Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

UNIVERSITAT POLITÈCNICA DE CATALUNYA

MASTER THESIS

TITLE: Resource allocation in disaggregated optical networks

MASTER DEGREE: Master's degree in Applied Telecommunications and Engineering Management (MASTEAM)

AUTHOR: Concetta Lluca

ADVISOR: Salvatore Spadaro

Albert Pagès

DATE: September, 3rd 2019

Title: Resource allocation in disaggregated optical networks

Author: Concetta Lluca

Advisor: Salvatore Spadaro

Albert Pagès

Date: September 3rd, 2019

Abstract

The recently introduced disaggregation model is gaining interest due to its benefits when compared with traditional models. In essence, it consists on the separation of traditional hardware appliances (e.g. servers, network nodes) into commodity components, which then are mounted independently for their exploitation into customized physical infrastructures. Such an approach allows telecommunication operators and service providers to appropriately size their infrastructure and grow as needed. One of the main key benefits of the disaggregation model is the break of the vendor lock-in, pushing towards interoperability between equipment from different vendor with minimum standardization of software and hardware specifications, allowing operators to build the best solutions for their needs. Moreover, efficient scaling is also an important benefit introduced by the disaggregation approach. Due to these benefits, among others, the disaggregation model is gaining momentum and is being adopted into multiple fields and domains of nowadays telecom infrastructures. In this regard, the scenario under study of this master thesis focuses on disaggregated optical transport networks. Disaggregation allows for more open and customized optical networks, reducing both capital and operational expenditures for infrastructure owners. However, despite of these positive aspects, disaggregated optical networks face several challenges, being the degradation of the network performance when compared to traditional integrated solutions the most important one. In this regard, this thesis investigates the impact of disaggregation in optical networks and investigates regeneration as a potential solution to compensate the performances' degradation. Under this premise, optimal solutions for regenerator placement, exploiting the inherent grooming capabilities of regenerators, are proposed and evaluated.

I would like to thank my advisor Salvatore Spadaro. He guided me during the time I spent preparing my thesis and that allowed me to work in a group of experts. Then, I would thank my co-advisor, Albert Pagès, a patient and professional guide that supported and guided me in a special way. I would like to express my gratitude to my family, my mother Rebecca and my grandmother Concetta, who permitted me to follow my dreams without leaving me alone, even miles and miles away. Thanks also to my sister Sabire, whom represented for me a constant support and a sincere friend during my study and life. Finally, I would like to thank all the people I met in the Master, old friends and new ones, first of all Yuanting, my roommate and my sweetest friend, a person that everyone would like to have in its life. All this would not have been possible without the support of these lovely people.

Thank you.

Concetta Lluca

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The nowadays growing popularity of cloud and multimedia services is spurring the increase of the traffic that global Data Center (DC) infrastructures need to handle [1], putting pressure on both intra- and inter-DC network (DCN) fabrics. This is driving the demand for highly scalable, flexible, and energy-efficient networks to support DCs' traffic. In this regard, fiber optics technologies-based networks are the prime candidate for meeting the requirements of future DC and telecom networks. The superior available bandwidth and achievable bit-rates, the low attenuation, the low energy consumption, the immunity to electromagnetic disturbances, among others, represent the main strengths of the optical fiber medium. As a result, optical fiber-based communications are widely recognized as the highest energy- and cost-efficient technique to offer ultra-large capacity for telecommunication networks [2]. Furthermore, it has also been considered as a promising transmission technology for future DCN infrastructures. Considering the characteristics of the traffic generated by the servers, such as locality, multicast, dynamicity, and burstiness, the emphasis of the research on DCNs has to be put on architectures that leverage optical networking to the greatest possible extent. These are the reasons why network operators are evolving towards optical network solutions as support for their transport infrastructure.

The Optical Internetworking Forum (OIF) defines "Optical Networking" [3] as a network infrastructure where switches and routers have optical integrated interfaces and are directly connected with fiber links in which Wavelength Division Multiplexing (WDM) technology can be used. Considering the new business model of "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. After a phase of decisive push towards the public cloud, also dictated by the difficulty of many companies to acquire their own private cloud, we are now witnessing a turning point towards a hybrid multi-cloud model in which general-purpose applications land on public clouds while those of core business are hosted on a private cloud. This emerging business model posits that everything from technology services through key business processes can be delivered as a service utility. As technology companies adopt XaaS, they realize that the capabilities required to succeed with XaaS are vastly different from the attributes of traditional business models. They face challenges not only in embracing the mechanics of new forms of service delivery but in maintaining the balance between third-party-driven process innovation versus shifting operational costs that are administered on a pay-per-use basis. To efficiently adopt the XaaS business model, a “more-open” infrastructure is required, able to face with a central control, through software interfaces, of features and functions of each network node, to support interoperability between different vendors’ equipment, and to build a flexible, reliable and cost-effective network architecture [4]. Consequently, operators are researching and investing in cutting-edge solutions, towards the transformation of the design, deployment, and operation of their networks into more open infrastructures, both in regards of software integration as well as data plane functions and system elements.

The disaggregation model, based on the latest IT technologies and architectures, has become one of the pursued approaches to respond to the novel requirements of optical transport networks. The major idea is based on decoupling the different network layers in contrast with the current integrated optical systems. What this concept tries to propose is 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. What people want to do now is a movement towards greater flexibility, avoiding vendor lock-in and enabling access to inexpensive products that involves disaggregation of individual network elements. By unbundling a single network function into separate hardware and software, and harnessing software installation capabilities to install any operating system on open white boxes, operators can achieve new levels of efficiency and agility. What they also ask is the introduction of software-orchestration to abstract the control layer from the physical layer, acquiring software-based control and automation features [5]. Such automation can be based on actively processing real-time network monitoring information and learning from the effects of the decisions taken to validate and provide optimal selection of network resources to satisfy new service demands and dynamically re-optimize existing service demands. Therefore, a key element of the disaggregated network is the optical performance monitoring that is expected to deliver the feedback needed for guaranteeing end-to-end (E2E) quality of transmission (QoT) and quality of service (QoS).

Disaggregated networks seem to be the perfect solution to meet today's demands but 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 and, 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. There are obviously other challenges, for instance, the integration of the system with open components and their maintenance and, very importantly, the speed and adaptation of the optical market in releasing standards and operating tools. The importance that disaggregated optical networking is taking makes it interesting to carry out the analysis regarding these issues. 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. This is due to the extra propagation losses that result in the reduction of the maximum transmission distance without regeneration of the optical signals (Transmission Reach – TR). The most important problem is given by the cost of optical regenerators, which is usually quite high, so operators need to understand whether this budget drawback exceeds the expected benefits brought by the disaggregated approach or not.

Based on the previous information, this thesis aims at an optimal planning of a disaggregated optical transport network considering the TR reduction of the optical signals, which arise when adding disaggregated equipment to the transport network. Furthermore, traffic grooming is also proposed, when considering optical signal regeneration operation, as an alternative to mitigate the extra cost associated to regeneration nodes. The ability to multiplex low traffic rates into a single optical channel, given by this technical approach, can improve the performance of the network and increase its capacity. As a summary, exploring different levels of penalty to the TR of the lightpaths introduced due to disaggregation, this thesis focuses on a network optimization problem, through the definition of an optimization model suitable for defining the exact position of optical regenerators, making the most of their capabilities while minimizing the potential cost of the optical network infrastructure.

2 RESOURCE DISAGGREGATION

2.1 RESOURCE DISAGGREGATION IN DATACENTERS

DC infrastructures comprise a large number of servers, each of which tightly integrates a small amount of various resources needed for a computing task (CPU, memory, storage) [7]. These computing resources are all connected to a single motherboard that can only be used by the applications running on one specific server. DC are able to simultaneously perform complex tasks and serve thousands of users at the same time but, to take full advantage of their capability, an alternative configuration has been proposed towards a disaggregated DC (DDC). By the use of such new configuration, where each resource type is built as a standalone resource "blade", DC operators have a flexible and granular control over individual resources across jobs. Such an approach also allows for independent resource technology evolution, enabling their deployment when needed. Utilization efficiency, energy consumption and flexibility are the most important features that disaggregation brings to the future DCs.

Disaggregation of IT resources has been proposed as an alternative configuration for DCs. In a DDC scenario, where the separate resource blades are interconnected via a network fabric, the network, which represents the key enabler for the DDC, should support the bandwidth and latency requirements of the communication that is currently inside the server. In addition, a management software is required to create the logical connection of the resources needed by an application.

The disaggregation model was firstly adopted in DC environments, with the aim of improving the computing resource utilization in view of the exponential growth of the market. The current 'server-centric' DCs consist of a fixed amount of computation (CPU), memory and storage resources integrated in a motherboard, as shown in Figure 1, [8]. However, various services, such as cloud computing and big data analytics, usually require different proportion of resources, causing low resource utilization in the "server-centric" DCs [9]. In this regard, the concept of rack-scale DDC has been widely investigated in the recent years, aiming to increase the efficiency of resource utilization in DCs. In the current DCs, the integrated servers are interconnected in a rack by a Top of the Rack (ToR) switch, as shown in Figure 1(a). In DDCs, blades containing one specific resource (i.e., CPU, memory, or hard drive storage) are interconnected through a switch that needs to support high capacity transmission, where the need of adopting optical technologies is obvious. Figure 1(c) shows an example of a rack scale DDC. A resource blade is able to hold more resources than the same type of such resources in an integrated server, which provides more flexibility for resource allocation. Figure 1(b) shows an example of a specific task (e.g. virtual machines, VM) in a DDC. The underlying infrastructure of DDC is transparent to the carried tasks. It means that communications between CPU, memory, and storage, which are implemented on the buses of motherboard in the traditional server, are now carried out by external optical links between resource blades in the rack of the DDC.

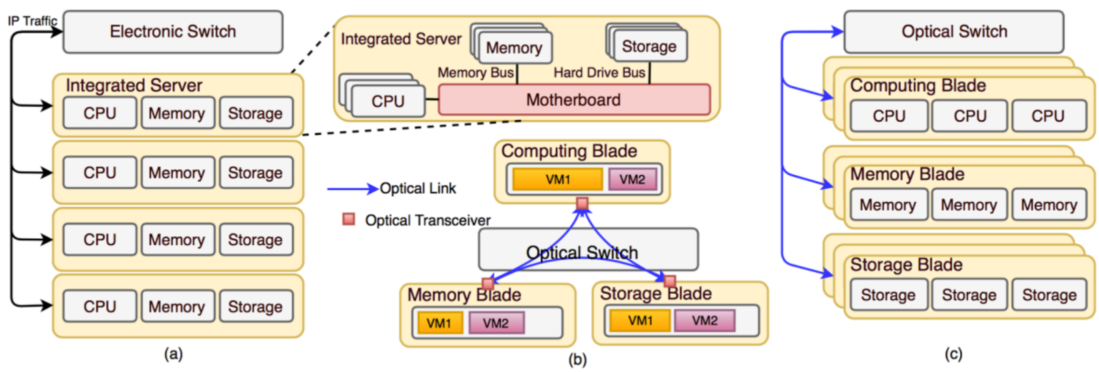

Figure 1 (a) A Rack in Traditional Data Center (b) Virtual Machine Deployment in Disaggregated Data center (c) Rack-scale, [8].

This new type of computing system, which is network-centric, can offer immense flexibility in regards of resource allocation, potentially maximizing the resource utilization while enabling new workflows and applications with few resource boundaries. However, a number of fundamental challenges arise on such communication-centric computer architectures, which need to be addressed. For instance, it is quite easy to support CPU-Storage communication with current optical transmission technology but it is extremely difficult to reach the high bit-rates required for CPU-Memory and CPU-CPU communications (e.g. up to several hundreds of Gb/s) by a single optical channel [8] [10]. Additionally, for the re-configurations of the data-paths to be effective, the end points connected to the optical switch must be time-synchronized at a very fine granularity (ideally few nanoseconds) [11]: many optical switches have relatively long reconfiguration time (~1 ms) which makes difficult a dynamically reconfiguration of its bandwidth during the running task. In spite of these challenges, in [9] authors demonstrated that IT resource disaggregation can improve DC efficiency by showing an optimal utilization of the DC infrastructure under a disaggregated model. The increasing in such scenario by 50% the number of service instances mapped over the decoupled resource blades compared to a server-centric architecture leads to a push towards the use of resource disaggregation within DCs.

2.2 Network Disaggregation

The aforementioned IT disaggregation approach represents a departure from the way networks and optical networks start to adopt the disaggregation model. In fact, disaggregation aims at providing a new degree of flexibility, allowing component migration and upgrades without vendor lock-in. Vendor support and cost efficiency are an excellent use case for open and standard interfaces, showing the benefits of a unified, model-driven development: IT disaggregation inspired the usage of its proposed model for other realms. There is a need to have better configuration management, a clear separation of configuration and operational data, while enabling high level constructs more adapted to operators' workflows supporting network-wide transactions, rollback capabilities and transactional semantics. Network disaggregation is driving unprecedented changes in the optical market mainly proposing the separation between the communications equipment according to their functions into independent hardware blocks (pluggable optics, transponders, and Optical Cross-connect (OXCs)/Reconfigurable Optical Add and Drop Multiplexers (ROADMs)) which are currently integrated by a close single-vendor system. Software-based management is then allowed by decoupling the control layer from the physical blocks. Furthermore, network disaggregation intends to separate the operating system from the hardware, enabling the development of commodity optical hardware, [12].

