller plays an important role in orchestrating the system. This figure represents how the
network can be managed in a multi-vendor strategy similar to a disaggregated optical line system. However, the interface interaction of SDN controller with other controllers on figure 2.17, can be modified into single vendor environment and represent an integrated approach that utilizes less APIs. As a result, on integrated system, there will be only one vendor for optical domain controller and NMS, figure 2.17. This means that only one vendor exists in the optical infrastructure and control management layers respectively and communicates with SDN controller.

On the below workflow scenario of an optical circuit set-up shown on 2.17, a carrier operator initiates connection management on the Network Orchestration level. At this point there a multiple actions need to be done for optical circuit set-up:

- SDN controller decides that the circuit should be connected between a) and b) vendor’s optical domains.
- SDN controller acquires information about network topology from Vendor Optical Domain Specific Controllers.
- After acquiring the suitable information, SDN controller instructs generic planning app to initiate path computation for the circuit.
- By the time path computation is confirmed and planned, the generic planning app sends the verified path to SDN controller.
- Finally, SDN controller instructs vendor optical domain controllers to initiate circuit set-up and at the same time vendor optical domain controllers initiate circuit set-up in each vendor domain [41].
Planning tool

Planning tool is in charge of computing solutions for each migration step. Problems that are related to network reconfiguration, planning, and network dimensioning, need to be solved through the use of planning tool [23].

Planning tool contains important functionalities such as:

- Optimization of the routing and equipment placement in order to fill in the traffic demands [23].
- Perform capacity planning and investigating ways to expand the network and dealing with increasing traffic on the network [23].
- Analyze the equipment costs and minimize respectively the expenses [23].
- Identify and examine the impact of failures in order to perform protection strategies and strengthen resilience [23].
- Visualize the information collected from the network that listed above [23].

Based on “Industry-Driven Elastic and Adaptive Lambda Infrastructure for Service and Transport Networks (IST IP IDEALIST)” project Network Planning Tool of 2014, MANTIS and Panning Tool for Optical Networks (PLATON) are two examples of network planning tools used today [24].
MANTIS: It is one of the first tool implemented for planning flexible networks and includes novel and efficient algorithms. MANTIS offers a repository for networks and algorithms by making possible to compare different approaches. As a result, benchmarking is performed. MANTIS modular architecture gives the capabilities of fast execution and efficient computation resource usage. In addition, MANTIS has the flexibility to be deployed into Cloud as well. The web-based interface combined with social related functionalities enables MANTIS to perform calculations of optical network reach online [24].

PLATON: It is a planning tool for facing problems of flex grid design, post-repair optimization and spectrum defragmentation. PLATON is preferred for deployment when a set of optical network planning algorithms are able to be executed using high performance and state-of-the-art hardware and software technologies [24].

2.2 Integrated/ Closed Optical Line Systems

Traditional DWDM Optical networks consist of transponders/muxponders, optical line system and system integration or management and control. Optical line system is composed of filters for multiplexing and demultiplexing the DWDM channels, Wavelength Selective switches (WSSs) for reconfigurable optical add-drop multiplexer (ROADM) and other functions such as amplifiers, power monitoring, Optical Supervisory Channel (OSC) and Optical time-domain reflectometer (OTDR) [3].

The Optical line system is integrated and managed from a proprietary network management system (NMS) [3]. NMS is combined with a propitiatory optical line system controller. Also, for management and control there is a software defined networking (SDN) controller which includes different application programming interfaces (APIs) for management that are based on generic YANG data modelling language models. Finally, planning tool is including for propitiatory management and control and specially to verify the optical reach for the network [8]. Figure 2.18 shows how an Integrated DWDM system looks like. It is important to mention that for the no disaggregation system all the components are offered from a single vendor apart from the SDN controller which has the freedom to be given by a different vendor as well.
2.3 Disaggregated /Open Optical Line Systems

The disaggregated or open optical line systems consist of the same hardware components with the closed optical line systems but the open optical line system deployment (line systems and transponders) is offered from multiple vendors. Disaggregation can be done into different levels.

In a partly disaggregated system for instance, all line system components (mux/demux, terminal amplifier, line amplifier and ROADM) can be supplied by a single vendor, while the terminal equipment such as: transponders are supplied by multiple vendors [2].

A fully disaggregated system has the capability to utilize multiple vendors for individual line system components and multiple vendors for supplying the individual components of the terminal equipment. However, is not always beneficial and efficient to deploy a fully disaggregated system due to the risk
of high operational complexity that comes along with lots of open interfaces for management [2].

Figure 2.14 shows how an open optical line system is built by different vendors’ contribution. On the management and control components there is a generic online planning tool which is connected with the different OLS controllers and NMS per vendor. Also, a global multi-vendor controller is communicating with the different OLS Controllers and NMS offered individually per vendor management.

Figure 2.19 Optical line system partly disaggregated

2.4 Requirement for Open Optical Line Systems

Open Optical line systems can influence the time for service delivery by reducing it into number of days due to a multi-vendor management tool deployment. In this multivendor environment, SDN controller and generic online optical planning tool can be responsible to deal with service delivery issues. Therefore, by pre-installing capacity to be used on the network can become advantageous since time to gain will be up to weeks [8].
For Operators like Telia Company that want to support the deployment of an open optical line system architecture is necessary to list down criteria that an O-OLS system needs to fill in. Based on Telia’s standards, an O-OLS system should provide a reach up to 3000 km for metro-regional system and a distance of 6000 km maximum reach for an interregional system. Coherent wavelengths of 200G will be used in the O-OLS implementation as it is next-generation and it is considered a tipping point for optical transport networks [8].

According to Nokia report [26], all long haul networks and interregional networks as well, can be built economically with 200G and offer double of capacity at lower cost compared to today’s 100G long haul. In order to have large bandwidth capacity and manage diversified bandwidth, cascaded ROADMs need to be utilized. Since the wavelengths will be reconfigured frequently because of high traffic demands in an interregional network, that cascadability of ROADM will be considered a necessary limiting factor [25,26]. As a result, Telia will prefer to use cascaded ROADMS due to above considerations.

Another requirement that needs to be taken into consideration is the utilization of both ROADMs and flex-grids as add/drop nodes. Utilizing both ROADM and flex-grids, can give benefits to a topology which requires high bandwidth. This is due to more efficient spectrum allocation through flex-grids. Also, having flex-grids along with ROADM can remove guard bands between channels and be able to use the most efficient spectral width for a DWDM signal/wavelength. Moreover, flex-grid ROADM are suitable for reducing network operation costs, building light-path on demand services or even converting fast light path restoration into viable strategy [27].

Regarding OLS network components and especially optical amplifiers, it is a requirement that the new system architecture will support both types of EDFA and RAMAN amplifier. Raman’s will most likely be needed when they are introduced more complex modulation formats and longer reach. EDFAs are the basis for all DWDM systems. Both of them support any bit rate and signal format, provide the utilization of the entire region of wavelengths, increase the capability of fiber-optic links by using WDM and give the
opportunity for all optical-networks to be implemented apart from point-to-point links [28].

In Network Diagnostics and Fault Management part of O-OLS system architecture, it is necessary to identify the total power consumption of each DWDM component such as: transponder power consumption, and OLS system power consumption including ROADM, amplifiers, etc. Therefore, for fault management, it is of interest to diagnose and report faults that are related to network media channel including the 96 available channels for the used wavelengths [8].
Chapter 3

Evaluation Methodology

In this chapter the evaluation methodology that is used throughout the master thesis is described.

Most of the networks have a typical life cycle which includes: planning phase, initial installation phase and teardown phase. Due to technology enhancements, updates on a network requires huge cost investment for its deployment. Furthermore, a comprehensive techno-economic study is important in order to estimate the required investment cost and business viability of the project [pg.~35] [7].

On the planning phase, operators are evaluating the profitability of any project by taking into consideration uncertainties that are based on user penetrations, revenues and market convergence [pg.~35] [7]. During the whole process of techno-economic analysis, comparison between the available technologies is taking place such that operators can wisely consider the benefits of each technological option they have. The most beneficial option will be preferred due to cost efficiency and being able to follow user requirements. As a result, the business assessments will enable providers to calculate their revenues and make conclusions about pros and cons of migrating towards new technological models or architectures [pg.~35] [7].

