Universidade Federal do Espírito Santo - UFES
Programa de Pós-Graduação em Engenharia Elétrica
Telecomunicações

A Fairness-Focused Spectrum Assignment Algorithm For Elastic Optical Networks

RODRIGO STANGE TESSINARI

Supervisor: Prof. Dr. Anilton Salles Garcia
Universidade Federal do Espírito Santo - UFES

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Área de concentração: Telecomunicações

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Prof. Dr. Anilton Salles Garcia
Orientador

Prof. Dr. Hélio Waldman
Universidade Estadual de Campinas

Prof. Dr. Joberto Sérgio Barbosa Martins
Universidade Salvador

Prof. Dr. Leandro Colombi Resendo
Instituto Federal do Espírito Santo

Prof. Dr. Marcelo Eduardo Vieira Segatto
Universidade Federal do Espírito Santo

Profa. Dra. Marcia Helena Maria Paiva
Universidade Federal do Espírito Santo

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Dedico esta conquista aos meus pais.

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"... if you know what you are doing, don't do it." (Prof. Jeff Kimble)

Abstract

In the past few years, Elastic Optical Networking (EON) emerged as the next generation core network technology, intended to surpass Wavelength-Division Multiplexing (WDM) weaknesses and limitations. WDM is the most successful and widely used technology in the backbone of the optical networks. However, in recent years Internet traffic in the core network has been doubling almost every two years, and predictions indicate that it will continue to exhibit exponential growth due to emerging applications such as high-definition and real-time video communications.

To keep pace with the always greater demand for bandwidth, EON relies on Optical Orthogonal Frequency Division Multiplexing (OOFDM) and advanced modulation technologies which enhance spectral efficiency and flexibility. OOFDM allows the aggregation of multiple sub-carriers to form super-channels, thus changing the paradigm of the network from fixed-size WDM channels to variable-sized EON channels that can reduce spectrum waste up to 60%. EON presents several other benefits such as high spectral and energy efficiency and flexible bandwidth adaptation over time. Despite all benefits, no technology is perfect, and the added EON efficiency and flexibility comes at the price of increased complexity and new problems, such as spectrum fragmentation and service unfairness.

A considerable amount of work has been done on both fragmentation and unfairness problems, introducing a broad range of solutions, which raises the following question: "how to compare existent solutions and how to identify which one is better suited for the required scenario?" In this context, it is presented the first contribution of this Doctoral Thesis, ElasticO++, an Elastic Optical Network Simulation Framework for OMNeT++. ElasticO++ is a framework created to enable testing a whole range of routing, modulation, spectrum assignment, defragmentation algorithms, parameters, and topologies. At present, the proposed framework is the first software available capable of working with fragmentation and defragmentation in dynamic network scenarios. The flexibility offered on the proposed tool allows both academia and industry to develop new algorithms and techniques for Elastic Optical Networks.

The second contribution of this Doctoral Thesis is the Zone-Based Spectrum Assignment Algorithm. The proposed algorithm is an attempt to solve the unfairness and fragmentation problems, taking advantage of the spectrum management concept. In this Doctoral Thesis, it is presented two versions of the technique: the static version and the dynamic version. The static version is intended to be used in cases where the information regarding the nature of the network traffic is known beforehand, whereas the dynamic version was developed as a solution in cases in which absolutely no information is known.

Keywords: EON, RMSA, Spectrum Allocation, Spectrum Defragmentation, Simulation, OMNeT++, Framework.

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List of abbreviations and acronyms

BBR	Bitrate Blocking Rate
CAPEX	Capital Expense
CS	Complete Sharing
CSV	Comma-Separated Values
DP	Dedicated Partition
DP-QPSK	Dual-Polarization Quadrature Phase Shift Keying
DZB	Dynamic Zone-Based Spectrum Assignment Algorithm
ElasticO++	Elastic Optical Network Simulation Framework for OMNeT++
EON	Elastic Optical Networks
FF	First Fit
GUI	Graphical User Interface
ILP	Integer Linear Programming
KSP	K-Shortest Paths
MBB	Make-Before-Break
NC	No Constraints
NED	NEtwork Description Language
NP-Hard	Non-deterministic Polynomial-time Hard
OFDM	Orthogonal Frequency-Division Multiplexing
OMNeT++	Objective Modular Network Testbed in C++
OOFDM	Optical Orthogonal Frequency Division Multiplexing
QPSK	Quadrature Phase Shift Keying
PCE	Path Computation Element
PSP	Partial-Sharing-Partitioning
QAM	Quadrature Amplitude Modulation

RBR	Requests Blocking Rate
RMSA	Routing, Modulation, and Spectrum Assignment
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RSA	Routing and Spectrum Assignment
RWA	Routing and Wavelength Assignment
SA	Spectrum Assignment
SDN	Software Defined Networking
SNR	Signal-to-Noise Ratio
SP	Simple Spectrum Partition
SS	Spectrum Sharing
SZB	Static Zone-Based Spectrum Assignment algorithm
WDM	Wavelength Division Multiplexing
XML	Extensible Markup Language
ZB	Zone-Based

Contents

1 Introduction

In the past few years, Elastic Optical Networking (EON) emerged as the “next generation” core network technology (16, 17, 18), intended to surpass Wavelength-Division Multiplexing (WDM) weaknesses and limitations (19, 20, 2). WDM is the most successful and widely used technology in the backbone of the optical networks. However, in recent years Internet traffic in the core network has been doubling almost every two years, and predictions indicate that it will continue to exhibit exponential growth due to emerging applications such as high-definition and real-time video communications (16).

Traditional WDM-based networks offer the possibility to establish rigid connections (wavelengths) at fixed rates, using optical channels modulated with a fixed modulation format and spaced at a 50 GHz fixed grid. As a result, the process of upgrading/modifying the network to adapt to changing traffic and network conditions becomes challenging (1, 19, 20, 2).

In contrast, EON relies on Optical Orthogonal Frequency Division Multiplexing (OOFDM) and advanced modulation technologies that enhance spectral efficiency and flexibility (16, 2, 21). OOFDM allows the aggregation of multiple sub-carriers to form super-channels. Through this aggregation, it is possible to ignore the guard band (i.e., a spectrum range used to protect neighbor channels from interference) between sub-carriers, thus changing the paradigm of the network from fixed-size WDM channels to variable-sized EON channels that can reduce spectrum waste up to 60% (22).

Elastic Optical Networking concepts have been firstly introduced by (19, 22) to improve flexibility. The term “elastic” refers to this ability of the network to adjust its resources dynamically, according to the requirements of each connection. With EON it is possible to use the optical spectrum with a finer granularity and in a more flexible way than WDM, by creating “elastic channels”; i.e., that can accommodate both “sub-” and “super-” wavelength channels according to each requested demand. By adjusting the spectrum assigned to a demand for its needs, EON has the potential to improve the overall network capacity, regarding resource utilization. In addition, EON presents several other benefits such as high spectral and energy efficiency and elastic over time bandwidth variation (19, 22, 23). In consequence of all those advantages, Elastic Optical Network is being considered as the technology for upgrading WDM networks (24, 17, 18).

Although several works have pointed EON benefits (19, 22), no technology is perfect, and the added efficiency and flexibility comes at the price of increased complexity and new problems, such as spectrum fragmentation losses (11, 25) and service unfairness (11, 26).

Whenever entities with variable sizes start to coexist in the same environment, fragmentation losses are introduced into the system. Two main strategies can be adopted to address the fragmentation loss problem: (i) prevent fragmentation before it happens (proactive behavior), or (ii) address fragmentation after its manifestation (reactive behavior). Proactive behavior is achieved with specific assignment algorithms (27, 28), whereas reactive behavior is accomplished in this context by defragmentation algorithms (7). In the other hand, Spectrum management techniques are commonly used for solving the unfairness problem. Usually, the spectrum is divided into partitions, where only services with similar characteristics can coexist. Several works have studied different forms of spectrum partition, including based on the class of services (14), by filtering requests by distance (12), or by using non-linear programming for optimizing the partitions sizes (11).

In this context, we present the Zone-Based Spectrum Assignment algorithm, an algorithm created to address both fragmentation and unfairness simultaneously. The former is dealt with by simply preventing it from happening since fragmentation losses occur only in heterogeneous systems (29), thus by restricting services in a way that only services with same spectral requirements can coexist in the same partition, it is possible to assume that the system is reduced to a homogeneous system (11). The latter problem is addressed by paying particular attention to each partition delimitation, ensuring that each partition has a capacity compatible with the traffic pattern of the network (i.e., can accommodate the same maximum number of connections proportional to the traffic pattern at a given time). In this matter, the proposed Zone-Based Spectrum Assignment algorithm is fairness-focused spectrum assignment algorithm with a proactive behavior, capable of increasing fairness levels and mitigating the fragmentation losses. The algorithm and its tests are presented in Chapter 4.

A considerable amount of work has been done on both fragmentation and unfairness problems, introducing a broad range of solutions, which raises the following question: "how to compare existent solutions and how to identify which one is better suited for the required scenario?" Usually, this is done whenever a new algorithm or technique is proposed, by comparing the proposal to some simple, well-known solution (27, 30, 31, 10), or by a survey publication that usually brings a qualitative comparison (16, 1, 32, 33). A major problem with both approaches is the difficulty in comparing published algorithms, particularly because of different simulation scenarios (e.g., network topologies, simulation setup) and, not rarely, missing information regarding simulation/testbed setup or other "hidden assumption and parameter" (16, 1, 27, 30, 31, 10, 32).

In this context, we present ElasticO++: an Elastic Optical Network Simulation Framework for OMNeT++. A framework created to enable testing a whole range of routing, modulation, spectrum assignment, and defragmentation algorithms, parameters, and topologies. We believe this framework has the potential to become a useful tool to help other researchers in their research projects, especially newcomers. The framework provides a set of instruments that allow rapid implementation, testing, and analysis of new algorithms; and enables a common and well-controlled environment for comparing existing algorithms. In its current version, the framework comes with ten traditional algorithms already implemented, which can be used standalone or in combination with new ones. ElasticO++ description, architecture, and particularities are described in Chapter 3, in addition to a showcase scenario.

1.1 Objectives

This thesis aims to contribute to the elastic optical networks and network simulation areas. Its general objective is to investigate and propose a solution to reduce the impact of the unfairness problem in EON. Two specific objectives (SO) are defined to accomplish the general objective:

- **SO1**: The development of a Spectrum Assignment algorithm to address the unfairness problem in Elastic Optical Networks.
- **SO2**: The development of simulation software capable of assisting the development of new solutions related to Elastic Optical Networks and thus providing a fair environment for comparing algorithms.

1.2 Contributions

This Doctoral Thesis presents the following contributions:

- Two new spectrum assignment algorithms, one for when the traffic pattern is known (Static Zone-Based Spectrum Assignment algorithm), and another one for more broad and dynamic scenarios, usable even when no information regarding the traffic pattern is available (Dynamic Zone-Based Spectrum Assignment algorithm).
- A new simulation framework for elastic optical networks, the first of its kind, capable of working with fragmentation and defragmentation in dynamic network scenarios (ElasticO++).

Following publications were obtained from those contributions:

- *Zone Based Spectrum Assignment in Elastic Optical Networks: A Fairness Approach* - Opto-Electronics and Communications Conference (OECC) 2015 (15).

- *ElasticO++: An Elastic Optical Network Simulation Framework for OMNeT++* - Optical Switching and Networking [*Qualis A2*] (34).
- *A Defragmentation-Ready Simulation Framework For Elastic Optical Networks* - Journal of Communication and Information Systems [*Qualis B1*] - Accepted for publication.

Other related publication obtained during this Ph.D. period:

- *"Arquiteturas de Plano de Controle para Redes Ópticas de Nova Geração Utilizando LSPs Hierarquicos"* - Book Chapter of "Telecomunicações: Teoria, Avanços e Aplicações" - Simpósio Brasileiro de Telecomunicaçoes (SBRT) 2013 (35).
- *"Proposta de Arquitetura OTN Switch Segundo as Recomendaçoes ITU-T"* - Simpósio Brasileiro de Telecomunicaçoes (SBRT) 2013 (36).
- *Proposal for Automatic Initialization and Configuration of the Control Channel for Optical Control Plane* - International Workshop on ADVANCEs in ICT Infrastructures and Services (ADVANCE) 2013 (37).

1.3 Text structure

The remainder of this Doctoral Thesis is divided as follows: Chapter 2 presents a brief overview on Elastic Optical Networks (EON). It covers important concepts related to the understanding of the proposals of this work, including routing, modulation, and spectrum assignment (RMSA) (Section 2.1), spectrum fragmentation, and defragmentation (Section 2.2).

Chapter 3 introduces ElasticO++ framework, the first contribution of this Doctoral Thesis. The chapter presents the most relevant related work (Section 3.1), a brief description of OMNeT++ basic concepts (Section 3.2), an architecture overview (Section 3.3), a section about how algorithms are implemented within the framework (Section 3.4), and finishes with a case study (Section 3.5) and discussions about the obtained results (Section 3.6).

Chapter 4 describes the second contribution of this Doctoral Thesis, the Zone-Based Spectrum Assignment Algorithm. The chapter presents related works (Section 4.1) and two versions of the technique: the static version (Section 4.2) and the dynamic version (Section 4.3). For both versions, the algorithm description, and simulation results are shown.

Chapter 5 concludes this Doctoral Thesis and discusses some opportunities for future works.

2 Elastic Optical Networks

This chapter presents a succinct overview about Elastic Optical Networks (EON). With the intent to keep this Chapter as short as possible, the focus is kept at key points necessary to the understanding of this Doctoral Thesis. Figure 1 provides an excellent overview of EON disciplines related to network planning and optimization. Figure 1 is divided into three parts: (i) input parameters expected in any optimization/planning software (e.g., network topology and traffic demand). (ii) Network optimization for flexible networks representing the operations possible to be performed (e.g., spectrum allocation/defragmentation), and (iii) network level performance metrics, or the expected output result (e.g., blocking probability or capital expense (CAPEX) necessary to realize the network).