The Open ROADM project [13] is one of the strongest works to move hardware-centric optical transport networks to an open software-centric system. ROADMs are key enablers of modern optical communication services to support the remote provisioning of the optical paths and reconfiguring the network logical topology. Some of the common optical modules that may exist in an ROADM architecture are Optical Multiplexer/Demultiplexers, Optical Power Splitter/Couplers, Tunable Optical Filters and Optical Switches. Another major building block of some ROADMs architecture's is the Wavelength Selective Switch (WSS). Using this module, any channel of any input port can be switched to any output port [14]. Several architectures have been deployed and discussed in the literature, for which Figure 2 shows one of them as proposed in [15]. Such architecture consists in an add/drop structure of each degree, with this module composed of a multiplexer, a demultiplexer, a WSS and a Splitter to provide scalability; two Optical Amplifiers in the input and output of each degree; and a centralized colorless and directionless add/drop structure for up to 8 channels. The architecture proposed provides also modularity. It is noticeable that optical power management, optical cross connect management and wavelength management can be done by using the ROADM architecture. In Figure 3, [16], a more simplified structure of a typical ROADM device with four input ports (P1 to P4) is depicted. Here we can observe all the ROADM's components: the WSS that permits the dynamic routing of any wavelength to and from any port and then seamlessly change connectivity as needed; the optical channel monitoring (OCM) that monitors the optical power of each wavelength and the variable optic attenuators (VOAs) that configures the attenuation of optical power in each wavelength.

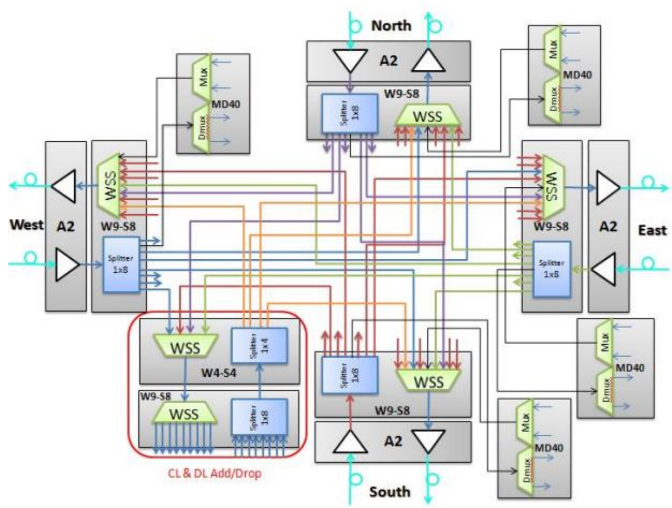

Figure 2 ROADM architecture, [15].

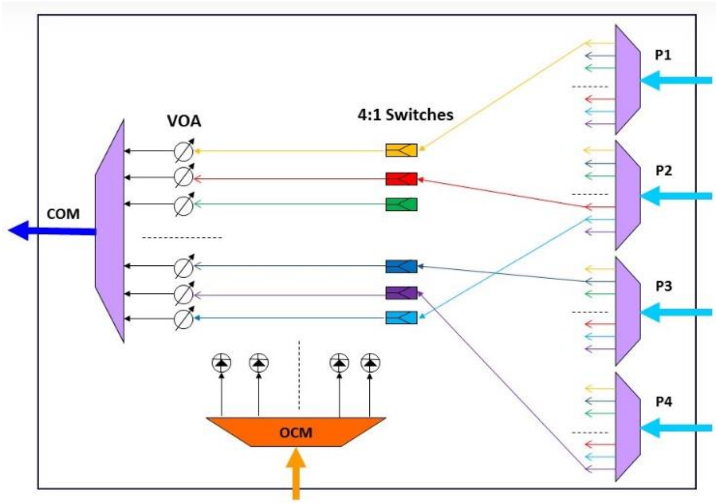

Figure 3 ROADM simplified scheme, [16].

ROADMs provide simplifications in the network and in the service provider's or carrier's processes: they reduce the number of necessary transponders to serve connections, operation and maintenance are greatly simplified, and installation and commissioning are quite easy to manage thanks to the interoperability property. In this regard, 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.

The Telecom Infra Project (TIP) [17] represents another community devoted to separate the hardware and software components of network architectures which are usually bundled together, with the goal of increasing efficiency and designing new solutions. Facebook, Telefonica, Hewlett Packard Enterprise, Telstra, Orange, among other five hundred companies are active in the project. Access, backhaul, and core networking plus their associated management are the three initial working areas of the TIP project, each of them addressed by a different project group. All of them focus on disaggregation of the hardware and software components of the network infrastructure to increase its efficiency and boost interoperability. One of the most important research group in the TIP project is the Open Optical & Packet Transport (OOPT), currently divided into five different subgroups, focusing on different parts of the stack: Disaggregated Cell Site Gateways (DCSG); Physical Simulation Environment (PSE); Converged Architectures for Network Disaggregation & Integration (CANDI); Controls, Information Models & Application Programming interfaces (APIs) (CIMA); and Disaggregated Network Platforms (DNP). In general, the OOPT group aims to define a Dense Wavelength Division Multiplexing (DWDM)-based 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 that is considered the industry's first open and disaggregated converged packet/optical transponder. Facebook, one of the biggest companies working on it, developed Voyager, which leverages DC technologies, as an open packet optical platform combining DWDM technology for metro and long-haul fiber optical transport networks with switching and routing functionalities. A clean separation of software and hardware is offered and it is proposed with open specifications, so any vendor can extend it with additional components, or provide different software and features for it. The goal of the live trial, in which many companies were involved, was to highlight the future of applying a disaggregated model to optical networks and to provide more flexibility to handle real time network dynamics using Voyager, combined with a Software Defined Networking (SDN) controller. The live trial showcased how the proposed architecture can be implemented over an existing optical infrastructure, delivering a capacity of 800 Gb/s per rack unit and, thanks to SDN, dynamically adapting the system modulation as fiber conditions change.

Both open projects, TIP and Open ROADM, with their specifications and technological evolution, potentiate the application of disaggregation in future optical transport networks, as shown by statistics provided in [5]. From the results obtained with a service provider survey, the authors detail the statistics obtained to assess the possible evolution of metro optical network technologies. Referring to the disaggregated approach, 38% indicated a preference for fully integrated line systems where only the transponders would be provided separately which aligns with a level of acceptance in the industry for an open line systems approach; 31% selects the option where components are provided as separate cards/modules that can be combined on a common shelf/platform; 19% prefers fully integrated hardware/software systems with open API support for management/control by third-party applications; 13% indicated a preference for components provided as standalone devices that can be stacked in a rack.

2.2.1 Optical disaggregation approach

Disaggregation of optical networks refers to a deployment model of optical systems, by composing and assembling open, available components, devices and sub-systems. As mentioned above, the disaggregation model involves decoupling the hardware components by their optical functions, into independent nodes, both the terminal system (e.g. transponder/muxponder), and the line system (e.g. 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 control system through open standards-based interfaces.

Traditional network systems based on optical technology are expected to be integrated by the equipment vendor. 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. It is also in such scenario that the disaggregation approach offers different solutions allowing operators to select the optical solution that best fit their needs and their budget, with the possibility of future scaling.

2.2.2 Benefits and challenges of disaggregation

There are many benefits that disaggregation offers to network operators that are faced with the current and future bandwidth demands, in terms of design, management and performance and cost. The replacement of all deployed equipment in the line system represents high costs to the provider, since technological advancement does not move at the same pace with optical technologies. Disaggregation solves this problem by supporting different generations' equipment. One of the main objectives of the disaggregation model is the break of the vendor lock-in. A disaggregated platform has the tendency to push against vendor lock-in more than an integrated equipment. As a result, interoperability between equipment from different vendors is achieved, with minimum standardization of software and hardware specifications, allowing operators to build the best solutions for their needs. An efficient scaling is also an important benefit introduced by the disaggregation approach. The operators could now design a network architecture without overprovisioning: the ability to meet the current required capacity is possible thanks to the opportunity to control by software the optical equipment, to use virtualized network functions and to be interoperable in the pool of technological innovations. When the traffic demand grows, operators are able to expand the infrastructure and meet the customers' needs without wasting resources. Alongside these benefits, in addition to a rapid upgrade deployment resulting from disaggregation, there are benefits related to lower operational expenditure (OpEx) and capital expenditure (CapEx). The efficient E2E management and control of the system offered by the functions virtualization and the software–based solution, leads to a better network operational process that is translated in lower OpEx costs. The same reduction takes place for the CapEx since network operators are able now, as explained before, to increase vendor diversity, which fosters innovation and competition with the result of a lower CapEx.

Despite all these benefits introduced by the disaggregation approach, there are some challenging aspects to be highlighted in this regard. High-level E2E system performance is difficult to maintain in the disaggregated solutions. Network elements belonging to different vendors make it difficult to implement a common standardized technology to be adopted by the optical nodes and assure interoperability. As a result, this compromises the network capabilities because some of the native functions in the equipment cannot be implemented in an open mode. This also translates into poor signal reception because the lightpaths lose power crossing the nodes, making the TR shorter; with disaggregation accentuating these losses due to node construction not being optimized. In order to compensate the TR's reduction, a larger number of regenerator nodes must be used in order to maintain the network performance. Moreover, closely linked to this challenge, arises the problem of power control for the employed optical channels. Optical carriers can vary on power level, modulation format, central frequency and spectral shape and the system must ensure an optimal power balance during all the transmission. Such possibilities have to be performed in the native functions as well for the new added wavelength. An automatic and per-channel power control is required to balance the carriers that are routed over the open network. Aside from these problems, standardization plays here a challenging role since software and hardware sources can be from different suppliers. As a result, the operators need to deploy the system blocks able to be aligned with standards and to coexist in the same system.

There are many other challenges that operators must face before moving on to a purely disaggregated approach. As a consequence, the way in which they decide to design the network architecture depends on many factors that must coexist in a varied environment which has to satisfy the needs of consumers and owners. However, aside from these challenges, separating networking equipment offers operators flexibility: by physically decoupling different resources, operators can more easily adopt the state-of-the-art in any particular technology having a finer-grained control over how they select, provision, and upgrade individual resources.

3 DISAGGREGATED NETWORK ARCHITECTURE

The optical transport networks need to be renovated by the disaggregated solutions in order to redesign the traditional optical system infrastructure in such a way as to achieve the promising objectives of the disaggregated network approach.

Historically, the optical transport market has been served by vertically integrated network solutions. Operators select a vendor for their network, and then all transponders, ROADMs, line systems and optical design tools are provided by this same vendor. As a result, operator choice becomes limited once the initial vendor selection is made. This inhibits flexibility and innovation, and further expands vendor lock-in as the network is maintained and expanded over time. Recently, the need for increased agility and flexibility has accelerated the introduction of software defined environments where the control and management planes of these resources are decoupled from the data planes so that they are no longer vertically integrated as in traditional compute, storage or switch systems and can be deployed anywhere within an optical network.

In general, optical networks include hardware elements (transponders/terminals and line system equipment), software operating systems and management/control software. A fully open optical network is defined as an architecture that includes open hardware supporting open APIs that can interact with and be managed by open source software. A schematic representation of this process is depicted in Figure 4.

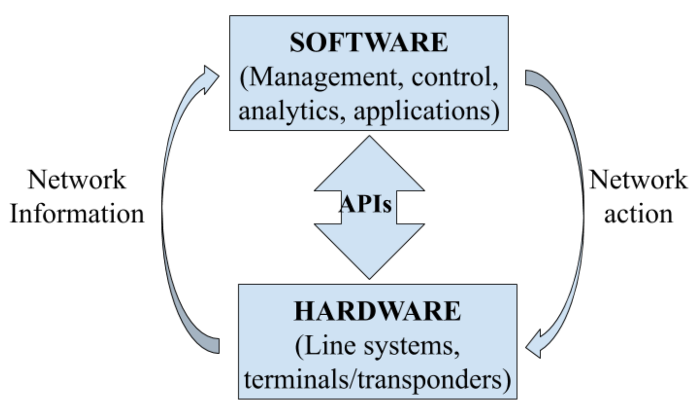

Figure 4 Software and hardware schematic process.

The today's proposed disaggregated devices are horizontally integrated, where the network operating system and the element management interfaces can be independently selected and easily integrated depending on each specific requirement. This results in a unique, tailor-made, product that is perfectly adapted for each application and for each of the operator's needs. The best combination of hardware and software can be now chosen by all the operators to best fulfill their requirements while eliminating vendor lock-in and anticompetitive sales or support practices. Moreover, both CapEx and OpEx can be significantly reduced. The combination of hardware disaggregation and the use of advanced software tools to control, configure and observe networks are expected to be major drivers towards the goal of having flexibility and agility.