Apart from cost factors, survivability, energy consumption, network maintenance, fault management and network dimensioning have great importance in network design and deployment. For this reason, different business models are going to be defined and analyzed in order to assess the project business viability, estimated cost or any other performance capabilities of various technologies before the deployment [pg.~35] [7].

3.1 Techno-economic evaluation framework

In order to make a successful comprehensive techno-economic evaluation and risk analysis an appropriate framework is necessary to be used. A generic framework that is proposed according to [7] is presented at figure 3.1. In this framework, it is depicted how different model relations are affecting the
phases of Network dimensioning, TCO and the outcome of techno-economic results. The structure of the framework is generic so that it can be used for different kind of networks [pg.~36] [7].

![Figure 3.1 Techno-economic evaluation framework](image)

Figure 3.1 Techno-economic evaluation framework, “figure 3.1. Techno-economic evaluation framework” [7].

### 3.1.1 Dense wavelength division multiplexing (DWDM) network model

Normally DWDM networks support a variety of network models that differ on network architecture due to vendors’ dependability. As a result, DWDM network components are available for deployment in a competitive price due to large number of suppliers involved. Vendors’ goal is to offer high network performance and high quality of service in a reasonable price. Based on that, defining suitable architectural models that will meet service requirements is crucial for building an efficient DWDM network model.

In today’s market Coriant, Infinera, Ciena, Fujitsu, ADVA and several others, are providing the DWDM components that are required for building
optical line system and transponder system. In this master thesis a today’s vendor model is used as a reference for fully deploying OLS and transponders.

3.1.1.1 Optical line systems (OLS) model

OLS model provided by today’s market vendor has been used as a reference in optical line system model [31]. This system can be a good example since it fills the capacity criteria for metropolitan, regional and interregional network such that can transport all kind of services with high efficiency. Moreover, the high capacity DWDM transmission system, allows up to 40, 80 or 96 optical channels which is conforming with the requirements listed on previous chapter 2.4 for the disaggregation of DWDM system. All optical channels can be transported up to Ultra Long Haul (ULH) distances by using the same fiber [pg.~4] [31]. For the techno-economic analysis OLS systems has the following features [pg.~5-7] [31]:

- It offers a scalable multi controller architecture.
- It provides a maximum transmission capacity of 9.6 Tbits/s (96 x 100 Gbit/s) per fiber with 50 GHz channel spacing.
- It consists of ROADMS for 40, 80 and 96 DWDM channels with ability to add/drop 100% of the traffic.
- Supports ULH networking with extended reach up to 2500 km due to
  - High performance optical amplifiers.
  - Optional Raman amplification.
  - Optional external laser pumps.
  - Forward Error Correction methods.
  - Powerful link control software to handle with the channel power levers.
- It offers an enhanced power control mode for advanced power control management.
- Utilize a cost-optimized line amplifier solutions from metro to ULH applications.
- Supports remote Network Elements (NE’s) as remote Network Termination (NT), containing remote management from network site through the use of a Generic Communication Channel (GCC).
- It provides Simple Network Management Protocol (SNMP) interfaces for management.
Network management of the system can be done by:

- Network Management System (NMS Core).
- Network Management System Craft (NMS CT).
- Network Management System Domain Unix (NMS DX)
- Web-based Craft Terminal.

### Table 3.1. Card types of vendor’s system

The equipment and pluggable cards, required for building OLS might change based on the tradeoff between performance and cost efficiency. A typical list OLS card items used for calculations and analysis is shown on Table 3.1.

However, building OLS system from a different vendor might have different standards to cover and the list of cards and pluggable optics might vary. As a result, each vendor that builds the OLS system should consider to offer high performance and a feasible cost for each separate OLS network element.

**3.1.1.2 Transponder model**

Based on vendor’s market, a transponder model of one vendor is selected as a reference model to utilize in the network architecture of integrated OLS
system. In the open/disaggregated OLS system, transponders of multiple vendors will be considered in order to evaluate the price competition.

Vendor’s transponder model for analysis has the following specifications [29]:

- It offers a considerable low cost for any single service (10G, 40G, 100G) of capacity.
- It is practical and economical concept since it enables to pay as the capacity grows incrementally from 10Gbps up to 1.6Tbps.
- It enables with capability to mix and match 10G, 40G, 100G clients according to network demands.
- The unused capacity does not impact the power performance due to the power-as-you-grow model.
- It can be easily adapted and deployed to future technologies using new sleds without the need for replacing and discard the whole structure of the system such as: entire chassis.
- It can reduce cost of deployment because of industry-leading low power consumption and higher density.

The vendor’s transponder model is consisted of a list of hardware module and components such that it can improve service application performance and enhance end-user experience with the best in class connectivity solutions. Modules and components are shown on Appendix B [30].

Vendor’s transponder can have mix of the above components in order to build a fully functional architecture. The transponder model that is used for the calculations and cost estimations for integrated/closed OLS architecture and which is re-formulated for the disaggregated/open OLS is depicted in Table 3.2 [30].

All of the above parameters that build DWDM model architecture are influenced from the market model, they are given as input on the network dimension tool and they are analyzed on business cost model.
### Transponder system

| Core | Chassis with fans and dc psus  
|      | Installation Kit (ETSI)  
| Module | FILLER PLATE, Single slot filler card (up to 4 per chassis)  
| Services Modules | Module 2 (40x10G, 10x40G, 4x100G)  
|      | Capacity License  
| Pluggable Optics and accessories | QSFP+ 4 x 10GE/LR4 for 40GE <-> 10GE with breakout fiber (w/o cable)  
|      | CFP2-ACO Generic High Performance  
|      | QSFP28 LR4 (10km) Single Rate (100GbE)  

Table 3.2. transponder components

### 3.1.2 Market model

DWDM market is growing due to the vast deployment of DWDM infrastructures that can support 40G and 100G speeds from most of the carrier's all over the world [32]. As a result, traffic growth is the driver for improving network speeds in order to provide better quality of service (QoS) [pg. ~37] [7] [32].

Evaluating the market related parameters such as: revenue churns [33] because of encouragement to automate the network management via SDN, operators tiered pricing due to changing market, user penetration [34] to switch from integrated to disaggregated OLS and vice versa, QoS that DWDM models provide and etc., is a very crucial step in planning phase. These variables can be given as input into the market model in order to make estimations of the possible revenues and provide speed-based plans based on technology shifts and the number of enabled users and machines to leverage connectivity [pg. ~37] [7] [32].

### 3.1.3 Network dimensioning

On the Network Dimensioning phase, it is figured out the required quantity of infrastructure that needs to be added on the network architecture periodically [pg.~37] [7]. In order to achieve successful network dimensioning, a network topology needs to be implemented and used as a reference model for the calculation process [35].
Reference network model can vary based on request for proposal (RFP) of vendor’s equipment. There is usually a requirement to define a time-plan for the implementation of the reference network. Consideration upon the building process of the network needs to be done so that to clarify whether a fully built reference network is offered during first year or a staged network that evolves yearly is given [35].

Components of DWDM network such add/drop multiplexer or ROADM, amplifiers, transponders and etc. are populated based on the traffic growth that reference network topology needs to handle with on yearly basis. Since TCO analysis will be performed in 5-year period the network dimensioning should be done for all traffic demands of optical line network within given time period. The traffic dependent calculations are based on the results of aforementioned models (DWDM model, market model) [pg. ~37] [7] [35].

In order to perform accurate estimations for traffic needs, in this study a traffic matrix has been used. On the traffic matrix, real values are utilized for validity of the results. In this type of DWDM networks all types of client interfaces that are expected, have been included. Traffic matrix contains bidirectional traffic among all nodes, including routing information. IP packet traffic growth is based on a percentage growth. In this way, access links are aggregated into regional and then into interregional links which makes the predictability better for the traffic growth. The traffic on access links can vary a lot while and when the traffic is aggregated the growth becomes more predictable and stable. Furthermore, link requirements need to be taken into account such as: fiber link length, span length, ROADM sites, possible amplifiers, number of routes. Thus, other requirements can be included such as: power space used, system utilization, latency for circuits and etc. [35].