Still related to Figure 1, the highlighted areas represent where this Doctoral Work fits into the big picture and which subjects are discussed within this Thesis. More specifically, the routing, modulation, and spectrum assignment (RMSA) problem and its constraints are presented in Section 2.1, whereas spectrum fragmentation and defragmentation in Section 2.2. More about simulation, input parameters, and expected outcomes are discussed in Chapter 3. Finally, as those related problems have an NP-hard nature, Chapter 4 presents the proposed heuristic to deal with them. For other topics not included in the latter sections, following literature is recommended as a more extensive information regarding other EON aspects:

- “Elastic optical networking: a new dawn for the optical layer?” (22). The article describes the drivers, building blocks, architecture, and provides an overview of the enabling technologies for the Elastic Optical Networking paradigm. It is the recommended starting point for newcomers in EON technology;
- *“Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies”* (19). In the paper, the authors review some of the existing technology and propose SLICE, a spectrum-efficient and scalable optical transport network architecture. SLICE is an architecture proposal for Elastic Optical Networking, which enables sub-wavelength, super-wavelength, and multiple-rate data traffic accommodation. The work also presents the technical challenges of SLICE;
- *“Elastic Bandwidth Allocation in Flexible OFDM-Based Optical Networks”* (2). That work explores the Routing, Modulation Level, and Spectrum Allocation (RMLSA) problem, as an update from the Routing and Wavelength Assignment (RWA) problem of traditional WDM networks, proving that is also NP-complete and presenting some algorithms to solve it. It also presents an ILP RMLSA algorithm that minimizes the spectrum used to serve a traffic matrix and also provides an evaluation of the

spectrum utilization benefits that can be obtained when compared to a traditional WDM network;

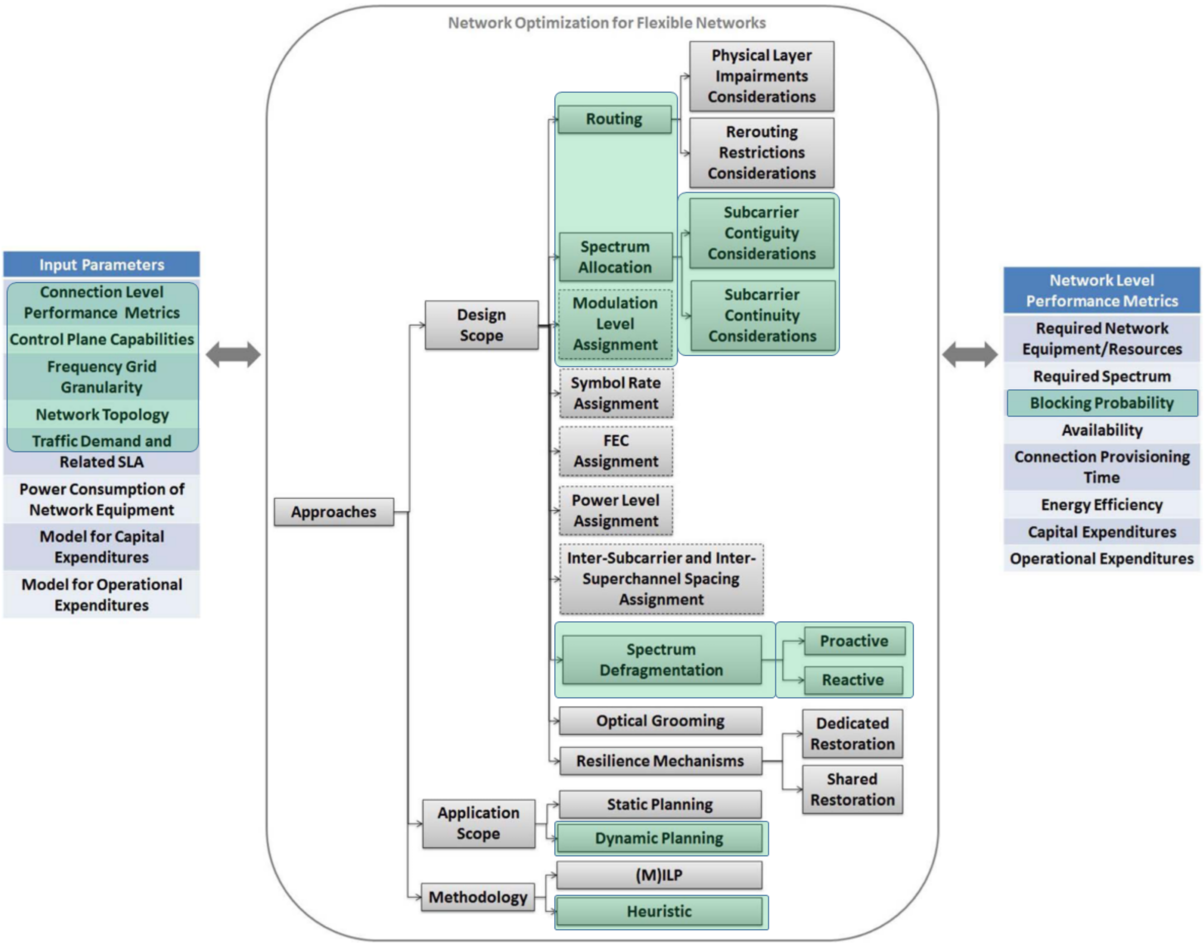

Figure 1 – An overview of EON disciplines related to network planning and optimization. Highlighted areas represent topics addressed in this Doctoral Thesis. *Adapted from: "A tutorial on the flexible optical networking paradigm: State of the art, trends, and research challenges"* (1).

- *"A Survey on OFDM-Based Elastic Core Optical Networking"* (16). In the paper, the authors present a comprehensive survey on OFDM-based elastic optical network technologies, including basic principles of OFDM, OOFDM technologies, architectures, and related key enabling technologies. The main advantages and issues of those technologies are also discussed;

- *"A tutorial on the flexible optical networking paradigm: State of the art, trends, and research challenges"* (1). In the work, it is provided a comprehensive view of the different parts composing the flexible networking technology paying special attention to interactions between different research fields. It also examines physical layer technological aspects, network optimization for flexible networks, and control plane aspects;

- *"Spectrum management techniques for elastic optical networks: A survey"* (38). In that work, a range of spectrum management techniques for elastic optical networks is reviewed and classified, including offline and online routing and spectrum assignment (RSA), distance-adaptive RSA, fragmentation-aware RSA, traffic grooming, and survivability;
- *"Routing and Spectrum Allocation in Elastic Optical Networks: A Tutorial"* (32). The tutorial paper covers the key aspects of elastic optical networks, including its characteristics, its operation principle, and performance regarding scalability and flexibility. Also, the paper reviews and classifies routing and spectrum allocation (RSA) approaches. Furthermore, various aspects, namely, fragmentation, modulation, quality-of-transmission, traffic grooming, survivability, energy saving, and networking cost related to RSA, are presented. Finally, the paper explores the experimental demonstrations that have tested the functionality of the elastic optical network and follows that with the research challenges and open issues posed by flexible networks;

2.1 Route, modulation and spectrum assignment (RMSA)

One of the key challenges in Elastic Optical Networks is how to optimize resource utilization within the network. This optimization has the potential to decrease network cost and energy consumption as well (19, 39). How to allocate resources among client's requests is defined as the Routing, Modulation, and Spectrum Assignment (RMSA) problem.

Historically, the RMSA subject in EONs evolved from the problem of calculating routes and wavelengths for connections in conventional WDM networks, called the Routing and Wavelength Assignment (RWA) problem. For each arriving request, the network needs to evaluate if there are enough free resources to attend that request. The network performs an *allocation algorithm* to search for resources, and if it finds, then the requisition is accepted by the network, thus creating a new connection and occupying those resources. If the allocation algorithm fails, the requisition is rejected. The minimum quantity of resources necessary to accomplish the received request is determined based on two factors: (i) by physical conditions along the lightpaths, such as signal-to-noise ratio (SNR), and linear and nonlinear distortions and (ii) the algorithms and heuristics used to optimize resource utilization (22). Notice that restrictions do exist and must be respected to perform the spectrum assignment correctly: *spectrum continuity* constraint, and the *spectrum contiguity* constraint (40).

The spectrum continuity constraint is inherited from the wavelength continuity constraint in WDM networks. This constraint states that the same wavelength must be maintained along the whole path between both end-points associated with the connection (i.e., lightpath). In EONs, instead of the same wavelength, the restriction obliges the use of the same frequency range in the lightpath. Spectrum allocation in EONs introduces another constraint regarding the available spectrum on each fiber link along the end-to-end route. As each optical channel may use a different amount of bandwidth, frequency-overlapping becomes a possibility and needs to be taken into account (2). Figure 2 illustrates both situations: all established connections use the same frequency range throughout the lightpath (spectrum continuity constraint) and respect the spectrum contiguity constraint without committing any spectrum overlapping (e.g., connections 2 and 3 could not coexist in the same link as they share the frequency range $f7 - f14$).

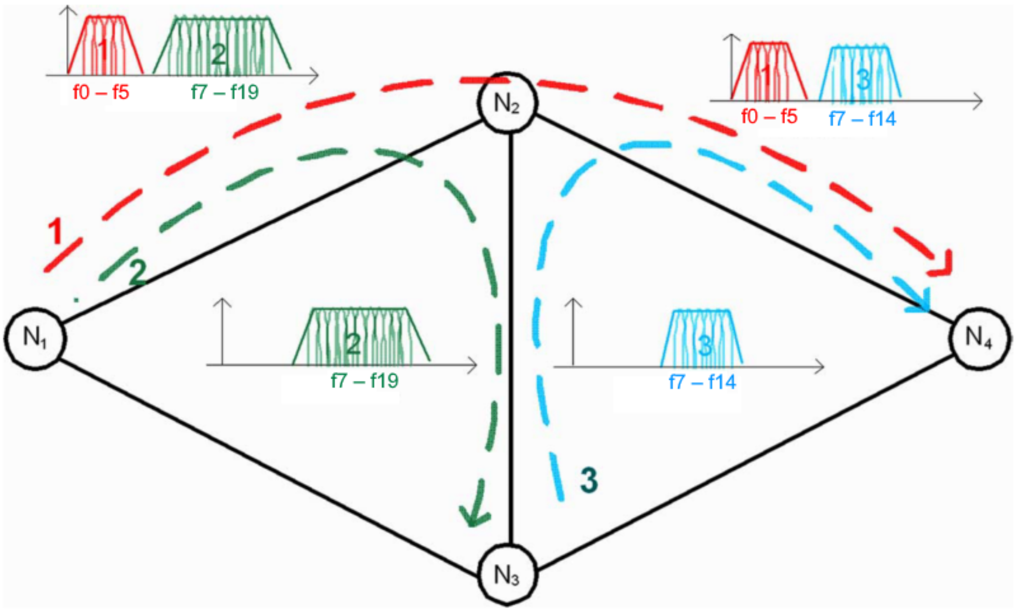

Figure 2 – Representation of EONs spectrum continuity and spectrum non-overlapping constraints. Connection 2 (green) and connection 3 (blue) can not share the same unidirectional link (e.g., N2-N4), as their frequencies overlap. *Source: Elastic Bandwidth Allocation in Flexible OFDM-Based Optical Networks (2).*

Moreover, recent technology advances allow the use of adaptive modulation schemes, enabling more flexibility and efficiency, as best suitable modulation can be utilized according to physical layer conditions (e.g., fiber length or signal-to-noise ratio). For example, an efficient and dense format (e.g., 64-QAM) could be selected for short distances, and more robust and less dense format (e.g., QPSK) for longer paths (20, 5). Modulation formats play a crucial role in the context of the RMSA problem as they translate between the bitrate requested by clients (usually in Gbps) and the bandwidth physically utilized to fulfill the demand (in GHz). Figure 3 shows this relation between modulation and bitrate: (a) the use of a wider spectrum range (i.e., more slots or subcarriers) implies in higher transmission rate, and (b) shorter distances enables more dense modulation schemes (2). It is important to state that a deeper evaluation of modulation schemes and other physical

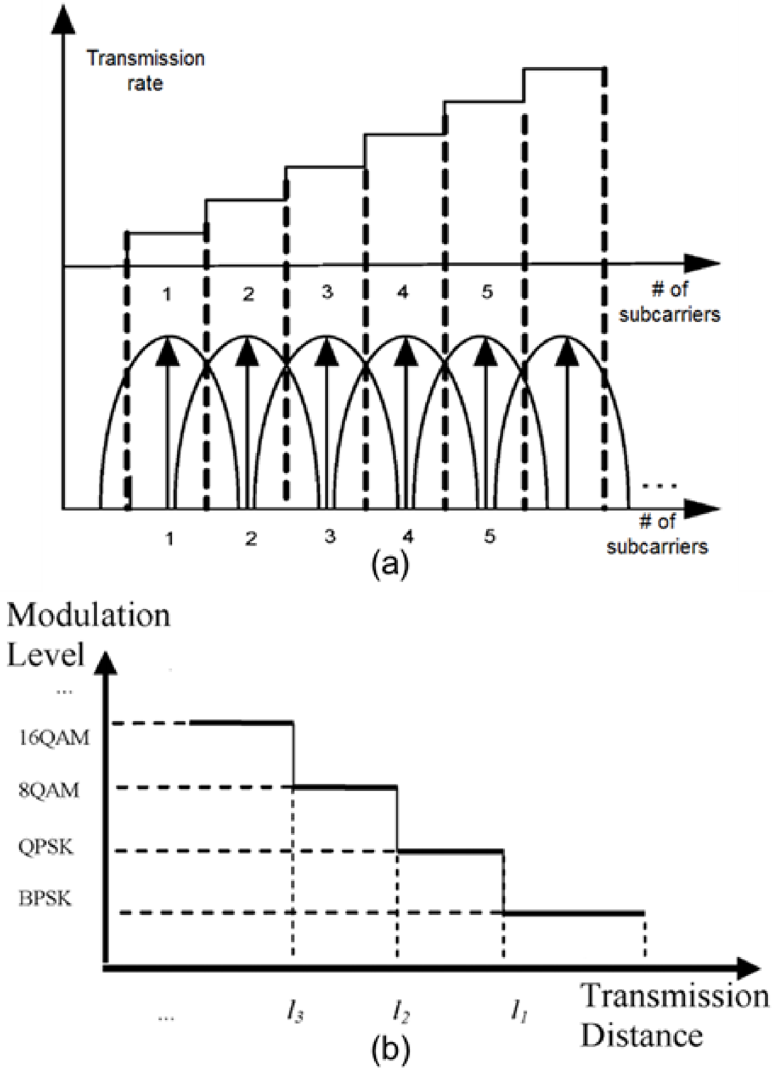

Figure 3 – (a) the use of a wider spectrum range (i.e., more slots or subcarriers) implies in higher transmission rate, and (b) shorter distances enable more dense modulation schemes. *Adapted from: Elastic Bandwidth Allocation in Flexible OFDM-Based Optical Networks (2).*

impairments are not in the scope of this present work, all data used was acquired from specialized works.

At this point, it is important to state different categories of the resource optimization problem. Two are the more common scenarios when discussing resource optimization: *static* (or *offline*) and *dynamic* (or *online*) scenarios (41).

In static scenarios all traffic demand is known beforehand, therefore it is possible to optimize resource utilization according to some metric (e.g., reduce the use of spectrum or smaller hop count average). As all demands are known, the optimization process is done offline and all calculation needed is done beforehand. As computational time is not an issue, optimization algorithms can take several minutes or even days to ensure optimized results. Usually, discussing the fragmentation problem in the static case is not very common since in general those solutions are typically used in the planning phase of the network, which is pretty much optimized. An exception is in pseudo-static scenarios, where multiple phases of allocation/release of resources are taken into account (29).

In the other hand, in dynamic scenarios, new requests arrive and leave randomly without any previous knowledge of the network. Provisioned connections end randomly as well. Because of the lack of information regarding traffic demand, all resource allocation must be done online, as quickly as possible while clients wait for an answer. Therefore, the processing time of algorithms cannot be too high, and as the RMSA problem is NP-Hard, usually heuristics are used (2, 42). Because of this more unstable environment, it is easily visualized that fragmentation losses will happen more often than in static scenarios. Fragmentation problem is discussed in Section 2.2.

It is important to notice that by resources, we are referring to a spectrum range. Currently, the minimum granularity of spectrum that can be assigned in an EON is a 12.5 GHz frequency range, and it is known as *frequency slot* or just *slot* (40). This terminology is used in the rest of the text.

Figure 4 illustrates an example of RMSA process in which the dashed rectangle represents optional steps. The RMSA process starts with a selection of a suitable route between desired source-destination nodes. After routing selection, it is necessary to define how much bandwidth (accounted in slots) is required to transport the requested bitrate. This definition is done by assigning a modulation format, according to link length, signal power, and other physical parameters. An optional spectrum management method can be used. Those management techniques usually consist of splitting the resources into partitions and establishing policies to use it. For example, some policies allocate only demands with same “total path length” (12) or “number of slots” (15) in the same partition. Finally, the last step in the RMSA process consists of finding the necessary number of contiguous slots on the links belonging to the selected route.

2.2 Fragmentation problem and defragmentation solution

In a dynamic network scenario, incoming requests are established and released in an entirely random fashion. This randomness induces spectral resources to be highly fragmented and consequently, “gaps” are unavoidably introduced leading to the so-called spectrum fragmentation problem, thus degrading spectrum utilization efficiency (3).