3.1 ARCHITECTURE DISAGGREGATION FOR OPTICAL NETWORKS

Open hardware, in today's market, assumes a broader meaning. One approach is optical equipment meeting specifications set by industry standards bodies and/or multi-source agreement projects such as AT&T's Open ROADM project or the TIP's Voyageur platform [13] [17]. This approach is driven by the equipment interoperability idea, enabling network operators to have more freedom in purchasing equipment from different vendors. The Open and Disaggregated Transport Networks project (ODTN), is an industry-wide and operator-led initiative to build an open source reference platform to achieve the goal of the disaggregated model exposed above. The project is focused in disaggregated DWDM systems, including transponders and Open Line System (OLS), amplifiers, multiplexers, all-optical switches and ROADMs. This project divided the design strategy into two phases: a first one focused with the design of a point-to-point solution; and a second one aimed at obtaining a completely meshed ROADM solution.

The first phase, without creating a new network infrastructure, aims to augment the existing layouts with more programmability and new features by the use of an SDN controller and open APIs enabled devices (e.g. Transponders (TRN)). Incompatibility issues, between different proprietaries of the protocol used, are avoided establishing connectivity between two pairs of transponders from the same vendor. Connectivity establishment is achieved by not only controlling with open APIs and models the transponders, but also the OLS in the middle [18]. In this phase, in order to achieve the goals set for it, different devices must support multiple operations: the transponders need to expose the APIs to discover port information and enable a cross-connect between line side and client side port with a given wavelength and optical channel; also with the OLS we have port information and, more than this, this device is able to provision a path between two transponder facing ports, for both the cases when the OLS exposes itself as a single component or a full mesh topology. The intermediate OLS controller is removed in phase 2, in order to obtain a full meshed ROADM solution.

Next, the second phase is aimed at enabling the OTDN platform for total control of disaggregated ROADMs. The disaggregation during this phase allows controlling a ROADM as whole, as shown in Figure 5 [18].

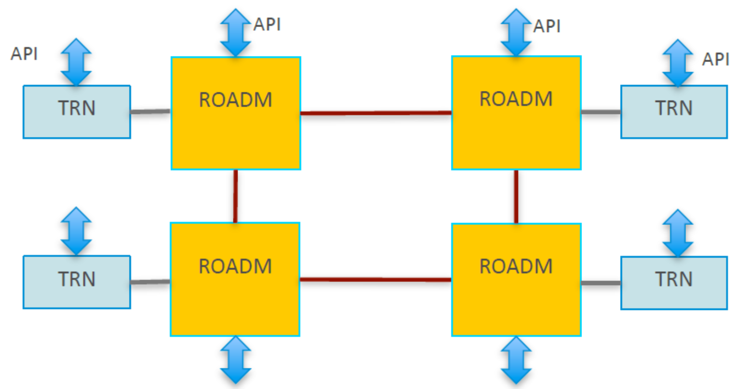

Figure 5 Disaggregated ROADM, phase 2, [18].

Figure 6 shows another possibility that allows monitoring every single component of the ROADM to meet design needs according to different situations. The APIs are used to define the interaction, the capability and the control of the ROADM devices. They enable the monitoring of the Execution Management System (EMS), located where the to/from network control is performed; the WSS and the amplifier are also connected via APIs as well as the acousto-optic switch (AOS) and the TRN.

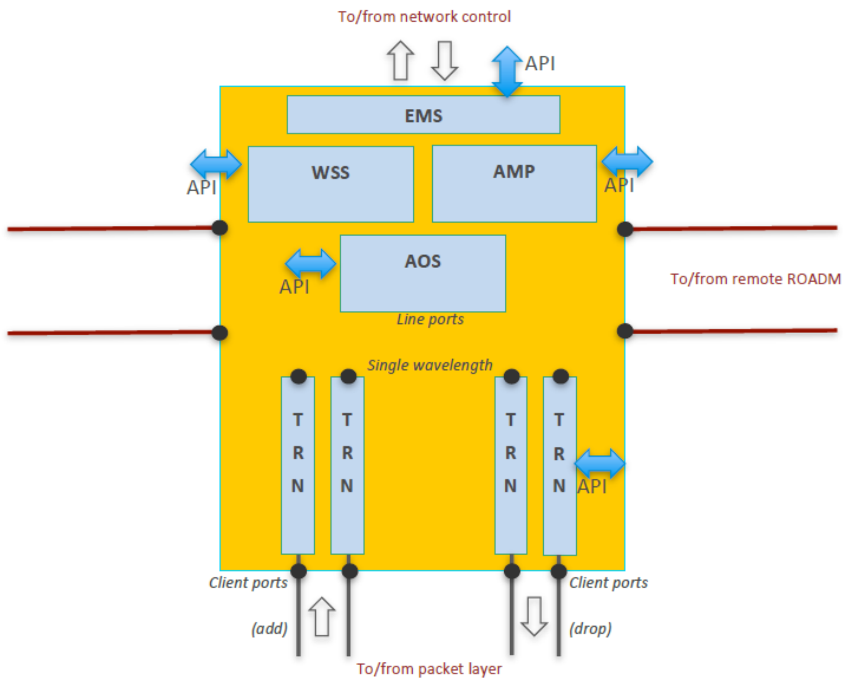

Figure 6 Disaggregated ROADM version 2, phase 2, [18].

The ODTN project has to be implemented in a way so that it can live and co-existing in deployed optical. While guaranteeing its compliance and interoperability with existing EMS/NMS (Network Management System) systems, it will enable operators to incrementally install disaggregated components.

The project discussed above is one of the most important in the field of disaggregation model, but not the only one. All the industry is moving towards this new wave of change that is bringing a new degree of flexibility, allowing component migration and upgrades without vendor lock-in, a trade-off in terms of current and potential performance. Nevertheless, the degradation of the network, due to the disaggregation approach, leads to having a shorter TR that is translated in having a higher number of regenerator nodes in order to compensate such decrease. As such, the network architecture must consider such consequence: it represents an important point in the design step since having a bigger number of regenerators leads to an increase in overall costs because of these costly devices.

4 TRAFFIC GROOMING

As explained previously, the increase of the number of regenerators needed at the optical network due to the disaggregation model represents a challenge. By adding these extra nodes, the additional penalties to the TR of lightpaths can be compensated, however, at the expenses of increasing the cost of the network. In order to mitigate or compensate the additional introduced CapEx and OpEx, the inherent traffic grooming and wavelength conversion capabilities of regenerator nodes could be exploited to make a more efficient use of the available optical spectrum. As such, the traffic grooming concept is addressed as a positive technique to take advantage of the extra regenerator nodes available in a disaggregated network. By aggregating multiple low-speed traffic connections into a single high-speed stream, traffic grooming essentially reduces the number of wavelengths (i.e., bandwidth) and devices needed to accommodate traffic in a WDM network (i.e. transponders at source and destination nodes of client traffic demands). The grooming of traffic demands must take place in the electrical domain and the number of needed transponders could remain the same or could increase in order to support additional optical-electrical-optical (O-E-O) conversions in the case that we want to employ more traffic grooming. As shown in [19], traffic grooming increases the utilization of network devices and, thus, reduces network cost and power consumption.

4.1 GROOMING ARCHITECTURES AND CHALLENGES

As next-generation optical transport networks evolve from 10 Gb/s to 100 Gb/s bit-rates, a key topic of investigation for service providers is focused on how to save network cost and to improve network performance. That is why, in the nowadays scenario, it is very important for the network operator to be able to “groom” the multiple low-speed traffic connections onto high-capacity circuit pipes. Different multiplexing techniques can be used for traffic grooming in different domains of optical WDM networks. The most important ones are listed below, [20]:

- Space-division multiplexing (SDM): partitions the physical space to increase transport bandwidth, e.g., bundling a set of fibers into a single network link, or using several cores within a fiber link.

- Frequency-division multiplexing (FDM): partitions the available frequency spectrum into a set of independent channels. The use of FDM within an optical network is named WDM, which enables a given fiber to carry traffic on many distinct wavelengths. WDM divides the optical spectrum into coarser units, called wavebands, which are further divided into wavelength channels.

Focusing on the WDM technology, we can see how the whole bandwidth of every fiber is potentially available for transmission, as many independent signals can be accommodated on the same physical link by using densely packed adjacent wavelengths. Another advantage of the WDM technology is that it allows a limited amount of static routing without electronic conversion. Upon arriving into a node, the signal travelling through a fiber is de-multiplexed into its composing wavelengths. Thanks to that, each wavelength channel can be treated independently: some of them are converted into electronic format for local treatment or for traditional routing while some other wavelengths are relayed through an internal fiber directly to an output fiber for retransmission. As such, it is possible to set up a lightpath where all intermediate nodes are transparent to it. It is in the traffic handling techniques, including multiplexing and conversion, that the grooming acquires its deep meaning and importance. This mechanism can be viewed in the node represented in Figure 7, [21], where there are two elements, laser and photodiode, necessary for the correct usage of grooming. Services are mapped to a trans-/muxponder at the ingress of the network, and then routed all-optically through intermediate ROADM/OXC devices, and recovered at the egress using another trans-/muxponder. This combination provides a point-to-point E2E wavelength connection across the network, with no intermediate O-E-O conversion, unless regeneration of the signal is required due to TR limitations. Wavelengths are routed and switched between their source and destination points using all-optical ROADMs or OXCs, with no capability to provide electronic switching at intermediate nodes within the core of the network. The ROADM solution realizes reconfiguration of wavelengths by blocking or cross-connecting of wavelengths. This ensures that the static distribution of the wavelength resource is flexible and dynamic. These devices can remotely and dynamically adjust the status of wavelength adding/dropping and passing through but they cannot perform subwavelength service grooming within and between wavelengths. Any re-grooming of traffic inside the network requires the termination and demultiplexing of wavelengths into their constituent client signals and grooming between trans-/muxponder ports, [21].

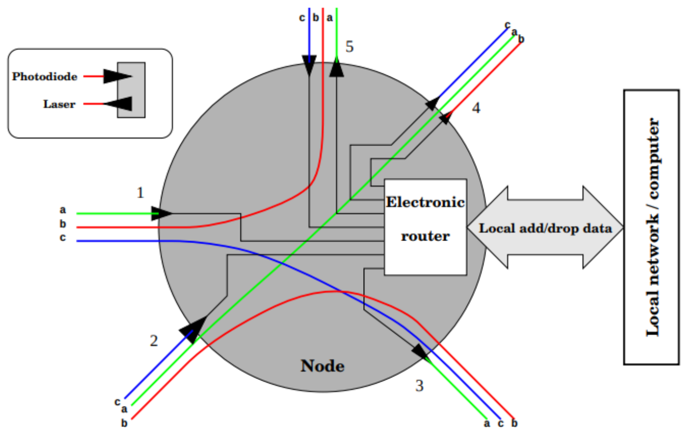

Figure 7 Traffic grooming operation inside a node, [27].

As already mentioned, grooming is an operation that multiplexes low-speed traffic connections onto high-capacity circuit pipes. This operation can only be done in the electrical domain, which implies that we can only groom connections either at the source of a demand or at an O-E-O regeneration site of a demand, the only two places where the signal reverts to its electrical form. Such a constraint imposes that wavelength channel availability must be carefully accounted for the established lightpaths in order to account for feasible grooming opportunities. Regenerators perform an important role when employing grooming because they do not only do the operations of Re-amplification, Re-shaping, Re-timing (3R), but they also allow for wavelength conversion otherwise unavailable to transparent lightpaths. Without conversion equipment, lightpaths must be assigned to distinct channels or wavelengths referred to as a distinct channel assignment (DCA), constraint that, combined with the wavelength-capacity constraint, leads to channel conflict and contention resulting in misallocation of bandwidth capacity and limitations on wavelength reuse. Grooming in this context attempts to better utilize the wavelength capacities. To better understand traffic grooming, we propose an example. In Figure 8, we can see a simple network topology composed of six nodes connected by links transporting three lightpath flows. Each of them, with an associated wavelength, contains a certain number of client flows that have to be served.

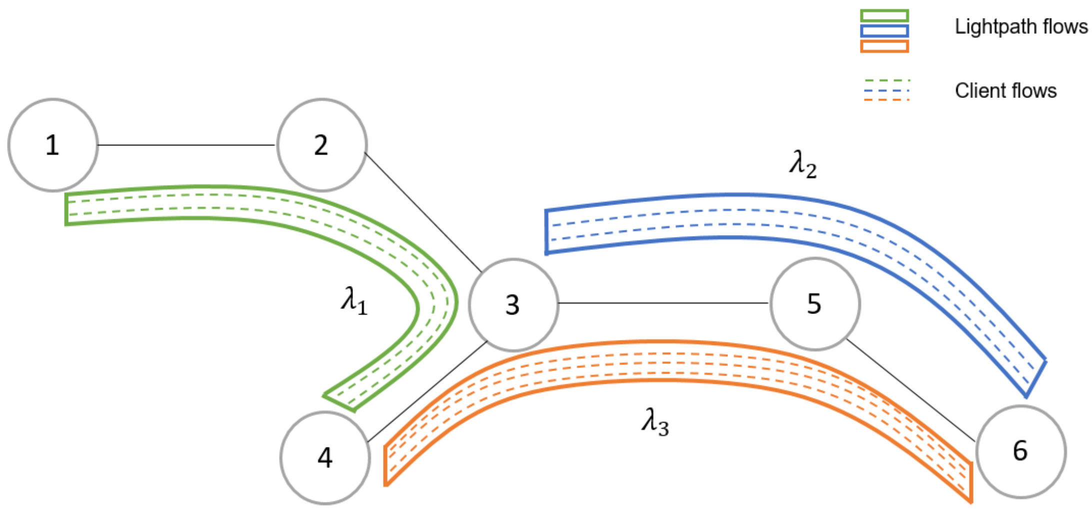

Figure 8 Network topology and flows associated to the links.

