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MASTER THESIS

TITLE: Evaluation of the Impact of Resource Disaggregation in Future Optical Transport Networks

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Abstract

The communications industry is experiencing constant transformation. Telecom operators consider Network Disaggregation a potential approach to redesign their current network architecture in order to thrive. It focuses on decoupling the optical transport hardware into independent functional blocks, combined with open-source orchestration systems, to abstract the control layer from the physical layer, acquiring software-based control and automation features. The key perceived benefits include reducing vendor lock-in, drive innovation and evolution, and offer flexibility to deploy the best-in-class equipment that fits the network needs, regardless of the supplier. However, there is uncertainty regarding the performance of a disaggregated system, with the introduction of interoperable open nodes to the network, a demerit on the reach of the propagated optical signals is expected compared to a traditional single-vendor system.

In this regard, this thesis evaluates the impact of disaggregation on the network performance, specifically, considering several levels of lightpaths' reach reduction, the average number of connections which are denied service is estimated. Since signal regeneration emerges as the straight answer to overcome the reach limitations, its influence on the behavior of the network is analyzed as well. Moreover, the traffic grooming concept is introduced as an alternative to improve the network performance. The idea is to take benefit of the additional optical to electrical conversions performed for signal regeneration and groom low rate traffic streams in the already established lightpaths, looking to increase the capacity of the network.

To this end, a network simulator was developed to test a disaggregated system under several conditions as varying the number of regenerators available in the network, allowing or not traffic grooming, and applying different modulation formats or connections' traffic profiles, all of them are compared to the behavior of a traditional integrated system. Overall the simulation results demonstrate an important decrease of the performance of the network as a function of the transmission reach reduction, forcing the use of additional regenerator nodes. Nevertheless, when implementing traffic grooming with a limited number of regenerators, a significant reduction of the network blocking probability is achieved. Thus, network operators must analyze if this benefit plus the advantages of an open model prevails to the cost generated by the additional OEO nodes.

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Thank you.

Daniela Barrera

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The optical transport infrastructure is constantly being adapted by the network operators, especially in terms of increasing the network capacity to address the growing traffic demand of the clients. Considering the new business model “everything as a service (XaaS)”, which offers software, platforms, and infrastructure as services, network operators have realized that the capacity of their current network architectures is deficient to support this tendency.

XaaS modifies the relationship between client and provider. As an example, a client can just request, to the network operator, an application service (e.g. video on demand) or, he can lease the infrastructure to control part of the storage, computing, and network resources being able to deliver his own on-demand services or applications to the final users [1]. Then, providers need the competence to handle several clients of different characteristics at the same time, continuously providing capacity scalability, high performance, and security.

Network operators have recognized that growing on size can provide the network bandwidth needed, although it leads to a costly and inefficient architecture[2]. Therefore, to adopt the XaaS business model, they require a “more-open” infrastructure, to be able to centrally control, through software interfaces, features, and functions of each optical node, to support interoperability between different vendors’ equipment, and, ultimately, to build a flexible, reliable and cost-effective network architecture [3].

Consequently, operators are researching and investing in cutting-edge solutions, towards the transformation of the design, deployment, and operation of their networks. Between the latest IT technologies and architectures, the disaggregation model has become one of the pursued approaches to respond to the novel requirements of optical transport networks [2]. This concept focuses on decoupling the different network layers in contrast with the current integrated optical systems. It proposes a separation among the hardware components, a dissociation between hardware and software, and between the control plane from the forwarding plane, to be managed all by an open source software-centric environment.

In fact, disaggregation in optical networks has already started. Service providers demand to vendors the separation of transponders from the line system, in order to support third-party wavelengths to be carried across the optical system. The requisite is to offer interoperability to allow the use of diverse vendors’ equipment, which enables network evolution, flexibility and fosters competition in the market. In addition, they ask for the introduction of software-orchestration to abstract the control layer from the physical layer, acquiring software-based control and automation features [4].

On this basis, different levels of disaggregation inside optical transport networks are considered, pointing as main benefits: drive evolution and innovation, break the vendor lock-in restraint existent in integrated systems, and potentially reduce network costs. [ ] These match with the needs of the communication carriers to meet the future customer requirements. However, there are several barriers to be addressed before implementing a disaggregated optical system that involves a diverse range of open hardware and software elements [5].

A key challenge is the impact on the network performance caused by adding disaggregated nodes to the network architecture. A performance trade-off for interoperability is given. Specifically, when traversing disaggregated nodes, the propagation losses of the lightpaths increase, due to lack of optimization of these (multiple-vendor) nodes, which cannot meet an improved spectral efficiency that is only available by fine-tuned single vendor systems [5]. Other concerns are the system integration with open components and their maintenance, and the pace of development of the optical market to release standards and operational tools.

This trend towards disaggregation in optical transport networks motivates further analysis to explore the effects of its implementation. According to [6], by inserting disaggregated equipment along the network, the additional propagation losses over the lightpaths, force the deployment of extra regenerator nodes, compared to a single-vendor system. It is a result of the reduction of the maximum transmission distance without regeneration of the optical signals (Transmission Reach - TR), caused by the extra propagation losses. Since optical regenerators are considered expensive equipment, augmenting their number highly increases the overall cost of the network. Therefore, operators must question if this budget drawback exceeds the expected benefits brought by the disaggregated approach, becoming a reason to drop out the network migration to an open model.

Based on the previous information, this thesis focuses on evaluating the variation of the network performance caused by the transmission reach reduction of the optical signals, which arise when adding disaggregated equipment to the transport network. Furthermore, considering the optical signal regeneration requirement, traffic grooming is proposed as an alternative to reduce the disaggregation impact. The ability to multiplex low traffic rates into a single optical channel is perceived as an opportunity to improve the performance of the network and to increase its capacity.

This study is done considering two network topologies and several simulation scenarios. At first, the disaggregation effect on the service blocking rate of the network is demonstrated. Different levels of penalty to reduce the TR of the lightpaths are applied, in order to simulate the influence of the disaggregated nodes. In addition, the results are compared with the behavior of a traditional single-vendor case, referred to as an integrated system.

Next, signal regeneration is allowed at every node in the network and the blocking probability statistics are obtained. Then, the performance outcome is analyzed when traffic grooming is implemented, triggering as regenerators all the nodes in the network, or just a specific number of them. Moreover, the average traffic rate of the simulated client-connections is modified to assess the “grooming” effect under different conditions. Lastly, the considered modulation formats are changed to vary the TR limits and, to evaluate their influence on disaggregated networks.

This thesis is structured as follows. Chapter 1 elaborates on the disaggregation approach, through an analysis of the state of the art related to this topic. The network disaggregation concept is explained along with its technology enablers, benefits, and challenges. The next chapter 2 presents the possible physical and control network architectures, which depend on the level of disaggregation desired. Chapter 3 explains the disaggregation drawback under analysis, the traffic grooming approach for an improved performance and the network scenarios evaluated in this work. Chapter 4, describes the simulation tool developed for this work. Then, the results obtained from the different simulation scenarios are evaluated in Chapter 5. Finally, the main conclusions and future work of this study are presented.

CHAPTER 1. IT DISAGGREGATION

Disaggregation is the new IT proposal to transform the next-generation data center and networking infrastructure, as described in the following sections. This concept is based on splitting functionalities into standalone modules, which can be software managed, and independently updated and optimized. The main objective is to efficiently support the growing communications market, by offering, to the service providers, a high degree of customization, dynamicity, and scalability, through disaggregated infrastructure.

1.1. Resource Disaggregation in Datacenters

The disaggregation model was, first, introduced in the data center (DC) environment, aiming to scale the capabilities of traditional DC architectures to respond to the future IT market [7]. In current server-centric DC infrastructure, server units are arranged in racks and grouped in clusters, as shown in Figure 1.1. Alternatively, resource disaggregation proposes to decouple the typically integrated servers into resource blades, i.e., to separate the servers' computing resources, such as CPU cores, memory or storage, into independent hardware modules, which are interconnected by a network fabric and organized in racks, as depicted in Figure 1.2.

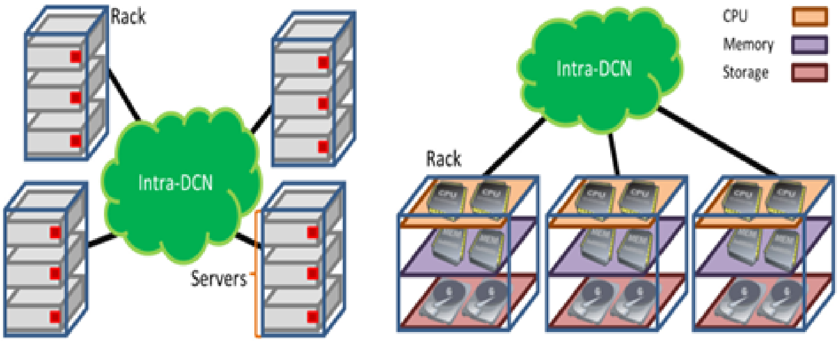

Figure 1.1: Server-centric (left) vs. Disaggregated (right) DC architecture [7].

Furthermore, the main objective of server disaggregation is to overcome the resource underutilization problem of traditional DCs, when provisioning Virtual Machines (VMs) to execute services and applications. A rigid resource configuration is employed, which causes high usage disparity of storage, memory and CPU resources. Specifically, a single server provides the required amount of computing resources for each VM, which are fixed and dedicated during the VM's lifecycle. The number of hosted VMs in the same server depends on the total set of resources requested by all the VMs, which must remain below the server's total resource capacity. However, if the server runs one or several VMs employing mostly one resource type, and it cannot provision more VMs due to the scarcity of this demanded resource type, the other resource types stay underutilized. It is a problem that grows with the traffic profile diversity of the heterogeneous applications to be executed.

For this reason, resource fragmentation is proposed, to physically separate the integrated components of the servers, from a single motherboard into independent blades. In this way, create a unique pool of shared resources being able to provide the exact amount of memory-CPU-storage that a VM requires, without blocking any other computing resources. Overall, the goal is to increase the number of VMs instances that can be allocated on top of the physical infrastructure. In addition, DC disaggregation drives modularity and evolution, since each functional blade can be optimized and upgraded individually. For each resource type, the latest available technologies can be adopted, independently of the market evolution rate of the other decoupled components. It is a benefit inaccessible for traditional DCs, due to the physical integration of the resources, representing a system performance limitation.

For network fabric, optical technologies are considered to interconnect the independent hardware blades. The intra-DC optical links must satisfy the strict high throughput and ultra-low latency requirements to communicate the different computing resources, achieving the former conditions of the connections carried inside the server motherboard (traditional DC), especially between the processing and memory blades [8].

Satisfactorily, the work developed in [9], demonstrates that DC disaggregation can boost data center efficiency. The authors focus on an optimized planning mechanism to allocate services on top of a shared DC infrastructure. Considering different network topologies, they quantify the required amount of computing resources when allocating heterogeneous service configurations. The study shows an optimal utilization of the DC infrastructure under a disaggregated model. It increases by 50% the number of service instances mapped over the decoupled resource blades compared to a server-centric architecture. Consequently, these results encourage the application of resource disaggregation inside DCs and foster research in optical technologies to support the intra-DC network features required to interconnect the independent resources blades.

1.2. Network Disaggregation

Focusing on the advantages of the disaggregation paradigm, this initiative is impacting the telecom industry as well. Network disaggregation is driving unprecedented changes in the way that the optical market has been managed until now. Mainly, it proposes to separate the communications equipment according to their functions into independent hardware blocks, like pluggable optics, transponders, and ROADMs, which are currently integrated by a close single-vendor system. Decoupling the control layer from the physical blocks is considered to allow software-based management. Furthermore, network disaggregation intends to separate the operating system from the underlying hardware, enabling the development of commodity optical hardware [10].

1.2.1. Related Work

Open ROADM project is one of the strongest works to move hardware-centric optical transport networks to an open software-centric system [11]. Open ROADM is an industry consortium that was started by AT&T, together with three equipment suppliers, Ciena, Fujitsu, and Nokia. Nowadays, the team has grown to 16 members, which includes parties like Cisco, Juniper, Deutsche Telekom AG and Orange S.A.

The project goal is to move proprietary ROADM systems to a fully software-controlled and open solution, driving higher flexibility to network providers to optimize their system as traffic grows over time. Focusing on functional disaggregation, they target three optical functions to be decoupled as independent/interchangeable blocks: pluggable optics, transponder, and ROADM. Figure 1.2 shows the proposed fully-disaggregated optical architecture and its components.

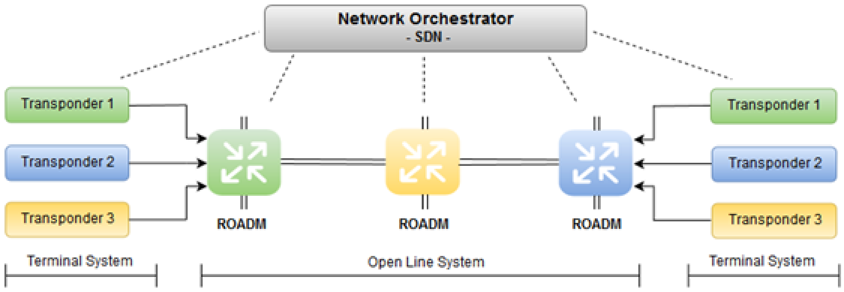

Figure 1.2: Disaggregated Optical System - by Open ROADM Project.