When connections are uniform regarding spectrum width, as in WDM networks, fragmentation is caused by the wavelength continuity constraint. Though there are wavelengths available on every link that constitute the path, there may not be a commonly available one on all links. This lack of continuity is called *inter-link* fragmentation and

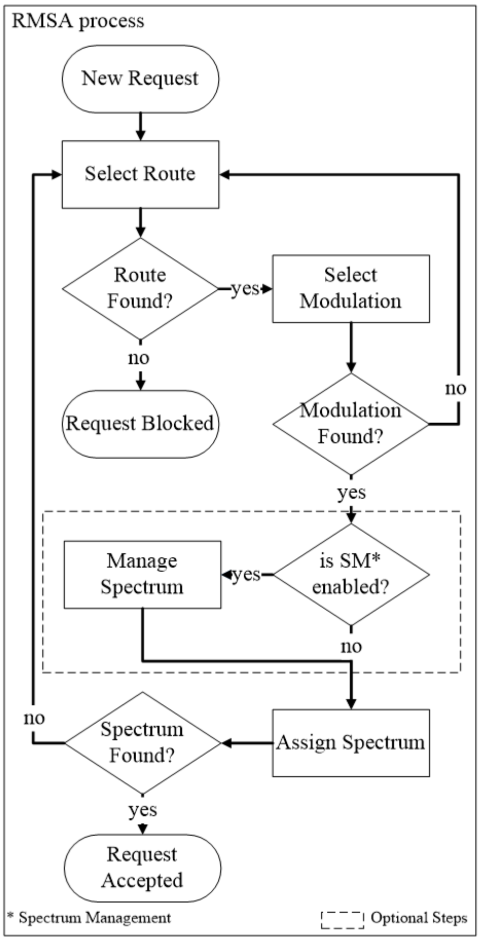

Figure 4 – An example of RMSA process.

exists in EON as well.

In addition to the continuity constraint, EON also experiences the contiguity constraint. This contiguity constraint in association with a heterogeneous environment leads to the second type of fragmentation, the *intra-link* fragmentation. In general, defragmentation algorithms try to reduce the intra-link fragmentation effect. Figure 5 illustrates both types of fragmentation.

Fragmentation losses lead to inefficient resource utilization and overall network performance degradation, increasing blocking probabilities as the unused slots remain scattered over the links and not enough contiguous spectrum slots may be available for new requests to be established. Several spectrum defragmentation techniques have been developed to prevent performance degradation. The primary goal is to rearrange existing connections in a way that available slots remain continuous, clearing more space for new incoming requests, thus reducing blocking probabilities. Four main spectrum defragmentation techniques are proposed in the literature: (a) reoptimization technique (4), (b) make-before-break (5), (c) push-and-pull technique (6), and (d) hitless technique (43) / hop tuning (7). Figure 6 illustrates these techniques (1).

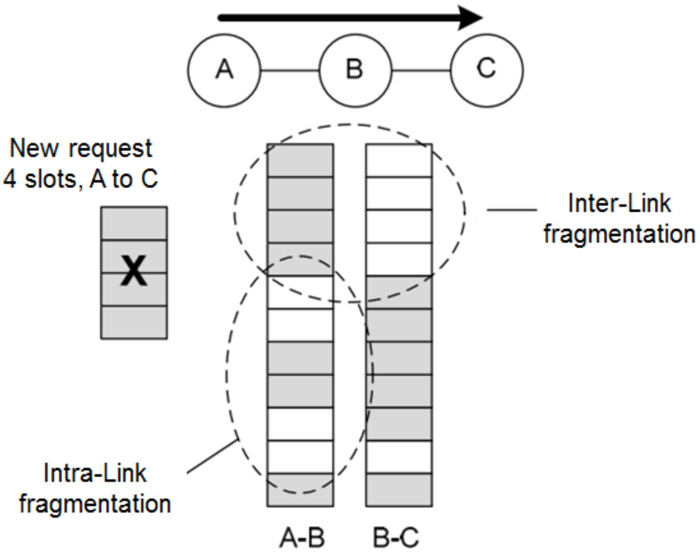

Figure 5 – Fragmentation problem in Elastic Optical Networks. *Adapted from: Distance-adaptive online RSA algorithms for heterogeneous flex-grid networks* (3).

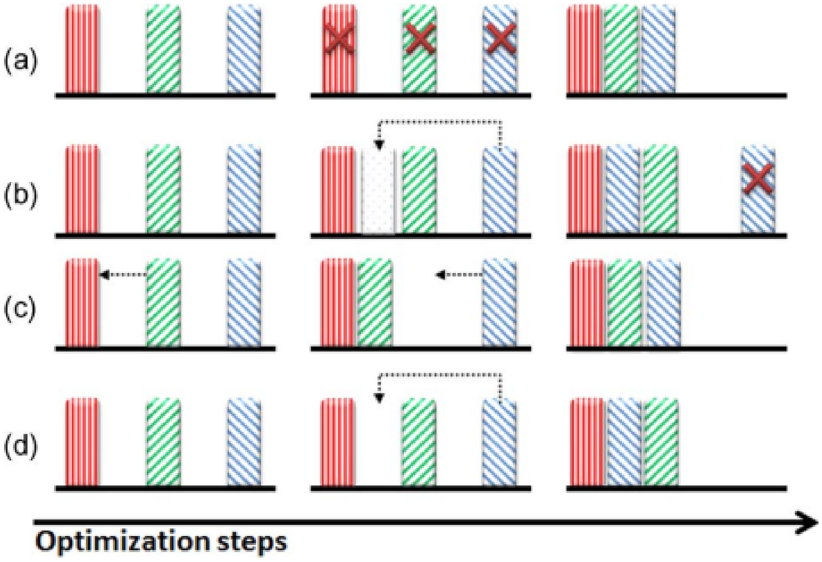

Figure 6 – Spectrum defragmentation techniques. (a) reoptimization (4), (b) make-before-break (5), (c) push-and-pull (6), and (d) hop tuning (7). *Source: "A Tutorial on the Flexible Optical Networking Paradigm: State of the Art, Trends, and Research Challenges"* (1).

The reoptimization method (4) suggests the use of algorithms to rearrange occupied slots in the beginning of the spectrum in an attempt to increase the possibility to allocate new connections as available spectrum is made contiguous, Figure 6 (a). In the make-before-break (5) when a request is blocked, the network tries to find an alternative route. If suitable connections are found, they need to be relocated to create space for the new request. This relocation is performed in the make-before-break manner (i.e., first resources are allocated and only then the old resources are released), Figure 6 (b).

The push-and-pull technique (6) consists in tuning connections across the spectrum without disruption or route change. With push-and-pull, it is not possible to leap over other connections (e.g., in Figure 6 (c), the blue connection would never end leftmost than the green connection). Finally, the Hitless (43) and Hop Tuning (7) techniques are a kind of merge between the make-before-break and push-and-pull methods. They consist in tuning the spectrum of connections, with more flexibility than the push-and-pull (allowing the leap across connections) and make-before-break (fewer resources are needed), but at a cost of more advanced (and expensive) equipment, Figure 6 (d).

In addition to the Defragmentation Algorithm, once a defragmentation is requested, it is recommended to evaluate if it is indeed required in order to prevent unnecessary operations that, depending on which algorithm is used, may be very costly (e.g., interrupting connections for a period). This prevention can be achieved by evaluating a Fitness Function, such as “Spectrum Compactness” (44) or “Utilization Entropy" (45). Figure 7 is an example of this defragmentation evaluation process described.

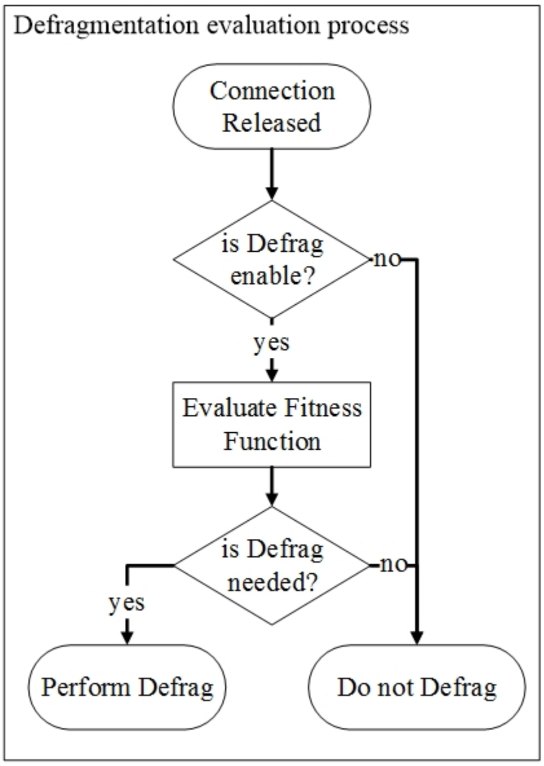

Figure 7 – An example of defragmentation evaluation process.

3 ElasticO++: an Elastic Optical Network Simulation Framework for OMNeT++

This chapter presents ElasticO++: an Elastic Optical Network Simulation Framework for OMNeT++, the first contribution of this Doctoral Thesis. The development of this work is driven to fulfill a gap found in academia. The proposed framework is aimed to simplify the creation and testing of new algorithms, by reducing the amount of time consumed with non-critical but yet necessary tasks, such as logging, data handling, and chart generation. Our intention is that the research community could use ElasticO++ as a "black box," thus focusing on the current problem and its solution. In the current version, our framework supports the RMSA problem only in dynamic scenarios. We developed the framework based on the following requisites:

R1. Perform Elastic Optical Networks simulations;

R2. Support fragmentation and defragmentation;

R3. Allow easy test of algorithms;

R4. Be flexible and easily upgraded if required;

R5. Capable of running batch simulations;

R6. Support of charts and statistics generation;

R7. Free software publicly available[1].

3.1 Related work

Before starting the development of the proposed framework, we searched for simulation tools capable of allowing implementation and testing of new algorithms for elastic optical networks, focusing on allocation and defragmentation scenarios. Two works have been found, both result of academic research, thus, non-commercial software. We did not find any commercial software capable of performing desired roles mentioned in Chapter 3.

- An elastic networks OMNeT++-based simulator (46);
- Net2Plan: The open-source network planner (47).

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[1] <https://bitbucket.org/Stange/elastico/>

"An elastic networks OMNeT++-based simulator" consists of a framework to OMNeT++ software, focused on simulating scenarios for testing algorithms and network architectures. According to authors, the tool is capable of simulating an active Path Computation Element (PCE) controller for Elastic Optical Networks, and is configurable, allowing implementing and testing new algorithms and architectures (46). However, the source code is not publicly available for download.

Net2Plan has its origins in 2011, designed as a teaching/learning tool at Universidad Politecnica de Cartagena in Spain. It is implemented in Java and currently provides four different tools: *offline network design*; *traffic matrix generation*; *online simulation*; and *reporting*, which permits generation of user-defined logs. Although Net2Plan was initially developed to simulate WDM Networks, it is being updated to work with EON as well. Unfortunately, as stated in (3), Net2Plan does not support Defragmentation Algorithms yet.

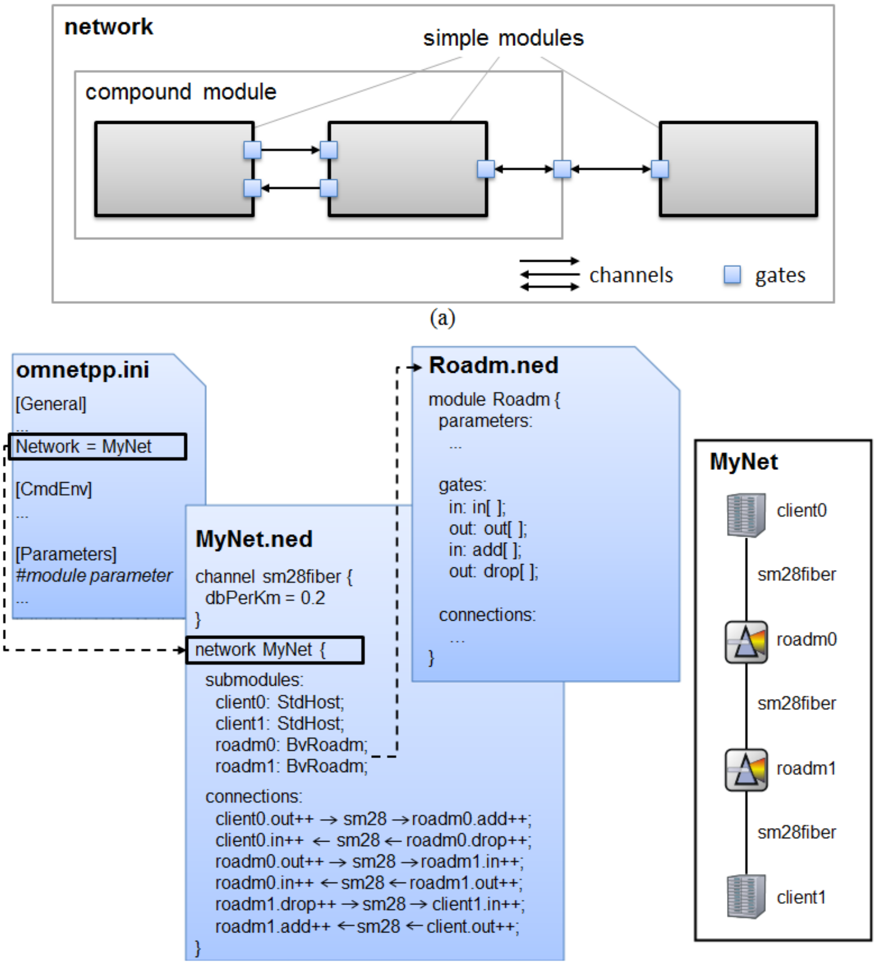
Since the gap still exists, we decided it was worthwhile to invest time and effort to create a new framework, specialized enough to handle specific details related to Elastic Optical Networks, but sufficiently flexible to be modified and used by other fellow researchers. Chapter 3 describes the architecture and main features, which we believe make our framework unique. As the proposed framework is an extension of OMNeT++ software (48), in the next section we present some basics about OMNeT++.

3.2 About OMNeT++

OMNeT++ is a discrete event simulator created in C++ for modeling communication networks, multiprocessors, and other distributed or parallel systems; and is one of the most popular simulators in the research area of communication networks. OMNeT++ is open-source and can be used under the Academic Public License that makes the software free for non-profit use.

A simulation in OMNeT++ is based on modules that contain desired behavior/functionality and are executed by the OMNeT++ simulation kernel. Those modules are called *simple modules* and are implemented by a combination of one or more C++ classes. Besides simple modules, there is also the compound module type, which provides aggregation of multiple simple modules and mechanism to define hierarchies between modules. Every module may have zero or more *Gates*. Gates are the input/output points to/from modules and may represent "physical" or "abstract" entities, i.e., an Ethernet port or an interface between network layers. Next, *Channels* are used to interconnect Gates, therefore defining the interconnections between modules. At least, one last component is necessary to create an OMNeT++ simulation, the *Network* type. The Network aggregates all previously mentioned modules, serving as a starting point of the simulation, Figure 8 (a).

Two files are necessary to launch an OMNeT++ simulation, an *NED file* (.ned) which contains the network description (including simulated modules and how they connect); and an initialization file (.ini), which provides values to be used in the simulation, Figure 8 (b). Also, extra configuration files (e.g., .xml files) can be linked as well.



(a)

```
omnetpp.ini
[General]
...
Network = MyNet

[CmdEnv]
...

[Parameters]
#module parameter
...
```

```
MyNet.ned
channel sm28fiber {
  dbPerKm = 0.2
}
network MyNet {
  submodules:
    client0: StdHost;
    client1: StdHost;
    roadm0: BvRoadm;
    roadm1: BvRoadm;
  connections:
    client0.out++ → sm28 →roadm0.add++;
    client0.in++ ← sm28 ← roadm0.drop++;
    roadm0.out++ → sm28 →roadm1.in++;
    roadm0.in++ ←sm28 ←roadm1.out++;
    roadm1.drop++ →sm28 → client1.in++;
    roadm1.add++ ←sm28 ←client.out++;
}
```

```
Roadm.ned
module Roadm {
  parameters:
    ...

  gates:
    in: in[ ];
    out: out[ ];
    in: add[ ];
    out: drop[ ];

  connections:
    ...
}
```

(b)

Figure 8 – (a) Relation of OMNeT++ components, adapted from (8). (b) OMNeT++ simulation description, adapted from (9).