For the Network dimensioning calculations, the European network shown on figure 3.2 is considered as reference network. The network represented on figure 3.2 is the final stage of built up strategy of the network. Its links are shown with different color to highlight the diversity between core sites in case of failures. As a result, there will always be a backup route even red, blue or green for all traffic flows on the network [35] [36].

Below there is a list of requirements that European network will cover and these key points are taken into account for network dimensioning.
European reference network requirements [36]:

- It consists of 31 core sites with add/drop traffic functionality.
  - ROADM sites can vary from 2 to 5 nodal degree (ND).
  - Based on ND of ROADM site different cards of multiplexers and demultiplexers should be used along with flex-grid, express-layer and CD add/drop functionality.
- It is composed of 40 amplifier sites.
- Provided DWDM system will have the capability to carry at least 10 Tbps in the C-band per node direction.
- Network should contain optimization for coherent transmission.
- Colorless (C) add/drop solution shall be used.

By the end of Network dimensioning phase all existing outputs from the calculations will be assigned as inputs on TCO model. In order to proceed with the TCO analysis, cost model data need to be gathered from the business model and be given as inputs to TCO model, as well.

![Figure 3.2 fully built reference network](image)

### 3.1.4 Business cost model

The business cost model for integrated optical line systems and disaggregated optical line systems need to be clearly defined due to their highly impact on TCO analysis. Typically, a business cost model for DWDM systems consists of a price list for the network hardware equipment, human
related resources, fault management and network power consumption. During a yearly basis process of price estimations, the above factors are usually influenced by cost erosions. Price drops are generally related to Butters' law of Photonics\(^2\), consumer price promises, pricing policies and vendor competition offers. As a result, the manufacturers are required to spot price or cost erosion at early stage and act in advance before price set adapts to yearly business cost model [39].

The price of network hardware components normally corresponds to a declining trend due to widespread market production, technology updates ready for deployment and the increase of market purchase. For the human related services such as: help desk, fault management and network maintenance price can vary based on the number of technicians required and the software automation strategy. In general, technicians’ salaries are increasing on a yearly basis due network life cycle which requires more action for maintenance and repair of network elements [pg. ∼37] [7].

Finding the suitable learning curve for making predictions regarding the reduction of each DWDM product cost might be a tricky task for an industry. However, a linear model as the one shown in the Equation 3.1 can be applied including price erosion impact [38]. Therefore, while defining the price reduction model, it is necessary to consider that the model leads to reasonable price band ladders for a product group, a slow rate of erosion in network services while as high as possible erosion on hardware, and ultimately higher revenues while protecting market share [37].

\[
P_i = P_0 + \alpha P_{i-1} \quad (3.1)
\]

---

\(^2\) Butters’ law says that the amount of data coming out of an optical fiber is doubling every nine months.\[\text{[link]}\] Thus, the cost of transmitting a bit over an optical network decreases by half every nine months.\[\text{https://en.wikipedia.org/wiki/Moore%27s\_law}\]
On the above equation $P_{i}$ it is demonstrated how the price on year (i) is affected by the erosion during the network life cycle. $P_0$ is used to define the initial price of the product (hardware equipment, human resources, etc.) on starting year zero of the project. The composite metric $\alpha$ represents the cost change on a yearly period of time. Parameter $\alpha$ has negative value when it is used for hardware calculations and positive value when it is utilized for finding the price for energy consumption or salaries.

In order to differentiate the price erosion estimations for closed OLS and open OLS two different business models are represented below.

**closed OLS business model:**
For the OLS hardware NEs it is estimated that value $\alpha$ will have a negative value ranging from 3% to 7%. The highest erosion values up to 7% is estimated for the Amplifier cards and ROADM cards since the initial price on year one is very high compared to core equipment for network setup and attenuators. For the transponder equipment 12% erosion will be used while performing the 5 year TCO analysis.

**open OLS business model:**
In the O-OLS business model, strategy of multiple vendors for offering the transponders components are taken into account, while one single vendor for deploying the OLS system is considered. In this case, open line system cost model will be given from equation 3.2.

$$C_{O-OLS\ (i)} = C_{Closed-OLS\ (i)} + C_{SpectrumLicense\ O-OLS\ (i)} \ (3.2)$$

In the above equation 3.2 the cost for OLS hardware for the open system is calculated by adding up the initial cost of hardware OLS used for the closed system on requested year (i) plus calculated spectrum license fee for O-OLS system for year (i). In order to calculate spectrum license for the O-OLS, 30% price reduction is applied on the used spectrum for the requested year which is related on total wavelength cost used for every single NE such as ROADM and amplifier on the network. For the transponder equipment 50% price reduction due to competition is estimated on year one for the open system 50% reduction and for the following years of TCO a 12% reduction.
All of the aforementioned cost models will reflect the cost classification of TCO model and they will determine the direct and indirect cost assessments during a network life cycle evolution.

### 3.1.5 Total cost of ownership (TCO) model

In this section all the above-mentioned outputs from Network dimensioning and cost model will affect the TCO model calculations and results. TCO model includes all costs that are an outcome of huge upfront investment needed in the network deployment phase, usually referred as capital expenditures (CAPEX) [pg. ~38] [7]. Moreover, all operational expenditures (OPEX), costs related to the operational phases are crucial part of the TCO model, as well [pg. ~38] [7]. Figure 3.3 represents how cost is classified and what are the different categories for CAPEX and OPEX which build the TCO model. The time period of performing the TCO analysis can vary based on the network built plan and vendor’s competition. A typical time stamp for analyzing the cost evolution can be between 5 and 10 years. For this master, thesis 5 years of TCO has been done.

![Figure 3.3 TCO model](image)

3.1.5.1 Capital expenditures (CAPEX)

Capital expenditures are referring to the cost required for deploying the DWDM network in terms of equipment and software infrastructure and it calculated on yearly basis. The equipment cost for this master thesis, is based on network hardware, management system, equipment (software and
hardware) installation, network releases and DWDM licenses and network hardware spare parts for replacing broken card elements and etc.

On the equation 3.6 is shown how the total cost of equipment is calculated. The total cost of network hardware includes the expenses that are coming from:

- core installation which includes:
  - rack arrangements,
  - shelves standards,
  - chassis boxes and installation kits,
- network element cards for OLS,
- service modules for transponders,
- pluggable optics and accessories for both OLS and transponders.

Also, equipment's price is calculated by adding up the cost incurred from DWDM management systems such as OLS NE controller card and NMS NE client card. Moreover, total cost from network licenses contains capacity licenses for transponders, channel licenses, NE licenses and etc.