Moreover, in Open ROADM, each physical block is controllable by a common software orchestrator (SDN controller proposed), through open standards-based APIs (written in data model YANG), to allow system automation, provisioning of services, collection of alarms and performance monitoring (using NETCONF interface) [12].

Table 1.1: High-level features of Open ROADM releases.

Release V1.2.1	**Release V2.2**
Metro networks reach up to 500km	Regional networks reach up to 1000km
100G line	100G line
All-ROADM system	In line amplifiers support
100G clients only	Xponder added for client subrates of 1G and 10G
Fixed Grid support	FlexGrid ready

The Open ROADM team defines the minimum interoperability requirements of each functional block to open the market. It enables the implementation of multi-vendor optical solutions, finally, breaking the proprietary lock-in. There have been two specifications releases, both focus on simplicity and commonality to keep the cost and development time of the open solutions to the minimum. The first specifications release defines open low-performance metro systems, and the second release adds functionalities to extend the disaggregation scope to regional networks. A comparison of the features proposed in each release is shown in Table 1.1.

Furthermore, Telecom Infra Project (TIP) is another emergent community, collaborating in new technologies, to define schemes and specifications to deploy open, affordable and resilient networks. Around 500 companies from across the industry are active within the project, including Facebook, Telefonica, Hewlett Packard Enterprise, Telstra, Orange, among others.

TIP works on three network areas: access, backhaul, and core and management. Research is held by several project groups. All of them are focused on disaggregation of the hardware and software components of the network infrastructure to increase its efficiency and boost interoperability.

One of the project groups, so-called Open optical Packet Transport (OOPT), aims to define Dense Wavelength Division Multiplexing (DWDM) open packet transport architecture. Therefore, the research involves topics like software-based management and control, open transponders, open line system, and packet-switch and router platforms.

The main networking solution of this group is the Voyager open transponder, which was contributed by Facebook. [13] It is considered the first "white box" transponder and routing system, which is based on optical DWDM transponder technology and packet technology (switching and routing). As a "white box" equipment, it supports an open-source operating system that is decoupled from the commodity hardware. Cumulus Linux developed an operating system to be used in the Voyager transponder, and Edgecore Networks supports the hardware design.

This transponder has been successfully tested in the field by several network operators, like Vodafone in Spain, proving that the Voyager can be implemented in real optical networks. The open transponder positive responded to the dynamic fiber conditions by adapting the system's modulation format, through a software-based controller. The controller adopted is Software-Defined Networking (SDN). [14]

Moreover, an important contribution from OOPT, to support the disaggregated model, is the first open-source planning tool, in development, for multivendor optical networks. [13]

Both open projects, TIP and Open ROADM, with their specifications and technological evolution, potentiate the application of disaggregation in future optical transport networks. Furthermore, proof of the operators thinking related to network disaggregation is presented in [4]. The authors detail the statistics obtained from a service provider survey, performed to assess the possible evolution of metro optical network technologies.

Regarding disaggregation adoption, the authors present a set of approaches, among which each operator chose one according to their preferences. A 38% indicated interest in a simple disaggregated model, where only the transponders are separated from the integrated line system. However, other 31% selected a fully disaggregated option, where optical components are provided as independent modules to be hosted by a common shelf. A 19% voted to preserve the integrated optical system, as long as it supports open APIs to allow software control and management by a third party application. The last 13% chose the fully open system as well, but considering standalone optical hardware to be placed over racks.

From this statistics, a common desire to adopt disaggregation inside transport networks can be concluded, even though at different levels. The majority of service providers demand at least transponders decoupling and interoperability, which boost innovation and reduce costs.

1.2.2. Optical Disaggregation Approach

Disaggregation applied to optical networking, as stated above, involves decoupling the hardware components by their optical functions, into independent nodes, both the terminal system: transponder/muxponder, and the line system: ROADM/amplifiers/WSS. In addition, it consists on separating the control logic from the hardware in each device, to be centrally controlled by a unique orchestrator through open standards-based interfaces.

In contrast, traditional optical networks have been tightly integrated by the equipment vendor. Along with the network elements, it provides a unified element management system (EMS), which is a closed source software. The EMS allows the control of the overall system. It is customized to improve the end-to-end performance of the network and to let the operator minimize the planning, operational and maintenance complexity. [3] In fact, having a unique supplier who is in charge of merging the technologies to integrate hardware and software, also means, that the supplier is the only source of support to the network operator in times of failure.

However, under this single-vendor model, operators are tied to the proprietary lock-in costs and developers cannot provide software controllers or planning tools that support different vendors' equipment, due to the close-source trend. Moreover, operators cannot purchase the equipment directly from hardware manufacturers, without developing their own software platform. All this is caused by the lack of standardization and interoperability support between integrated proprietary networks. [5]

In its place, the network disaggregation field offers diverse options. One of them is to replace the current network nodes by optical white boxes, consisting on commodity (general-purpose) hardware controlled by an open source operating system, which is developed for optical devices. Another solution is to enable minimum interoperability support between different proprietary equipment that can be controlled by a unique open management system. [10] The common objective is to make available for operators a range of optical technology alternatives. With the option to purchase, independently, the different hardware and software blocks from multiple vendors, operators can select the ones that best fit their needs and their budget, with the possibility of future scaling.

Openness is an essential part of the disaggregation approach, covering from the control software and orchestrators, the interfaces (APIs) between hardware and software, to the hardware itself. The open concept seeks to broaden the optical market, simplify integration through interoperability and boost automation by means of the open interfaces.

The disaggregation model is projected to meet the current and future requirements of the optical systems, including smaller metro/regional networks to large-scale end-to-end systems. In addition, it unlocks the market to a new generation of hardware and software suppliers specialized in open concepts.

There are significant technologies which are enablers to disaggregation, and additional benefits as well as challenges that should be considered in order to adopt this model. Those are detailed in the following sections.

1.2.3. Network Disaggregation Drivers

The well-known Cloud Computing model allows users to remotely access different resources, including applications, platforms, computing power or storage, in a ubiquitous manner (anytime, anywhere). It highlights technologies, which are considered by the IT environment, to be inherited to the networking architecture and to enable the same dynamicity and flexibility to its services. Between the technologies mentioned, can be found: virtualization, software-based automation, commodity hardware, separation of control and forwarding planes and open source systems.

Software-Defined Networking (SDN) and Network Functions Virtualization (NFV), are two main cloud technologies, which are complementary between each other. The first is based on disaggregating the control plane from the forwarding plane, and the last on disaggregating the hardware from the software functions, which provide automatic resource provisioning and a centralized management and control of the system. These two are under standardization and keep evolving. Hence, SDN and NFV are already adopted by the optical transport and became key enablers for network disaggregation. [2]

These abstractions inside the network, allow moving its design to a software-centric environment that can be responsive, on demand, to the customer requests, without the need to physically touch the network. Also, they enable to break the proprietary lock-in limitation, since multiple vendors' equipment can be controlled through open interfaces (APIs) by a unique open orchestrator, ensuring an end-to-end performance control, and software-based planning, operation, and monitoring of the network.

The interoperability problem between different vendors equipment relies on the power control and monitoring of wavelengths from the third-party interfaces, also called alien wavelengths. Only a per channel power monitoring, operated by the network controller, gives enough input information to the link control algorithms, to fight signal attenuation and guarantee a successful connection. A per channel power monitoring is now available for all optical systems and it is also a driver for disaggregation. [5]

In optics, newly performance improvements in coherent 100G technology, become a disaggregation enabler as well. It increases the lightpaths transmission reach, making tolerable the extra propagation losses caused by a disaggregated network. As a result, longer-distance connections can be established, which before could only be driven by an integrated solution. The advanced techniques used are: non-differential encoding, advanced soft forward error correction, and pulse shaping. Additionally, this technology allows flexi-rate interfaces, supporting extra modulation schemes which result in higher line rates (150G/200G). [15]

Finally, supporting the disaggregation model, there are multiple efforts to develop common specifications for the optical equipment. The Open ROADM Project or the Telecom Infra Project, introduced before, seek to define minimum interoperability specifications to be adopted by the majority of optical (software and hardware) suppliers. In this way, an open network where end-to-end optical interconnections carried by multiple parties' equipment can be possible

1.2.4. Benefits of Disaggregation

Disaggregation brings out multiple advantages for network operators. The characteristics, listed below, allow operators to face current and future customers' bandwidth demand, in terms of design, management, performance, and cost. [3] [5]

- **Multiple generations' equipment support:** Coherent DWDM technologies have evolved five generations since 2008. This evolution rate produced a variety of transponder equips with different capabilities, like transmission speed and reach, developed by multiple vendors in the market. However, optical technologies for the line system elements do not increase at the same rate, and replace all deployed equipment in the line system represent high costs to the provider. Disaggregation solves this problem by supporting multiple generations' equipment. Moreover, it allows taking advantage of the longer useful life cycle of line system elements compared to the transponders life cycle.

- **Break the vendor lock-in:** This is one of the main objectives of the disaggregation model. Standardize minimum hardware and software specifications for the optical network elements and, more importantly, force to support interoperability between equipment from different industry vendors, allow operators to choose their hardware and software blocks independently and to build a solution that best meets their budget.

- **Boost innovation:** Breaking the vendor lock-in inside the optical market prompts innovation and competitiveness to develop the latest optical technologies. The different suppliers fight to be ahead of their industry rivals.

- **Deploy vendor-specific innovations:** In disaggregation, the approach of hardware decoupling by functionality allow to replace each block in the network without impacting the others. Therefore, operators can select and deploy the latest software and equipment innovations from any vendor, which are interoperable, according to the specific requirements of their transport network.

- **Efficient scaling:** With the option to deploy optical equipment mostly controlled by software, develop a solution based on virtualized network functions, and moreover, combine different vendors' innovations, is possible for an operator to deploy a network architecture without overprovisioning, i.e. meeting the current required capacity. Disaggregation allows network operators to grow the infrastructure according to the increase in demand over time. This will prevent investing, in advance, for not consumed resources, that generate extra maintenance costs, and whose maximum capacity may never be used.

- **Rapid upgrade deployment:** In a software-centric environment, any novel feature or functionality can be deployed, in a short time, to all or only to a specific amount of optical equips along the network. The operator can test the upgrade in a small area and then replicate it to the rest of the network without any physical contact with the equipment.

- **Lower operational expenditures (OpEx):**Through virtualization and software-based management and automation, the network operational processes are improved, decreasing costs. They provide an efficient end-to-end management and control of the system, with a broad view of the network for planning and monitoring.

- **Lower capital expenditures (CapEx):** Lower investment costs for network operators is a consequence of breaking the vendor lock-in. It generates competence (new pricing models) between well-established suppliers and prompts different business opportunities for smaller vendors and, especially, for software and hardware manufacturers that now can sell directly to operators. All these market modifications, in general, reduce the costs of the optical infrastructure.

1.2.5. Network Disaggregation Challenges

Before releasing in the market a disaggregated solution intended for optical transport networks, suppliers have to overcome fundamental challenges to be able to deliver the promised benefits of the disaggregation model.[3] [2] And, likewise, the service providers must consider some deployment and operational obstacles, prior to adopting an open system inside their networks. Some of the challenges are explained in this section.

- **Network performance degradation:** An important limitation to adopt disaggregated networks is the complexity to guarantee a high-level end-to-end system performance. [5] In a traditional optical network, vendor-specific innovations are implemented to fine-tune the system parameters, between the WDM line system and the terminal interfaces, in order to increase capacity and reach of the optical signals. Some vendor innovations include automatic link control, power control and amplification technologies, which maximize the end-to-end network performance.

  On the other hand, a disaggregated system must focus on the handoff process of multiple carriers, between network elements belonging to different vendors. Hence, a lowest common technology is standardized to be adopted by the optical nodes and assure interoperability. However, this compromise reduces capabilities of the network, since some “native” features of the equipment are not available in open mode. Mainly, a poorer tuning of the individual lightpaths’ power-level at the output of each open node is achieved, which increases the propagation losses of the signals and shortens their total TR.

  A direct result of this network performance degradation is the need for increasing the number of regenerator nodes to compensate the lightpaths’ TR reduction. However, the high cost of this type of nodes rises the overall cost of the network, becoming a no-affordable solution for some operators.

- **Automatic power control:** It is a consequence of the previous challenge. The optical carriers can vary on power level, modulation format, central frequency and spectral shape, however, the system must ensure optical power balance during the transmission, treating single or multi-carrier channels, without difference between native or alien wavelengths in each open node. An automatic and per-channel power control is required to balance the carriers that are routed over the open network. It allows reconfiguring filters and transmission parameters to reduce signal propagation issues caused by the disaggregated equipment.

- **Control and management software:** The developed software tools have to guarantee the proper operation of services across a multi-vendor mesh network, delivering capabilities, via open APIs and information models, to the open equipment. In addition, since the software sources can be different suppliers, they have to develop the software blocks align with standards to coexist in the same system.