ElasticO++ is fully compatible with OMNeT++ Graphical User Interface (GUI). It is possible to run simulations in the graphic environment (Tkenv), which can be very useful for interacting and observing the simulation behavior more closely. It is also possible to use command line environment (Cmdenv) instead. Since Cmdenv mode speeds up the execution considerably, it is used most of the time. We developed scripts to automate the handling of results from simulations so that users can experience the enhanced speed of Cmdenv without missing any valuable data.

3.3 Architecture overview

The proposed framework is divided into three main parts: *Extra Tools*, *Equipment*, and *Controller* (Figure 9). Extra Tools is a set of scripts created to automate time demanding tasks, such as data handling and chart generation. Two main features are worth a highlight: *i) CSV (Comma Separated Values) Handler script* is responsible for aggregating each simulation result and preparing it to be used by the *ii) Chart Generator Script*. Chart Generator Script reads organized data stored in .csv files and creates ready-to-plot files, with statistics such as standard deviation, variance, and 95% confidence interval. Currently, the framework supports three "chart outputs formats": Microsoft Excel, OriginLab Origin software, and Python Matplotlib library.

Equipment represents a simple implementation of some conventional equipment found in an optical network, such as transponders, Reconfigurable Optical Add-Drop Multiplexer (ROADM), and optical fiber. We created a new OMNeT++ channel to represent an "elastic optical fiber" with parameters such as attenuation and input/output power; those parameters can be used to choose which modulation scheme to use. It is worthy to mention the *Request Generator* module, in which is possible to configure different traffic patterns to be utilized in the simulation.

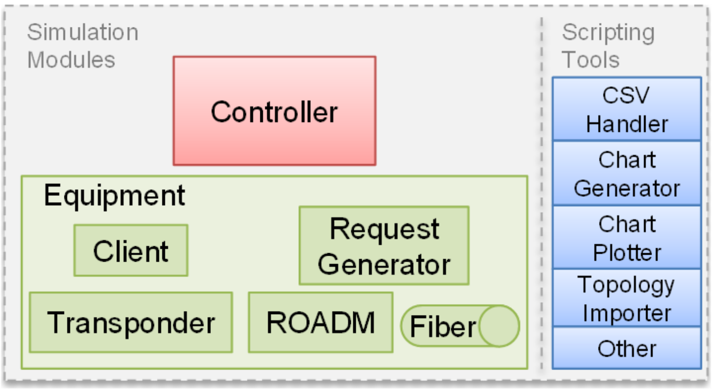


Figure 9 – Framework architecture description.

Finally, the most important part of ElasticO++: the *Controller*. It is composed of several modules as shown in Figure 10. Those modules can be categorized into three groups: *setup*, *storage*, and *execution*. Setup modules are activated only at the beginning of the simulation to coordinate other modules (e.g., *Scheduler module*), and to detect network topology and resources (e.g., *Topology Manager*). Topology Manager stores all information collected in *Topology Table* module for later use by execution modules. *Route Table* and *Connection Table* complete the storage group, keeping, respectively, routes found during Setup Phase and information regarding active connections during the Execution Phase.

Modules involved in the Execution Phase of the simulation forms the third and last group. We explain these modules throughout an example. When a new request (solid black line in Figure 10) arrives at the controller, it is received by the *Admission Controller*. The Admission Controller is the interface between equipment and other controller modules, and its primary job is to convert the format of received information to a "common data structure" understood by all other modules of this group. This data structure is particularly interesting as it greatly improves the flexibility of the framework, simplifying the process of adding new parameters to the framework, thus removing the need to modify function call between Controller Modules. New parameters could be added to create new and more complex algorithms. Those data structures also guarantee backward compatibility as long as previously implemented parameters are not removed. As Figure 11 shows, there are at the moment three different data structures used by Controller' modules: AllocationRequest, AllocationRestriction, and AllocationResult.

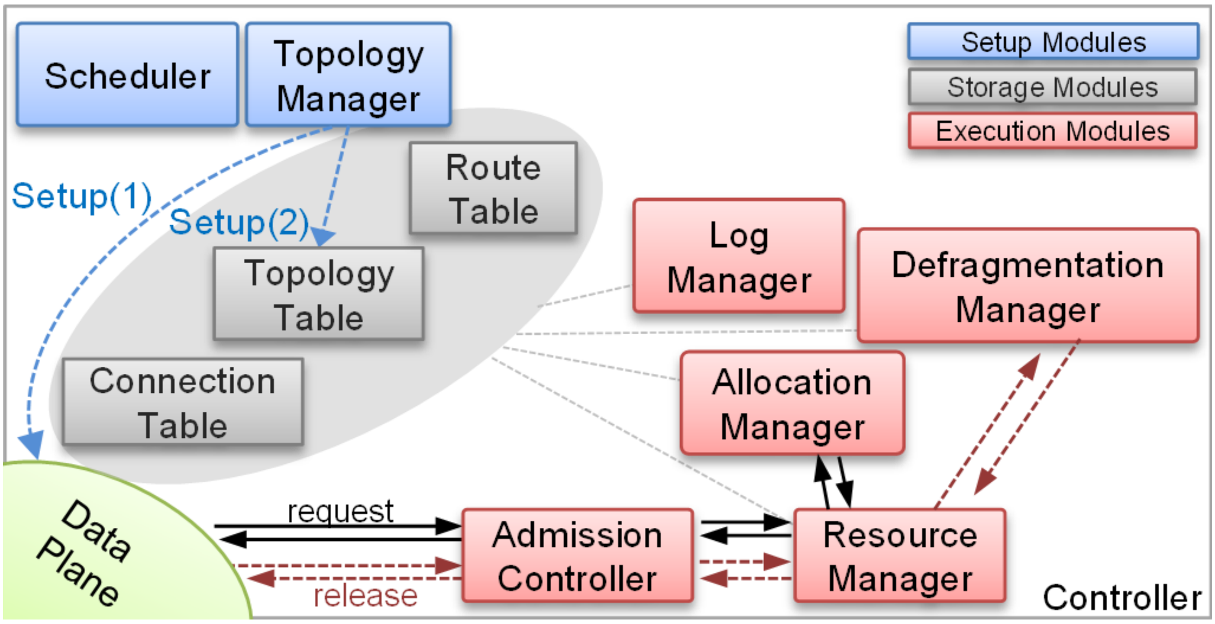


Figure 10 – Controller modules.

Still, the Admission Controller forwards the request to the *Resource Manager* module, which is responsible for coordinating the Allocation Manager and the Defragmentation Manager, create/remove connections from the Connection Table, and call the Log Manager to create simulation logs. The *Log Manager* module is responsible for maintaining statistics and log reports, and in the current version of the framework is capable of generating a simulation result (in a human understandable format) and generating a .csv version to be read by module *CSV Handler* previously mentioned. Next, the *Allocation Manager* is responsible for assembling, managing, and executing *allocation algorithms* (Section 3.4), runs an algorithm to try to find resources to attend the request. Once the allocation algorithm runs, it updates the AllocationResult object and returns it to Resource Manager. At this point the AllocationResult can carry a success or a fail, in both cases, the Resource

```
struct AllocationRequest {
    int source;
    int destination;
    int bitrate;
};

struct AllocationRestriction {
    int lower_slot_index;
    int higher_slot_index;
    bool is_spectrum_constraints_disabled;
    bool is_spectrum_managed;
    int num_slots;
    int route_index;
    long route_id;
};

struct AllocationResult {
    string allocation_log;
    long connection_id;
    int lower_slot_index;
    string modulation;
    int number_of_slots;
    bool rejection_after_defragmentation;
    int rejection_cause;
    long route_id;
    bool success;
    bool success_after_defragmentation;
};

struct DefragmentationRequest {
    long connection_id;
    int lower_slot_index;
    int num_slots;
    long route_id;
    int situation;
};

struct DefragmentationResult {
    string defragmentation_log;
    int moved_connections;
    bool success;
};
```

Figure 11 – Controller common data structures associated with allocation.

Manager will activate the Log Manager to update statistics with this particular request and result, and then, only in the event of success, it will update the Connection Table, thus creating a new connection. At last, an answer is returned to the requesting client informing either a connection ID or rejection.

The release process (dashed red line in Figure 10) work in a very similar way to the admission process. The exception is when the release request reaches the Resource Manager module it is not forwarded to the Allocation Manager. Instead, the connection is terminated and optionally the *Defragmentation Manager* module is called if defragmentation is enabled in the .ini file. After this process, the same way as Admission Process, Log Manager is called, statistics are recorded, and an answer is returned to the requesting client informing the termination of the requested connection.

3.4 Algorithms

We developed an architecture that focuses heavily in algorithm re-utilization. The idea is to create, in a distinct way, smaller algorithms to handle specific problems and then put them together using C++ pointers and inheritance. Since the concept is the same in both Allocation and Defragmentation Algorithms, we explain the main concept using Allocation Algorithm as an example, covering Defragmentation Algorithms by similarity.

An Allocation Algorithm in EON context can be divided into four parts: three RMSA parts plus the Spectrum Management part[2]. To implement it, we created four base classes, one for each of the four mentioned parts. Each class is an abstract class with two basic methods that are needed to be implemented to be used: a *setup* method and a *class-specific* method to call the functionality. In addition to those four base classes, we implemented a fifth base class, called *AllocationAlgorithm*. This *AllocationAlgorithm* class is used internally in the AllocationManager module as an interface to any *RmsaAlgorithm* created by users, allowing, for instance, the use of different logic for RMSA to be tested in the future.

It is necessary to implement two methods to create a new inherited Allocation-Manager class: *assignResources()* that calls class-specific methods (such as *assignRoute()* mentioned above); and a *setup()* method, responsible for initializing all base classes. Figure 12 illustrates the relationship between base classes. By combining independent base algorithms, it is possible to form unique allocation algorithms just by specifying which one to use in a new class, inherited from AllocationAlgorithm class (e.g., RmsaAlgorithm in Figure 12). For instance, the RmsaAlgorithm class implementing a standard K-Shortest Paths DP-QPSK Spectrum Sharing First Fit algorithm needs only twenty lines code.

Defragmentation Algorithms follow the same logic, but instead of five base classes, it uses only three: an algorithm class, a fitness function class, and an interface class. Table 1 provides a summary of base algorithms implemented in the current version of the framework. Those algorithms are *in-house* implementations of the classical algorithms. More information regarding ElasticO++ can be found at the projects repository site: <https://bitbucket.org/Stange/elastico/>. In the next Section 3.5, it is presented a showcase of the framework features.

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[2] Spectrum Management was created separately from Spectrum Assignment because different combinations can be used in this way, for example, a Spectrum Partition based algorithm can be used in addition to a First Fit or a Random Fit.

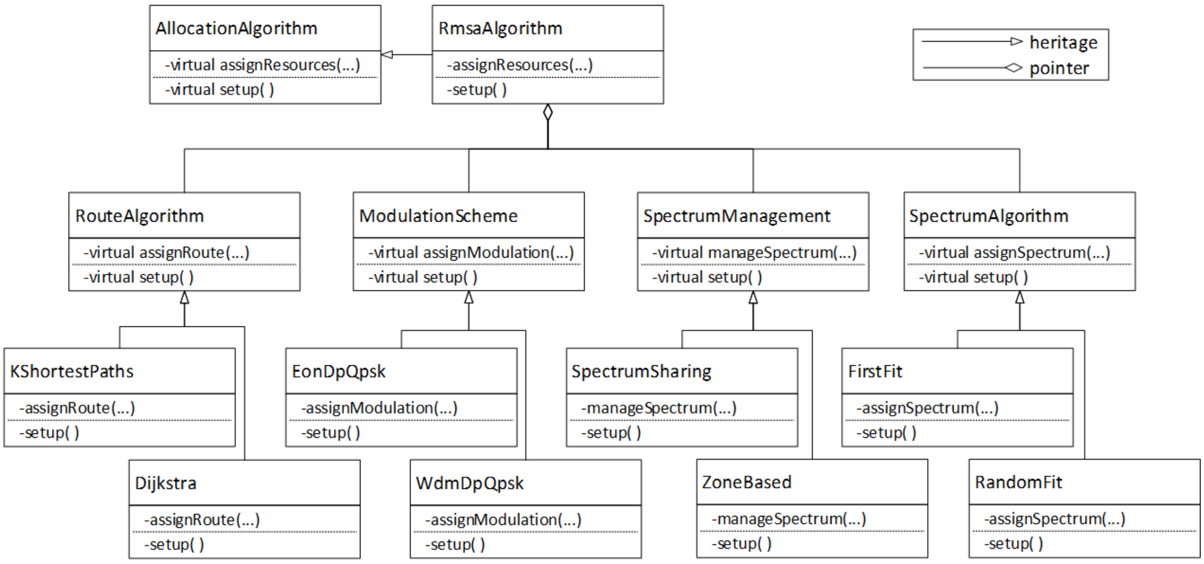


Figure 12 – Relationship of classes related with Allocation Algorithms.

Table 1 – Base algorithms implemented.

Acronym	Name	Type
DIJK	Dijkstra (49)	Routing
KSP	K-Shortest Paths (50, 51)	Routing
EDQPSK	EON DP-QPSK (22)	Modulation
WDQPSK	WDM DP-QPSK (22)	Modulation
SS	Spectrum Sharing (11)	Spectrum Management
ZB	Zone Based (15)	Spectrum Management
FF	First Fit (20)	Spectrum Assignment
RF	Random Fit	Spectrum Assignment
MBB	Make-Before-Break (5)	Defragmentation
SC	Spectrum Compactness (44)	Fitness Function

3.5 Case Study

Some experiments were performed to evaluate ElasticO++ features. Our framework was implemented on OMNeT++ 4.6. All simulations were executed on a Windows 10 64-bit PC using a Core i5-3570k 3.4 GHz and 8 GB RAM. The highest memory consumption for all experiments was less than 30 MB. Each simulation is executed using a single thread, but since the proposed framework can take advantage of multiple threads, total simulation time is reduced considerably by running simulations in parallel. Some factors impact in memory consumption: the number of requisitions per simulation (increases log size), the size of the network topology and the network load (increases information stored in the tables). Some other factors affect CPU consumption: network size (increases routing algorithm calculations), total spectrum available in each fiber (increases spectrum allocation algorithm calculations) and enabling defragmentation algorithm (raises the overall number of operations).

The objective of this section is to present some of the capabilities and flexibility of the developed framework. A case study is proposed, in which we established a "baseline" algorithm without defragmentation. We then choose four other algorithms, each one being a variation of the baseline. For the last comparison, we enabled the defragmentation algorithm to work with the baseline algorithm. More about the algorithms is covered in Section 3.5.1.

3.5.1 Setup and algorithms

Simulations were performed using American topology NSFNET, composed of 14 nodes and 21 bidirected links (7). In this test, we configured 360 slots ($360 \cdot 12.5$ GHz $= 4.5$ THz) as maximum bandwidth available per fiber (C-band).

A dynamic network operation scenario is simulated with new requests arriving at λ Poisson rate and holding time exponentially distributed (with a normalized mean of $1/\mu = 1$). Network load is given by $\rho = \lambda/\mu = \lambda$ (Erlang). In each simulation run, 10^6 requests are generated, and for each chart's point, 30 simulations with different random seeds. Each new request is composed of a source, destination, and bitrate requirement; following a uniform distribution. In this particular scenario, four services are provided by the network with bitrates of 40 Gbps, 100 Gbps, 400 Gbps, and 1 Tbps. For each arriving request, the controller evaluates if the network has enough resources available, as shown in Figure 13 (a).

Table 2 – Case Study algorithms.