For O-OLS additional cost due to spectrum license used is included in the total network hardware cost. This cost is calculated from the equations 3.3, 3.4 and 3.5. Firstly, on equation 3.3 it is summed up the cost of OLS system when the network is fully built where K denotes the number of year in the TCO analysis. Then the total OLS cost in a fully network will be multiplied by 0.3 metrics to find out the used spectrum of the network based on the traffic growth of the network, as it is shown on 3.4 equation. On equation 3.5, the cost of used spectrum is divided by N which is the total number of years in TCO in order to find the yearly cost for spectrum license. This yearly spectrum license cost is added on closed OLS cost per year in order to calculate the new O-OLS cost on a yearly basis.

\[
\text{Tot } OLS_{fully\ built}^{\text{cost}} = \sum_{i=1}^{K} OLS_{cost}^{\text{(3.3)}}
\]

\[
\text{Used Spectrum}_{\text{license}}^{\text{cost}} = 0.3 \cdot \text{ToT } OLS_{fully\ build}^{\text{cost}}^{(3.4)}
\]

(3.5)
In addition, the total cost for Network hardware spare parts is a one-time fee which needs to be calculated on the first year of TCO. This cost is related to depot geographically distribution. In European reference network, 4 spare depots are used which are distributed accordingly in order to provide as fast as possible in terms of hours, the replacement of broken components. For OLS components since only one vendor provides the network components there is not any difference in strategy between closed and open OLS for offering the hardware elements. However, on spare part management for O-OLS case, transponder vendors’ specific parts need to be replaced by the same vendor. As a result, the cost of transponder hardware components is multiplied by the number of vendors to supply the requested transponder hardware elements.

\[
\text{YearlySpectrum}^{\text{cost}}_{\text{license}} = \frac{\text{Used Spectrum}^{\text{cost}}_{\text{license}}}{N} \quad (3.5)
\]

\[
\text{Tot}^{\text{cost}}_{\text{Equipment}} = \text{Tot}^{\text{cost}}_{\text{NetworkHardware}} + \text{Tot}^{\text{cost}}_{\text{NetworkLicenses}} + \text{Tot}^{\text{cost}}_{\text{Network Hardware spares}} + \text{Tot}^{\text{cost}}_{\text{Installation and Commissioning}}
\]

(3.6)

\[
\text{Tot}^{\text{cost}}_{\text{NetworkHardware}} = \sum_{i=1}^{N} \Pr_{eq}^{eq} \cdot \text{Qty}_{eq}^{eq} \quad (3.7)
\]

The cost that needs to be paid for installation and commissioning is the outcome of hardware and software installation and commissioning. By taking the 10% of the total cost of OLS and transponders yearly it can be found out the yearly hardware cost for installation and commissioning. The software installation cost, is 10% of NMS and Vendor controllers and it paid only on year one of TCO. These installation and commissioning cost differ for OLS and O-OLS due to differences in costs for OLS, transponders and software deployment.

On all the above total cost calculations as it is shown on equation 3.7, the price of equipment (i) is multiplied by the quantity of NEs such as: amplifiers and ROADMs per node. Since the network is dynamically built, N that denotes the existing number of nodes on year one can vary during a five year TCO.
analysis. As a result, on the fifth year (N=5) some equipment can be re-utilized by the updated network case thus influencing the total cost of equipment.

Software infrastructure is mainly related to the expenses needed for interface configuration between SDN controller, NEs (Transponder, OLS), Alarm collection and NMS. All the costs that are coming from network configuration APIs are one time fees which are paid on first year of the total TCO model. Assuming that the closed OLS and open OLS have different interfaces for management as it is shown below on figure 3.4, cost for development interfaces and license can differ. On table 3.3 is represented the list of interface costs including cost for NMS and Vendor controllers for closed OLS and open OLS respectively.

Table 3.3. Interface costs
As a result, total software infrastructure is equals to total cost of interfaces for development and interface licenses on equation 3.8.

$$\text{Tot}_{\text{SoftwareInf}}^{\text{cost}} = \text{DevelopInterf}_{\text{cost}} + \text{LicencesInterf}_{\text{cost}} \quad (3.8)$$

In order to estimate the overall CAPEX even for closed OLS or O-OLS equation 3.9 should be used.

$$\text{CAPEX} = \text{Tot}_{\text{Eq}}^{\text{cost}} + \text{Tot}_{\text{SoftwareInf}}^{\text{cost}} \quad (3.9)$$

### 3.1.5.2 Operational expenditures (OPEX)

Operational expenditures contain all the expenses which are strongly connected with DWDM network operation during its life time. An operable network lifetime is ended and being replaced by new technology. Operational costs due to energy-power consumption of the network hardware components,
fault management, preventive maintenance and help desk are the main categories of OPEX.

Energy - Power consumption expenses are related to yearly energy consumption of the network hardware such as: OLS and transponders. The cost for power consumption is the outcome of multiplying the price per watt hour (eg. SEK/Wh) of an electrical unit by the sum of energy consumption of active components on the network during the year. Power consumption is an accumulative cost which means that on the last year of TCO, the price will represent the total energy consumed from year one. The below equations 3.10, 3.11 and 3.12 show the cost calculation for Energy consumption on DWDM network.

\[
\text{\text{Tot}}_{\text{Energy consumption}} = \text{\text{Tot}}_{\text{OLS energy}} + \text{\text{Tot}}_{\text{transponder energy}} \quad (3.10)
\]

\[
\text{\text{Tot}}_{\text{OLS energy}} = \sum_{i=0}^{K} \left\{ \sum_{j=0}^{N} \left[ f(j) \cdot m(j) \right] \right\} i \cdot \text{price}_{\text{power}} \cdot \frac{\text{yearly Wh}}{1000} \cdot \text{cooling factor}, \forall f(j) \neq l(j)
\]

(3.11)

\[
\text{\text{Tot}}_{\text{transponder energy}} = \sum_{i=0}^{K} \left\{ \sum_{j=0}^{N} \left[ k(j) \cdot n(j) \right] \right\} i \cdot \text{price}_{\text{power}} \cdot \frac{\text{yearly Wh}}{1000} \cdot \text{cooling factor}, \forall k(j) \neq n(j)
\]

(3.12)

On the equation 3.11 the \( \sum_{j=0}^{N} \left[ f(j) \cdot m(j) \right] \), represents the power watt of every single component on each NE. The \( \sum_{i=0}^{K} \left( \sum_{j=0}^{N} \left[ f(j) \cdot m(j) \right] \right) i \), denotes the total power consumption of all OLS components (N) of all network elements (K) for a given year. The result of the sigma will be multiplied with price for power, the yearly watt-hours and the metric of cooling the system. This will give the total cost for OLS energy. In a similar process the cost of power consumption for transponders is calculated on equation 3.12. In order to find out the total yearly cost for power consumption, it is required to add the total cost of transponder and OLS as it is done on equation 3.10.

Fault management cost includes the expenses that are required for managing the number of failures in the network during its operational time.
Fault management in DWDM networks includes DWDM problems (OLS system and transponders), fiber problems and problems occurred due to learning integration period faults which can applied on the open optical line system architecture because of its high complexity (many APIs) of management. On the equation 3.13 below, it is represented the total cost of DWDM fault management. This cost, is the outcome of a statistic metric representing the overall DWDM faults occurred in the network (operator’s reference) multiplied by the number of Network Elements on a yearly basis, multiplied by the cost for identifying the problem on the system plus the cost of card delivery to the technician mentioned as Delivery Cost on 3.13. Also, average cost of contractor required to fix the fault occurred in DWDM system is added on the total cost for DWDM fault management. On the equation 3.14, the total cost of fibers fault management is calculated in a similar process with the total cost of DWDM fault management. The differences are connected with the number of links are utilized on the equation instead number of NEs, and apart from delivery cost, there is a technician cost which is taken into consideration for manual configuration of patch cable failures. By adding up all of the above total costs for fault management of DWDM and fibers, it is possible to calculate the overall total yearly cost of fault management on the network as it is shown on equation 3.15.

\[
\text{Tot}_{\text{fault management DWDM}}^{\text{cost}} = \text{statisticsMetric}_{\text{DWDM}} \cdot \text{numNEs}_{\text{current year}} \cdot \text{identifyingProblemCost}_{\text{DWDM}} + \left( \text{statisticsMetric}_{\text{DWDM}} \cdot \text{numNEs}_{\text{current year}} \cdot \text{DeliveryCost} \right) \\
+ \left( \text{statisticsMetric}_{\text{DWDM}} \cdot \text{numNEs}_{\text{current year}} \cdot \text{AverageCost}_{\text{Concam}} \right)
\]

(3.13)

\[
\text{Tot}_{\text{fault management fibers}}^{\text{cost}} = \text{statisticsMetric}_{\text{fibers}} \cdot \text{numLinks}_{\text{current year}} \cdot \text{identifyingProblemCost}_{\text{fibers}} + \left( \text{statisticsMetric}_{\text{fibers}} \cdot \text{numLinks}_{\text{current year}} \cdot \text{TechnicianCost} \right)
\]