- **Vendor-neutral design and planning tool:**Each vendor works with customized design tools tailored to their own equipment and technology, in order to provide a full optical network solution to the customers. They release to the market a limited and close version of it, sharing the minimum possible proprietary specifications, which in addition are complex and high priced. These restrictions make impossible to develop a network design and planning tool considering elements from different vendors.

However, a true vendor-neutral tool that is able to model the behavior of interoperable/open equipment and the specific parameters of each vendor, is fundamental for communication providers to adopt an open network. Standardization, required for disaggregation, states shared specifications between the open equipment, representing a key advantage for the development of the common design tool.

- **Deployment challenges:** Before adopting a disaggregated system, the operator has to consider the degree of responsibility on the design, operation, and maintenance that will rely on them and, expressly, on their technical team. With a proprietary solution, the supplier is in charge to integrate the technology and deliver a final network architecture meeting the requirements of the operator, and, in case of failure, they are responsible to sort out any problem.

  Meanwhile, depending on the level of disaggregation chosen, the provider may need a specialized team, to analyze the vendors' options for each hardware and software component of the network, to finally build an open and customized solution. Also, in the case of a system break, the technical team will need, if it is possible, to identify the source of failure and its responsible party, to know to which vendor call for support.

  Moreover, in function of the size and purpose of the network, the providers may need to decide if the lower costs and benefits of disaggregated equipment represent an advantage, against the extra technical team resources required for their operation and maintenance.

CHAPTER 2. DISAGGREGATED NETWORK ARCHITECTURES

To redesign the traditional optical system infrastructure, different levels of disaggregation, both for the hardware and software layers, can be applied to the optical transport networks. Therefore, several disaggregated architectures can be determined, which are detailed in the following sections.[3] [16]

2.1. Physical Layer Decoupling

A traditional optical system is represented in Figure 2.1, where the green color in all the elements indicate that a unique vendor is in charge of their integration. The proprietary optical system is managed by the vendor's NMS, and consists of the terminal system: transponders/muxponders and a line system composed of multiplexers/demultiplexers, wavelength selective switches, ROADM, amplifiers, etc.

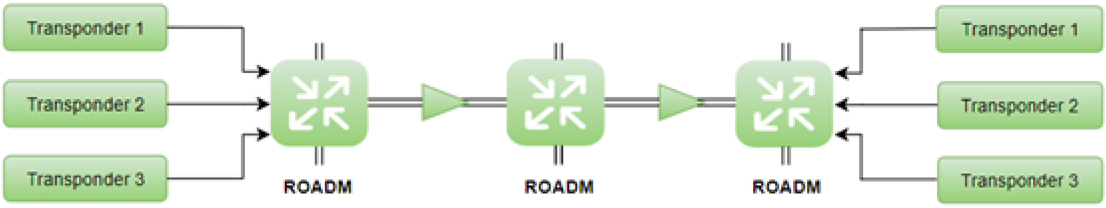

Figure 2.1: Traditional Optical System – Physical Layer.

It is worth describing the ROADM node, or reconfigurable optical add-drop multiplexer, which works as an optical switch to propagate in different directions the optical signals across the network. A ROADM equip consist of WSS modules, splitters and multiplexers/demultiplexers to allow a dynamic configuration of its ports to add/drop the propagated wavelengths. The ROADM ports can support 3 functions or a combination of them. The ports can be colorless (any wavelength can be assigned to any port), directionless (any wavelength can be routed to an output port on any direction) and/or contentionless (multiple input signals of the same wavelength can be routed to a single add/drop structure), and, most important, these port functions can be controlled by software without a physical rewiring, enabling automation.

Furthermore, network disaggregation includes a functional decoupling of the optical equipment, including the transponders/muxponders and the multiple elements of the line system (amplifiers, ROADMs). There are several deployment options by increasing the level of disaggregation between the elements.

The simpler scheme separates the network into two segments, the terminal equipment, and the line system. It guarantees interoperability between transponders/muxponders chosen from different vendors and the elements of the line system that is integrated by a unique supplier, as shown in Figure 2.2. An advantage of this approach is the support of multiple generations' transponders coupled to the same line system. In the graph, the multiple colors represent the elements provided by a different vendor.

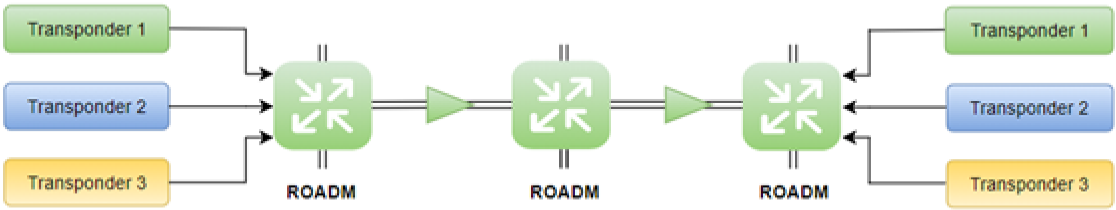

Figure 2.2: Transponders/muxponders interoperability with the line system.

The next disaggregation evolution, indicated in Figure 2.3, powers interoperability between line systems from different suppliers. At least one ROADM node should count with the capability to handoff the lightpaths from one vendor's line system to another, and focus on adjusting the optical signals ("native" and "alien" wavelengths) to ensure end-to-end transmissions.

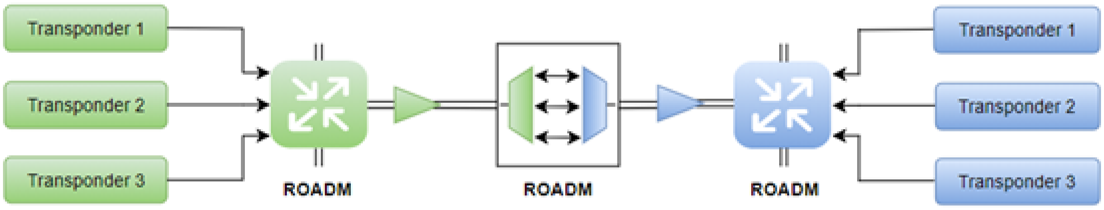

Figure 2.3: An interoperability point between line systems.

Following, Figure 2.4 represents the architecture proposal from the Open ROADM project. It shows an open line system only composed of ROADMs nodes that can belong to different suppliers, thus, the ROADMs are connected between them without intermediate amplification along the network spans. The operators can also choose terminal systems supplied by different vendors.

Under this architecture, each ROADM node becomes a point of interoperability, where an efficient link control is required to properly handoff the lightpaths between the multi-vendor equipment, and reduce the propagation loss effect of open nodes, guaranteeing end-to-end performance.

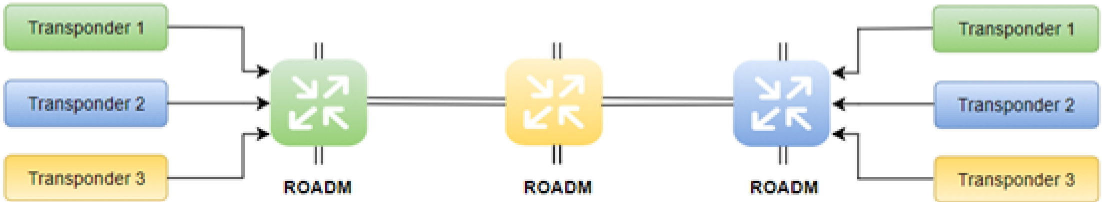

Figure 2.4: ROADMs Open Line System.

The last architecture, showed in Figure 2.5, is an extension of the previous case. It includes amplification modules across the multiple spans in the line system, which can also be supplied by numerous vendors. It is a full disaggregated approach, where each element can be selected according to the requirements of the operator, not being influenced by a unique vendor. Noticed that, in general, due to standardization and interoperability, the level of disaggregation is increased at the expense of performance, since each open node impacts on the propagation losses of the optical signals reducing their end-to-end power budget.

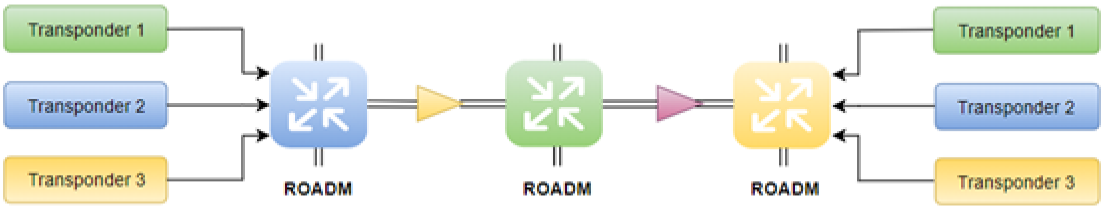

Figure 2.5: Full Open Line System.

2.2. Control Architectures

Apart from the physical-layer functional decoupling, disaggregation also proposes a multilayer network orchestration approach. The control and management of an integrated system, as shown in Figure 2.6, is composed of a dedicated NMSs for the routing equipment, and for the terminal and line systems, respectively. Both NMSs are controlled by a global orchestrator to have an overall view of the network, which is developed by the same vendor. Moreover, each layer communicates with the upper layer and/or lower layer through proprietary interfaces.

In case, the third layer orchestrator is not provided by the supplier, the global control of the network is performed by the technical support team of the network operator, which implies manual-intensive coordination of several NMSs tools and longer delivery time for the services.

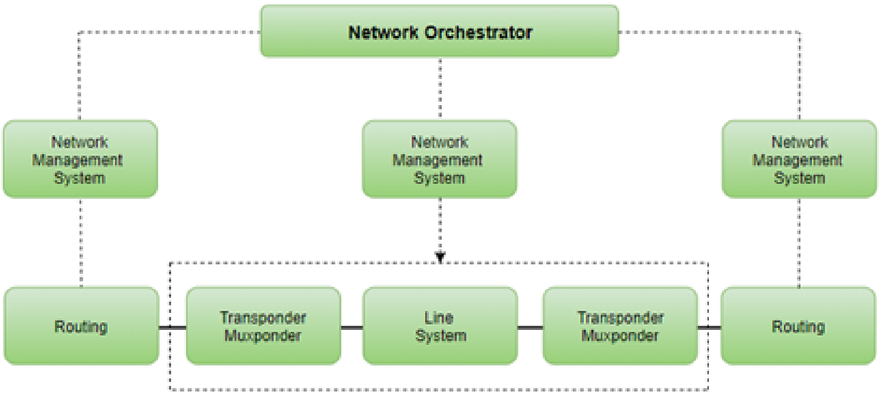

Figure 2.6: Traditional Optical System – Control/Data Layer.

From this scenario, the first alternative to manage a physical-layer disaggregated system is shown in Figure 2.7. Now, the routing hardware, the transponders/ muxponders and the different elements from the line system, which are administered by the independent software from the respective supplier, can be managed by an overall open-software control tool.

The open orchestration tool allows automation of several processes and a transparent communication with the vendor controllers. This software platform that manages the network, can generate workflows for the different equipment and transmit them through open interfaces, which are supported by the individual controllers in the second layer. However, the communication between the hardware and its controller is driven by closed interfaces. This limits the hardware control just to the specific functions released by the vendor that can be configured through open APIs in the upper layer.

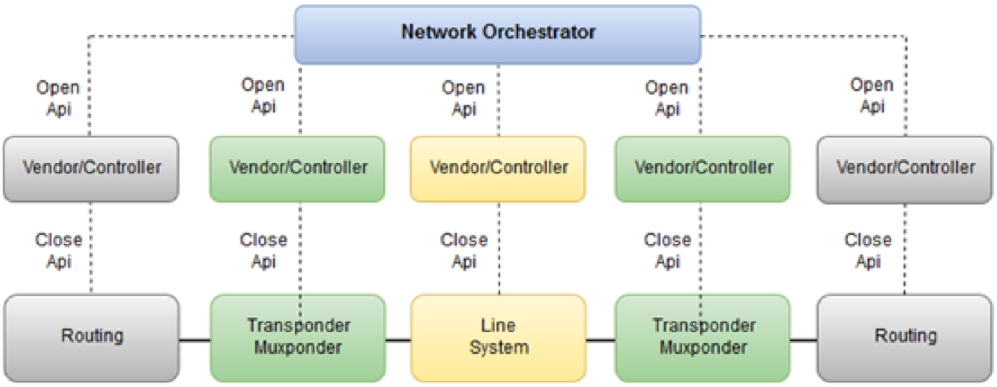

Figure 2.7: SDN orchestration plus individual vendor controllers.

Figure 2.8 shows a fully vendor-agnostic solution. The hardware elements can be directly accessed by the orchestrator through open APIs, and the individual controllers, which are mounted on the orchestrator platform, can be developed by any supplier. In consequence, the network operators can select both hardware and software independently, completely breaking the vendor lock-in restraint.