Algo-#	Description
Algo-0	K-Shortest Paths EON DP-QPSK Spectrum Sharing First Fit
Algo-1	*Dijkstra* EON DP-QPSK Spectrum Sharing First Fit
Algo-2	K-Shortest Paths *WDM DP-QPSK* Spectrum Sharing First Fit
Algo-3	K-Shortest Paths EON DP-QPSK *Zone-Based* First Fit
Algo-4	K-Shortest Paths EON DP-QPSK Spectrum Sharing *Random Fit*
Algo-5	K-Shortest Paths EON DP-QPSK Spectrum Sharing First Fit + *Spectrum Compactness Make-Before-Break*

For this case study, we established a "baseline" allocation algorithm (Algo-0). This baseline algorithm is a combination of the following base algorithms: Yen's K-Shortest Paths (50, 51) as the routing algorithm; EON DP-QPSK (22) as the modulation scheme; Spectrum Sharing (11) as the management technique, and First Fit (20) as the spectrum assignment. Since these algorithms are often used as a benchmark in publications, we chose to use them as well. We compare Algo-0 against four other algorithms: each one changing one of the four base algorithms, as presented in Table 2. Algo-1 uses Dijkstra Shortest Path algorithm (49) instead of Yen's algorithm; Algo-2 is a representation of WDM technology (22); Algo-3 introduces a spectrum management technique, Zone-Based partitioning (15); and Algo-4 uses Random Fit as the spectrum assignment algorithm.

We also run simulations combining Algo-0 with enabled defragmentation, using Make-Before-Break (5) as Defragmentation Algorithm and Spectrum Compactness as Fitness Function (44). All RMSA algorithms follow the flowchart presented in Figure 13 (a), whereas defragmentation evaluation follows Figure 13 (c). Simulation results are presented in Section 3.5.2.

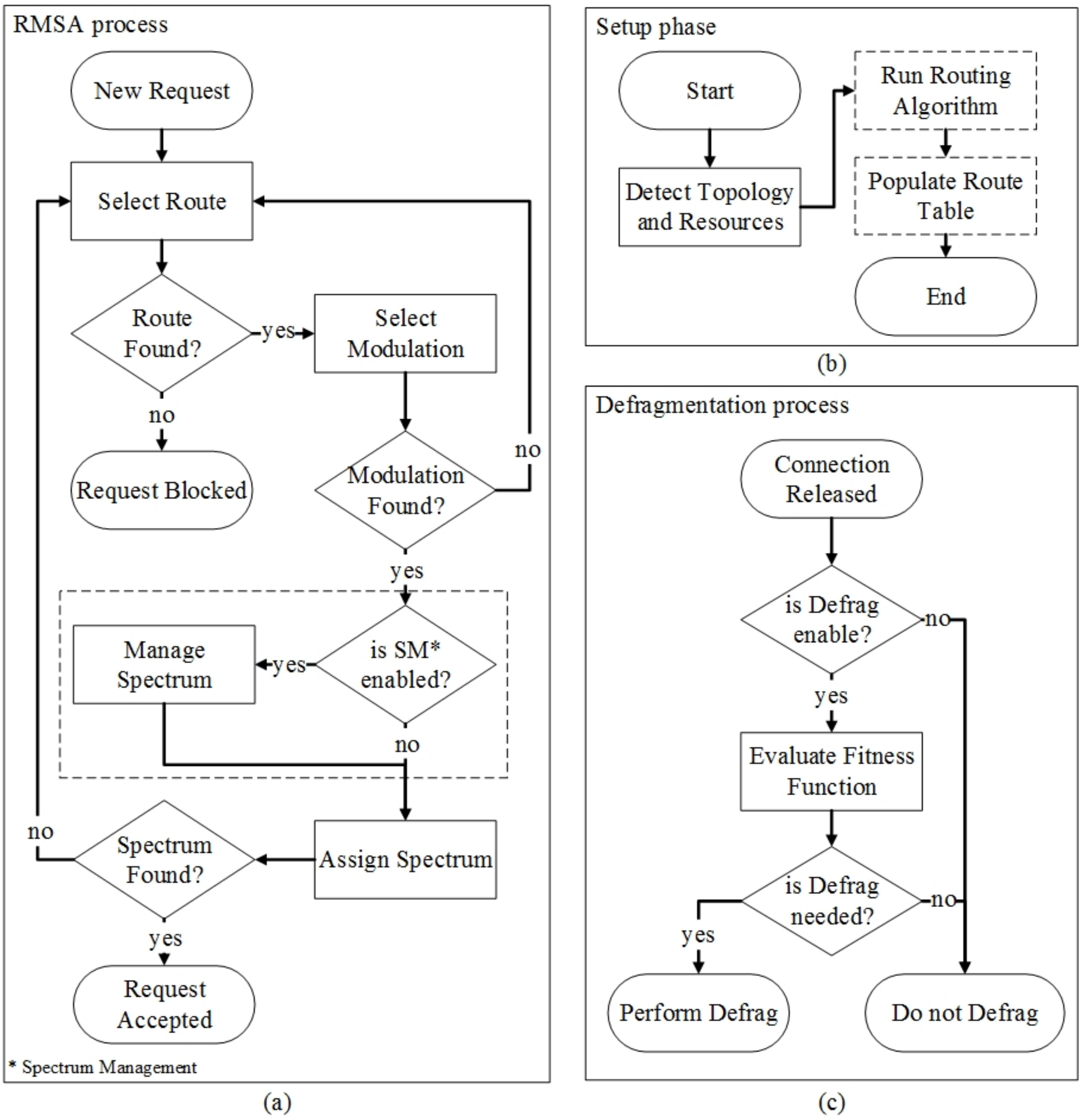


Figure 13 – (a) RMSA process, (b) setup phase, and (c) defragmentation evaluation process.

3.5.2 Results

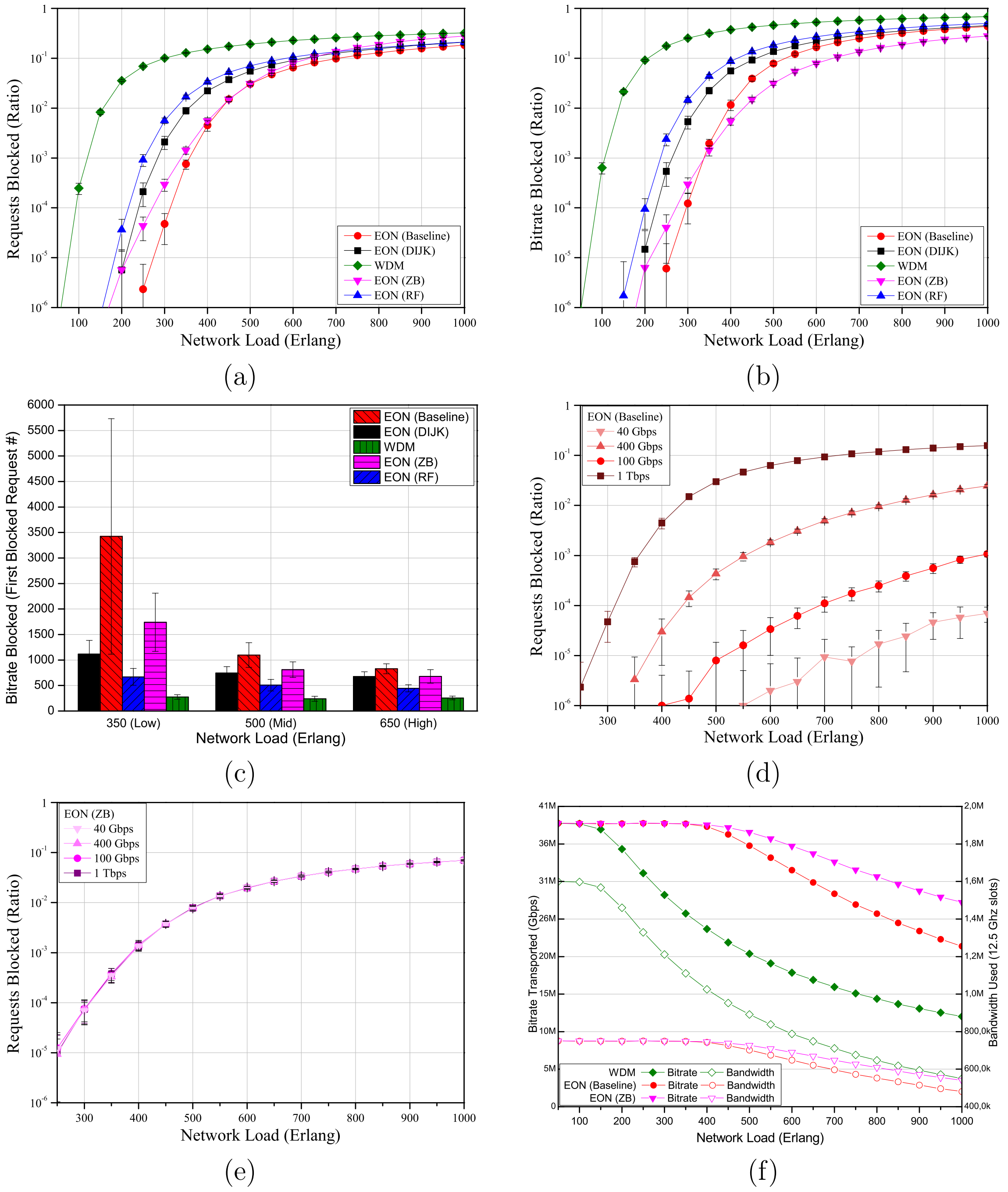
Our intention with this chapter is to present the framework capabilities, and we want the reader to focus on the tools available to analyze the results, as the results presented in this section are already know by the community. Figure 14 shows all results obtained from the case study.

Figure 14 (a) and Figure 14 (b) present requests and bitrate blocked ratio, respectively. Both charts can be used to evaluate the general behavior of tested algorithms. The requests blocked ratio is defined as the number of requests blocked at the end of the simulation divided by the total number of requisitions generated, whereas the bitrate blocked ratio is given as by the ratio between the total bitrate blocked and the total bitrate requested. Figure 14 (c) shows the number of accepted requests before first rejection in the network.

Figure 14 (d) and (e) show fairness for baseline algorithm and Zone-Based variant, respectively. The service fairness is evaluated by comparing the service requests blocked rates between all service types. In charts (d) and (e) each curve accounts for a different service, and the closer the curves are, the fairer is the Allocation Algorithm. An analysis of the Zone-Based algorithm performance is presented in Chapter 4.

Figure 14 (f) is a doubled Y-axis chart utilized for analyzing spectrum efficiency of tested algorithms. The right Y-axis represents the total bandwidth used (solid shapes) to transport the total of bitrate requested (left Y-axis, curves with white shapes). This view is interesting to evaluate the efficiency of the technology and the algorithms used. The higher is the ratio between the bitrate transported and the bandwidth used, the more efficient is the method analyzed.

In Figure 15, charts (a), (b), and (c) show results related to the use of a Defragmentation Algorithm. Chart (a) is the same chart as Figure 14 (a), which in this context used to analyze if using a Defragmentation Algorithm can achieve any gain. In this example, the defragmentation increases the performance of the network, by allowing more requests to be accepted. Chart (b) shows how many times the Defragmentation Algorithm was activated (left Y-axis, the black curve with squares), and the number of moved connections (right Y-axis, the blue curve with circles). Chart (b) can be used to measure how well the fitness function and the defragmentation activation threshold perform, by observing if unneeded defragmentation activation occurs (e.g., small amount of moved connections). It is important to notice that the “moved connections count” metric can be used by RMSA algorithms as well, representing the number of connections disrupted during allocation of new requests. The number of disrupted connections can be an important benchmark for those algorithms as it may impact overall network quality of service. At last, chart (c) presents a metric about simulation performance. Although it is not a very precise measurement method, it serves well to observe in practice if the simulations are becoming slower because of the complexity of the tested algorithms. As the times acquired are dependent on computer hardware, it is possible to establish a baseline (the EON, red curve in this example) and then compare the performance results with other algorithms. As defragmentation algorithms, in general, are very demanding, the simulation time increases up to 60% in this example.

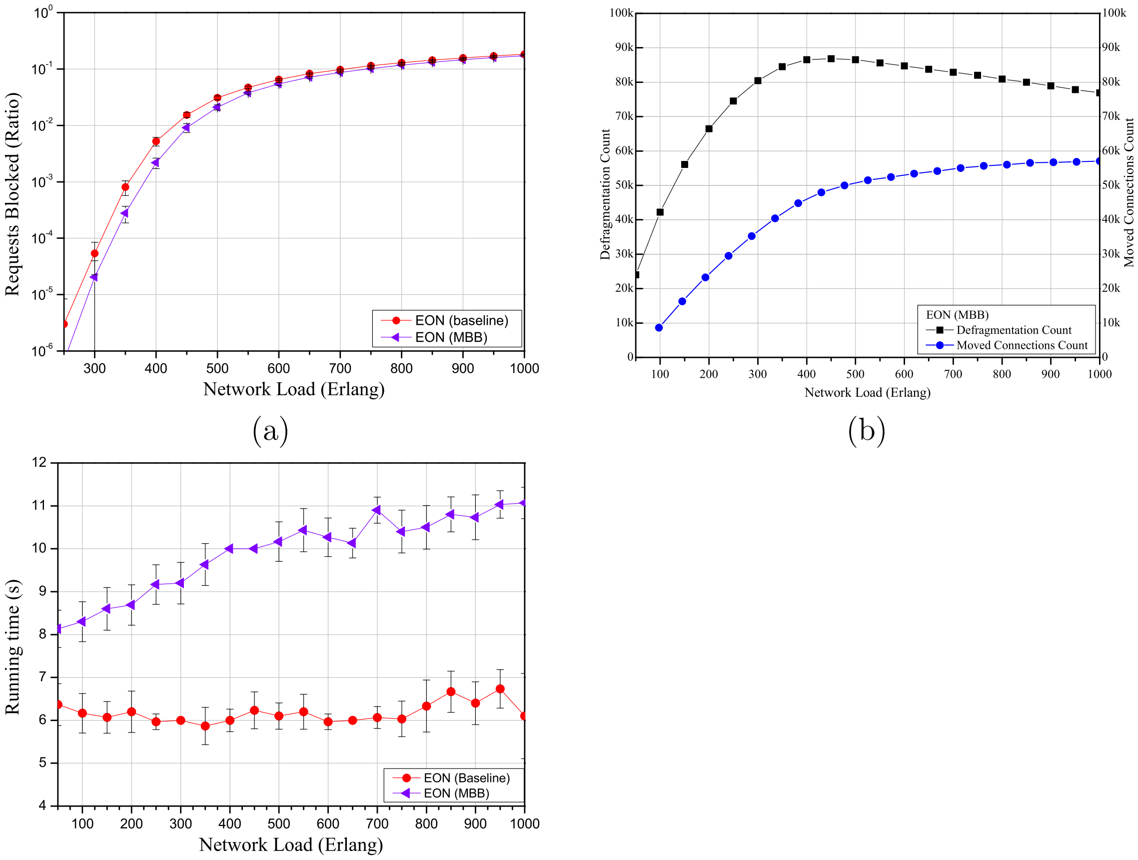


(a) (b) (c) (d) (e) (f)

Figure 14 – Allocation results: (a) Requests blocked ratio; (b) Bitrate blocked ratio; (c) Number of requests accepted before the first block; Fairness between services: Baseline Algo-0 (d), and Zone-Based Algo-3 (e); (f) Relationship between bitrate transported and bandwidth used in the process.