(3.14)

\[
\text{Tot}_{\text{overall fault management}}^{\text{cost}} = \text{Tot}_{\text{fault management DWDM}}^{\text{cost}} + \text{Tot}_{\text{fault management fibers}}^{\text{cost}}
\]

(3.15)
Preventive maintenance cost is composed of outgoings for maintaining the network equipment in order to lessen the likelihood of failures [43]. Preventive maintenance includes internal troubleshooting and it requires an investment in time and resources [43]. In this study, it is calculated on a yearly basis. Total cost required for preventive maintenance is the average cost of man hours per year gathered from Telia network carrier, multiplied by the network percentage of selected country. The percentage factor is based on the fact that DWDM networks are not having the same geographic distribution between countries. As a result, maintenance need to be applied on the given network topology. The equation 3.16 shows how the total preventive maintenance cost is conducted and $NumOf\text{ manhours}_{\text{yearly}}$ is the total number of man hours spent on preventive management which was found out that it is equal to one man year.

$$\text{Tot cost}_{\text{preventive maintenance}} = \text{manhour cost} \cdot NumOf\text{ manhours}_{\text{yearly}} \cdot \text{networkpercentage}_{\text{country}}$$

(3.16)

Help desk consists of the people who are managing inbound incidents of network remotely through a ticketing system. Based on the seriousness of ticket, different levels of escalations can occur until ticket resolution is complete [44]. In order to calculate help desk cost, installation basement which is related to hardware and associated licenses (OLS, transponders) is utilized. This cost is calculated yearly since it is strongly connected with network hardware that can vary from year to year. Help desk is an accumulative cost which means that on the last year of TCO, the price will represent the total support offered on the network from year one. On the equation 3.17, the total cost for help desk is the outcome of taking a percentage of the total cost for installation basement. This percentage is obtained by the operators and it is estimated to be around 2.5 percent of aforementioned cost for hardware installation.

$$\text{Tot cost}_{\text{help desk}} = 0.025 \cdot IB$$

(3.17)

Summing up all the total cost categories of OPEX will give the overall yearly cost for the operational expenses on a closed and open OLS network respectively. The overall yearly OPEX is represented on equation 3.18. For
internal work for fault management on the open system architecture, 20 percent additive cost is applied on year 1 and 2 due to fault integration period. Fault integration period is associated with the estimation of required time to stabilize the maintenance and management of the DWDM system. This period is estimated to take longer for learning the open OLS network due to its higher complexity in terms of management.

\[
\text{OPEX} = \text{Tot}^{\text{cost}}_{\text{energy consumption}} + \text{Tot}^{\text{cost}}_{\text{fault management}} + \text{Tot}^{\text{cost}}_{\text{preventive maintenance}} + \text{Tot}^{\text{cost}}_{\text{help desk}}
\]

(3.18)

On the following chapter 4 all the outputs of TCO are going to be evaluated and analyzed for both systems closed and open OLS. The evaluation of techno-economic results is the last phase of the generic techno-economic evaluation framework and seems to be of vital importance in order to make conclusions for the cost distributions among years of analysis.
Chapter 4

Evaluation results

This chapter describes the evaluation results of techno-economic analysis that has been performed for closed optical line system and open optical line system.

Firstly, a thorough analysis of total cost of ownership evolution within a 5-year period is discussed. Details about the costs classifications regarding the initial price offers due to business model strategy are represented.

The total cost investments of deploying an integrated DWDM compared to the total cost investments of developing a disaggregated DWDM are depicted. Based on that, an operator who is interested in building one of the two suggested architectures will be able to analyze the project profitability for a five-year period of time. Total cost investments are divided into categories that compose the final price investment for DWDM architectural models. Due to cost categorization, it can be easy to understand the most cost demanding parts for deployment.

Since the TCO is related to the total cost requirements for capital expenses and operational expenses, an evaluation of capital expenses for building an open OLS compared to the CAPEX needed for closed OLS is done. Also, evaluation of total OPEX required for closed OLS in contrast with open OLS is discussed. In both suggested architectures, is studied the overall cost estimations for OPEX and CAPEX during the five years of cost calculations.

All the necessary costs for performing the techno-economic analysis are traffic dependent. This is based on the fact that DWDM network is built up on a yearly incremental process and its capacity is evolving in accumulative way. As a result, network hardware updates, maintenance of network and management activities need to be performed on yearly basis. In this case, an increase or decrease of network traffic can lead to cost variations that can influence the performance of the network. For this reason, it is important to utilize multiple traffic case scenarios on the cost calculations in order to evaluate the performance of the network with cost efficiency.

Finally, a cost analysis, assuming different price reduction due to vendors’ competition can be considered during the evaluation of results. Changing the
business cost model and utilize a different traffic case scenario can affect and change the values of TCO analysis.

4.1 Techno-economic evaluation results

In order to perform a TCO Analysis a shopping list provided by vendors and network traffic evolution needs to be utilized. This will lead to assumptions about the required expenses for the network. Since the Optical Network can be divided into line and terminal side, there are two different shopping lists that are related to OLS and transponders respectively.

The unit prices\(^3\) for all the components required to build an OLS system can be found in internal master thesis version of Telia. As it was discussed on chapter 3 section 3.1.4 there is a price reduction of 3%. In the price list there is a Q-ty which represents the total number of components per Network element (ROADM, amplifier) for European network topology. In an open OLS spectrum licenses needs to be calculated since they are paid separately. Using the equation 3.2 of chapter 3, it can be possible to calculate the new cost for line system that considers an additional charge for spectrum license used.

For transponders, another price list that can be also found on internal master thesis version of Telia is representing the initial unit price\(^4\) on year one and the number of transponder components that are related to core, service modules and pluggable optics on a yearly basis. As it was mentioned on chapter 3 section 3.1.4 on an integrated OLS, transponders initial total price is reduced by 12% from year 2 until the final year of TCO. On a disaggregated OLS system there is 50% reduction of transponder initial price used for closed OLS which is applied on the first year of TCO analysis. For the next years a 50% price erosion of the already 12% erosion on closed transponders model is applied.

The capacity evolution of European reference network during the five-year period of TCO Analysis influences the total costs estimation required for a fully operational integrated or disaggregated optical network. The figure 4.1 below shows how network capacity is evolving between years. The below equation 4.1 is utilized to calculate the total yearly capacity of the network. On

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\(^3\) all prices have been normalized with the transponder box price
\(^4\) all prices have been normalized with the transponder box price
the equation 4.1 the traffic matrix of network dimensioning model in chapter 3 section 3.1.3 is used to sum the number of 10 Gigabit per sec (Gbps) and 100 Gbps utilized per node for the European network yearly, where N is the yearly number of nodes.

![Capacity Evolution Graph](image)

**Figure 4.1 Capacity evolution**

\[
\text{Network Capacity} = \sum_{i,j=1}^{N} \left[ 10f(i,j) + 100f(i,j) \right], \; \forall i \neq j \tag{4.1}
\]

The x-axis shows the number of Gigabit per second (Gbps) and the y-axis shows the number of year. On year 2018 the capacity is 1310 Gbps and it is increasing at 1470 Gbps on 2019, 1350 Gbps on year 2020, 420 Gbps on year 2021 and 2090 Gbps on year 2022. Due to yearly capacity increase, it can be concluded that the total cost is increasing on a yearly basis but cost variations are expected because of differences in traffic growth.

Summing up all the yearly costs that are connected with capital and operational expenses for both closed OLS and opened OLS conclusions can be made about the economic efficiency of the two different proposed
architectures (closed OLS, opened OLS). On figure 4.25 it can be seen that OPEX for opened OLS is more expensive for years 2018 and 2019 due to fault learning integration period that is estimated to take two years to get know the more complex management, configuration and maintenance of the O-OLS. For the rest of years, the total OPEX cost is exactly the same for both systems. Regarding the CAPEX, it can be seen that on year 2018 there is a higher cost for the O-OLS compared to closed OLS and this can be applied due to one-time fee more expensive costs paid for Software deployment and installation and commissioning due to O-OLS software management complexity. Also, more expensive one-time fee costs are paid for Network Hardware spares because of multiple vendors that are offering the transponder components in the disaggregated approach. For the rest years of TCO, CAPEX on O-OLS seems to be more beneficial in comparison with closed OLS. Because of the fact that the aforementioned costs are related to yearly network capacity there are significant differences among years for both architectures. It is noticed to have the least cost on 2021 which corresponds to the least capacity growth of the network (420 Gbps).