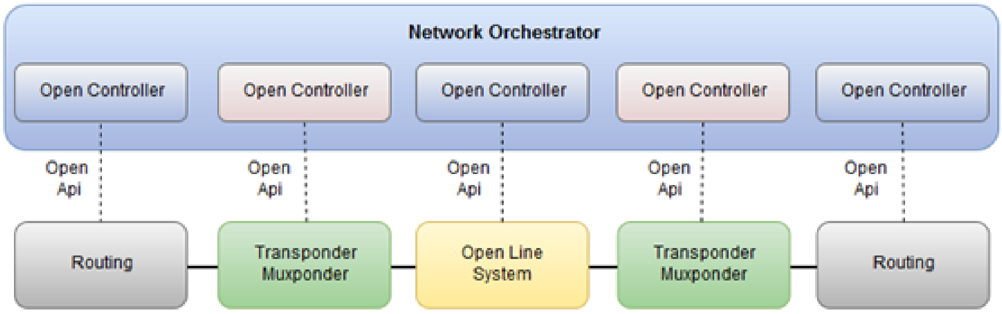

Figure 2.8: Fully Disaggregated Solution.

This final scenario enables the ultimate disaggregated approach, where all the control logic from the network elements is moved to the upper layer, leaving the alternative to emerge optical “white boxes”. [17] Thus, the operator can deploy general purpose hardware, load the open operating system for optical equipment of their preference, and virtualized the networking functions of the nodes. It also allows running third-party applications, tools, and virtualized services, like firewall, analytics, network analyzers, etc, in any network element.

CHAPTER 3. IMPACT OF DISAGGREGATION IN NETWORK PERFORMANCE

The thesis suggests an alternative viewpoint to face one of the challenges of adopting a disaggregated model inside the optical transport networks. This proposal is specified below, along with a detailed description of the different simulation scenarios planned to address and demonstrate the network performance limitation driven by disaggregation.

3.1. Problem Statement

As mentioned in 1.2.5., interoperability implies to route different-nature optical signals through multi-vendor nodes in the network. The open system should support variable channel widths and channel spacing, multi-carrier groups and advance modulation formats. However, to enable interoperability, some features of the proprietary equipment are simplified upon being implemented in the common open nodes, thus, the same level of performance optimization of the network cannot be reached. This limitation involves a reduction of the TR of the lightpaths routed through open nodes, which decreases the number of end-to-end optical connections that can be established and served by the system.

A straight solution to overcome the TR restraint is to deploy additional regenerator nodes over the network, which perform an OEO (optical-electrical-optical) conversion of the signal. The purpose is to correct, in the electrical domain, the signals' distortion and noise accumulated during propagation, and restore it to its original shape before being forwarded again as an optical signal, to the destiny node. Unfortunately, regenerators are expensive equipment, and operators have to deploy them strategically to avoid a high increase in the overall cost of the network.

The interoperability problematic is evaluated in [16], where a comparison about the average number of OEO interfaces required, between a disaggregated network and a single domain proprietary system, is performed. The study is carried out over two networks. According to the simulation results, when deploying a disaggregated network, a higher number of regenerator nodes are required to fight the propagation losses inserted by the open equipment. Therefore, the operator has to evaluate if the operational and economic benefits offered by an open solution overcome the extra expenses derived by the additional regenerators needed, not becoming a drawback to implement the disaggregation approach.

To face this shortcoming, a network simulator was developed in this thesis to evaluate the performance decay of a disaggregated network. Different levels of TR penalty are considered, simulating the effect caused by adding open equipment in the network, and for each case, the service blocking probability is calculated. The performance is also compared with the behavior of a network which is integrated by a unique vendor, meaning a 0% TR penalty.

3.2. Traffic Grooming Approach

Furthermore, the traffic grooming concept is addressed as a positive technique to take advantage of the extra regenerator nodes available in an open network. By implementing traffic grooming, low rate traffic demands can be multiplexed to share the total bandwidth of a lightpath, which allows optimizing the capacity and resources of the system. However, the technology to transport multiple bit streams in the same optical channel requires an electrical layer until now. Therefore, the proposal is to groom additional traffic in already established lightpaths, taking benefit of the optical to electrical conversions performed to regenerate them, when they are limited by the TR penalty of an open environment.

In order to illustrate the traffic grooming approach, a four ROADM nodes network, showed in Figure 3.1, is considered as an example to allocate optical connections to four traffic streams, which are detailed in Table 3.1. Four cases are analized: integrated system, disaggregated all-optical system (no regenerators), disaggregated system with regeneration (one OEO node), and disaggregated system supporting traffic groomig.

The links implement WDM (Wavelength Division Multiplexing) technology, thus, each optical fiber can transmit several multiplexed lightpaths, which must be assigned different wavelengths. It is considered a total data rate of 40Gbps for each lightpath and a TR of 1200Km.

Table 3.1: Traffic Streams Features.

Bit Streams	Source Node	Destination Node	Traffic Rate
S1	A	C	20Gbps
S2	A	C	10Gbps
S3	A	D	20Gbps
S4	C	D	15Gbps

The first case represent a single-vendor (S-V) integrated network. Independent lightpaths (with different wavelength - λ) are allocated for each bit stream, as indicated in Figure 3.1. S1 and S2 shared the source and destination nodes, however two different wavelengths, $\lambda 1$ and $\lambda 2$, are needed for their transmission. Since a lightpath must use the same wavelength on all the links between the source and destination nodes (wavelength continuity constraint), S3 is assigned to $\lambda 3$ on all the links along the A-D path. S4 is allocated to $\lambda 1$ that is free in the C-D span.

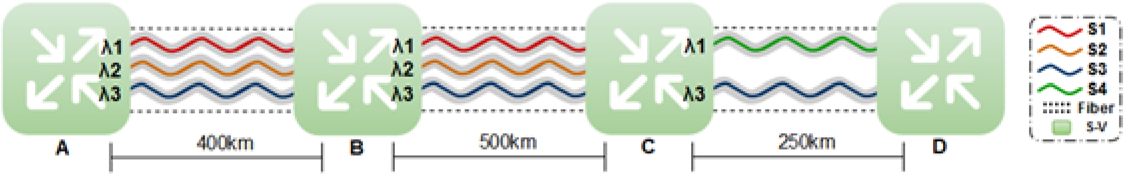

Figure 3.1: Lightpaths allocation for a set of demands in an integrated network.

Next, a disaggregated system is considered, thus a 10% TR penalty is applied to the lightpaths, representing the additional propagation losses caused by the open nodes. It is an all-optical system, showed in Figure 3.2, no regeneration nor traffic grooming are available. S1, S2, and S4 are assigned the same ligthpaths of the previous case. However, S3 is blocked due to the 10% TR penalty. The TR of the lightpaths is reduced to 1080km and the distance between S3 source node (A) and its destination node (D) is longer (1150km), so, S3 cannot be allocated.

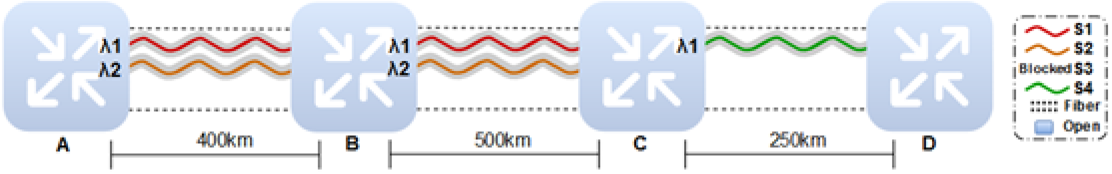

Figure 3.2: Lightpaths allocation for a set of demands in a disaggregated network.

For that reason, in the third case (Figure 3.3), regeneration is supported. Specifically, OEO interfaces are offered in node C for regeneration. In this way, S3 is transmitted through a lightpath ($\lambda 3$) that can be regenerated in C to be able to reach its destination node D. The wavelength resources engaged in this scenario, for all the bit streams, are the same ones used in the first case (Figure 3.1). The difference is that now, with an open system, the extra cost of the regenerator (Node C) has to be consider.

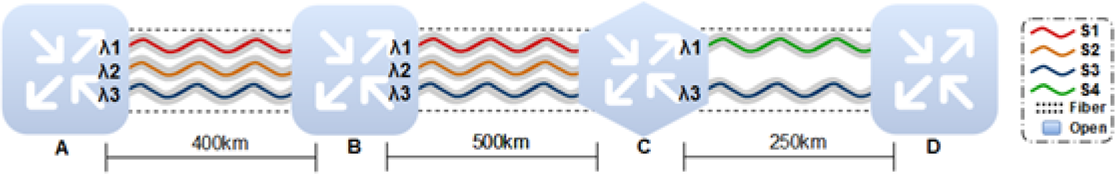

Figure 3.3: Lightpaths allocation for a set of demands in a disaggregated network when node C is a regenerator.

Finally, traffic grooming is adopted, as a technique to redistribute the resources of the open network, taking benefit of the presence of the regenerator node C. As shown in Figure 3.4, less resources are required to serve the same four bit streams. S1 and S2, whose total traffic rate is lower than 40Gbps (lightpaths maximum speed), can be multiplexed in the same lightpath ($\lambda 1$) between the shared source and destination nodes, A and C. Furthermore, since the established lightpath $\lambda 2$ has to be regenerated in node C to reach the S3's destination node, this OEO conversion can be exploit to multiplex the S4 bit stream with S3 and be transmitted together through one lightpath ($\lambda 2$) in the span C-D. Notice that the data rate of S3 plus S4 is also lower than 40Gbps.

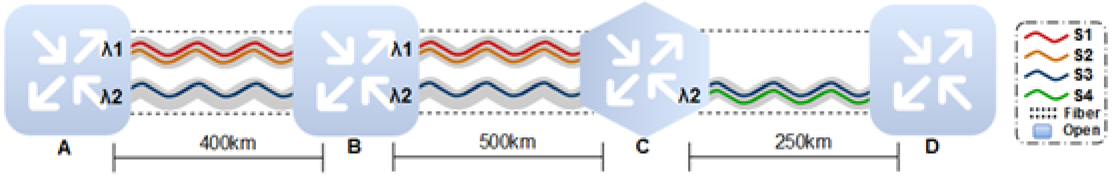

Figure 3.4: Lightpaths allocation for a set of demands in a disaggregated network with regeneration (Node C) and traffic grooming.

Comparing to the previous case (Figure 3.3), each optical link: A-B, B-C and C-D, has one wavelength left free ($\lambda 3$), which were reserved before to transmit the same four streams, however, now they can be used to serve additional traffic. On this basis, the traffic grooming approach is expected to distribute the optical resources more efficiently when a disaggregated system is implemented, improving its performance.

3.3. Network Simulation Scenarios

Towards the evaluation of the impact on the performance of an optical network when implementing a disaggregated model, several network simulation scenarios are proposed.

Two network topologies are studied. The Deutsche Telekom (DT) network, with 12 nodes and 20 links, and an average node degree of 3.3. It has an average link length of 243 Km and a 1019 Km network diameter. The DT topology is displayed in Figure 3.5.

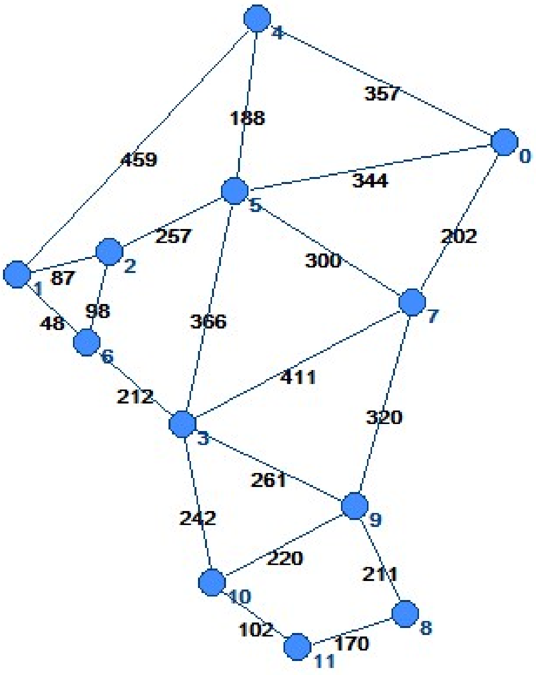

Figure 3.5: Deutsche Telekom network Topology.

The second network, showed in Figure 3.6, is the National Science Foundation (NSF) network, with 14 nodes and 21 links. It has an average node degree of 2.8, an average link length of 1022 Km and a diameter of 4500 Km, in fact, the average physical distance of the NSF links is larger than the average length of the DT network links.

WDM technology is selected to transport several lightpaths along the fiber links. Thus, for both networks, in all the simulations, the number of wavelength channels supported by each WDM link was fixed to 40. To establish the transmission reach (TR) limit of the lightpaths, the model in [18] is considered.

The authors expose a table summarizing the transmission reach estimations of an optical channel in function of different modulation formats and MCFs (Multicore Fiber), they are based in the Gaussian-Noise model. For the DT network, and taking into account its diameter as a distance reference to prompt regeneration inside the network, the 32-QAM modulation format is chosen. Thus, the TR limit is set to 1200 Km. On the other hand, a 16 QAM modulation format was assumed for the NSF network, which implies a TR limit of 2000 Km.