3.6 A note on comparing simulation results

This section is dedicated to discussing how ElasticO++ results compare with works published along past years. From a myriad of works available, we chose two papers to serve as a baseline for our outcomes: a bandwidth blocking ratio simulation from (10), and a service fairness analysis from (11). We chose those works because they provide enough



(a)

(b)

(c)

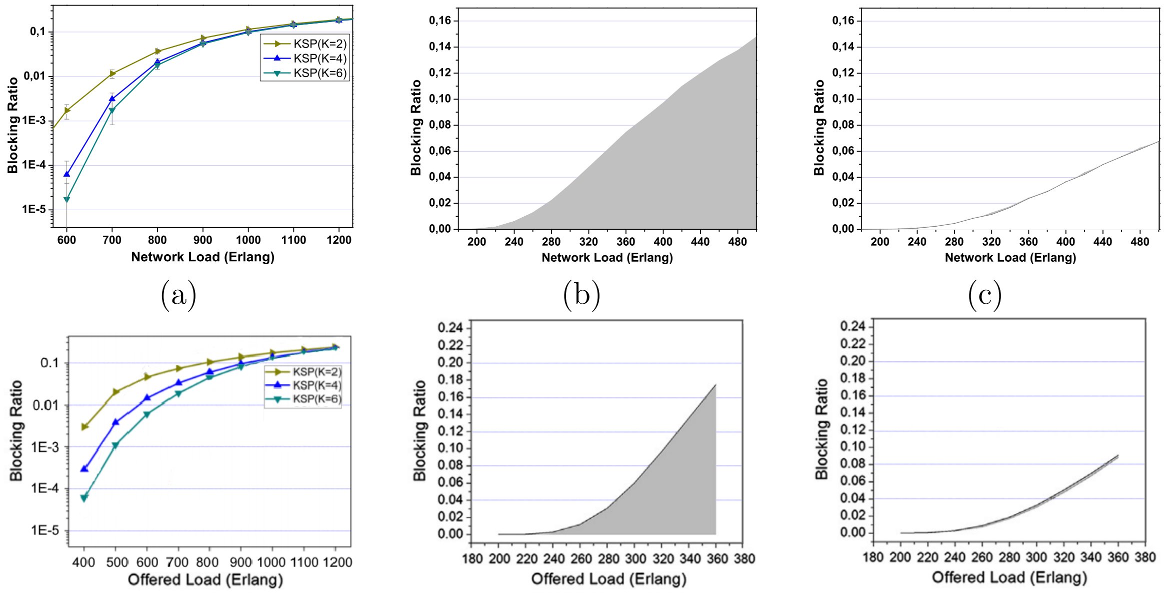
Figure 15 – Defragmentation results: (a) Comparison between baseline algorithm with and without defragmentation; (b) Relationship between Defragmentation count and the total number of connections moved in the process; (c) Average simulation time.

information to reproduce their results and are relevant to the field. We ran simulations on *in-house* implementations of the algorithms to compare their results with ours. To help in the comparison, we formatted our charts likewise the compared ones.

The first comparison test is intended to simulate the bandwidth blocking ratio when varying the parameter K from the K-Shortest Paths (KSP) algorithm (i.e., the number of calculated routes for each node pair in the network). K assumes values 2, 4, and 6. The full setup is available in Section 4 of (10). Figure 16 (a) shows the results obtained using our framework. After investigation of Figure 16 (a) and Figure 16 (d) adapted from (10), we conclude that the *same behavior* is obtained. We also identified some scale differences among charts (see below).

The second simulation is intended to test the service fairness among Complete Sharing (CS) and Dedicated Partition (DP) spectrum management schemes. Services are rated at 100 Gbps, 400 Gbps, and 1 Tbps. The metric chosen to evaluate service fairness is the difference between services blocking ratio; the smaller is the difference, the fairer is the solution. The full setup is available in Section 4 of (11). Figure 16 (b) and Figure 16

(c) present the results obtained using our framework for CS and DP respectively. The gray area expresses the difference between the highest and the lowest blocking ratio of the distinct services. After analyzing Figure 16 (e) and (f), extracted from (11), we can observe that *same behavior* and scale differences are again obtained.



(a) (b) (c)

(d) (e) (f)

Figure 16 – (a) Bandwidth blocked ratio results of K-Shortest Path algorithms, for K = 2, 4, and 6. Comparison of service fairness among spectrum management schemes. The gray region represents the difference between the highest and the lowest blocking ratio of different services. (b) Complete Sharing. (c) Dedicated Partition. (d) Is an adapted version of Figure 1 (a) from (10). (e) and (f) are respectively Fig. 6 (b) and (c) from (11).

Different from other research fields, in our field, it is unusual to find benchmarks, databases, or full numerical results from papers to be replicated. Indeed, one of our motivations with ElasticO++ is to provide a common environment to compare solutions. A simulation is not necessarily a final and deterministic result about something. Instead, it is a start and gives an impression of some behavior.

It is very challenging to replicate results exactly, mainly due to the following reasons:

- Data is not 100% available: sometimes some necessary details are not given proper attention, e.g., which loading balance algorithm is used, or if Dijkstra's algorithm is weighted by hops or by link length;
- Input parameters are inconclusive: e.g., network topology; NFSNET has several versions which vary in the number of links and the placement of those links (32, 52, 53, 54). Even when topologies do match, different weights can be assigned to the edges, thus potentially leading to slightly different results (3, 52);

- Hidden simulation parameters: e.g., what is the K value in the K-Shortest Paths algorithm?;
- Randomness is usually heavily involved: e.g., stochastic distributions, random seeds;
- Arbitrary decisions are taken (e.g., dropping X number of events before accounting for results, or using new-and-specific metrics to express results).

With that in mind, regardless of the differences found in our tests, we have confidence that the presented results validate our framework.

4 Zone-Based Spectrum Assignment Algorithm

This chapter covers the second contribution of this Ph.D. Thesis, the Zone-Based Spectrum Assignment Algorithm. The technique is presented in two versions: the static version and the dynamic version. The static version is intended to be used in cases where information regarding the nature of the network traffic is known beforehand, whereas the dynamic version was developed as a solution in cases in which absolutely no information is known.

The main objective of the Static Zone-Based Spectrum Assignment algorithm (SZB) is to mitigate the unfairness problem. The algorithm divides the spectrum into zones and ensures a strict assignment policy to them. The SZB algorithm is presented in Section 4.2. An extensive analysis of the algorithm performance is discussed in Section 4.2.1. On the other hand, the goal of the Dynamic Zone-Based Spectrum Assignment algorithm (DZB) is monitoring the requests received by the network, and from those infer a suitable traffic pattern that is used to calibrate delimitation of the mentioned zones, following the SZB algorithms. The DZB algorithm is presented in Section 4.3 whereas a brief qualitative result is presented in Section 4.3.1.

4.1 Related work

This section presents the related works that influenced and helped to develop the proposed Zone-Based Spectrum Assignment Technique. Only works related with spectrum management partitioning are addressed here. Related works are divided into two groups: solutions focusing the unfairness problem and solutions focusing on solving the fragmentation problem.

4.1.1 The unfairness problem

The work *"A study on dynamic spectrum assignment for fairness in elastic optical path networks"* (12) proposes a division of the spectrum grouping connections by its number of hops. It also controls dynamically the size of each partition depending on the blocking probabilities. In the proposed scheme, all connections belonging to "lower bands" can be assigned to "higher bands" (e.g., Band 1 connections could use Band 2 and Band 3, and Band 2 connections could use Band 3). Figure 17 shows an example of three bands division. The proposal also covers dynamic controlling of the partitions, as presented in Figure 18. It uses blocking probabilities to calibrate the partitions, giving more spectrum to partitions with more blocking ratios. In the example of Figure 18, the bandwidth of the group that has the higher blocking probability (Band 1) is increased, while decreasing the bandwidth of the one that has the smaller blocking probability (Band 3). Although it achieves some degree of fairness, the method can lead to fragmentation as the partitions are not exclusive for one group. As long hop connections tend to occupy more spectrum to transmit same rates in comparison to short hop ones (i.e., the longer the path, the sparser is the modulation used), within the network connections with different sizes may coexist, characterizing a heterogeneous environment. The work (12) is considered related since it uses spectrum management to classify connections and prevent unfairness, but it differs from the proposed method of this Doctoral work since it does not attempt to limit the effects of fragmentation.

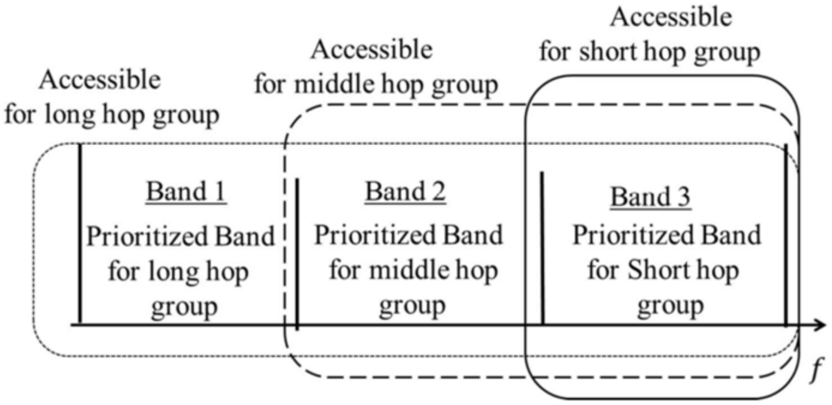
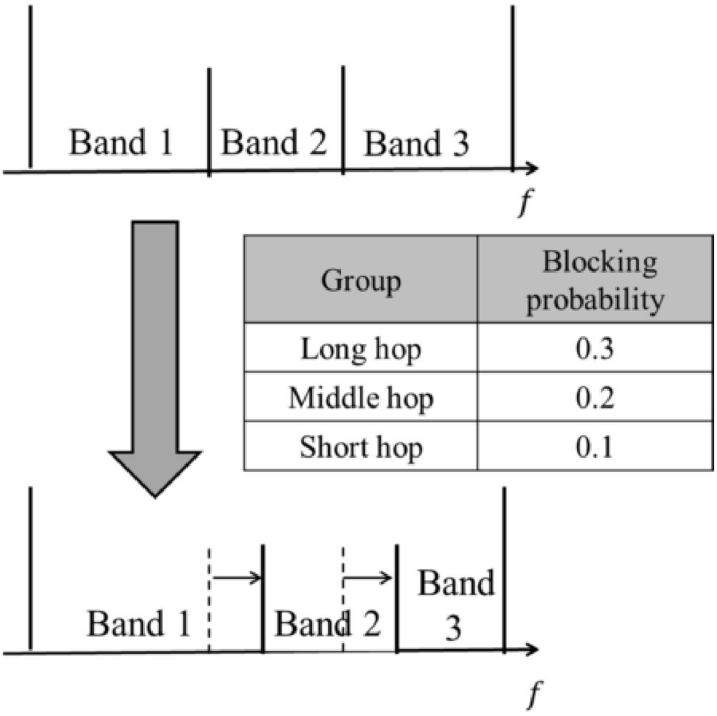


Figure 17 – Prioritized bands for each group: Short, Middle, and Long hops. *Source: "A study on dynamic spectrum assignment for fairness in elastic optical path networks"* (12).

The work *"Distance-adaptive online RSA algorithms for heterogeneous flex-grid network"* (3) proposes the Partial-Sharing-Partitioning (PSP) scheme. The scheme divides the spectrum into $S + 1$ partitions, where S stands for the number of existing services in the network. The last partition ($S + 1$) acts as an *overflow partition*, shared among all the services. Upon reception of a request for a service type k, the PSP controller tries to assign it into the dedicated partition for service k. If not possible, then the controller attempts to allocate the newcomer connection to the shared partition. If the request can not be allocated either in the proper partition nor the shared, the request is then blocked. The size of the shared partition is represented by a percentage of the total spectrum available. The rest of the spectrum is equally distributed among the services. As an example, Figure 19 (a) presents a 25%-PSP in which 25 percent of the total bandwidth is reserved to the shared partition. It is important to note that a 0%-PSP defines a division without shared resources, *Dedicated Partition* (DP), as shown in Figure 19 (b). It is also worth mention that a 100%-PSP, Figure 19 (c), implies that all the resources are shared, and there are not any dedicated partition. This last case is also called *Spectrum Sharing* (SS). The work (3) is considered related to the developed Doctoral work as it divides the spectrum based on the types of services. However, it differs for two reasons: (i) the use of a common shared partition (which leads to fragmentation into the network), and (ii) it



Group	Blocking probability
Long hop	0.3
Middle hop	0.2
Short hop	0.1

Figure 18 – Example of dynamic bandwidth control. *Source: “A study on dynamic spectrum assignment for fairness in elastic optical path networks”* (12).

does not divide the spectrum proportionally to services individual requirements.

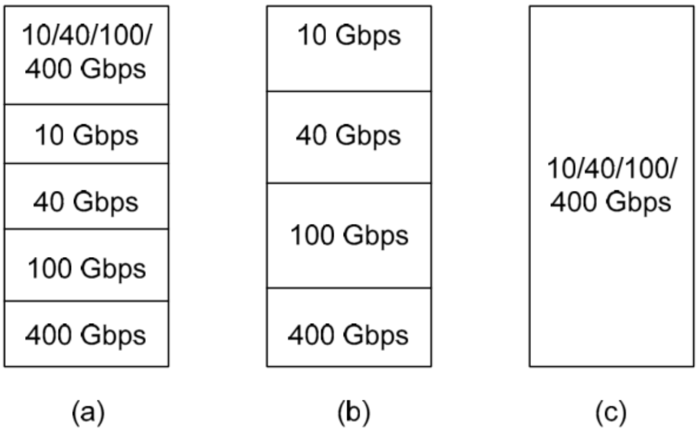


Figure 19 – Partial-sharing partitioning (PSP) with different percentages of shared spectrum: (a) 25%, (b) 0%, and (c) 100%. *Source: “Distance-adaptive online RSA algorithms for heterogeneous flex-grid networks”* (3).

4.1.2 The fragmentation problem

Works presented next are focused on the fragmentation problem. The work *“Alternative routing and zone based spectrum assignment algorithm for flexgrid optical networks”* (13) proposes an assignment policy and a path routing mechanism based on the maximum capacity available. The objective of the policy is to minimize the number of rejected requests by reducing the spectrum waste (i.e., fragmented). Figure 20 illustrates how the RSA algorithm works. The spectrum is divided into partitions, one for each possible type of services in the network (two zones in the Figure 20 example). Zone $z1$ is completely available whereas zone $z2$ has some occupied slots (gray slots). A new request r will be allocated to the preferred zone $z1$ using a first-fit algorithm. If it is not possible, r will be assigned to the non-preferential zone $z2$ using a last-fit algorithm. Once more, there is a trade-off involved in allowing a mix of connections within the same partition, as it characterizes a heterogeneous environment, possibly leading to fragmentation losses. The work (13) relates to this Doctoral work since it uses a very similar algorithm to define the partitions, but it differs because it uses the zones in a priority manner, and not in a restrictive manner.

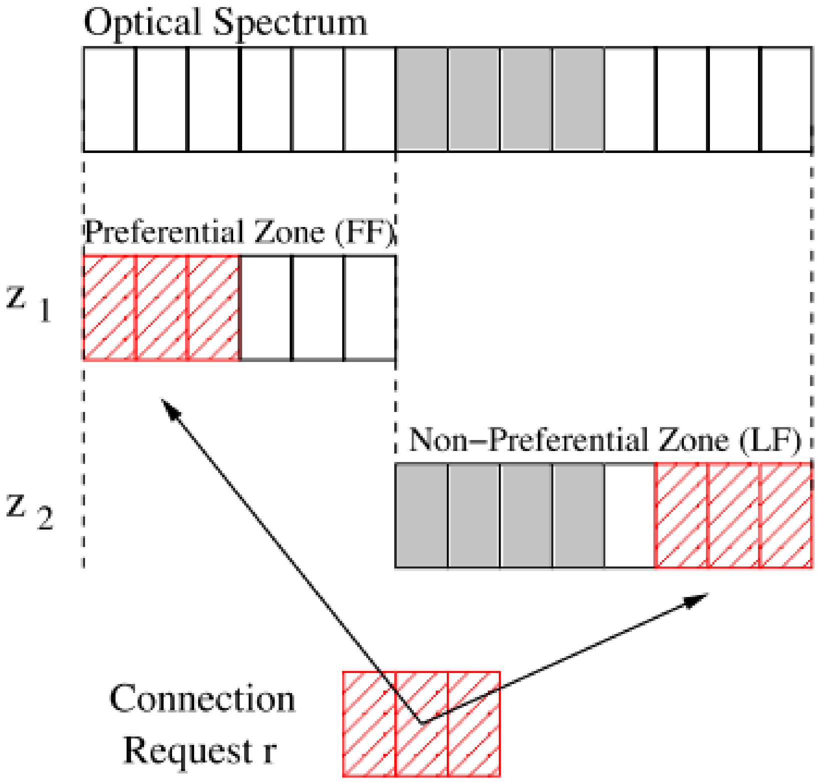


Figure 20 – Example of zone-based assignment policy. *Source: "Alternative routing and zone based spectrum assignment algorithm for flexgrid optical networks"* (13).