![Figure 4.2 Yearly TCO C-OLS vs O-OLS](image)

**4.2 Total cost investments**

The techno-economic results need to be evaluated in total for whole period of time that TCO is being performed. By this way will be easier to understand

---

5 all the unit prices have been normalized into transponders’ box price
the total cost investments of introducing O-OLS or closed OLS respectively in the market.

As it can be noticed at figure 4.3\(^6\) below x-axis has 1 value to denote the totality of TCO in 5 years. The total CAPEX of closed OLS seems to be 32.28% more expensive from the total CAPEX of O-OLS needed for all five years of TCO analysis. However, the total OPEX of O-OLS seems to be 3% more expensive from the total OPEX of closed OLS.

![OPEX & CAPEX in 5 years](image)

**Figure 4.3 Five years TCO analysis**

In order to realize which architecture is more beneficial the total TCO for the whole 5 years of investment needs to be considered. From the figure 4.5\(^7\) it can be concluded that O-OLS can offer 27% benefit in total for 5 years investments. This assumption though is conducted for the given traffic growth of European network and might differ when introducing different traffic evolution on the network. In next sections, the impact of CAPEX into OPEX during 5 years of TCO will be analyzed thus the case of handling with different traffic on the network in relation to network performance and cost efficiency.

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\(^6\) normalized prices on transponders’ box price

\(^7\) normalized prices on transponders’ box price
As it has been noticed from previous sections 4.1 and 4.2 the most costs of TCO investments during a five-year period of time are spent for Capital expenses and particularly for equipment deployment and installation.

On figure 4.6 below a CAPEX detail analysis has been done. Starting for year 2018 the cost for open optical line system is higher compared to cost for closed optical line system. This is due to spectrum license price which 30% additional price divided over used spectrum of channels added every year to cover network capacity. This additional cost on O-OLS is used to keep track of used capacity in the system and this cost need to be paid by the vendor. On the same year 2018, it can be seen that closed transponders are more expensive for deployment in comparison with open transponders. Since it is noticed the same yearly price erosion on the open and closed transponders there is 50 % price reduction due to competition, which justifies the cost efficiency in open transponders. Also, on year 2018 from one time fees applied to software deployment, development and license interfaces are more expensive for O-OLS architecture. This is connected with fact that O-OLS introduces higher

---

8 prices are normalized on transponders box price
level of system complexity and requires more interfaces for management. Therefore, hardware spares for open transponders are more expensive due to more vendors involved to supply transponder components. In addition, software installation and commissioning is higher for O-OLS because there is extra cost for the NMS for transponders and the vendor controller of optical line system.

For the rest of the years until 2022 open OLS cost seems to be more expensive compared to closed OLS due to extra cost for spectrum license. However, hardware installation and commissioning is more expensive for closed OLS because there is not any price reduction on transponders. As a result, open type transponders are significantly cheaper in contrast with closed type transponders for all five years of CAPEX detail analysis.

Figure 4.6 CAPEX detail analysis

In order to distinguish total CAPEX investment needed for O-OLS and closed OLS all costs for the whole period of analysis have been gathered. On figure 4.79, it is depicted that open OLS is 29% more expensive for closed OLS while open transponders 50% cheaper for closed transponders. Open total

9 prices are normalized according to transponder’s box price
hardware installation and commissioning is 31% cheaper compared to closed one. Checking the cost of equipment which is the most expensive CAPEX cost and includes OLS and transponders for both architectures, it can be understood that the total cost for equipment is 36% more in the integrated OLS architecture. However, software deployment is

Figure 4.7 CAPEX investment
30% more in the disaggregated OLS architecture. Thus, the impact in terms of money is insignificant compared to equipment deployment since the software deployment is paid only on first year of TCO.

Operational expenses seem to influence the TCO Analysis as well regardless the fact that the total cost spent for OPEX is less from total cost spent for CAPEX. The importance of OPEX is connected with network operations during network’s lifetime and for this reason detail analysis on OPEX cost classification has been done.
On figure 4.8 above it can be seen that the costs for power consumption of transponders and OLS system remain the same in both system architectures because there is not any change in the number NEs and their functionality in the optical network. There is a difference though in O-OLS applied to the way power is monitored. As it has been described on chapter 2 due to more optical controllers, more complex SDN APIs and management of the system since O-OLS is using more advanced techniques for power monitoring. However, for the level of disaggregation that is analyzed on this master thesis would not be any difference on the power consumption of hardware components (OLS and transponders).

For years 2018 and 2019 it can be noticed that O-OLS has 20% additional costs for Fault management of DWDM components (ROADM, amplifiers, transponders) and fault management of fibers, due to additional two years of fault learning integration period. For the same reason preventive maintenance cost on 2018 and 2019 is higher for the O-OLS. Costs applied for help desk are equal for both integrated and disaggregated OLS all five years. Help desk cost is based on an accumulative cost policy which means that help desk cost is more on year 2022 from previous years. For years 2020, 2021 and 2022 all different OPEX categories are adding extra costs on optical network lifecycle but there is not any difference for the two compared OLS architectures.

10 prices are normalized according to transponder’s box price
The following figure 4.9 shows the OPEX impact for whole five years per OPEX category. Going through the total investments for closed OLS and O-OLS it can be concluded that O-OLS cost for fault management for DWDM problems and fiber problems is 5% more expensive compared to closed OLS. Also, cost of preventive maintenance for O-OLS is 8% more expensive from maintenance required in the integrated system.

![OPEX 5 years investment](image)

Figure 4.9 OPEX five years’ investments

To have a better understanding of how CAPEX and OPEX are ranging over the five years of TCO Analysis, the difference of O-OLS from initial price closed-OLS (including all expenses of systems) known as delta price can be calculated. Then the result of the above subtraction will be divided by the closed-OLS price in order to take the delta percentage per year. Positive value will show that O-OLS CAPEX or O-OLS OPEX price has been increased. Negative value will represent that O-OLS has been decreased and zero value will show that there was not any change between closed and open OLS in the CAPEX or OPEX costs.

---

11 prices are normalized on transponder’s box price
Figure 4.10 Delta CAPEX and delta OPEX

As a result, on year 2018 CAPEX price of O-OLS has been increased by 14.28% and OPEX price of O-OLS has been increased 16.11%. On year 2019 CAPEX price of O-OLS has been decreased 22.83% while OPEX price has been increased by 14.90%. On year 2020 O-OLS CAPEX price has been decreased 28.42% while OPEX price remained the same for both O-OLS and closed OLS. For the rest of years O-OLS CAPEX price reduced by 41.39% and 42.32% which means that it was almost the half price of the closed OLS while OPEX prices remained the same for both systems.

4.4 Sensitive total cost analysis

In previous sections of Chapter 4, it has been seen that O-OLS seems to be more beneficial for deployment in terms of money. However, the TCO Analysis has been carried out for the original traffic volume of the network and considering a specific business model for price reduction in transponders due to competition. Optical network lifecycle can be possibly likened to a game theory model since traffic can vary independently from business model strategies [45]. Based on that, different traffic case scenarios within the same business model can have different TCO results since network hardware installation, management and maintenance are highly depended on the network traffic. However, pricing is done based on vendors’ competition in order to maximize profit and market share. As a result, this section shows how TCO results can be influenced by having different traffic on the network but keeping the same business model for transponders. Moreover, a case that
estimates changes in business model of transponders by having the same traffic in the network is presented.

**Traffic volume cases:**

On figure 4.11, it is depicted how network capacity is evolving in five years’ period of time by assuming that network has half traffic volume of the original, five times traffic volume of the original and ten times traffic volume of the original.