Traffic grooming can be performed E2E in such scenario in order to enhance the channel utilization in the optical network. The E2E traffic grooming mechanism multiplexes the low-rate traffic requests that have the same source-destination pair onto a high-rate lightpath.

Nevertheless, traffic grooming opportunities are limited to traffic flows sharing the same source and destination while being routed over the same physical path, reducing the benefits introduced by grooming. With the introduction of regenerators, and as a consequence, additional points of O-E-O conversion, more exotic grooming combinations can be performed, allowing traffic of different sources and destinations to be multiplexed together, hence employing better the available optical spectrum. To exemplify this phenomenon, let us assume that node 3 in the previous network is now equipped with regeneration capabilities (see Figure 9). To obtain a better usage of resources, the orange lightpath, if it has enough capability, can share its resources by adding into itself the green client flows to transmit over the link connecting node 3 to node 4 and converting its wavelength λ_1 to wavelength λ_3 . The same could happen with the blue lightpath: its client flows can be groomed together with the orange path from node 6 to node 3 converting λ_2 to λ_3, while the orange client flows continue to travel over the network to reach the destination node. Such possible scenario is depicted in Figure 9.

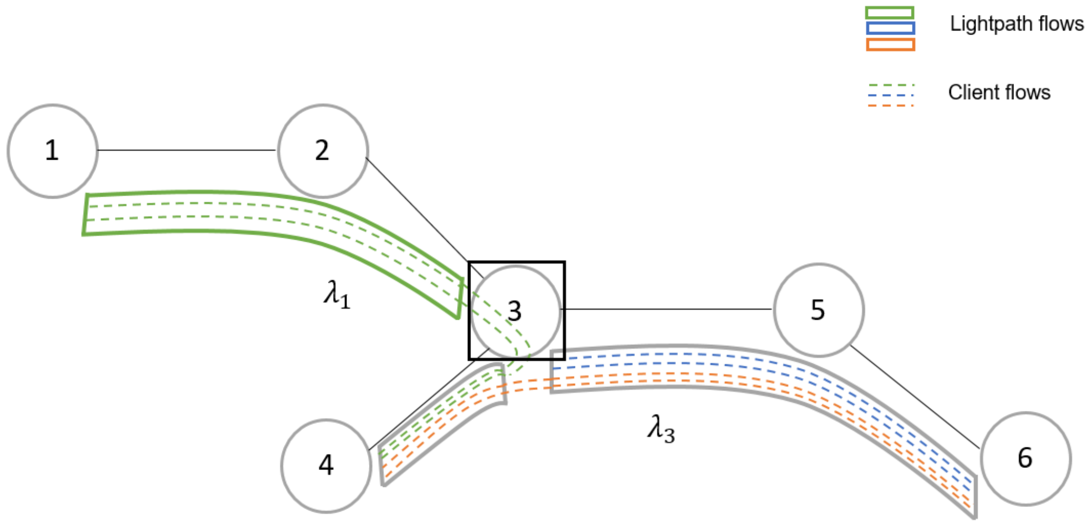

Figure 9 Network flows exploiting grooming and regenerator equipment.

As conclusion, the efficient placement of regenerators and electronic grooming equipment at optical nodes for a given network topology allows for a better support of traffic demands in the network, reducing the number of employed optical channels. As shown in [22], the optimal joint placement of regenerator and grooming allows minimizing the network design cost when compared with cases in which regeneration placement and traffic grooming stages are tackled independently. Given this feature, the following sub-section presents the optimization problem under study, which considers joint regenerator placement and grooming to compensate the TR penalties introduced by disaggregated optical networks in aims to minimize the number of regenerators needed.

5 PROBLEM STATEMENT

The problem of providing routes to lightpath requests and assigning a wavelength on each of the links along the path in optical networks is called the routing and wavelength assignment (RWA) problem. RWA is one of the main problems in WDM optical networks. Moreover, in transparent WDM networks, data is transmitted from its source to its destination in optical form, without experiencing any optical-to-electrical and electrical-to-optical conversion. Transparent optical channels should allow E2E communications regardless of bit rates, signal formats and modulation type. Nevertheless, optical signals encounter some impairments as they are switched, multiplexed and amplified along its route during propagation. Due to these impairments, the distance that an optical signal can propagate while satisfying the QoT requirements is limited. This distance is called the TR. Consequently, an optical signal has to be regenerated in order to go beyond this limit distance. Regenerators are used to regenerate the optical signal by converting it to an electrical signal, regenerating the electrical signal and then converting it back to an optical signal, with the possibility of provide wavelength conversion that results in an effectively reduction of wavelength collisions, thereby improving wavelength resource utilization. This process, O-E-O conversion, enables the optical signal to reach long distances; however, it is expensive due to power consumption, high equipment and maintenance costs of the regenerators. Therefore, the need of minimize the number of regenerators for optimally balancing the overall cost and the quality of the connections to be established is required. The optimization problem of regenerators placements and the minimization of the number of them is named regenerators placement problem (RPP). More than that, due to the disaggregated model, the degradation of the network leads to have a shorter TR that is translated in having a higher number of regenerator nodes. This problem can be smoothed by using the traffic grooming operation that has to be addressed in the proper way.

The aim of this work, and of the network designers, is to optimize the resource allocations in this kind of scenario because of the CapEX and OpEX of the regenerators, considering the grooming approach in disaggregated optical networks.

In this section we state the grooming, routing and wavelength assignment (GRWA) problem combined with the RPP. The objective of the optimization problem is to find the optimal number and location of the regenerator nodes, when they are needed, by addressing the traffic grooming operation, to allocate the incoming demands according to the current resources state. With this in mind, the considered optimization problem can be formally stated as:

Given:

1. an optical network represented by the direct graph $G = (N, E)$, where *N* represents the set of network nodes and $E = \{(i,j),(j,i) : i,j \in N, i \neq j\}$ is the set of edges. For each edge, we use o_e notation to represent the origin node of such link and t_e for the termination node; moreover, for each edge, the parameter denoted as l_e represents the physical length of such link.

2. a set of wavelength channel W per physical link. The size of the assumed set is considered to be enough to allow for the allocation of all traffic demands. The capacity of a wavelength channel has been denoted as C. Therefore, a non-blocking scenario is considered, putting the aim of the optimization problem on the planning of the regenerators.

3. a set of incoming demands D. Each demand $d \in D$ is represented by the tuple (o_d, t_d, b_d), where o_d represents the origin node of demand *d*, t_d is the destination node of demand *d* and b_d is the bit-rate of traffic demand *d*.

4. a set of incoming links to the node $n \in N$, that is denoted as δ_n^-.

5. a set of outgoing links to the node $n \in N$, that is denoted as δ_n^+.

6. the transmission reach of optical signals without regeneration, *TR*.

Find the regenerator locations considering traffic grooming for the incoming demands subject to the following *constraints*:

1. *flow conservation*: for each demand and node, the sum of the inflow at that node must be equal to the sum of the flow out of the node. The flow conservation constraint is valid for nodes other than the source and termination nodes.

2. *flow non*-bifurcation: we want to ensure to route the commodities so that each commodity follows a single path.

3. *capacity constraint*: the sum of the bit-rates of traffic demands allocated into a particular wavelength channel over a specific physical link must not exceed the capacity of the optical channel, also when we groom multiple signals into it.

4. *wavelength continuity constraint*: the allocated wavelength for the lighpaths must remain the same between points of O-E-O conversion,

that is, between source and a regenerator, between two regenerators, or between a regenerator and the destination of a lightpath. Wavelength conversion capabilities may be exploited at regenerator nodes.

5. *wavelength capacity constraint*: in order to being able to transport an optical signal, we must ensure that the capacity of the employed wavelength is sufficient to accommodate the traffic demand.

6. *transmission reach constraint*: the problem of degradation of the signal has to be solved by using regenerators. Each of them is placed in the exact location where the *TR* limit is exceeded due to a requested demand that the lightpath established, or the edge composing it, is longer than this limit distance.

7. *traffic grooming constraint*: traffic demands can only be groomed at points of O-E-O conversion, that is, either at their source node or at intermediate regenerator nodes.

with the *objective* to minimize the number of regenerators in the network.

In the following sections, we introduce two solutions for optimally tackling the presented optimization problem: an Integer Linear Programming (ILP)-based algorithm and a heuristic-based algorithm for the scenarios in which the scalability of the ILP may be challenged.

5.1 ILP-BASED ALGORITHM

In this section the proposed ILP algorithm to optimally address the problem previously explained is introduced. The ILP-based mechanism proposed has been formulated by using the decision variables introduced below:

$x_{d,e,w}$ Binary; 1 if traffic demand d ∈ D employs physical link e ∈ E and wavelength w ∈ W; 0 otherwise.

$v_{d,n,w}$ Positive real; denotes the distance of node n ∈ N from the last regenerator (or from the source) for wavelength channel w ∈ W and traffic demand d ∈ D.

$r_{n,w}$ Binary; 1 if network node $n \in N$ is equipped with a regenerator for wavelength channel w ∈ W, 0 otherwise.

$z_{d,n,e,w}$ Positive real; variable used for the linearization procedure.

The ILP formulation proposed is detailed in what follows:

$$(1)\quad minimize \sum_{n\in N}\sum_{w\in W} r_{n,w} + \varepsilon \sum_{d\in D}\sum_{e\in E}\sum_{w\in W} x_{d,e,w}$$

subject to

$$(2)\quad \sum_{e\in\delta_n^+}\sum_{w\in W} x_{d,e,w} - \sum_{e\in\delta_n^-}\sum_{w\in W} x_{d,e,w} = \begin{cases} 1, & if\ n = o_d \\ -1, & if\ n = t_d\ , \\ 0, & otherwise \end{cases} \qquad \forall\ d \in D, n \in N$$

$$(3)\quad \sum_{d\in D} b_d x_{d,e,w} \leq C,\quad \forall\ e \in E, w \in W$$

$$(4)\quad v_{d,n,w} = 0\ ,\qquad \forall\ d \in D, n \in N, w \in W, n \neq o_d, t_d$$

$$(5)\quad v_{d,o_e,w} + l_e x_{d,e,w} \leq TR\ ,\quad \forall\ d \in D, e \in E, w \in W$$

$$(6)\quad v_{d,n,w} \leq TR\big(1 - r_{n,w}\big),\qquad \forall\ d \in D, n \in N, w \in W, n \neq o_d, t_d$$

$$(7)\quad v_{d,n,w} \leq \sum_{e\in\delta_n^-}\big(z_{d,n,o_e,w} + l_e x_{d,e,w}\big)\ ,\qquad \forall\ d \in D, n \in N, w \in W, n \neq o_d, t_d$$

$$(8)\quad v_{d,n,w} \leq \Big(\sum_{e\in\delta_n^-}\big(z_{d,n,o_e,w} + l_e x_{d,e,w}\big)\Big) - r_{n,w}TR\ , \qquad \forall\ d \in D, n \in N, w \in W, n \neq o_d, t_d$$

(9) $$-r_{n,w} \leq \sum_{e \in \delta_n^+} x_{d,e,w} - \sum_{e \in \delta_n^-} x_{d,e,w} \leq r_{n,w} \ , \quad \forall\ d \in D, n \in N, w \in W, n \neq o_d, t_d$$

(10) $$z_{d,n,e,w} \leq TR\, x_{d,e,w} \ , \qquad \forall\ d \in D, n \in N, w \in W, e \in \delta_n^-\ n \neq o_d, t_d$$

(11) $$z_{d,n,e,w} \leq v_{d,e,w} \ , \qquad \forall\ d \in D, n \in N, w \in W, e \in E$$

(12) $$z_{d,n,e,w} \leq v_{d,e,w} + TR\big(x_{d,e,w} - 1\big) \, , \qquad \forall\ d \in D, n \in N, e \in E, w \in W$$

(13) $$x_{d,e,w} + x_{d',e,w} \begin{cases} \leq 2, \ if\ o_d = o_{d'}\ and\ t_d = t_{d'} \\ \leq r_{o_e,w} + 1, \ if\ o_d \neq o_{d'}\ and\ t_d \neq t_{d'}\ or \\ \quad if\ o_d = o_{d'}\ and\ t_d \neq t_{d'}\ or \\ \quad if\ o_d \neq o_{d'}\ and\ t_d = t_{d'} \\ \leq r_{t_e,w} + 1, \ if\ o_d \neq o_{d'}\ and\ t_d \neq t_{d'}\ or \\ \quad if\ o_d = o_{d'}\ and\ t_d \neq t_{d'} \end{cases} \quad \forall\ d, d' \in D, w \in W, d \neq d'$$

Objective function (1) aims to minimize the number of regenerators to be placed in the network, as shown in the first term. The additional term is considered to avoid unnecessary traffic allocations due to the sides effects of the flow conservation constraint, with ϵ<<1. Constraint (2) is the flow conservation constraint for each of the traffic demands, also avoiding the bifurcation of the flow (i.e. a traffic demand will only be assigned with a single E2E physical path). Constraint (3) is the capacity constraint, that is, the total bit-rate of the demands employing a specific wavelength in a physical link should be equal or smaller than the wavelength capacity. Constraints (4)-(8) serve to properly account for the TR of optical signals, depending on the presence of regenerators along the path, that is, to give a proper value to variables $v_{d,n,w}$. Lastly, constraint (9) restricts the wavelength continuity constraint to intermediate nodes that do not have regeneration capabilities for the specific wavelength channel. That is, if a node is not a regenerator, all optical signals bypassing the node must maintain the same wavelength channel at the node input as well as at the node output.