Finally, the work *"Spectrum management in heterogeneous bandwidth networks"* (11) tackles both unfairness and spectrum fragmentation problems. The work proposes a partitioning scheme based on the possible services types in the network. The partitions are established proportionally as the amount of resources required by each service of this kind (i.e., a request j that needs the double of the bandwidth of a request k will be designated to a partition with the double the size). As a consequence of each partition carrying only connections with the same size, each partition is effectively reduced to a wavelength-routed network, thus eliminating the intra-link fragmentation losses. The authors have formulated the problem of calculating the optimum partition division as a non-linear optimization problem. As the input of the optimization problem, it is necessary to inform data such as blocking ratio and traffic intensity for each existing service in the network. This division method is what differs the work (11) from this Doctoral work. The static version of our proposed method (Section 4.2) does not require blocking ratios as an input of the algorithm nor traffic intensities for the dynamic version (Section 4.3). Once more, trade-offs are involved as the method in (11) provides the optimal divisions at a cost of solving an optimization problem. Our method does not guarantee the optimal solution but is much less complex as it takes only two simple equations to be solved instead of an Integer Linear Programming (ILP) problem.

A quick summary of related works is presented in Table 3, which also includes the second proposal of this Doctoral work, the Zone-Based Spectrum Assignment technique, described in the next sections.

Table 3 – A summary of related works.

Work	Year	Fragmentation	Unfairness
"A study on dynamic spectrum assignment for fairness in elastic optical path networks" (12).	2014	✗	✓
"Distance-adaptive online RSA algorithms for heterogeneous flex-grid network" (3).	2014	✗	✓
"Alternative routing and zone based spectrum assignment algorithm for flexgrid optical networks" (13).	2014	✓	✗
"Spectrum management in heterogeneous bandwidth networks" (11).	2014	✓	✓
"Static Zone-Based Spectrum Assignment technique" (15).	2015	✓	✓

4.2 Static Zone-Based spectrum assignment algorithm

As described in Chapter 2, intra-link fragmentation losses happen when connections with different "sizes" coexist altogether in the same link. In consequence of that, the idea of Zone-based spectrum assignment algorithm is to divide the spectrum transforming the expected heterogeneous environment in a set of smaller and homogeneous environments (i.e., partitions).

Before continuing with further explanations, some clarifications are needed. From now on, following terminology is used:

- A *request* (or requisition) stands for a new client requesting resources from the network. A request is composed of a triple (*source*, *destination*, and *bitrate*).
- Different *requests types* with varied bitrate requirements are called *services* or *services types*, e.g., 40 Gbps, 100 Gbps.
- Once a request of a determined service type is accepted, it becomes an *active connection* or just a *connection.*
- Each connection occupies resources (or bandwidth). As said in Chapter 2, the basic "size unit" in EONs is the 12.5 GHz *frequency slot* or just *slot.*
- Whenever is said *connection size*, it is meant the *number of slots* it is occupying in the fiber.

In summary, new *requests* require resources (*slots*) from the network to transport the requested demand (*bitrate*) from a *source* node to a *destination* node. If the network accepts it, the requisition becomes a *connection.*

The proposed method takes advantage of spectrum management to address both fragmentation and unfairness problems by paying particular attention to partitions delimitation, ensuring coexistence of similar services within each partition and ensuring each partition has the same capacity (i.e., can accommodate the same maximum number of connections at a given time). Homogeneity is guaranteed since each partition only supports connections with the same size. Such homogeneity mitigates the effects of intra-link fragmentation. Although the fragmentation is not completely removed, this division ensures that every single fragment of the spectrum has enough space to accommodate at least one connection, therefore not being a problem anymore. It is worth mentioning that homogeneity does not influence the inter-link fragmentation.

What differs this proposal from previous works is the division method used to establish the zones. The idea is to maintain the same maximum number of connections for each possible service type, adjusted by the traffic pattern. For example, supposing three service types are coexisting in the same network and uniform traffic; the spectrum would be divided into three zones, holding X connections each. In total, 3X connections could exist at the same time, X connections per service type. This concept is illustrated in Figure 21. In Figure 21 (a) the zones are configured based on uniform traffic with the ratio 1:1:1 between services types, implying in the same maximum number of connections accommodated within each zone simultaneously (i.e., four for each service type). Figure 21 (b) and (c) illustrate how the zones are influenced by non-uniform traffic patterns, the ratio 1:1:2 results in doubling Type3 connections, whereas the proportion 4:1:1 implies in four times more Type1 connections.

To describe the zones division it is introduced the following notation:

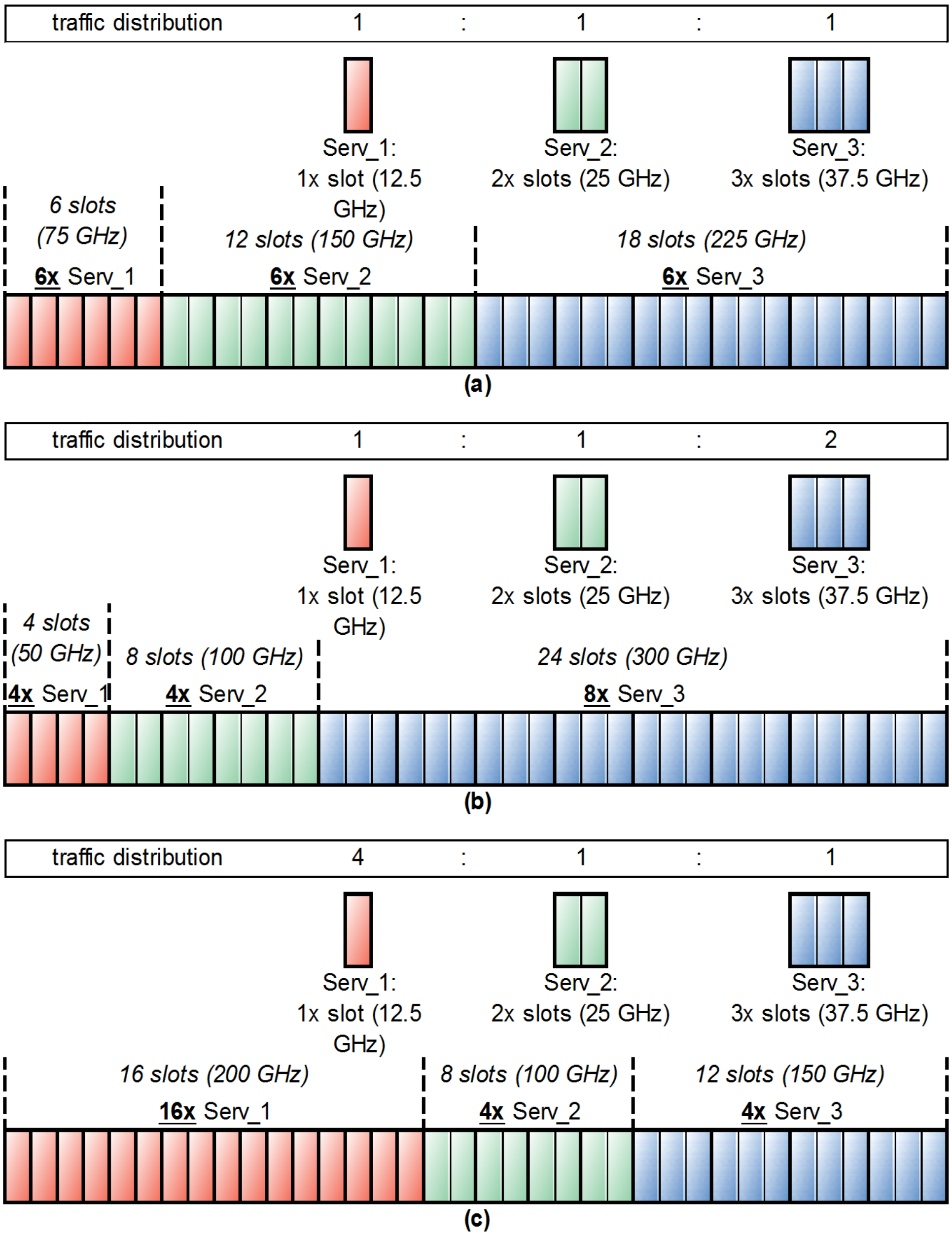


Figure 21 – Illustration of different zone configuration, based on various traffic patterns. (a) Uniform traffic (1:1:1) implies in the same maximum number of connections accommodated within each zone simultaneously. (b) Non-uniform pattern (1:1:2) results in doubling Type3 connections. (c) Non-uniform pattern (4:1:1) implies in four times more Type1 connections.

B_{max} : Total bandwidth available in each link (in 12.5 GHz *slots*).

St : Set of all possible service types, $St = \{St_1, St_2, ..., St_n\}$ (also in *slots*).

Tr : Set of traffic ratio for each service type, $Tr = \{Tr_1, Tr_2, ..., Tr_n\}$.

K : Maximum number of connections allowed simultaneously within each zone (before traffic ratio compensation).

Zc : Set of zones capacities, $Zc = \{Zc_1, Zc_2, ..., Zc_n\}$ (e.g., $Zc_1 = 36$ means 36 slots are reserved for zone Zc_1 that contains only services St_1),

where K and Zs are defined as follows:

$$K = \left\lfloor \frac{B_{max}}{\sum_{i=1}^{n} St_i \, Tr_i} \right\rfloor \tag{1}$$

$$Zc_i = K \; St_i Tr_i \tag{2}$$

Using Figure 21 (c) values, $B_{max} = 36$, $St = \{1, 2, 3\}$, and $Tr = \{4, 1, 1\}$, Equation (1) gives $K = 4$ and Equation (2) gives $Zc = \{16, 8, 12\}$. The value $K \, Tr_i$ gives the maximum number of connections that can coexist simultaneously at any given time for service type St_i whereas the Zc_i represents the number of slots needed by the zone to support those connections.

Figure 22 illustrates how the Zone-Based spectrum assignment technique compares to other methods presented in Section 4.1. Same values of the Figure 21 are used (i.e., connections with sizes from 1 to 3 slots, 36 slots per link, and uniform traffic pattern). Figure 22 (b) shows how connections could be allocated without any spectrum management; this is called Spectrum Sharing (SS). One simple way to manage spectrum is dividing it into partitions with the same number of slots. It is called Simple Spectrum Partition (SP) Figure 22 (c) (14). Figure 22 (d) shows Partial Sharing Partitioning – 25% (PSP-25), with a shared zone that can be used as an “overflow zone” (13). Finally, Figure 22 (e) illustrates the proposed Zone-Based partitioning (ZB), which fixes the same maximum number of connections within each partition (15).

Our method was developed to work using as less information as possible, and only data it is believed to be easily retrieved from the network. For instance, blocking rates are not necessary as inputs such as in (11), beeing instead, one of the possible outcomes to be analyzed. Previous works (35, 37) suggest that the needed information (e.g., network topology and the maximum amount of resources available) could be extracted from the network by making use of available management plane software in conjunction with intelligent control plane, such as PCE (Path Computation Element), or SDN (Software

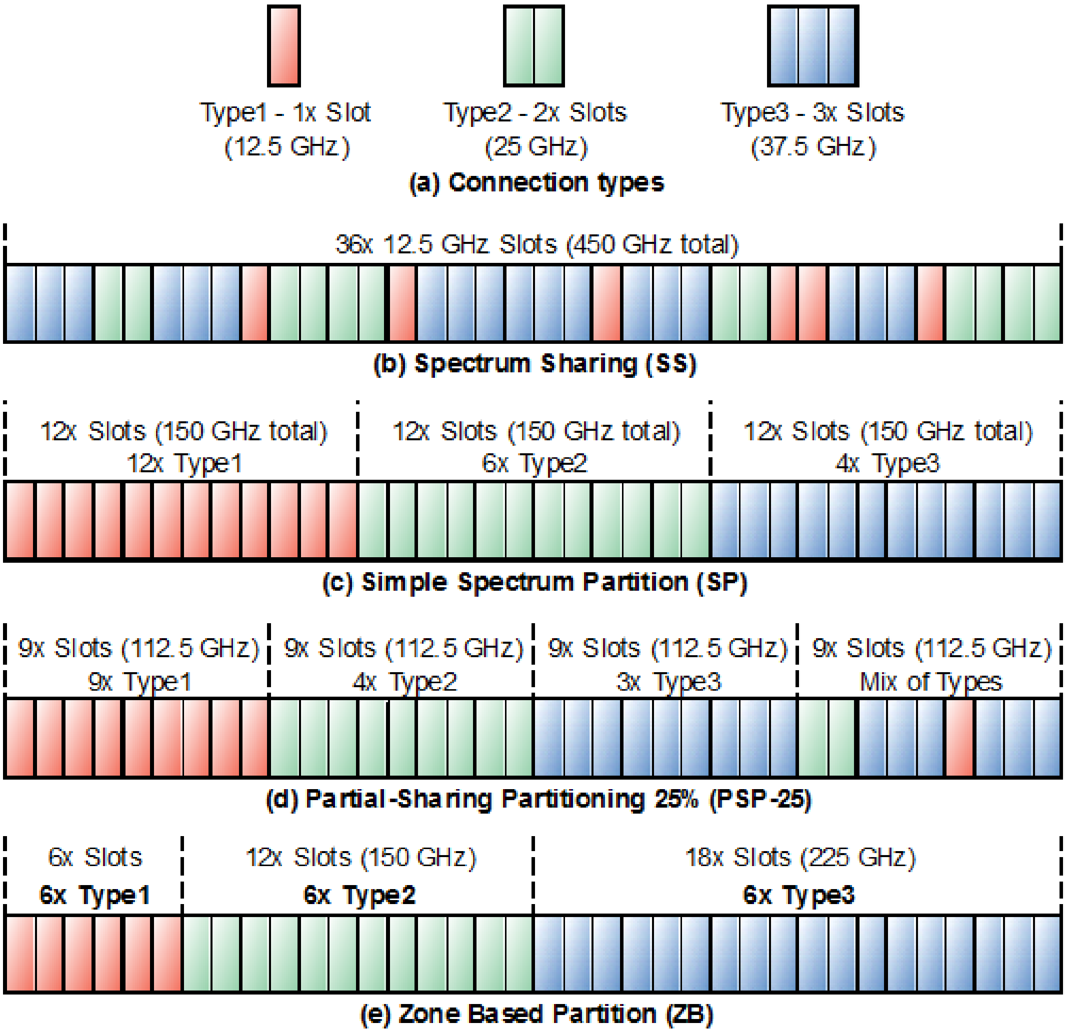


Figure 22 – (a) The four services types from this example. (b) Spectrum Sharing (SS): no particular policy. (c) Simple Spectrum Partition (SP): all zones with same size (14). (d) Partial-Sharing Partitioning 25% (PSP-25): a shared zone occupying with 25% of the total available spectrum (13). (e) Zone-Based partitioning (ZB): equal maximum number of connections within each zone (15).

Defined Network) for example. In the next section it is presented how the Static Zone-Based Spectrum Assignment algorithm performs.