![Network Capacity (Gbps) in 5 years period](image)

**Figure 4.11 Traffic case scenarios**
Figure 4.12 CAPEX and OPEX analysis traffic based TCO results including the CAPEX and OPEX differentiation can be seen on figure 4.12\textsuperscript{12}. In all cases of traffic total CAPEX of closed OLS seems to be more expensive for total CAPEX of O-OLS and it varies from 17\% in half traffic volume to 45\% in ten times higher traffic volume. However, the total OPEX of O-OLS in all traffic scenarios is more expensive compared to closed OLS but this cannot be easily recognized from the above figure 4.12 because the difference is really short and it ranges from 1\% to 3\%.

\textsuperscript{12} the prices have been normalized according to transponder’s box price
Summing up total CAPEX and total OPEX of closed and O-OLS in all different traffic cases, gives the overall TCO applied to four different traffic volumes considered in the optical network. From the figure 4.13\textsuperscript{13}, can be concluded that O-OLS TCO reduced 21% from closed OLS TCO in the initial traffic growth of the network for five years. Also, O-OLS TCO reduced from OLS TCO 17% assuming half traffic growth, 39% in 5 times traffic growth and 43% in 10 times traffic growth. The above results imply that maximizing the network capacity evolution by 5 and 10 times the initial value in five years’ period of time can give extremely advantageous TCO results for O-OLS architecture.

**Transponder price erosion case:**

Since transponders price influence the total profit of the optical network, different price erosions due to vendors’ competition can applied for transponders cost in O-OLS. On figure 4.14\textsuperscript{14}, it has been utilized the initial traffic growth of the optical network by taking into account three different models of the yearly transponders price reduction. Also, the overall impact of yearly price erosion into O-OLS CAPEX compared to yearly closed OLS CAPEX can be seen. Using a 10% erosion on transponders on the initial traffic growth of the network, it increases by 25% the total CAPEX on O-OLS, and decreases meaningless by 1-4% the O-OLS CAPEX on next years of analysis.

\textsuperscript{13} prices have been normalized according to transponder’s box price
\textsuperscript{14} prices normalized on transponder box price
However, by applying 30% and 50% erosion on transponders, the O-OLS CAPEX is increased by 22% and 16% on 2018 and it has an average decrease of 18.4% and 30% respectively for the next years. Table 4.4 sums up the CAPEX results applied on transponders price erosion cases calculated on the initial traffic volume of the network.

![Figure 4.14 CAPEX price erosion cases](chart)

**Table 4.4 CAPEX results applied on erosion**

<table>
<thead>
<tr>
<th>Price erosion</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% erosion on transp.</td>
<td>O-OLS CAPEX increased 25%</td>
<td>O-OLS CAPEX increased 1%</td>
<td>O-OLS CAPEX decreased 3%</td>
<td>O-OLS CAPEX decreased 1%</td>
<td>O-OLS CAPEX decreased 4%</td>
</tr>
<tr>
<td>30% erosion on transp.</td>
<td>O-OLS CAPEX increased 22%</td>
<td>O-OLS CAPEX decreased 11%</td>
<td>O-OLS CAPEX decreased 15%</td>
<td>O-OLS CAPEX decreased 21%</td>
<td>O-OLS CAPEX decreased 23%</td>
</tr>
<tr>
<td>50% erosion on transp.</td>
<td>O-OLS CAPEX increased 16%</td>
<td>O-OLS CAPEX decreased 23%</td>
<td>O-OLS CAPEX decreased 28%</td>
<td>O-OLS CAPEX decreased 41%</td>
<td>O-OLS CAPEX decreased 42%</td>
</tr>
</tbody>
</table>

![Figure 4.15 TCO results price erosion cases](chart)
OPEX expenses has not been analyzed for the different price erosion models applied in transponders due to the fact that operational expenses do not influence from price competition on transponders. By adding up the total CAPEX investments for five years, including total OPEX investments, it is possible to take the TCO results for all cases of price erosion described above. As a result, on figure 4.15, it is shown that on 10% erosion O-OLS TCO increased by 4% from closed OLS TCO, while on 30% and 50% erosion O-OLS TCO decreased by 9% and 21% from closed OLS TCO. This gives the conclusion that the more erosion is applied on transponders in regards with an average traffic case scenario, the more beneficial is the TCO for O-OLS.

To sum up, changing input parameters such traffic volume or business model for transponders can influence that TCO results and give different conclusions for TCO comparison between O-OLS and closed OLS. This means that techno-economic analysis for open optical line systems is highly depended on the traffic volume and business model parameters.

4.5 Network performance and cost efficiency

The above results of TCO analysis have been applied to the interregional European optical network which covers 3000 km distance of maximum reach and can offer at least 10 Tbps capacity. Based on that, it has been demonstrated that open optical line system is more beneficial and cost efficient when it is needed to handle with 20650 Gbps, 41300 Gbps median values of network capacity during five years as it is shown on table 4.5. This is due to the fact that cost saving occur when network capacity is significantly maximized.

<table>
<thead>
<tr>
<th>Traffic volume cases</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>Median Capacity (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial traffic</td>
<td>1310</td>
<td>2780</td>
<td>4130</td>
<td>4550</td>
<td>6640</td>
<td>4130</td>
</tr>
<tr>
<td>half traffic</td>
<td>655</td>
<td>1390</td>
<td>2065</td>
<td>2275</td>
<td>3320</td>
<td>2065</td>
</tr>
<tr>
<td>5 times traffic</td>
<td>6650</td>
<td>13900</td>
<td>20650</td>
<td>22750</td>
<td>33200</td>
<td>20650</td>
</tr>
<tr>
<td>10 times traffic</td>
<td>13100</td>
<td>27800</td>
<td>41300</td>
<td>45500</td>
<td>66400</td>
<td>41300</td>
</tr>
</tbody>
</table>

Table 4.5 Median network capacity

In the TCO results for the initial traffic volume of European network, has been found that in closed OLS architecture 18% of TCO is corresponding to optical line system while 56% of TCO is transponders costs. However, on the O-OLS network it has been found out that 36% of TCO is referring to transponders cost and 30% of TCO is the optical line system cost. As a result
of the above statistics, terminal optics (transponders) are influencing a lot the TCO especially in closed OLS architecture. So, by increasing the traffic volume of European network and by utilizing the case of 30% to 50% erosion on transponders for O-OLS, it is expected to have considerable reductions on O-OLS TCO compared to OLS TCO.
Chapter 5

Conclusion and future work

This chapter demonstrates the conclusions for optical line systems as a resultant of TCO comparison study between integrated and disaggregated OLS. Also, future directions of Open optical techno-economic analysis are highlighted.

Based on the techno-economic evaluation results, O-OLS architecture seems to be a cost efficient implementation for optical line systems. O-OLS can introduce considerable TCO savings compared to closed OLS while scaling up the average traffic volume of an interregional optical reference network (European network), by 5-10 times of capacity needs. This conclusion of providing good network performance and cost efficiency at the same time can lead O-OLS to be preferred from closed OLS for deployment.

The TCO comparison of the two suggested model architectures has been emphasized on their level of disaggregation. As a result, a fully integrated system has been compared with a partly-disaggregated system due to constraints that are associated with level of disaggregation. This is due to the fact that a fully open optical line system can make the system integration difficult, bring risks in system stability and it might increase OPEX [1].

An O-OLS architecture can introduce more cost for the yearly deployment of optical line system due to extra expenses needed for the used spectrum licenses. The additional spectrum licenses paid on the O-OLS are in order to give the flexibility and compatibility while choosing the transponder components from a number of vendors. Moreover, the vendors’ competition in transponders, reduces their percentage cost in the TCO due to yearly price erosion policy for transponders. Since transponders cost is one of the highest expenses for O-OLS, this influences the cost model. O-OLS cost model can give considerable economic benefits compared to closed OLS and introduce a compatible architecture of best mix and match components.

All the information gathered and utilized for the study are considering the particular DWDM network of a EU country. However, all the mathematical equations and models utilized for finding out CAPEX, OPEX and TCO are...
generic. As a result, it is possible to change the parameters of business models in all mathematical equations. In this way, the economical differences between integrated and disaggregated system can be analyzed by utilizing any kind of DWDM network topology that supports either average or low or high traffic volume.