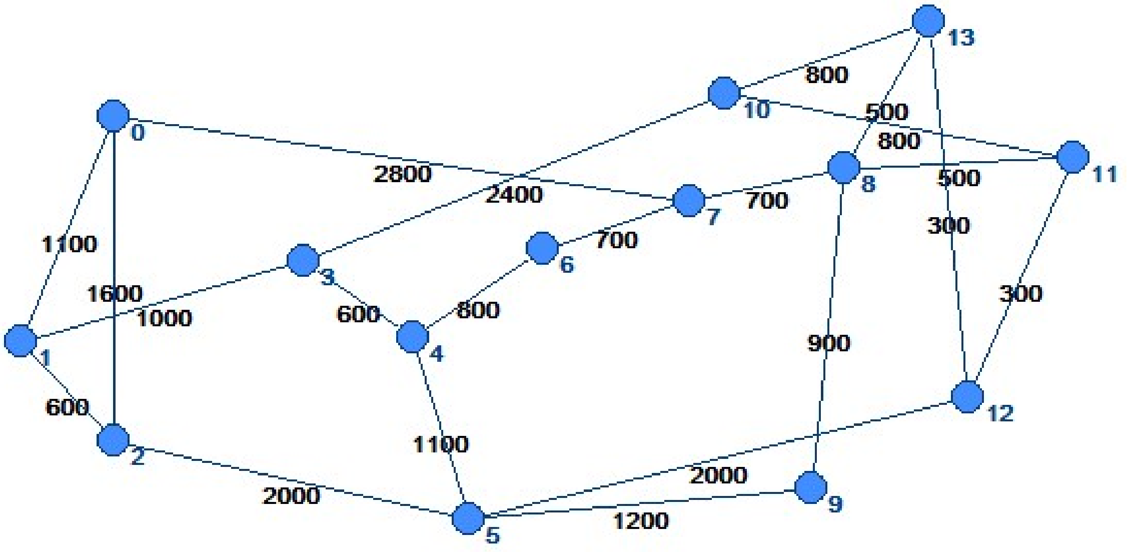

Figure 3.6: NSF network topology.

Four main case studies are carried out. First, the direct impact of disaggregation on the networks is evaluated by imposing different percentages of TR penalty (10%, 30%, 50%). These penalties represent the reduction of the signal propagation distance caused by interoperability issues between open equipment. This open network performance is compared to an integrated system, i.e., without any penalty. For this case, two simulation scenarios are proposed. Initially, regeneration is not supported, thus all the connections that exceed the TR limit are blocked. Next, regeneration is allowed at every node in the network, therefore the optical signals can be regenerated every time they require, and the only reason for blocking a connection is when not enough wavelength resources are available.

Second, the traffic grooming capacity is enabled. Since we are interested in evaluating the grooming effect on the performance of the network, based on its level of regeneration, three simulation scenarios are planned: without any regenerator node in the network, when all the nodes are OEO interfaces, and when just 30% of the nodes in the networks can behave as regenerators. For the last scenario, the nodes chosen as regenerators are the ones with the highest degree in the network. Once again, the TR penalty percentages are modified between 0% and 50%, triggering lightpaths regeneration more frequently with the higher penalties. With traffic grooming, it prompts different resource allocation patterns, whose impact on the behavior of the integrated and open network is analyzed.

In order to assess the influence of the end-to-end connections traffic demand, their average traffic rate, which is uniformly distributed, is varied in the third case study. Considering a 30% of the nodes as regenerators, two traffic rate options are considered. Specifically, the traffic rate of all the connections can vary between 0 to 50Gbps, or between 50 to 100Gbps.

Finally, fourth, the network modulation format is changed. Since it directly modifies the TR of the lightpaths, it can be modified both for relax or push the effect of disaggregation and assess the highest modulation format or spectral efficiency supported by the network to maintain a minimum level of performance.

Table 3.2 and Table 3.3 specified the simulation scenarios proposed for each network topology, which are derived from the case studies described before.

Table 3.2: DT Network Simulation Scenarios.

DT Network				
	Modulation	Regenerator Nodes	Grooming	Event Traffic Rate
Scenario 1 (SS1)	32-QAM	0%	No	<100Gbps
Scenario 2 (SS2)	32-QAM	100%	No	<100Gbps
Scenario 3 (SS3)	32-QAM	0%	Allow	<100Gbps
Scenario 4 (SS4)	32-QAM	100%	Allow	<100Gbps
Scenario 5 (SS5)	32-QAM	30%	Allow	<100Gbps
Scenario 6 (SS6)	32-QAM	30%	Allow	>50Gbps
				<50Gbps
Scenario 7 (SS7)	64-QAM	30%	Allow	<100Gbps

Table 3.3: NSF Network Simulation Scenarios.

NSF Network				
	Modulation	Regenerator Nodes	Grooming	Event Traffic Rate
Scenario 8 (SS8)	16-QAM	0%	No	<100Gbps
Scenario 9 (SS9)	16-QAM	100%	Allow	<100Gbps
Scenario 10 (SS10)	16-QAM	30%	Allow	<100Gbps
Scenario 11 (SS11)	8-QAM	30%	Allow	<100Gbps

CHAPTER 4. NETWORK SIMULATOR

The network simulator was developed in Java Programing Lenguage. It focuses in establishing end-to-end optical connections to serve a set of network traffic demand, taking into account the available resources (Wavelengths number, channels capacity, grooming capability) and the imposed restrictions of the network (Transmission reach penalties). As an output, the network blocking probability is calculated. This metric is a measure of the grade of service, it represents the probability that an event (a customer transmission request) can be denied of service due to the network conditions.

4.1. Simulator Dynamics

The description of the simulator is divided into five sections, which are detailed below.

4.1.1. Network Topology

First, the chosen network topology is generated by reading a text file, which contains the distance matrix that characterizes the network. The distance matrix indicates the existent links and specifies the distance between each pair of nodes in the network.

The nodes are based on a ROADM architecture, supporting the colorless and directionless add/drop capabilities. Each node object stores the uplinks and downlinks connected to it for routing purposes and a boolean attribute to indicate if the node can behave as regenerator or not.

The links objects, in turn, are specified by the respective source and destination nodes, a cost (the physical distance of the link), and the number of wavelengths that can be multiplexed (WDM link) and transport at the same time through the link. The default number is 40 wavelengths.

4.1.2. Events Generation

A customer transmission request is referred to as event. Every time a simulation is executed, a set of events are generated to evaluate the behavior of the selected network under the different scenarios. The specified number of events (100000 by default) are created arbitrarily, meaning that each event obtains, randomly: a source and destination nodes to establish the connection, the rate or traffic demand, and a start and termination time of the transmission.

An event involves a pair of actions in the simulation timeline. First, the beginning of the transmission when the needed resources for the connection are allocated and reserved. Second, the event termination when the same resources are released.

The start and the duration of a transmission are calculated in function of two parameters, a holding time (HT) and an inter-arrival time (IAT). HT represents the duration of the connection, and IAT is the time between consecutive connection requests. This values allow to stress or relax the network in each simulation, by varying the number of simultaneous living (active) events.

4.1.3. Routing and Resource Allocation

For each event, the k shortest distance paths are calculated. To this end, all the possible paths, from source to destination, are precomputed and ordered in function of the paths' total cost, to select the k shortest ones sequentially.

Each path is composed by several adjacent links to connect the source and destination nodes of the event. At the same time, in direction of the destination node, the links are grouped in different subpaths, when the cost of the subpath plus the cost of the next adjacent link exceeds the TR boundary, i.e., the path is divided in several subpaths, each time that a lightpath routed through it will require regeneration to not miss the connection. Figure 4.1 shows the composition of a path created from node A to node D.

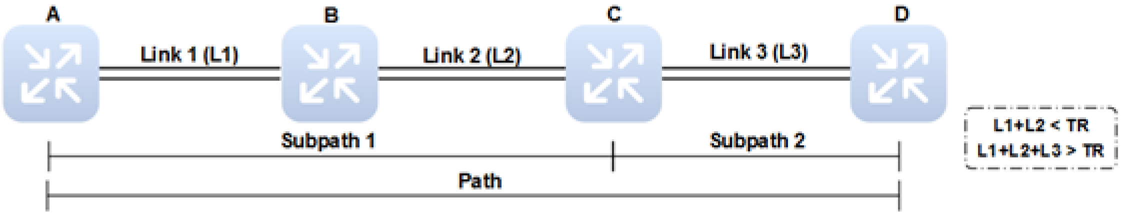

Figure 4.1: Simulator composition of an optical path (A-D).

Following this, if optical signal regeneration is not considered in the simulation scenario, only the paths consisting in a unique subpath, or in other words, the paths where the total cost of the links from source to destination do not exceed the TR limit, can be taken into account to transmit the traffic demand.

Next, analyzing in order the k shortest paths (lower cost first), the connection is established when is possible to allocate a lightpath to the single subpath. A lightpath is set up if all the links belonging to the subpath have a common free wavelength to be assigned.

In case, none of the k shortest paths has been allocated a lightpath due to lack of wavelengths resources, the event, in turn, is blocked. On the contrary, if the event is successful, the resources used are reserved during the transmission time. When the event is completed the reserved wavelengths are again available to be assigned to new connections.

4.1.4. Traffic Grooming Implementation

Implementation of traffic grooming means inserting new traffic rates into active lightpaths created in previous events, as long as the lightpath' maximum bandwidth is not exceeded and the traffic streams can be multiplexed in the lightpath' root node (EO/OEO conversion required). When the lightpath is created, its maximum bandwidth is establish in accordance with the traffic rate of the served event. Two options are configured, a maximum channel bandwidth of 40 Gbps when the event' transmission rate is under 40 Gbps and a channel bandwidth of 100Gbps if the event' traffic rate is between 40Gbps and 100Gbps.

During the simulation, when a new event takes place, all the active lightpaths are considered to carry its traffic demand if they fulfill the next conditions. The unoccupied capacity of the lightpath has to be equal or higher than the rate of the event, the lightpath' root/end node must be a regenerator or the source/destination node of the new event, respectively, and its links must belong to one of the k shortest paths precomputed for the event.

After identifying the prospect active lightpaths, those that are adjacent are connected to each other to build a complete route for the event, from source to destination, and in this way, groom the traffic demand exhausting already used resources and liberating others to increase the capacity of the network.

In case that creating a full route to groom the traffic demand is not possible, the longer partial routes of active lightpaths are considered sequentially, and the allocation of new lightpaths is requested to complete the transmission paths. Later, if none of the options succeed, a new lightpath or set of lightpaths from source to destination are requested to route the traffic stream, allowing regeneration in the OEO nodes when the TR limit is met. And lastly, in case of failure, the event is blocked.

With grooming, the routing algorithm to find the k shortest paths slightly varies. When all the nodes act as regenerators, the respective links of a path are separated into subpaths each time that the joint cost of the links exceeds the TR margin. For resource allocation, all the links inside the same subpath must share a free wavelength channel to be assigned as a lightpath, however, independent lightpaths (different wavelengths) can be reserved in each subpath.

Furthermore, if only a specific amount of nodes are regenerators, the paths are build based on them. When a link cannot be added to a subpath, due to the TR limitation, it can start a new subpath to keep creating the path, only if the root node of this link is an OEO interface. Or else, the new subpath can be set up sooner using a regenerator node of the previous subpath. Finally, if none of this options allow the building path to reach the destination node, this possible route is dismissed.

4.2. Input/Output Simulation parameters

The following parameters can be set up each time a simulation is executed:

- Distance matrix: The behavior of different network topologies can be tested.
- Number of events: To fix the number of connections or customer traffic demands to be transmitted through the network.
- Holding Time (HT) and Inter-Arrival Time (IAT): The duration and frequency of events can be changed to stress or relax the capacity of the network.
- Traffic Load: The traffic rate of each event is generated randomly between two fixed boundaries.
- K: The number of shortest paths considered to allocate the traffic streams.
- Wavelengths Number: Specifies the number of channels that can be multiplexed inside an optical link.

- Transmission Reach (TR) Limit: Indicates the maximum distance that a lightpath can be carry over an optical fiber without regeneration.
- Disaggregation Penalty: This is a reduction percentage directly applied to the TR limit, to model the restriction of a disaggregated system. Thus, this value allows determining the maximum propagation losses, due to disaggregation, that a network can support to deliver a tolerable end to end performance.

When the simulation finishes, the next figures are printed to analyze the behavior of the network under the initial conditions.

- Connection Blocking Probability: It represents a network service quality index. It is the percentage of the amount of blocked connection requests over the total number of bandwidth requests during the simulation time.
- Groomed TS/ Partial Groomed TS/ New Connections: The number of totally groom traffic streams, partially groom streams (a section of the path requires new resources), and new connections (New lightpaths are allocated across the connection path).
- Regeneration counting: It indicates the average number of simultaneous regenerated signals inside an OEO node. The total number of signal regenerations in the node during the whole simulation is also printed.

CHAPTER 5. RESULTS AND DISCUSSION

After executing each simulation scenario detailed in Table 3.2 and Table 3.3, the obtained statistics are evaluated in this chapter. The objective is to determine the impact of disaggregation in the network performance and verify the potential reduction of the connections blocking ratio when traffic grooming is supported, comparing against a typical integrated system.

Every time a simulation is executed, a set of 100000 events are generated to evaluate the selected network under the different scenarios. When the routing algorithm precomputes the K shortest paths between a pair of nodes, a value of $K = 3$ is assumed.