On the other hand, if the node is a regenerator, wavelength conversion capabilities may be exploited. In the formulation of the problem came out some non-linear constraints that have been linearized by the use of a binary variable that leads us to obtain the constraints (10)-(12). The last set of constraints, (13), ensures the right allocation of grooming. This operation can only be done in the electrical domain, which implies that we can only perform such operation either at the source of a demand or at an O-E-O regeneration site of a demand, which are the only two places where the signal reverts to its electrical form.

5.2 HEURISTIC-BASED ALGORITHM

In this section we introduce a heuristic approach in order to solve our GRWA problem combined with the RPP. It has been widely demonstrated in literature that the regenerator placement problem is NP-complete [23] as well as the GRWA problem [24]. It means that our case study belongs to the class of NP-complete problems that are the hardest in the NP: as the size of the problem grows the time required to solve the problem using any known algorithm increases rapidly. For this reason, the ILP becomes computationally intractable for large problem instances and we need some heuristic to solve our problem effectively. Our heuristic is based on a greedy iterative mechanism that makes every iteration an optimal choice, from a set of pre-calculated set of candidate solutions, which in our case are the paths. Next, the updating of the candidate solution elements and, subsequently, the mechanism then proceeds with the next iteration until the paths are fully assigned or the candidate set is empty. Let us define a new set representing the candidate set P, being p an element belonging to this set. Every element of P is the shortest path between a pair of nodes in the network. Every time we want to take a decision and assign the resource to accomplish the traffic demands, we perform a check about the available resources and we update them each time a path is employed. Depending on the length of the edges, respecting all the constraints, regenerators are placed in a way so that their number is minimized. A short description of the algorithm is shown in the following pseudo-code to explain our problem that has been subdivided in two phases. This is done in order to better explain how we model the GRWA problem. At the beginning, in the first phase, the analysis of the Routing problem and then, in the second phase, we solve the Grooming and Wavelength Assignment problem. The first phase is the one where we build the shortest path and the second one involves the operations of resource allocation and updating and regenerator placement. We use a shortest-path first-fit algorithm. The two subproblems, resumed in the two phases, are solved sequentially: once the path set is built, lightpaths are created in order to allocate all the traffic demand requests and the wavelength assigned to them respecting all the resources allocation constraints. All the resources are tracked in each step so that, by checking that they are not exhausted, there is the ability to use traffic grooming and therefore better exploit lightpaths capability. During the second phase, regenerators are placed respecting the rules explained earlier in the text. In the following pseudo-code, the updating of the wavelength resources is referred to the updating of the wavelength status and capacity, after each operation that involves their usage and so that change their characteristics.

Inputs*: G, N, E, W, D, P, TR;* **Output***: Sol*

Phase 1: Pre-processing

P ← shortest paths set

Phase 2: Execution

for *d* = 0 to |*D*| **do**

P_d ← set of candidate paths

allocated = false

if $P_d \neq 0$ **then**

    for $p_d = 0$ to $|P_d|$ **do**

        if *remain_capacity* < *minimum_capacity* **then**

            set *remain_capacity* = *minimum_capacity*

        if *minimum_capacity* ≥ BR_d **then**

            for $l = 0$ to $|P_d|$ **do**

                add lightpath *l* to demand *d*

                update the capacity of p_d

                update wave_capacity

        allocated = true

    if allocated = true **then**

        for $e = 0$ to $|P_{d}\_links|$ **do**

            update *length* of link *e*

```
            if length = TR then
                if dest_link (e) ≠ dest_last_element (P_d) then
                    add regenerator to dest_link
                    set length to 0
            else if length > TR then
                add regenerator to source_link
                cost = length_link
    if reg_index = 0 then
        for w = 0 to |W| do
            set wave_status to true
        for l = 0 to |P_d_links| do
            for w = 0 to |W| do
                wave_status = wave_status & wave_status (l)
        for w = 0 to |W| do
            if wave_status = false then
                capacity = total_capacity − BR_d
                create lightpath
                add lightpath to P_d
                for e = 0 to |P_d_links| do
                    update wavelength status resources
    else
        create a subpath
        int r = 0
        for e = 0 to |P_d_links| do
            add link to subpath*
            if r < reg_index − 1 then
                if dest_link = reg_index (r) then
```

for w = 0 to |*W*| **do**
set wave_status to true
for s= 0 to |subpath*| **do**
for w = 0 to |*W*| **do**
wave_status = wave_status&wave_status (*l*)
for w = 0 to |*W*| **do**
if wave_status = false **then**
capacity = total_capacity $- BR_d$
create lightpath
add lightpath to P_d
for $s = 0$ to subpath* **do**
update wavelength status resources
if reg_index ⊂ subpath_source **then**
add regenerator to subpath_source
if reg_index ⊂ subpath_dest **then**
add regenerator to subpath_dest
r++
else
if dest_link = dest_P_d_link **then**
for w = 0 to |*W*| **do**
if wave_status = false **then**
capacity = total_capacity $- BR_d$
create lightpath
add lightpath to P_d
for $s = 0$ to subpath* **do**
update wavelength status resources
if reg_index ⊂ subpath_source **then**

```
                    add regenerator to subpath_source
                if reg_index ⊂ subpath_dest then
                    add regenerator to subpath_dest
            r++
end.
```

6 NETWORK SIMULATOR

In order to study the presented scenario and evaluated the introduced optimization techniques, a network simulator has been developed. The network simulator has been developed in Java Programming Language. The aim is to establish an E2E optical connection to serve a compendium of demands considering the network resources and constrictions: wavelength number and channel capacity are addressed in the proper way as well as the TR and grooming penalties are respected. As an output, the minimized number of regenerator used in the deployed simulation in different scenarios.

The CPLEX Optimizer program has been used to solve the ILP optimization problem. The following sections elaborate on the internal details of the simulator that allow for the representation of the optical network as well as the traffic demands that serve as foundation for the aforementioned optimization problem.

6.1 NETWORK TOPOLOGY

The network topology is generated by selecting a .txt file that contains the distances matrix of a specific network. Such matrix describes the existent links of the network and the relative distances associated to these edges.

The nodes are modelled so that each of these object stores the incoming and outgoing link connected to it as well as an identifier to locate it into the network itself.

The links objects are characterized by the respective source and destination nodes, a cost representing each physical length and a vector of wavelength that can be multiplexed (WDM links) and transported through each of the links.

The wavelength objects are described by a boolean variable used to indicate if a wavelength is used or not, by an indicator of its capacity and by an identifier as in the nodes case.

6.1.1 Events generation

The set of traffic demands is generated every time that the program is executed: the generation of each demand takes place randomly so source and destination nodes, as well as the rate of traffic demand are casually assigned; the number of demands can be set arbitrarily.

In the implementation of the ILP algorithm, the routing and resource allocation problem is performed by selecting all the possible paths in the network.

In the case of the heuristic, the shortest distance paths are calculated for each generated event. All the possible shortest paths are precomputed and then a list containing the candidate paths, connecting a given source-destination pair in the network with minimum total length/cost, is created. Several adjacent links to connect the source and destination nodes of the event, grouped together, form a path. It could happen at the same time that, in direction of the destination node, the links are grouped in different sub-path: if the cost (length) of the sub-path plus the cost (length) of the next adjacent link exceeds the TR boundary, the path is divided in several sub-path. This is done to avoid loss of connection every time that a lightpath routed through such path will require regeneration.

6.1.2 Input/output simulation parameters

In order to execute the simulations, the developed program accepts a list of input parameters that allow constructing the desired scenario. In particular, the input parameters are as described below:

Distance matrix: it is a square matrix containing the distances, taken pairwise, between the elements of the set of nodes, in km. Different network topologies can be used to create the scenario.

Demands set: it is the randomly generated set of demands that will be used in the execution.

Number of demands: represents the number of considered traffic demands to be allocated over the network.

Number of wavelengths: specifies the number of channels that can be multiplexed inside an optical link.

Capacity: the maximum capacity of the wavelength.

Transmission reach (TR): it is the maximum distance a lightpath can travel in an optical fiber without regeneration.

Besides the presented input parameters, the simulator generates as output a log file which contains relevant information in regards of the obtained results. More specifically, the file the time needed to solve each of the two proposed approaches (ILP and Heuristic), the number of regenerators placed in the network, with the associated wavelengths, and their exact position considering all the constraints and the objective function explained in the previous chapter. An optimality gap between the solutions obtained analyzing both cases is also obtained.

7 RESULTS AND DISCUSSION

In this section, we show the analysis of the results obtained by evaluating the behavior of our optimization model in different scenarios. A comparison between the ILP-based model and the Heuristic-based one is shown. The impact of the disaggregation model, which blocks demand due to the TR problem, is evaluated. Moreover, the proof of the importance of the regenerator placements in a disaggregated network is estimated also by the traffic grooming approach that makes the resource allocation more efficient.

7.1 NETWORK SIMULATION SCENARIOS

The evaluation of the results has been done by using a network having a simple topology composed by 8 nodes and 20 directed links. The length of such links is randomly produced (in a range between 400 and 600 km) and in average is equal to 488 km. The nodal degree is 2.5 and the topology of this basic network is shown in Figure 10.

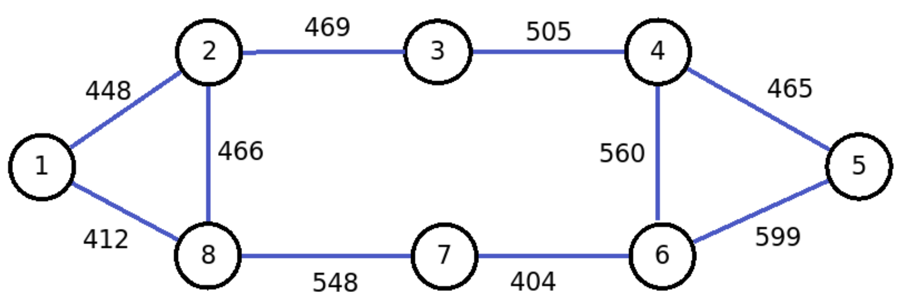

Figure 10 Simple network topology

In order to evaluate the performance of a network in a real environment, we employed three different kinds of networks: the Deutsche Telekom (DT), the British Telecom (BT) and the European Optical Network (EON) network, listed in ascending order of size.

The BT network, shown in Figure 11, has 22 nodes connected by 68 directional links. The average length of such links is 81 km, the average nodal degree is 3.09 and the diameter of the network is equal to 1026 km.

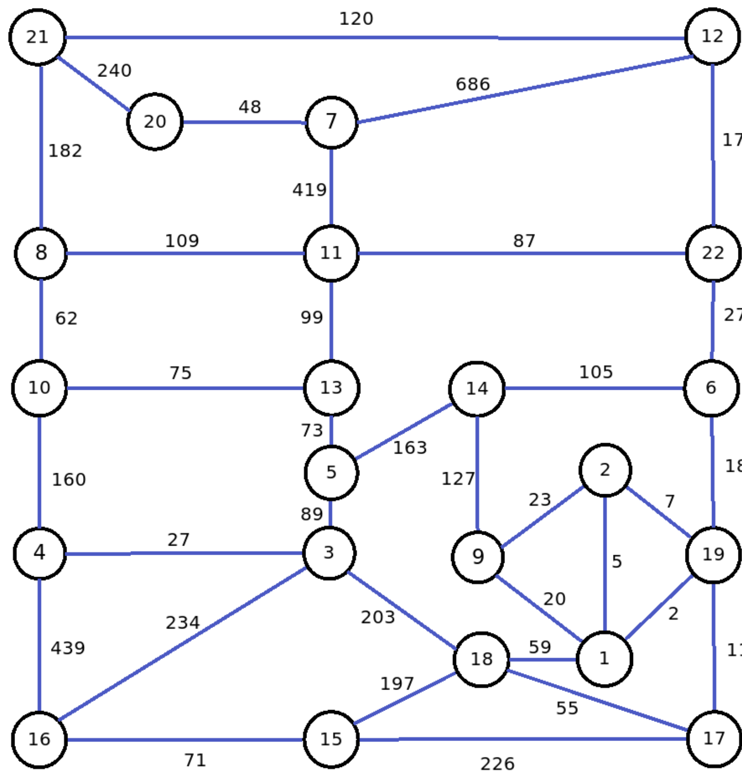

Figure 11 BT network topology

The DT network has a number of node equal to 12 connected by 40 directional links with an average link length of 243 km and a network diameter of 1019 km. The average nodal degree is 3.33. The topology of this network is represented in Figure 12, where on each edge the physical length of the link is represented.