For future implementations, the economic consequences of introducing a fully disaggregated optical line system in comparison with partly-disaggregated system will be investigated. Moreover, case scenarios that support long haul networks will be considered thus redefining the cost model to cover new optical network requirements.

- **Business viability of open optical line systems**
  
  On the evaluation results it has been demonstrated that O-OLS can offer a high CAPEX reduction during five years’ period of TCO while give an insignificant increase of OPEX. CAPEX reductions were mostly based on price erosion on transponders due competition, while OPEX increase was based on system fault learning integration period.

  Introducing O-OLS as a pioneering optical line system architecture comes along with the considerable benefits that O-OLS is offering compared to integrated OLS such as: decouple photonic layer from transport layer, no vendor lock-in, maximize network customization, allow smooth evolution [48], SDN APIs for orchestration of multivendor transponders’ boxes and vendor controller management system for OLS and etc.

  In order to ensure that O-OLS will operate profitably, operators that are supporting the disaggregated optical line architecture have to invest in O-OLS deployment. Finding out the suitable vendors that will accept the time plan of building an O-OLS, will incur costs and create revenue [47].

- **Constraints associated with level of disaggregation**
  
  The level of disaggregation that an open optical line system will introduce, is strongly connected with a number of challenges for system integration, transmission performance, fault location and interconnection standards [1].

  For the successful system integration advanced monitoring, commissioning and configuration software is required. This is important for reassuring that the complex and sophisticated transmission system of O-OLS will deal with accidents, natural disasters and various faults on the network. In this way,
transmission performance will be improved, optimal efficiency will be achieved and per-bit transmission costs will be reduced [1].

In a multi-vendor optical network, cooperation between all parties is of vital importance. High openness can be achieved in a partly and fully disaggregated approach that corresponds to number of vendors involved with line and terminal equipment and network management. As a result, no single vendor is in charge of fault management for the entire network. Therefore, actions of fault demarcation and fault location are difficult to be handled [1].

There are no interconnection standards that are mapping to optical-layer openness due to high complexity in optical transmission. Opening up the optical layer of the network can be applied to point-to-point short haul and metro networks. However, not all levels of disaggregation can be suitable for operators’ complex mesh networks that support a range of service types and granularities, massive-pass through sites and significant traffic fluctuations [1].

- **Open optical line systems and sustainability**
  
  An open optical line system architecture that is based on best mix and match line and terminal hardware equipment can minimize carbon footprints and power consumption. Service modules, pluggable optics and accessories and NE cards for either line system or transponders will depend on innovation, depreciation and renewal cycles. A high innovation rate can lead to high depreciation rate and shorter renewal cycle. However, innovation in the optical fiber is considerable slow with renewal cycles of decades [3]. Changing DWDM line systems technologies have become indefinable, in order to offer high speed and best quality of service in the optical network.

- **Future work of open optical line system techno-economic analysis**
  
  In terms of future work, a techno-economic analysis between a partly-disaggregated with a fully-disaggregated optical line system will be performed. This analysis will investigate how open line system can achieve higher scalability, flexibility and cost effective line solution by utilizing open ROADM initiative and multi-source agreement. Open ROADM design has already been proposed by AT&T [52], Fujitsu and others, as a drive innovation for multi-vendor capabilities in the line system and increasing the flexibility in metro-networks [49]. So, the purpose of the new techno-economic analysis is to
estimate the TCO savings if the open line systems are fully open. The case scenarios will be applied to metro and long-haul networks that need to handle with enormous amount of traffic.

Due to the fact a fully open architecture can make more difficult to estimate the costs for used spectrum licenses, a game theory based model [50] for pricing, wavelength and flow assignment in multiwavelength open optical networks will be considered. As, “Game Theoretic Pricing and Optimal Routing in Optical Networks” [50] proposes, Internet service provider (ISP) bandwidth demands and the routing and wavelength allocation can be modeled using Bertrand duopoly. Taking advantage of the proposed principle in [50], it will be investigated what can be the most beneficial model for pricing the used spectrum in the network during its network lifecycle.
References


Appendix A

- **1.6T DCI Optical Transport Platform**
  It is a high capacity platform in 1U, for data center interconnect, cloud and colocation providers, and high capacity applications. Figure 2.5 shows how the product is released in the market [15].

![PL-2000DC](image)

Figure 2.5 1.6T DCI Optical Transport Platform [15]

- **Layer-1 DWDM Encryption**
  this product can offer highly flexible platform for secured transport of up to 8 services of storage and data applications over dark fiber with configurable GCM-AES-256 encryption per service. Figure 2.6 shows how the product is released in the market [15].

![PL-1000TE-Crypto](image)

Figure 2.6 Layer-1 DWDM Encryption [15]

- **200G ADM for Long Haul**
  1U platform with low power consumption and high 200G density feature set. Ideal for metro and long haul applications. It is built in with encryption per service or per uplink. Figure 2.7 shows how the product is released in the market [15].
PL-2000AD

Figure 2.7 200G ADM for Long Haul [15]

- **Universal 1G to 40G Transponder**
Universal DWDM/CWDM 622M to 40G 1U transponder, supporting up to 8 transponders with a flexible mix of industry standard protocols. Figure 2.8 shows how the product is released in the market [15].

PL-1000TE

Figure 2.8 Universal 1G to 40G Transponder [15]

- **200G ADM for Short Haul**
1U platform with low power consumption and the highest 200G density feature set in the market. It is unique to be used for short haul and encryption applications. Figure 2.9 shows how the product is released in the market [15].

PL-2000ADS

Figure 2.9 200G ADM for short haul [15]

- **WDM Sub-10G Transponder**
Highly flexible metro CWDM/DWDM 1U platform for transport of storage, data, voice, and video applications over dark fiber. Figure 2.10 shows how the product is released in the market [15].

Figure 2.10 WDM Sub-10G Transponder [15]

- **200G Single Wavelength Muxponder**

An advanced 200G single wavelength 1U platform for next generation data center interconnect and metro applications. The product supports encryption per service or per uplink. Figure 2.11 shows how the product is released in the market [15].

Figure 2.11 200G Single Wavelength Muxponder [15]

- **10G DWDM Transponder**

10G metro DWDM Ethernet 1U transponder, for transport of data, TDM and storage applications. Figure 2.12 shows how the product is released in the market [15].
**100G Long Haul Muxponder Transponder**

100G coherent DWDM muxponder/transponder solution for long haul applications. Figure 2.13 shows how the product is released in the market [15].

**Coriant Groove G30 DCI Platform**

G30 Groove is an innovative stackable transport solution for cloud and data center networks that supports capacity of 3.2 Terabits. It offers WAN Cloud Connectivity services and can handle with 10G, 40G, 100G client side services. G30 Groove offers a programmable DWDM line interface that bandwidth management and performance optimization for high capacity transmissions varied from 100G to 400G can be done. Therefore, it includes DWDM Optical Multiplexing/Demultiplexing functions and optical amplification functions [29]. Figure 2.14 shows Coriant’s product release in today’s market.
Figure 2.14 G30 DCI platform, “Figure 1 G30 DCI platform” [30]
Appendix B

- Chassis which is composed of:
  - 4 slots
  - USB port
  - Eth1 interface
  - Console interface

- Fan modules consisted of:
  - 4 slots
  - control board
  - fan and fan tray

- Power modules which are formed of:
  - 2 slots
  - 2 Alternating Current (AC)/Direct Current (DC) power modules providing redundancy if one of them stop working.

- Pluggable modules contain module 1 and module 2:
  - Module 1 with total capacity 4 x 100G supports:
    - 2 X CFP2-ACO line side cards
    - 4 X QSFP28 client side cards
  - Module 2 with maximum capacity 400G in a combination of 40 x 10G, 10 x 40G, 4 x 100G supports:
    - 2 X CFP2-ACO line side cards
    - 4 X QSFP28 or 10 X QSFP+ client side cards