In addition, the inter-arrival time (IAT) parameter is always set to 1, and the holding time (HT) value is modified, approximately, between 300 and 1000. The variation of the HT value allows forcing a busy or a quiet connections-schedule to the network.

The statistics obtained when considering the DT network topology are analyzed in first place, followed by the results collected with the NSF network for comparison.

5.1. DT Network – Impact of disaggregation

To begin with, the problem statement is proven based on the simulation scenario SS1. A 32-QAM high modulation format is assumed, i.e. the transmission reach limit for each lightpath is 1200 km. Moreover, a uniform traffic distribution between 1Gbps to 100Gbps for each requested event is set up.

Figure 5.1 exhibit the impact that different levels of penalty generate on the performance of the DT network. Remind that the penalty percentages are inflicted on the lightpaths' maximum propagation distance. Thus, for example, a 50% penalty corresponds to a reduction of the TR limit to 600Km.

When the integrated system is considered, i.e., no penalty is applied (0%), the blocking probability of the requested connections increases from 1.7% to 30%, subsequent to the network load growth. HT is varied from 300 to 900, which stress the network and contributes to augment the number of blocked events due to the scarcity of resources.

Remarkably, applying a system penalty of 10% a pretty similar network performance is observed compared to the integrated case. This demonstrates that a certain level of signal transmission degradation, caused by the disaggregated equipment, can be supported without deteriorating the overall performance of the network. Achieving this condition in a network pushes forward the deployment of the disaggregated system.

However, when the penalty is higher (30% and 50%), a bigger blocking rate gap can be noticed. Specifically, with a 50% penalty, the difference is an additional blocking percentage of 12% when the network load is high (HT=900), and 33% blocking difference with the lowest traffic load (HT=300). This poor performance of the DT network is a consequence of the fact that most of the lightpaths are blocked mainly due to the TR condition, i.e., they cannot reach their destination nodes without signal regeneration, even though the wavelength resources can be available.

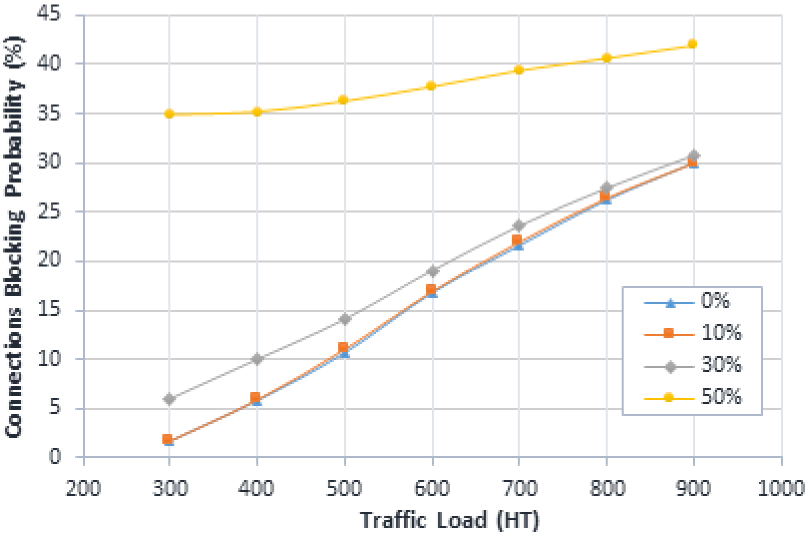

Figure 5.1: Connections blocking probability of SS1 vs. network traffic load, considering different TR penalties.

Therefore, the introduction of open equipment without a proper interoperability mechanism that preserves the end-to-end transmission performance can lead to a relevant blocking ratio raise. Though the blocking probability variation depends on the level of degradation of the lightpaths' power budget, most often, any increment is an unacceptable outcome for network providers. For this reason, in this work, regeneration is triggered to solve the TR restriction and traffic grooming is implemented as a technique to mitigate the network behavior under the disaggregated conditions.

Interestingly, Figure 5.2, shows the statistics obtained from the simulation scenario SS2, where traffic grooming is not supported, but regeneration is permitted in all the ROADM nodes in the network. Therefore, since the optical signals can always be regenerated, there is no service restriction consequent of the transmission reach limitations, and the capability to route traffic demands relies on the number of wavelength resources available. In fact, it results in a blocking ratio pretty similar for all the TR penalties at each traffic load step, as shown in the graph.

Furthermore, a blocking ratio reduction can be pointed compared to the values obtained in SS1, especially, considering the largest penalty (50%). When the network load is minimum (HT=300), around 1.4% of events are blocked, which is a big difference comparing to the 35% of the previous case. It represents that, in SS1, the cause of blocking of more than 30% of events was the TR restriction, since now, just 1.4% are blocked for lack of wavelength resources. With a heavier traffic load (HT=900), the blocking probability decreases to 30%, getting similar to the value obtained from the integrated system in SS1 and SS2. Thus, in the integrated network, the events are actually blocked for insufficient resources, meaning that does not rely on regeneration to improve its performance.

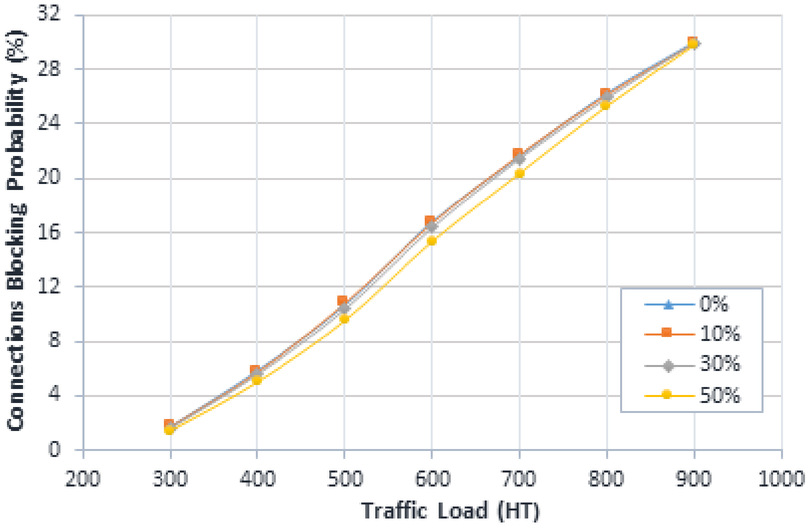

Figure 5.2: Connections blocking probability of SS2 vs. network traffic load, considering different TR penalties.

5.2. DT Network – Grooming Effect

Next, traffic grooming is implemented. According to SS3, Figure 5.3 shows the DT network behavior when grooming is allowed but none regenerator nodes are considered. Thus, only end-to-end lightpaths can be established, and two or more traffic streams can be multiplexed in the same optical carrier if its capacity is not exceeded and they share the source and destination nodes.

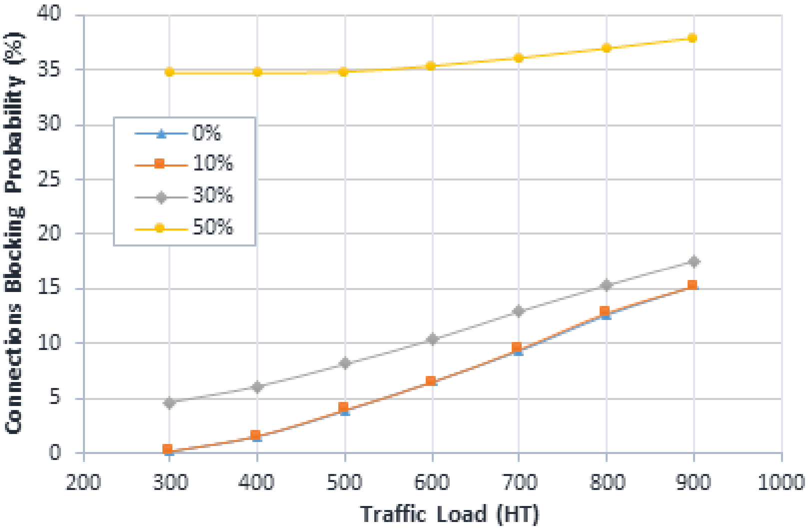

Figure 5.3: Connections blocking probability of SS3 vs. network traffic load, considering different TR penalties.

It was stated before that an integrated system (0% penalty) for the DT network does not depend on regeneration, though an improved resource allocation driven by traffic grooming notably reduces the connections blocking probability. Before, both for SS1 and SS2, with the highest network load (HT=900), a 30% blocking probability was obtained, however, now it is reduced by half to 15%. With a lower network load, the gap is shortened but the network performance is still better with SS3.

Considering the results in Figure 5.3, when different TR penalties are applied, the network blocking probability is reduced compared to SS1, however without regeneration, the impact of the open equipment cannot be overcome, resulting impossible to reach or excel the performance of an integrated system.

Therefore, in the simulation scenario SS4, shown in Figure 5.4, regeneration and traffic grooming are combined. The traffic streams can be groomed to an active lightpath at any node (all regenerators), as long as the bandwidth resources are sufficient. The purpose is to analyze how the resource allocation pattern changes, in terms of blocking probability, when more regeneration is required due to the different levels of TR reduction.

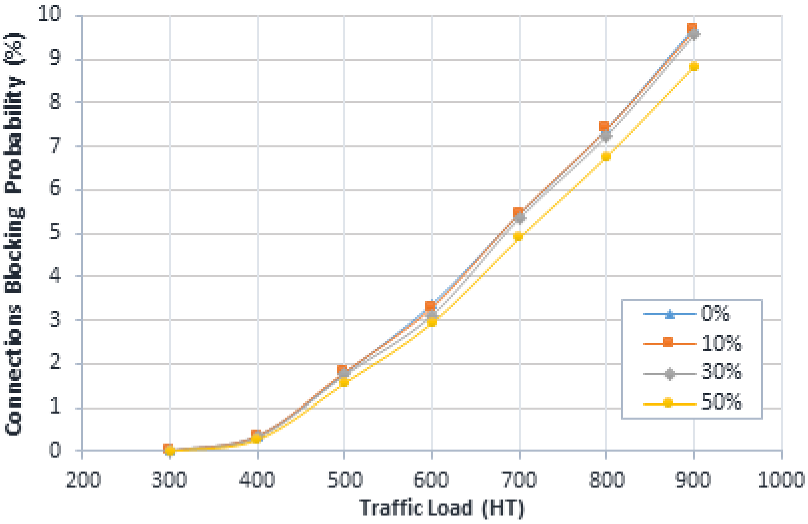

Figure 5.4: Connections blocking probability of SS4 vs. network traffic load, considering different TR penalties.

As expected, grooming brings a relevant reduction of the network blocking ratio, even when the requested demand is dense. It can be observed that considering an integrated system (0% penalty), with HT=900, the maximum blocking probability reaches 9.7%. And with the minimum traffic load, the blocking is almost zero (0.012%).

Regarding the appealing grooming capacity when augmenting the TR penalty from 10% to 50%, the performance of these disaggregated cases is highly similar to the results obtained with an integrated system. In fact, while increasing the TR penalties, the blocking probability gets lower comparing to the integrated case. A trend that continues with any traffic load forced to the network.

For example, with the highest HT value to stress the network (HT=900), the blocking ratio of an integrated system is 9.7%. In comparison, for a disaggregated model suffering 10% TR reduction, the number of blocked events slightly decrease to 9.66%. Moreover, with larger penalties, 30% and 50%, the connection blocking goes down to 9.56% and 8.83%, respectively. This means that the consequence of increasing the number of regenerators and the traffic grooming support can be highly appreciated in terms of improving the performance of an open network. However, the number of OEO interfaces impact directly to the overall cost of the network. Therefore, deploying regenerators at every node can represent an inaccessible cost to the majority of service providers, becoming an unfeasible solution.

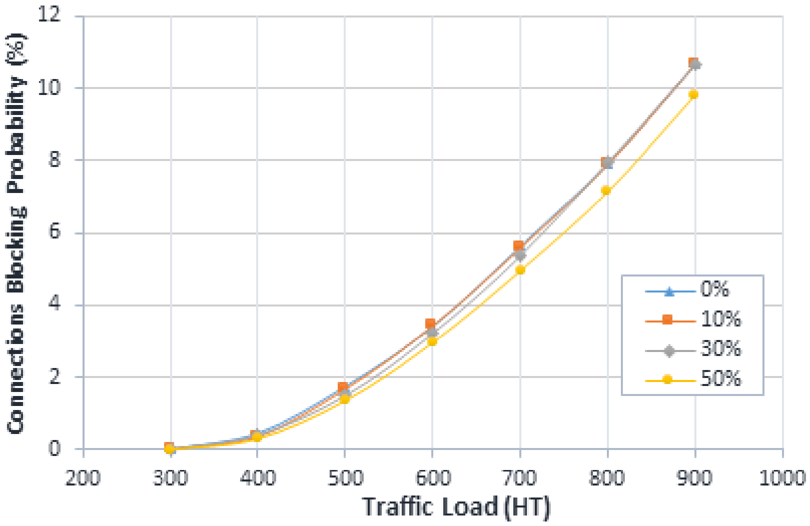

Figure 5.5: Connections blocking probability of SS5 vs. network traffic load, considering different TR penalties.