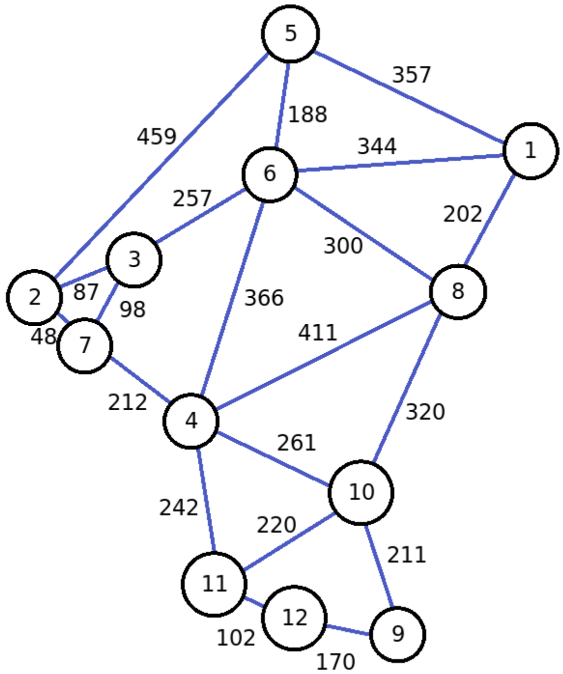

Figure 12 DT network topology

Our third choice is the EON that has a number of nodes equal to 16 and 24 edges. The average length of such links is 455 km, the average nodal degree is 1.6 and the network diameter is 1332 km. The topology of this network is depicted in Figure 13.

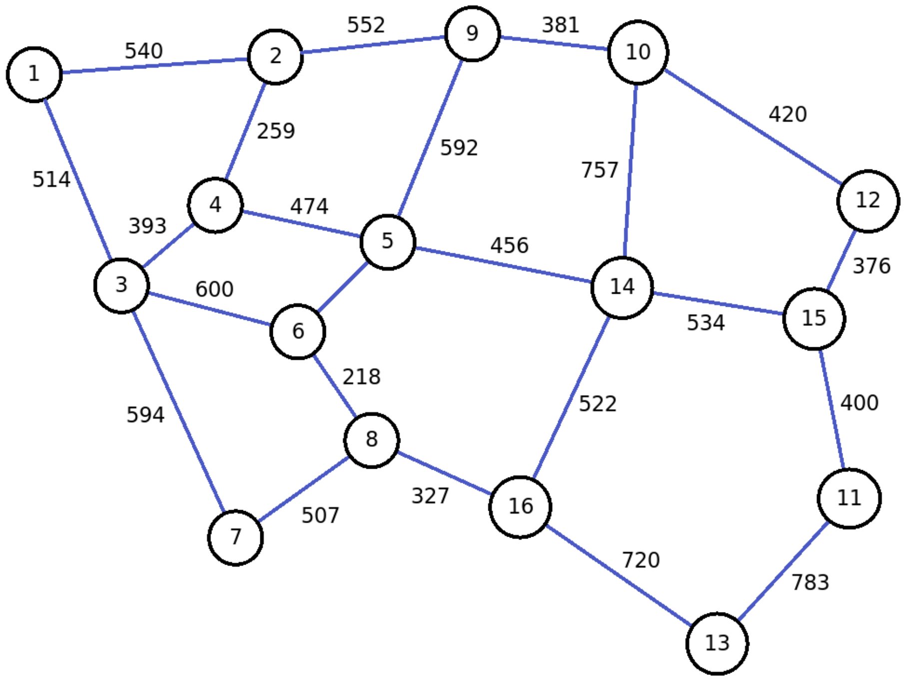

Figure 13 EON network topology

7.2 NETWORK SIMULATION RESULTS

The analysis of the results has been done in three steps: one simulation to evaluate the impact of the disaggregation model, one for the comparison between ILP-based model and the heuristic method and the last one for the regenerator placement problem with the use of traffic grooming. For all the simulations we chose the 400 Gb/s quadrature phase shifting key (QPSK) modulation format, for which the TR limit for each lightpath is equal to 1385 km. The sources and the destinations of traffic demands are uniformly distributed among the network nodes and the bit rate per demand ranges from 10 to 100 Gb/s in steps of 10.

7.2.1 Impact of disaggregation

In order to evaluate the impact of disaggregation we employed our heuristic method allocating from 100 to 1500 demands with a step of 100 and a number of 120 wavelengths. The number of repetition per data point is 500. In the first following set of results, the scenario does not take into account the regeneration process.

To effectively understand such impact in all the networks discussed in section 7.1, we assumed different level of penalties: 0%, 10%, 20%, 30% and 40%. The value of the penalty percentages is inflicted on the lightpaths' maximum propagation distance (e.g., a 10% penalty corresponds to a reduction of the TR limit to 1246.5 Km). When no penalty is applied (0%), the case of an integrated system is simulated. A comparison parameter is the blocked demand: the blockage is due to the incapacity of establishing a lightpath because of insufficient TR.

Figure 14 shows the impact of disaggregation in the BT network by relating the number of demands and the number of blocked ones, as we also show for the others analyzed networks. It can be noticed how the impact of disaggregation starts to appear when the penalty is equal to 30%, represented by the value of r equal to 0.7. Such value brings to have a number of 19 blocked demands when the number of requests is 1500; for 40% of penalty the disaggregation model has a more negative impact leading to have more than 100 blocked demands for the same number of requests of the previous case.

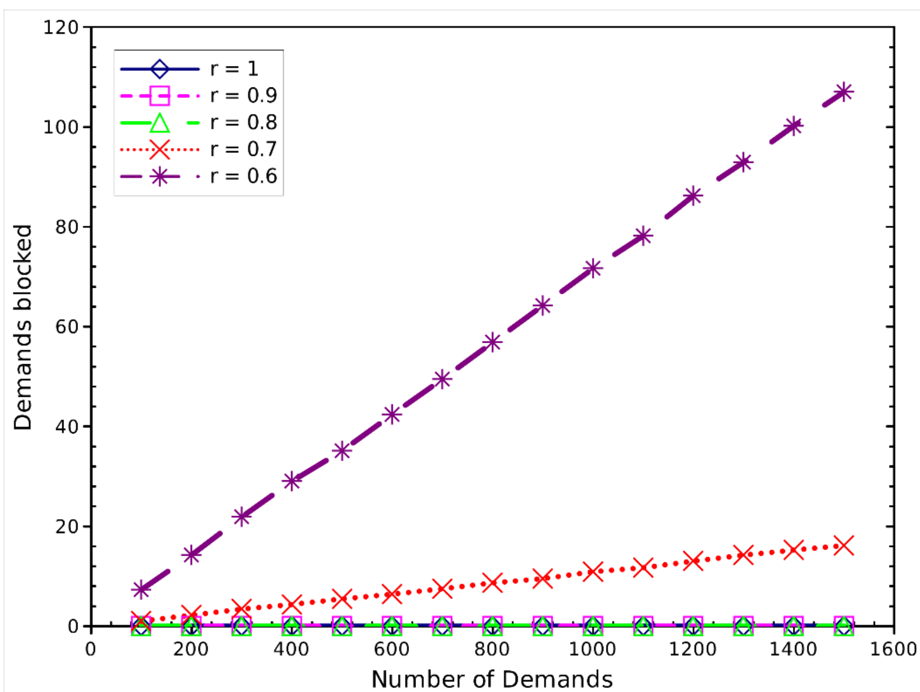

Figure 14 Impact of disaggregation in BT network

The same discussion can be done analyzing other scenarios: the DT network and the EON, shown in Figure 15 and 16, respectively.

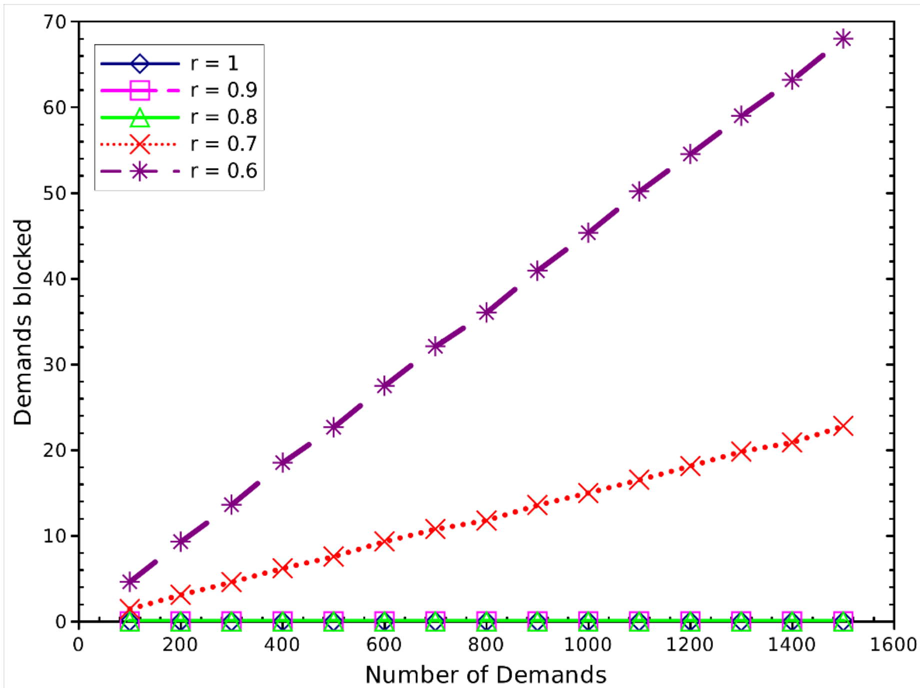

Figure 15 Impact of disaggregation in DT network

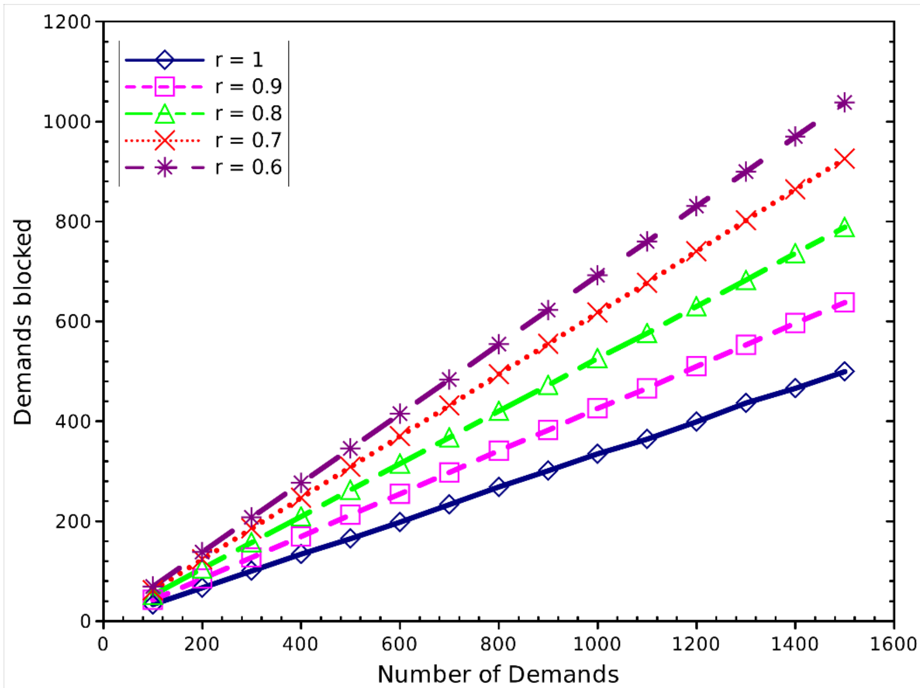

Figure 16 Impact of disaggregation in EON network

For the DT network we can notice a similar behavior to the one of the BT, where the disaggregation leads network's degradation starting from a penalty of 30%. A different result is obtained for the EON: the number of blocked demands starts being different than zero from 0% penalty, hence a degradation of the network also in an integrated scenario. Increasing the penalty has a significant negative effect on the experienced blocking: disaggregation needs the positioning of additional devices in order to maintain the correct fulfillment of the traffic demand requests.