With the former statement, the next simulation setup, SS5, is performed. In this case, only a specific amount of nodes (30% of the total nodes) are OEO interfaces. Since the criteria considered to classify the nodes as regenerators is based on selecting the ones with the highest degree, the fourth-degree nodes are chosen for the DT network. The IDs of the nodes are 3, 5, 7, 9, which can be identified in Figure 3.5.

Figure 5.5 illustrates the results of this approach. It is important to highlight that the tendency of better network performance while increasing the transmission reach restrictions continues. Comparing to the previous case, SS4, the connections blocking probability is similar when traffic grooming is implemented having fewer regenerators. For example, considering the densest traffic load (HT=900), previously, the average blocking ratio for all system penalties was around 9.5%. In this case, it increased to around 10.65% for the 10% and 30% TR penalties and, just to 9.8% with the largest penalty (50%). Furthermore, this outcome leads to a significant conclusion. Since a similar network performance can be accessed with a much lower number of regenerators, the service providers do not need to arrange OEO interfaces at every node to take benefit of the grooming benefits.

Furthermore, considering traffic grooming and including few regenerators to overcome the disaggregation restriction, leads to a superior open network performance compared to the integrated system in SS1 and SS3. To show this, Figure 5.6 compares the DT network values obtained with an integrated system without traffic grooming (0%-SS1) and applying grooming (0%-SS3), both cases without any regenerator node, with the values gotten from a disaggregated system that supports traffic grooming and deploys four regenerator nodes (SS5), and considering several TR penalties.

Taking into account a maximum 5% blocking probability for the DT Network, the integrated model without grooming (0%-SS1) can support a traffic load corresponding to HT=400. In contrast, the disaggregated system (SS5) can handle a heavier traffic demand, equivalent to HT=700, even if the open equipment causes a 50% TR reduction for the lightpaths.

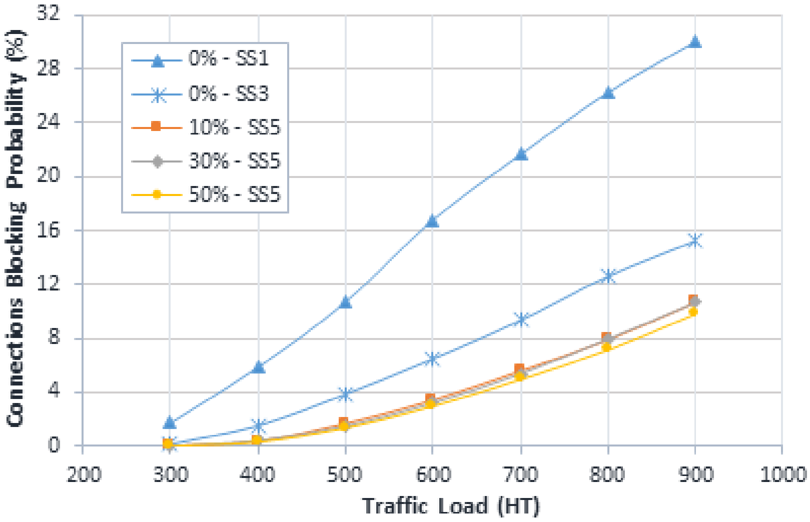

Figure 5.6: Performance comparison between an integrated system (w/ and w/o grooming) vs. an open system (w/ grooming) considering different TR penalties - in DT network.

Following, traffic grooming is implemented in the integrated system (0%-SS3) to improve the DT network performance, thus, with HT=400 the blocking percentage goes down to 1,5%. Still, the expected benefit of traffic grooming when the network count with additional regenerator nodes is demonstrate, since a lower blocking probability of around 0,36% is achieved by the open system (SS5), with all TR penalties considered. In fact, although there is only a small difference in the blocking rate between all TR penalties considered, the results in Figure 5.6 show that when more regeneration is required, as with 50% TR reduction, a lower blocking probability of the system is reached, due to additional traffic that can be groomed in each regenerated lightpath favoring the resource allocation.

5.3. DT Network – Events Traffic Profile Influence

Considering these positive results, the traffic profile of the requested connections is also varied to evaluate its influence on the behavior of the network. Following the simulation scenario SS6, first, the traffic rate of each event is limited between 50Gbps to 100Gbps, thus, higher connections have to be allocated across the network.

In Figure 5.7 the blocking probability vs. network load is presented. The blocking probability increases from 1.6% to 30% in accordance with the network load growth. And, examining the small difference between the disaggregated cases and the integrated one, the tendency is: the higher the TR penalty, the lower the blocking rate.

The overall behavior of the network is comparable to the results obtained in the simulation scenario SS2, regarding that traffic grooming is not implemented in SS2, and in this case, the majority of events cannot be groomed as well, due to the traffic rate size. Thus, the blocked demand increases to 30% with larger HT values like before.

In the next case, conversely, when the maximum traffic rate of each event is 50Gbps, the higher flexibility for resource allocation arises, boosting the grooming capacity. Therefore, when analyzing the network loads previously considered (HT from 300 to 900), a remark-

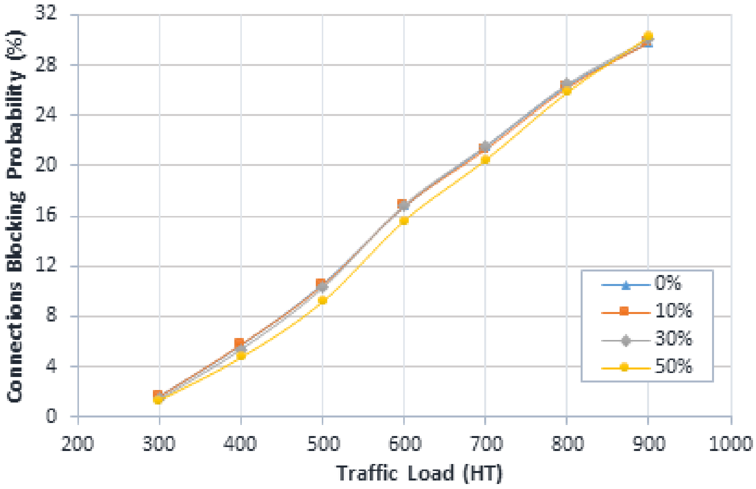

Figure 5.7: Connections blocking probability of SS6 vs. network traffic load, considering different TR penalties and a traffic profile above 50Gbps for each event.

able blocking probability under 1% is obtained, maintaining similar values between the integrated and the disaggregated systems, as shown in Figure 5.8.

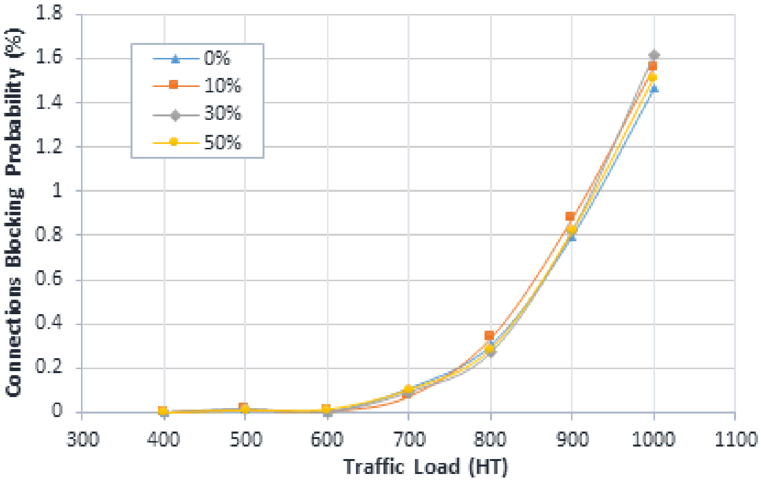

Figure 5.8: Connections blocking probability of SS6 vs. network traffic load, considering different TR penalties and a traffic profile under 50Gbps for each event.

Then, is important to highlight that providers must also consider the traffic profile of their network in order to evaluate the impact of adopting a disaggregated model. As shown in Figure 5.8, a huge performance benefit can be obtained when the average traffic rate of the events is low.

5.4. DT Network – Modulation Format Variation

The simulation scenario SS7 is based on setting a higher modulation format which implies shorter propagation distance for the optical signals. In this way, the network is taken to an extreme situation to evaluate its performance when disaggregation is considered.

For this scenario, a 64-QAM modulation format is assumed, restraining the transmission distance of each lightpath to 600 km. And, a uniform traffic distribution between 1Gbps to 100Gbps is established again.

Previously, in SS5, with a short number of OEO interfaces a significant blocking ratio improvement was achieved for all TR penalties. To make a comparison, the same regenerators are considered this time, combined with traffic grooming as well.

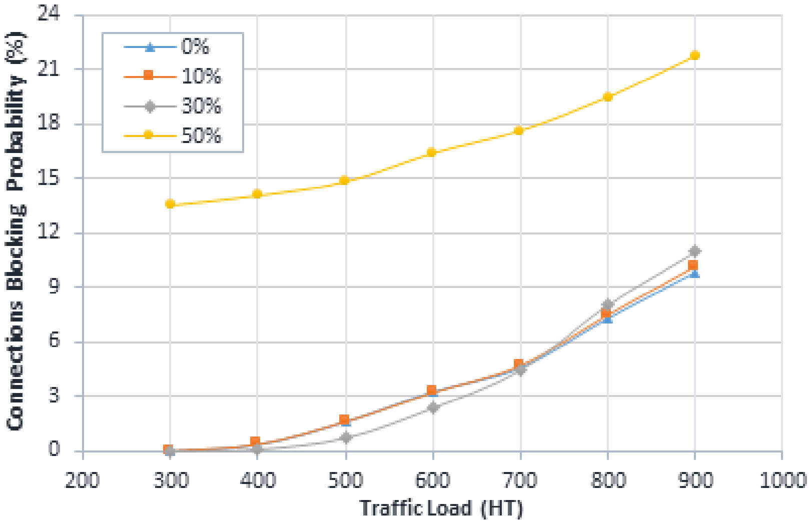

Figure 5.9: Connections blocking probability of SS7 vs. network traffic load, considering different TR penalties.

The results are shown in Figure 5.9. Notably, similar to SS5, with 10% and 30% TR penalties, a blocking ratio trend between 0.01% and 11% is obtained for all, the integrated option and the disaggregated cases. However, there is an important change of the blocking probability when a 50% penalty is applied. For example, considering the highest traffic load (HT=900), it increases to 21.8% compared to 9.8% in SS5. It shows that a breaking point exists regarding the level of TR degradation that the system can support without highly increasing its blocking probability. Thus, according to SS7, the DT network can support a 64-QAM modulation format, maintaining its blocking probability under 10%, as long as the lightpaths TR reduction stay under a specific level, otherwise, the lower modulation format should be used.

5.5. NSF Network – Impact of disaggregation

To complete the study, the NSF network is tested with similar simulation scenarios. The objective is to analyze the influence of the topology on the conclusions derived from the preceding network.

A lower modulation format is considered, 16-QAM, since the NSF network characterizes for a larger average link distance, which urges signal regeneration more often. The corresponding transmission reach limit is 2000 km. Once again, a traffic rate between 1Gbps to 100Gbps is assumed for each requested connection.

Figure 5.10 shows the results to the simulation scenario SS8, where no regenerator nodes

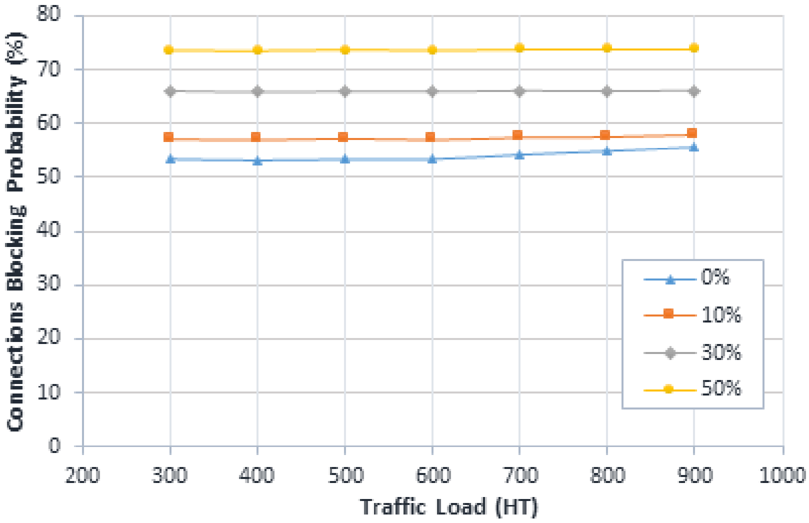

Figure 5.10: Connections blocking probability of SS8 vs. network traffic load, considering different TR penalties.

are deployed in the NSF network. As expected, when increasing the penalty percentages applied to the TR limit, the blocking probability increases as well. Explicitly, it rises from around 53% in the integrated case to 74% with the maximum penalty (50%). In the graph, the steady behavior of the blocking rate, which is independent of the network traffic load and recurrent with each penalty applied, indicates that most of the events are blocked by the TR limit and not due to lack of wavelength resources, even in the integrated case. Note that these blocking percentages obtained are unacceptable for any optical system.