The degradation of the performance in each network is a consequence of the fact that most of the lightpaths are blocked due to the TR condition: without signal regeneration, even though the wavelength resources are available, the lightpaths cannot reach their destination nodes. One potential solution to overcome such a problem is the utilization of regenerators at network nodes, allowing for the compensation of blocking due to TR problems. Even if the placement of regenerators represents one solution to overcome the network degradation due to the disaggregated model, they are costly devices and the network operators have to carefully plan their networks to keep their cost at acceptable levels, offering a good tradeoff between the increase of demand acceptance and the associated extra cost due to the regenerators. For this reason, in this work, the minimization of the number of regenerators is triggered to solve the TR restriction and traffic grooming is implemented to mitigate the network behavior under the disaggregated conditions, making the resource allocation more efficient.

7.2.2 ILP vs. Heuristic

For the comparison of the two proposed models in chapter 5, we set a number of demands equal to 50 and 10 wavelengths for the scenario shown in Figure 10. The number of repetitions per data point is 5. Table 1, shows a comparison between the ILP-based model and the Heuristic. In terms of execution time is very noticeable how better is the Heuristic method respect to the ILP: for this last method we need more than 12 hours to reach the optimal solution; on the contrary, the execution of the Heuristic ended in some milliseconds. The table also highlight the efficiency of the proposed Heuristic: the gap, in average, shows that the algorithm is not the best one but it reaches very good results, near to the optimal ones. For these reasons, the heuristic algorithm will be employed in order to evaluate the optimal regenerator placement in disaggregated optical networks and how this is affected by the different levels of penalties considered in the presented study.

Table 1 ILP vs Heuristic

	ILP		*Heuristic*		
r	**# Reg**	**Time (h)**	**# Reg**	**Time (ms)**	**Gap (%)**
1	4.8	>12	5.4	45.8	13
0.9	5.4	>12	6.4	39.6	18.86
0.7	7.9	>12	9.4	58	23.05
0.5	9.6	>12	12.2	75	27.02

We can also notice, from such table, the relation between *r*, representing the level of disaggregation in the network, and the number of regenerators. Decreasing the value of *r*, the number of regenerators increases, as we expected based on the study on the impact of the disaggregation model, shown in the sub-section 7.2.1.

7.2.3 Regenerator placement results

As we already mentioned, the ILP-based model becomes computationally intractable for large networks and we need some heuristic to solve the proposed problem. The aforementioned presented heuristic mechanism has been employed in our simulations to showcase the optimized number of regenerators in for the several considered network scenarios. These simulations have been done employing 120 wavelengths and allocating from 100 to 1500 demands with a step of 100, as we did for the study about the impact of disaggregation. The number of repetitions per data point is, in this case, equal to 500.

First, the analysis of the regenerators' placement in the relative small BT network is shown in Figure 17.

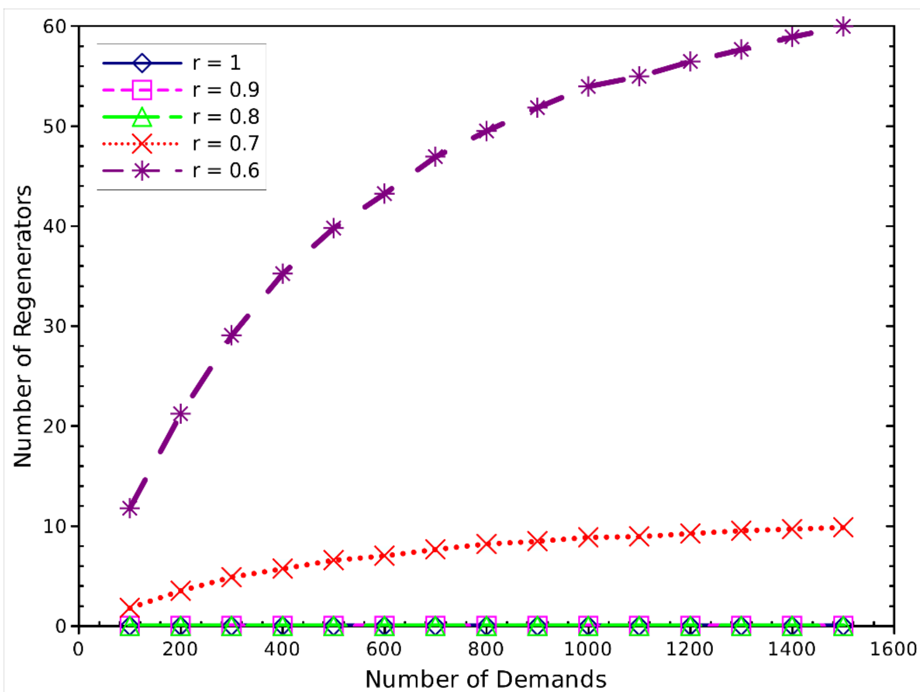

Figure 17 Regenerators in BT network

It can be appreciated that up to a value of r equal to 0.7 (i.e., penalty 30%) the effects of the disaggregation model are non-existent. As a consequence, we can notice that additional devices (i.e. regenerators) are not needed. Nevertheless, starting from this value, the reductions on the TR start to be noticeable, hence regenerators need to be deployed in the network in order to successfully allocate all traffic demands. For a 30% of penalty, we need 10 regenerators for 1500 demands to ensure that all the requested can be served and not anymore blocking due to the TR limit happens. With a higher value of r, equal to 0.6, in other words with a 60% penalty, the number of regenerators starts to increase up to approx. 60.

The simulation for the DT network is shown in Figure 18. For this medium size network the same conclusions in regards of the impact of disaggregation as in the BT network are reached, with slight differences in the number of allocated regenerators due to the differences on the network topology and average path length. Particularly, we obtain a number of regenerators equal to 8 for 30% of penalty and equal to 23 for r equal to 0.6, in the case of 1500 demand requests.

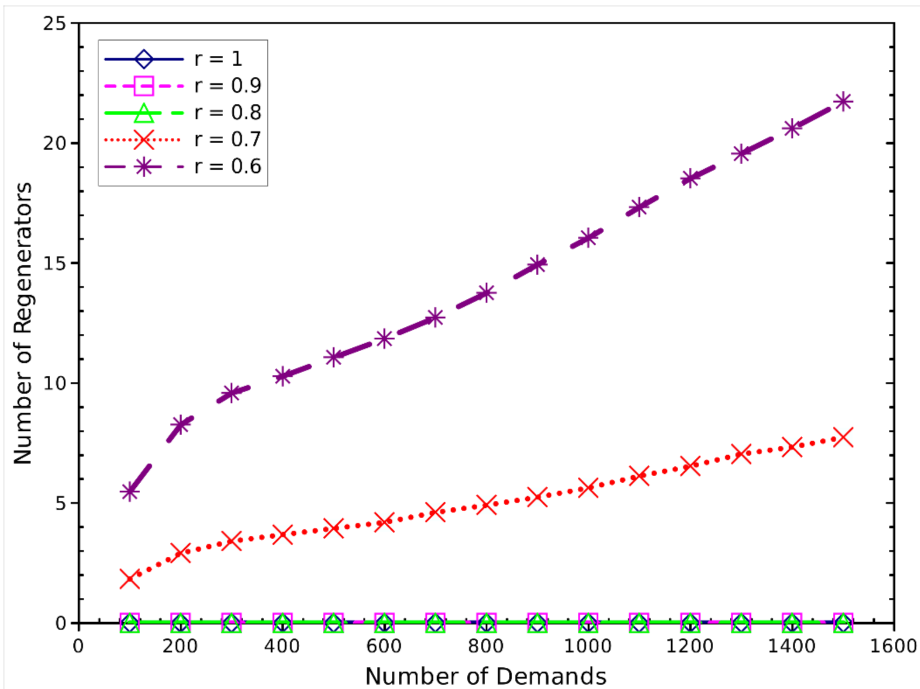

Figure 18 Regenerators in DT network

Figure 19 shows the results obtained for the EON network. For this kind of network, it is clear that the number of regenerators is different from zero starting from the case where no disaggregation is deployed. This is due to the fact that the distances between pair of nodes is larger than the ones that we have in other networks. The size of the network plays an important role in the regenerators placement problem: with a number of demands equal to 100 we still need approx. 40 regenerators in the case of no disaggregation (equal to zero in the previous cases), that is doubled when the level of penalty is maximum, 40%.

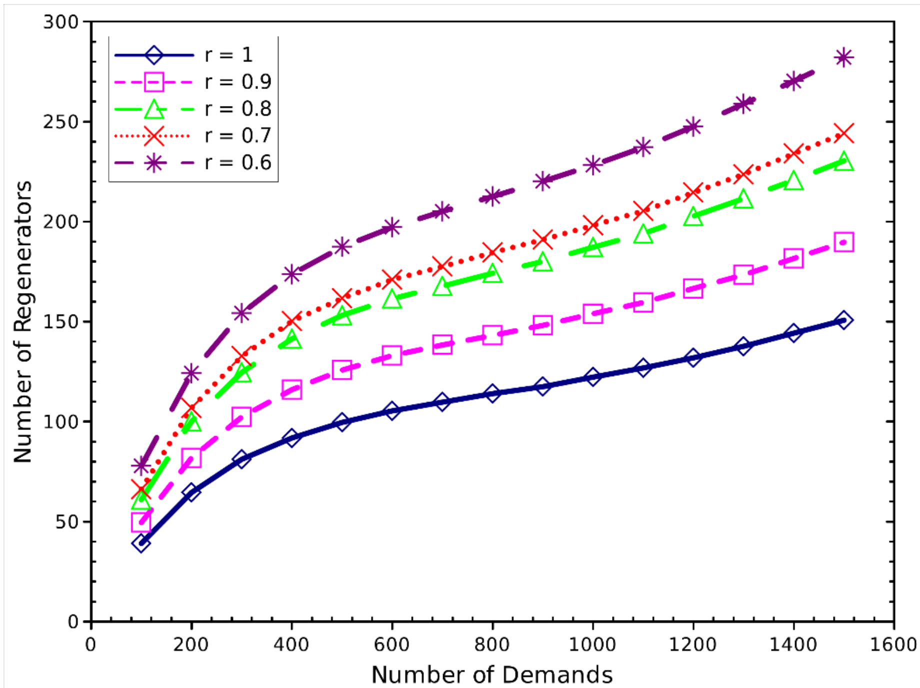

Figure 19 Regenerators in EON network

7.2.4 Traffic grooming enhancement

The following plots show another important result. We can see how the number of regenerator per allocated demand is not increasing as the number of demand increase, on the contrary it decrease. This is an important proof of the importance of the traffic grooming approach that leads to have a better resource allocation: with respect the number of allocated demands the increase of the number of regenerators is not linear, but has a more smooth behavior, as the curves evidences, highlighting that grooming allows for a graceful scalability on the number of regenerators. For this reason, the implementation of traffic grooming permits better performance in terms of costs, because we are reducing the number of additional devices, and in terms of energy consumption by direct consequence.

In the BT scenario, shown in Figure 20, we can see how the number of regenerator per allocated demand goes from roughly 0.1 for 100 demands to 0.04 for 1500 demands, in the case of r equal to 0.6.

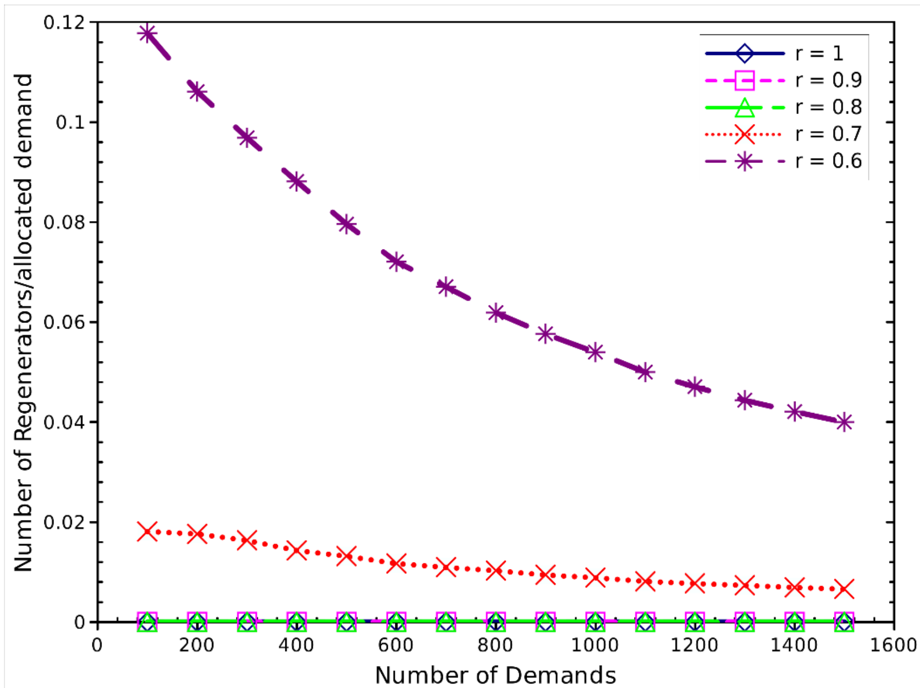

Figure 20 Traffic grooming effect in BT network

In the following, Figure 21 and 22 show the same behavior in the DT network and EON, respectively.