5.6. NSF Network – Grooming Effect

Pursuing a better network performance, the next simulation scenario, SS9, triggers traffic grooming and allows regeneration at every node in the NSF network. Evidently, a significant reduction of the network blocking rate is achieved, mainly because the OEO interfaces remove the TR limitation for the optical signals. The statistics are shown in Figure 5.11, where the maximum connections blocking probability is 7.4% with a network load of HT=900 and the lowest is 0.01% with HT=300. Thus, comparing to SS8, the blocking rate decreases more than 40%.

Following, the next simulation scenario, SS10, implements traffic grooming but includes only five regenerator nodes, representing a 30% of the total. The fourth-degree nodes are the highest degree nodes in the NSF network, with Id=5 and Id=8. The next three nodes to complete the 30% are the Id=3, Id=7, and Id=10 nodes, which are chosen between all the third-degree nodes of the network. All of them can be recognized in Figure 3.6.

The results, showed in Figure 5.12, demonstrate that the blocking rate is reduced compared to the initial scenario (SS8), however since this network highly requires regeneration, the values of SS9 cannot be reached. Considering the integrated system, the blocking probability is 0.3% with the lowest traffic load (HT=300), and with a bigger load (HT=900) rises to 28.5%. Notably, a similar performance is achieved with a disaggregated system that reduces by 10% the lightpaths TR limit. However, a bigger gap is caused by the larger

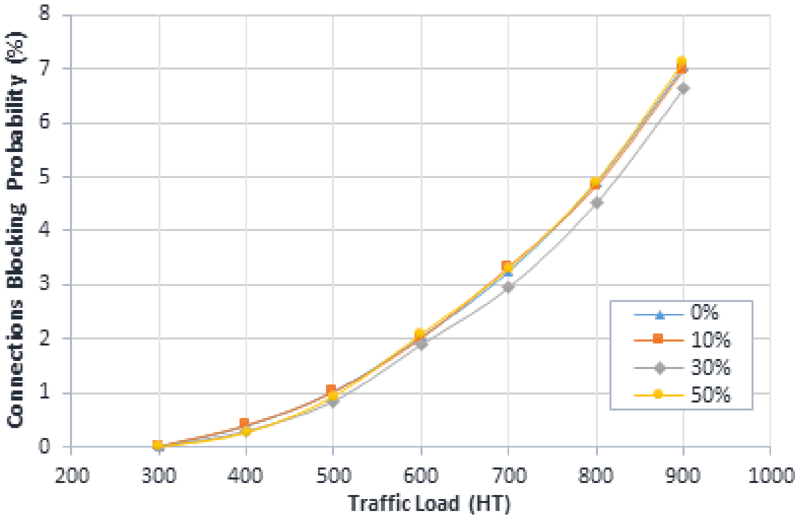

Figure 5.11: Connections blocking probability of SS9 vs. network traffic load, considering different TR penalties.

penalties, 30% and 50%, where the blocking probability, with HT=900, increases to around 30.4% and 37.5%, respectively.

Observe that, under this scenario SS10, a blocking rate less than 5% was achieved, although only considering the lower network loads, HT=300 and HT=400, and that the open system forces a TR reduction of 10%. Nevertheless, it is a significant improvement driven by traffic grooming and the addition of regenerators (5 OEO nodes), compared to a blocking probability more than 50% prompt by the integrated system without regeneration (SS8).

5.7. NSF Network – Modulation Format Variation

Finally, as the last test to improve the blocking probability of the NSF network, a lower modulation format is implemented in the simulation scenario SS11. An 8-QAM modulation format is used, which corresponds to a TR limit of 3400Km.

According to Figure 5.13, with SS11, the amount of blocked events is significantly reduced. In fact, a blocking rate under 5% is reached with all the TR penalties, though the traffic load supported by the network is different in function of the penalty caused by the open system. For example, to maintain a 5% blocking percentage, with a 30% TR penalty the maximum network load supported is HT=600, and with a 50% restriction, the traffic load that can be served by the disaggregated network decreases to HT=400. In addition, compared to an integrated system under this scenario, a similar blocking rate trend is obtained by an open system with a 10% TR restriction.

In conclusion, a stronger dependence of the NSF network on regeneration is observed. Thus, its performance is more sensitive to the TR penalties, resulting difficult to equal the behavior of an integrated system, having the same number of regenerators, if a TR reduction of 30% or 50% is produced by the open equipment, even implementing a lower modulation format.

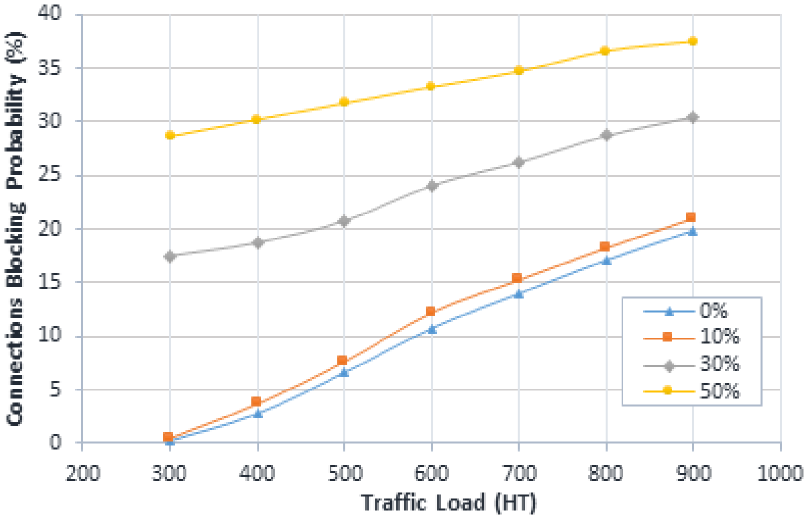

Figure 5.12: Connections blocking probability of SS10 vs. network traffic load, considering different TR penalties.

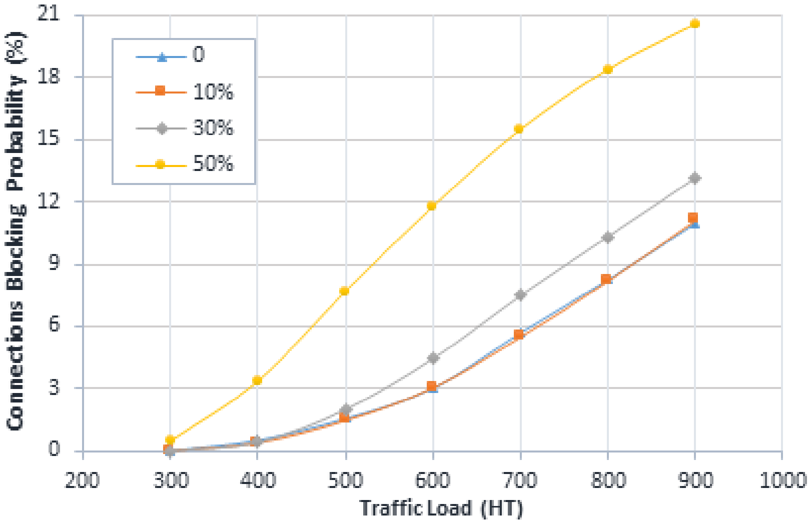

Figure 5.13: Connections blocking probability of SS11 vs. network traffic load, considering different TR penalties.

CONCLUSIONS AND FUTURE WORK

Both IT and Telco industries are searching for alternatives and open solutions to redesign the current datacenter and networking architectures, to keep up with the constant growth of the bandwidth-hungry applications market. In this sense, the concept of disaggregation is gaining momentum as a potential approach, as detailed in Chapter 1. It is worth to note that carriers are actively contributing to open solutions by efforts in the standardization process, and developing open-source, software-controlled networking architectures.

Among the several benefits of disaggregation when brought to optical transport networks, the following can be noticed: proprietary lock-in breakdown, competitive pricing, simplified and common equipment specifications to support interoperability, innovation and evolution boosting, market expansion to open community and hardware manufacturers, and lower CapEx/OpEx. Moreover, service providers have the possibility to select the best deployment option that fits their business needs.

In particular, the optical network disaggregation approach is based on breaking the hardware equipment into independent functional blocks (e.g., transponders, pluggable optics, ROADMs). Such open nodes are combined with controllers, orchestration systems, and open APIs for an end-to-end system management and control.

However, disaggregation drives significant challenges as well. Among others, a significant impact comes from the additional power losses (when compared to optimized proprietary solutions) experimented in the disaggregated optical nodes, affecting the optical connection's end-to-end power budget. This implies a reduction of the transmission reach (TR) of the lightpaths, that requires the use of less spectrally efficient modulation formats or the use of additional regeneration sites.

In this context, the main objective of this thesis is to quantitatively evaluate the influence of using disaggregated nodes, when several levels of TR reduction are considered, by estimating the number of connections which are denied service due to this issue. Moreover, the traffic grooming concept is introduced, driven by the necessity to deploy regenerator nodes to overcome the TR limitation, in order to analyze the tradeoff between the grooming approach and disaggregation. Two networks topologies are tested, different connections traffic profiles and modulation formats are considered.

The numerical results of the DT network show that without regeneration a maximum network traffic load represented by HT=400 can be supported for an integrated network to maintain a blocking probability under 5%, and similar values are obtained by a disaggregated system with a TR penalty under 10%. This result implies that a TR penalty boundary exists, where adding regenerator nodes to the open network is not needed, since its performance can be greatly similar to an integrated system, i.e., if vendors can develop an efficient disaggregated system, so that the total losses caused by the open nodes stay under the mentioned boundary, no additional costs to deploy extra regenerator nodes have to be considered when adopting disaggregation.

However, considering larger penalties, 30%, and 50%, with the same traffic load (HT=400), the DT network performance is downgraded to 10% and 35% of blocking rate, respectively. Thus, under this conditions, additional OEO interfaces are required along the network to overcome the reduction of the lightpaths transmission distance caused by disaggregation, which reflects on increasing the network blocking rate, as detailed above.

Furthermore, when a limited number of regenerators are strategically added to the DT network to address the TR limitations and, also, traffic grooming is adopted, remarkably, a lower blocking rate equal to 0.36% is achieved by the open system, which corresponds to a traffic load of HT=400, considered to compare with the integrated system. This behavior is repeated with all the TR penalties studied since the blocking probability difference between applying a 10% or a 50% TR restriction is minimum. Moreover, according to the simulations, when the traffic rate of the end-to-end connections is lower than 50Gbps, the blocking rate rests under 2%, even for a network load of HT=1000.

Overall, these results reveal the advantage of adopting traffic grooming in an open network that includes more regenerator nodes compared to an integrated system. Since additional traffic flows can be groomed every time a lightpath is regenerated, which is more frequent due to the TR penalty of the open nodes, the resource allocation of the system is altered and a lower blocking probability is achieved. Therefore, with higher levels of TR reduction, the blocking rate values are actually better.

The NSF network simulations show that the benefits of disaggregation depend on the topology. The simulation SS10 shows that, with HT=400 as network traffic load, an 18.7% and 30.2% blocking probability are obtained with 30% and 50% TR penalties. Just with the lower TR penalty (10%) a blocking rate under 5% is achieved. Although, if a lower modulation format is used, considering the same traffic load, less than 5% blocking rate is reached with all the TR penalties. Therefore, when the average size of the network links and/or the TR penalty of the disaggregated system are too large, increasing the system blocking probability if not enough regeneration is available, a lower modulation format can be implemented until reaching the network performance desired.

In this regard, network disaggregation becomes a promising approach. Service providers can determine the additional costs of deploying OEO nodes in the network and compare it to the performance improvement driven by these nodes together with traffic grooming adoption. They must consider this benefit plus the advantages of an open model to evaluate its implementation in optical transport networks.

Future work will focus on detailed network simulations, by implementing a physical layer model to derive the losses generated by the disaggregated nodes. The objective is to precisely estimate the transmission reach reduction for each lightpath, as a function of the number of nodes traversed. After that, analyze once more the grooming effect in a disaggregated system.

In addition, different algorithms, which develop different criteria to select the best nodes to perform regeneration, can be tested, in order to evaluate their effect in the blocking rate of the open system.

Sustainability considerations

The disaggregation approach focuses on simplicity to develop common optical equipment mostly controlled by software, being part of the design to minimize the power consumption of the nodes. In addition, disaggregation prevents overprovisioning, which also represents a reduction in energy consumption, since it is not necessary to deploy equipment in advance to meet a possible future demand. Regarding the economic point of view, one of the main benefits of network disaggregation is to break the vendor lock-in and boost competitiveness between the optical suppliers. This will stimulate a lower cost of the devices available in the market.

However, it must be taken into account the cost and energy requirements of the additional regenerator nodes needed to overcome the lightpaths power-budget reduction, driven by the open equipment.

Ethical Considerations

Network security is a critical topic since the implemented system must preserve the confidentiality and integrity of the transmitted data. In this sense, the disaggregation of optical transport networks must provide the same or better security mechanisms than the ones implemented in integrated optical systems, in both the physical and control layer of the network architecture.

Moreover, the decoupling of hardware and software at each optical node generates the possibility to run third-party tools in any network element, thus, between them, the best security applications for the system can be selected to be installed.

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