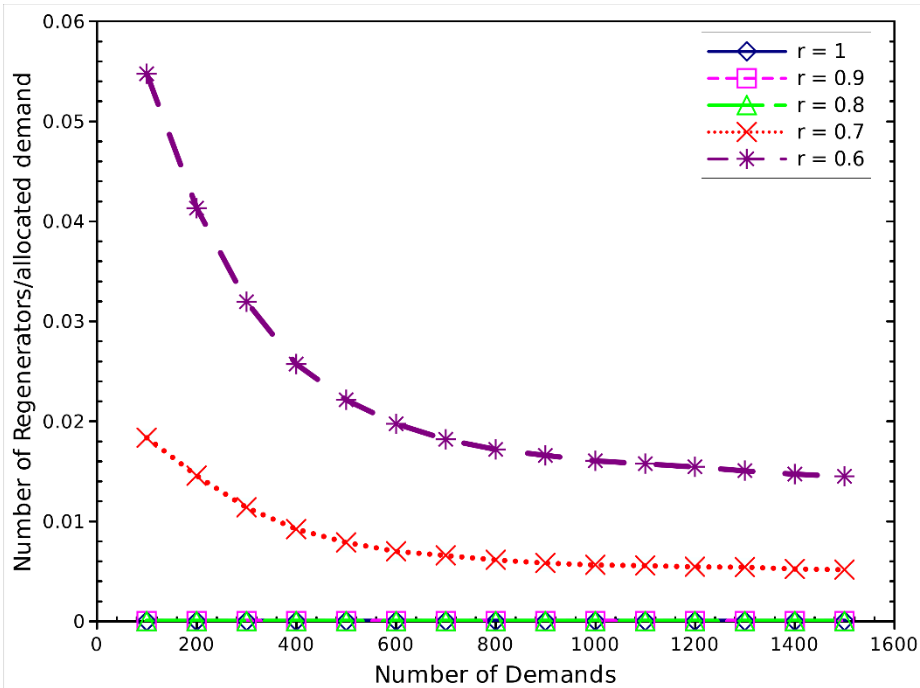

Figure 21 Traffic grooming effect in DT network

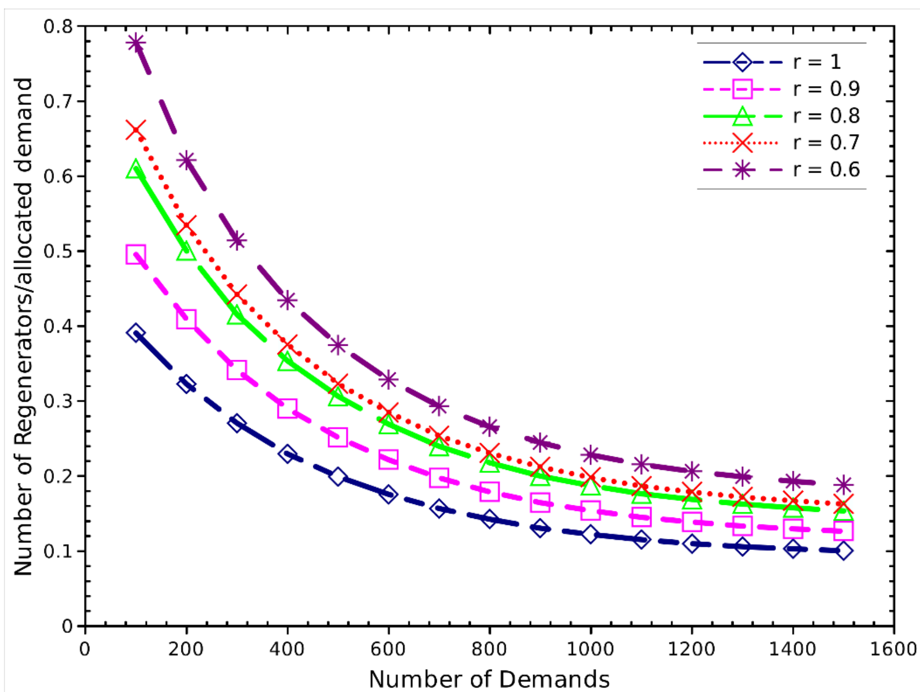

Figure 22 Traffic grooming effect in EON network

8 CONCLUSIONS AND FUTURE WORKS

Both service providers and network operators are moving towards a disaggregated-based approach in order to redesign current datacenter and networking architectures, to keep up with the constant bandwidth-hungry applications market's growth. The concept of disaggregation brings benefits in optical networks as well as challenges that have to be solved in order to maintain the network performances. It has been shown that disaggregation is a key-enabler for interoperability, vendor lock-in problem, flexibility, evolution boosting as well as innovation but, at the same time, may result in significant negative impacts in the network performance due to the additional power losses (when compared to optimized proprietary solutions) experimented in the disaggregated optical nodes. For different values of penalty, meaning that we can experiment different level of disaggregation in an optical network, it can be obtained different results and act on them in order to recover the integrity of the network quality. Different solutions can be adopted and one of them is to place regenerators as an advanced equipment able to recover the signal quality having the abilities to retime, reshape and regenerate it. Placing regenerators plus the use of the traffic grooming approach could make the network operators capable to better design the infrastructure avoiding blocking due to the disaggregation side-effects and to achieve a better resource usage.

Future works will serve to establish whether the positioning of additional devices, i.e. regenerators, can be a good choice also from an economic point of view. What will have to be done will be the understanding whether these special nodes can adversely affect the network economic balance or not. Moreover, and related to the last discussed point, a future work will focus on the study of the transponders allocation and minimization.

Sustainability considerations

Network infrastructures are usually energy and power-hungry. In this regard, disaggregation plays an important role: the common optical devices are mostly monitored by software, contributing to minimize the power consumption of the nodes; overprovisioning is prevented contributing to a further reduction of the energy consumption. However, it will be important to carefully take into account the additional energy consumption due to the placement of additional nodes, such as regenerators.

Ethical considerations

The disaggregation approach permits network operators and service providers to face with a world where the freedom of choice without vendor lock-in is possible. On such ecosystem multiple vendors, companies, organizations, and individuals can build on, contribute to, and certify against, working in a common open platform. This new scenario is not only disaggregating the hardware and software components of the network but also the industry: disaggregation enables the possibility to have a less centralized market, avoiding the appearance of monopolies in the monetary system.

ACRONYMS

AOS	Acousto-Optic Switch
API	Application Programming Interface
BT	British Telecom
CANDI	Converged Architectures for Network Disaggregation & Integration
CapEX	Capital Expenditure
CIMA	Controls, Information Models & APIs
DC	Data Center
DCA	Distinct Channel Assignment
DCN	Data Center Network
DCSG	Disaggregated Cell Site Gateways
DDC	Disaggregated Data Center
DNP	Disaggregated Network Platforms
DT	Deutsche Telekom
DWDM	Dense Wavelength Division Multiplexing
E2E	End-to-End
EMS	Execution Management System
EON	European Optical Network
FDM	Frequency-Division Multiplexing
GRWA	Grooming, Routing and Wavelength Assignment
ILP	Integer Linear Programming
NMS	Network Management System
OCM	Optical Channel Monitoring
ODTN	Open and Disaggregated Transport Networks
O-E-O	Optical-Electrical-Optical
OIF	Optical Internetworking Forum

OLS	Open Line System
OOPT	Open Optical & Packet Transport
OpEX	Operational Expenditure
OXC	Optical Cross-Connect
PSE	Physical Simulation Environment
QoS	Quality of Service
QoT	Quality of Transmission
QPSK	Quadrature Phase Shifting Keying
ROADM	Reconfigurable Optical Add and Drop Multiplexers
RPP	Regenerator Placement Problem
RU	Rack Units
RWA	Routing and Wavelength Assignment
SDM	Space-Division Multiplexing
SDN	Software Define Network
TIP	Telecom Infra Project
ToR	Top of the Rack
TR	Transmission Reach
TRN	Transponder
VM	Virtual Machine
VOA	Variable Optic Attenuators
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch
XaaS	Everything as a Service

References

[1] CISCO, "Cisco Visual Networking Index: Forecast and Trends.," 2017–2022. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html. [Accessed 2019].

[2] R. Rajiv, S. Kumar and S. Galen, Optical Networks, USA: Morgan Kaufmann Publishers, 2008.

[3] O.-O. I. Forum, "OIF," [Online]. Available: https://www.oiforum.com/. [Accessed June 2019].

[4] I. Corporation, "Infinera whitepaper. “Future-proof Open Line Systems for Cloud Scale Networks”.," USA, 2017.

[5] H. Adams, "Trends in Metro Optical Networks," March 2018.

[6] J. Santos, N. Costa and J. Pedro, "Cost-Effectiveness Assessment of Transport Networks based on Disaggregated Optical Plataforms," in *2017 Optical Fiber Communications Conference and Exhibition (OFC)*, Los Angeles (USA), January 2017.

[7] A. D. Papaioannou, R. Nejabati and D. Simeonidou, "The Benefits of a Disaggregated Data Centre: A Resource Allocation Approach.," *IEEE,* pp. 2-3, 2017.

[8] C. Yuxin, D. Marilet and L. W., "Resource Disaggregation Versus Integrated Servers in Data Centers: Impact of Internal Transmission Capacity Limitation," in *2018 European Conference on Optical Communication (ECOC)*, Rome (Italy), Semptember 2018.

[9] A. Pagès, J. Perellò, F. Agraz and S. Spadaro, "Optimal VDC Service Provisioning in Optically Interconnected Disaggregated Data Centers," *IEEE COMMUNICATIONS LETTERS,* vol. 20, no. 7, pp. 1353 - 1356, July 2016.

[10] Gao P. X., "Network Requirements for Resource Disaggregation," in *Proceedings of the 12th USENIX Symposium on Operating Systems*

Design and Implementation (OSDI ’16), Savannah (USA), November 2016.

[11] B. H. and P. Costa, "Bridging the Last Mile for Optical Switching in Data Centers," in *Optical Fiber Communication Conference 2018*, San Diego (USA), March 2018.

[12] K. Rundberget, ""OPEN” and its Impact on Engineering, Design, Operations and Profitability in the Communication Network," in *Optical Fiber Communication Conference*, San Diego (USA), March 2018.

[13] "Open ROADM MSA," 2015. [Online]. Available: http://www.openroadm.org/home.html. [Accessed 16 7 2019].

[14] C. J. Uniphase, "White Paper, “A Performance Comparison of WSS Switch Engine Technologies”," in *21st Iranian Conference on Electrical Engineering (ICEE)*, Mashad (IRAN), 2016.

[15] V. Abedifar, S. Shahkooh and A. Emami, "Design and simulation of a ROADM-based DWDM network," in *21st Iranian Conference on Electrical Engineering (ICEE)*, Mashad (Iran), May 2013.

[16] "PacketLight networks," [Online]. Available: https://www.packetlight.com/applications/roadm. [Accessed 27 06 2019].

[17] "Telecom Infra Project," 2016. [Online]. Available: https://telecominfraproject.com/. [Accessed 16 7 2019].

[18] O. N. F. (ONF), "Open Disaggregated Transport Network, information reference design," ONF, 2019.

[19] M. Dharmaweera, Y. Zhao and L. Yan, "Traffic-grooming- and multipath-routing-enabled Impairment-Aware Elastic Optical Nework," *Journal of Optical,* vol. 8, no. 2, pp. 58-70, 2016.

[20] K. Zhu and B. Mukherjee, "A Review of Traffic Grooming in WDM Optical Networks: Architectures and Challenges," *Optical Networks Magazine,* vol. 4, no. 2, pp. 55-64, 2003.

[21] M. Brunato and R. Battiti, "A Multistart Randomized Greedy Algorithm for Traffic Grooming on Mesh Logical Topologies," in *IFIP Advances in Information and Communication Technology*, vol. 114, New York (USA), Springer, 2012.

[22] A. N. Patel, C.Gao and J. P. Jue, "Traffic Grooming and Regenerator Placement in Impairment-Aware Optical WDM Networks," in *14th Conference on Optical Network Design and Modeling (ONDM)*, Kyoto, Japan, 2010.

[23] A. Sen, S. Murthy and S. Bandyopadhyay, "On Sparse Placement of Regenerator Nodes in Translucent Optical Networks," *IEEE,* pp. 1-2, 2018.

[24] O. Awwad, A. Al-Fuqaha and A. Rayes, "Traffic grooming, routing, and wavelength assignment in WDM transport networks with sparse grooming resources," *Computer Communications,* vol. 30, no. 18, pp. 3508-3524, 2007.

[25] J. Perelló, J. M. Gené, A. Pagès, J. A. Lazaro and S. Spadaro, "Flex-Grid/SDM Backbone Network Design with Inter-Core XT-limited Transmission Reach," *IEEE/OSA Journal of Optical Communications and Networking (JOCN),* vol. 8, no. 8, pp. 540 - 552, August 2016.

[26] K. Oluwatoyin, A. Odunola and A. Yusuph, "Grooming Telecommunications Network: Optimization Replicas and Techniques," April 2019.