4.2.1 Simulation setup

This section presents some simulations performed to evaluate how the Static Zone-Based spectrum assignment (SZB) algorithm behaves under different conditions. The objective is to determine how the proposed algorithm performs regarding both the unfairness and the fragmentation problems mentioned before in this text. As Equations (1) and (2) show, the SZB is dependent on the traffic transported by the network. Therefore, it is interesting to evaluate how the algorithm responds to varied traffic patterns. We are also intrigued to verify if the proposed algorithm can decrease the performance impact of the intra-link fragmentation. In total, five tests are presented, comparing four different algorithms using three different metrics.

The five tests have the intention to explore the limitations of the Static Zone-Based algorithm, proposing scenarios that are believed to be good and bad for the proposed technique. Proposed tests are:

- Test T0: utilizes uniform traffic and an optimum ratio between service types and the maximum bandwidth available. Between the tests, T0 is considered the best case scenario for the SZB algorithm.
- Test T1: also uses uniform traffic distribution but with a mismatch proportion between parameters, which causes a spectrum waste for the SZB algorithm.
- Test T2: uses a non-uniform traffic ratio between services, increasing the ratio of heavier services (i.e., 1 Tbps).
- Test T3: utilizes a non-uniform traffic ratio between services but increasing the proportion of lighter services (i.e., 40 Gbps).
- Test T4: is intent to test if and how much a defragmentation algorithm influences the Static Zone-Based algorithm performance.

All simulations were performed using ElasticO++. It was utilized the American topology NSFNET, composed of 14 nodes and 21 bidirected links (7). In all tests besides test T1, the maximum bandwidth available per fiber link (B_{max} in Equation (1)) is configured to 360 slots ($360 \cdot 12.5$ GHz $= 4.5$ THz) (C-band). Test T1 uses 359 slots as maximum bandwidth. A dynamic network operation scenario is simulated in all simulations, following the Erlang model with new requests arriving at λ Poisson rate and holding time exponentially distributed (with a normalized mean of $1/\mu = 1$). Network load is given by $\rho = \lambda/\mu = \lambda$ (Erlang). In each simulation run, 10^5 requests are generated, and each chart point is represented by the average of 30 simulations with different random seeds. Error bars represent the standard deviation.

As described in Section 3.5.1, each new request is composed of a source, a destination, and a bitrate requirement. In all tests, four different service types are allowed in the network with bitrates of 40 Gbps, 100 Gbps, 400 Gbps, and 1 Tbps. Those bitrates are translated to the set of service types $St = \{3, 4, 7, 16\}$ (in slots) after applied an implementation of the DP-QPSK modulation format and considering a 10 GHz guard band, according to the Table 1 in (22) [1]. Note that four connections of 100 Gbps are

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[1] In a more realistic (or optimized) scenario, the modulation format utilized should be dependent on the links distances and conditions. Although ElasticO++ can handle those situations, it was adopted the same modulation format to all requisitions regardless of the distances to reduce the complexity of the tests.

different from one connection of 400 Gbps regarding spectrum utilization. This difference is due to the fact that OFDM can form super-channels, aggregating sub-carries, ignoring the guard band between them, thus increasing spectrum utilization. As the focus of this Doctoral work is not the physical layer, no physical impairments are considered. Still related to the service types, each test follows a set of traffic ratio between services. Tests T0, T1, and T4, uses a uniform ratio of 1:1:1:1, $Tr = \{1, 1, 1, 1\}$ (i.e., 25% probability for each service type per new request), whereas T2 and T3 utilizes a non-uniform ratio of $Tr = \{3, 1, 1, 10\}$ and $Tr = \{10, 1, 1, 3\}$ respectively. For each new requisition, the controller evaluates if the network has enough resources to allocate the request, thus creating a new connection and occupying resources. If rejected, the requisition is blocked, and the blocking statistics are updated (Figure 4 - Section 2.1).

In each test besides test T4, four RMSA algorithms are compared. As discussed in Section 3.4, each RMSA algorithm is composed of four parts: a routing algorithm, a modulation scheme, a spectrum management technique, and a spectrum assignment algorithm. Since the focus of this chapter is the spectrum management and assignment, and as an effort to reduce the number of variables, each RMSA algorithm tested shares the same routing algorithm and the modulation scheme, thus reducing this test to an SA (Spectrum Assignment) problem. The routing algorithm chosen is the Yen's K-Shortest Paths (50, 51), using $K = 5$. Link lengths are also not considered in this test, as explained before. Therefore Yen's algorithm selects the shortest routes by evaluating the number of hops. The modulation scheme used is the DP-QPSK and it is assumed that DP-QPSK modulation can be assigned to all connections with no problems (22). The compared algorithms are:

- SP_FF: Simple Spectrum Partition (14) and First Fit.
- SS_FF: Spectrum Sharing First Fit (20).
- SS_NC: Spectrum Sharing with No Constraints.
- SZB: Static Zone-Based Spectrum Assignment.

The Simple Spectrum Partition (SP_FF) algorithm divides the spectrum equally between services types. For example, with a bandwidth of 360 slots and four services types, each partition would have 90 slots regardless any other characteristic as shown in Figure 22 (c). It is expected that this SP_FF algorithm performs better in test T3, in which a higher proportion of less demanding requests is generated. This result is expected since it divides the spectrum equally between partitions, and the partitions for the smaller connections can hold more connections simultaneously. By the same reason, test T2 should be the worst. Since the algorithm does not take into account any traffic or service characteristic during the partitioning, it is expected to be a very unfair algorithm.

The Spectrum Sharing First Fit (SS_FF) is very often used as a benchmark in publications of new assignment algorithms. It is a good overall solution regarding blocking rates but, as no policy concerning spectrum allocation is employed, SS_FF is expected to be more unfair as the difference in size of the services types increases. Performance-wise, it is the most important from the algorithms to compare to the SZB algorithm. SS_FF is illustrated in Figure 22 (b).

At least, the Spectrum Sharing No Constraints (SS_NC) algorithm is an attempt of creating a baseline comparison. SS_NC algorithm ignores both elastic optical network constraints discussed in Section 2.1. In this way, when it is searching for resources to attend a new request, it examines the available resources in each link as an integer parameter, without verifying if the slots are contiguous within each link neither if the slots are continuous throughout all the path. This algorithm is not an optimized solution nor can provide the best results possible. It is just an attempt of evaluating what could be done considering the order of arrivals and termination of the connections if the equipment utilized to implement optical networks did not have cited limitations. Table 4 summarizes the tests, setup differences and algorithms used.

Table 4 – A summary of the simulated tests.

Test	B_{max} (slots)	Traffic Ratio	Algorithms tested
T0	360	Uniform (1:1:1:1)	NC, SS, SP, SZB
T1	359	Uniform (1:1:1:1)	NC, SS, SP, SZB
T2	360	Non-uniform (3:1:1:10)	NC, SS, SP, SZB
T3	360	Non-uniform (10:1:1:3)	NC, SS, SP, SZB
T4	360	Uniform (1:1:1:1)	SS, SS + Defrag, SZB, SZB + Defrag

Three metrics are used to evaluate algorithms performance in following tests: requests blocked rate (RBR), bitrate blocked rate (BBR), and service fairness (RBR_{Sti}). RBR is defined by Equation (3):

$$RBR = R_b/R_t, \tag{3}$$

where R_b represents the number of requests blocked at the end of the simulation and R_t is the total number of requisitions generated. Likewise, the BBR is given by Equation (4):

$$BBR = B_b/B_t, \tag{4}$$

where B_b is the total bitrate blocked, and B_t is the total bitrate requested. Finally, the service fairness is evaluated by comparing the service requests blocked rates (RBR_{Sti})

between all service types. RBR_{Sti} in defined by Equation (5) as follows:

$$RBR_{Sti} = R_{bSti}/R_t, \tag{5}$$

where R_{bSti} stands for the number of requests blocked of service type St_i and R_t is the total number of requisitions generated. The greater is the difference between the blocked rates the more unfair is the algorithm in the scenario analyzed.

4.2.2 Results

The test T0 is set with a uniform traffic ratio ($Tr = \{1, 1, 1, 1\}$) and maximum bandwidth $B_{max} = 360$ that combined with the service types ($St = \{3, 4, 7, 16\}$) results in an integer value of K (Equation (1)), and therefore no spectrum waste to SZB algorithm.

T0 results are presented in Figure 23, organized in the following manner: (a) and (b) display request blocked rates (RBR) and bitrate blocked rates (BBR) respectively. (c), (d), (e), and (f) show the RBR values of the different service types for each of the four algorithms simulated.

Analyzing Figure 23 (a), as expected, SS_NC algorithm presents the best performance concerning RBR, followed by SS_FF and SZB, and at last by SP_FF algorithm. It is possible to observe that SS_FF outperforms SZB in most load values. At very high loads, SZB tends to block more than all other algorithms due to the restrictive zone allocation policy. This blocking happens in situations where one zone is entirely occupied due to a non-uniform burst of requisitions, while other zones may still have free resources. As SZB zone assignment is restrictive, requests are blocked even when there are available resources in the network.

Figure 23 (b) shows that SZB performs worst than SS_FF at light loads, but starts achieving better BBR results after 350 Erlang load. Not surprisingly, SS_NC and SP_FF obtained the best and the worst BBR results respectively.

Regarding the fairness results, Figure 23 (c) shows the results achieved by the Simple Partition (SP_FF) algorithm. Since the spectrum is divided equally between the service types, the zones assigned to the less demanding services can accommodate more connections simultaneously. In this particular scenario, the partition designed to 40 Gbps requests can hold up to 30 connections simultaneously, against only five 1 Tbps connections. Figure 23 (d) presents the results of the Spectrum Sharing First Fit (SS_FF) algorithm. As SS_FF does not apply any spectrum management method, the higher is the bitrate requirement of the requisition, the higher is the probability of being blocked. Comparing the results of Spectrum Sharing No Constraint (SS_NC) and (SS_FF), it is noticeable how the curves are much closer, thus indicating a fairness increased. The same effect is much more evident in the Static Zone-Based algorithm (SZB), Figure 23 (f), in which there is virtually no difference between the services RBR.

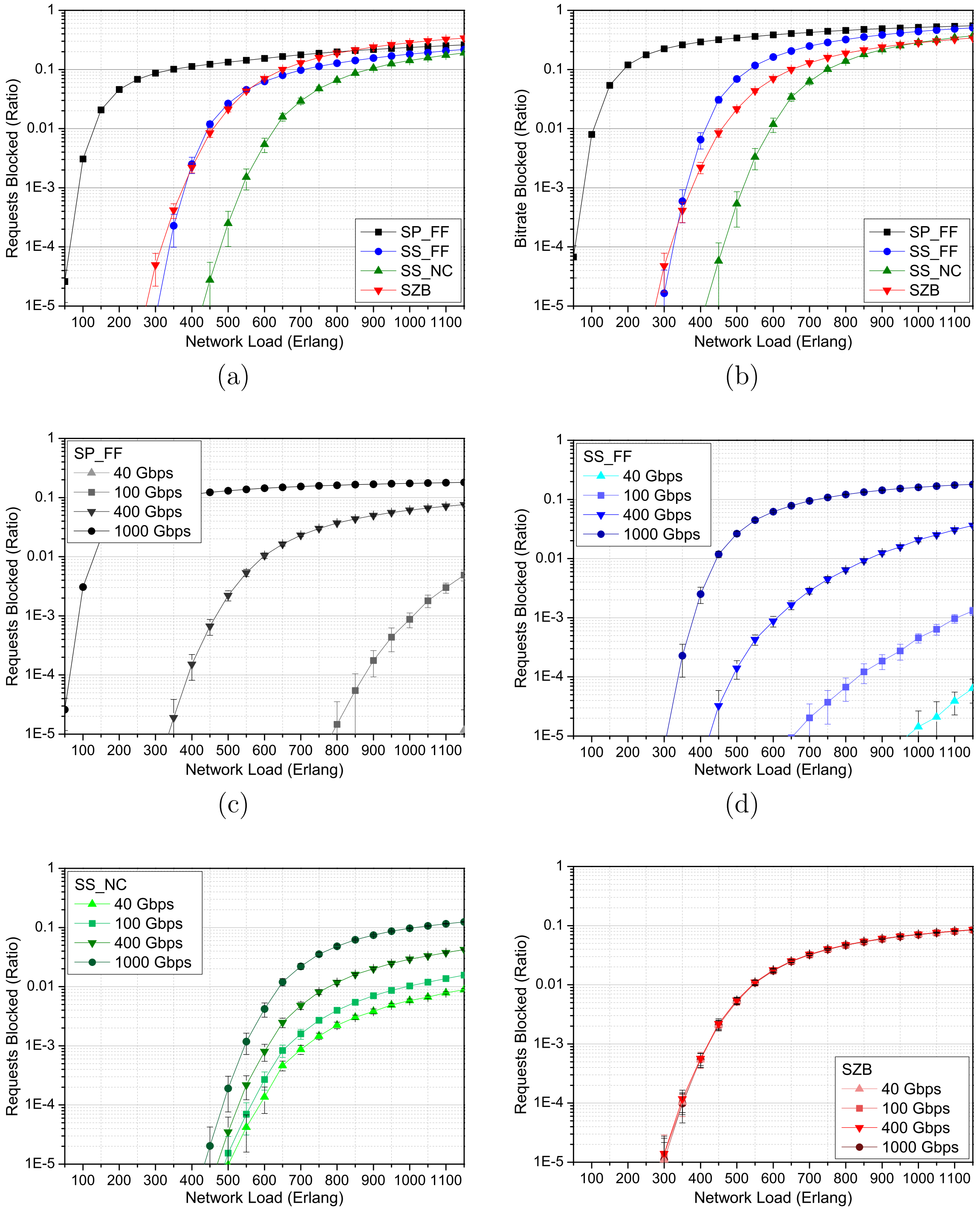
Test T0 shows signs that there is a relation between RBR, BBR, and fairness in this scenario. When the network load increases, and if the environment is unfair, then a higher rate of smaller connections is accommodated (reducing RBR relatively to a less unfair environment). Since smaller requests have a higher probability to find a suitable path through the network, those requests tend to occupy more and more resources, restricting the viable paths to more demanding services, thus increasing their RBR and the overall network bitrate blocked rates. A more fair environment may reduce the probability of a less demanding service getting accepted by the network (i.e., increasing overall RBR), while increasing the allocation chance of bigger connections, thus decreasing overall BBR in uniform scenarios.

Likewise, test T1 is configured to use a uniform distribution, reducing the maximum bandwidth available in each link from $B_{max} = 360$ to $B_{max} = 359$. This change induces a mismatch between St and B_{max}, implying in a spectrum waste for the SZB algorithm. Equation (1) gives $K = 11$, rounded down from 11.97, whereas Equation (2) gives $Zc = \{33, 44, 77, 176\}$. Adding Zc values, it is possible to verify that only 330 slots are used effectively. This test exploits what may be the biggest weakness of SZB algorithm, as only one slot ($\approx 0.28\%$) can cause waste as higher as 29 slots ($\approx 8.1\%$). The Simple Partition (SP_FF) technique also suffers from the mismatch, a total of 3 slots ($\approx 0.8\%$) without accounting for intra-zone waste. None of the other algorithms compared suffer from spectrum waste. It is important to note that with a different combination of parameters, this waste can be even higher, and therefore it is an important aspect to keep track when using SZB-like algorithms.

As a consequence of the wasted spectrum, SZB performs worse when comparing to test T0 in both RBR and BBR metrics, but as Figure 24 (a) shows, despite the waste, SZB still performs better than SS in loads higher than 400 Erlang. Although the rounding of the parameter k causes the described undesired waste effect, it enhances fairness even in mismatching scenarios, Figure 24 (b). The fairness results from the other algorithms are omitted since they are almost indistinguishable from the results of Figure 23.

Test T2 is set to use a non-uniform traffic ratio between service types, prioritizing the arrival of heavier demands. The ratio used is $Tr = 3, 1, 1, 10$, implying in the following proportion between services: 20% for 40 Gbps, $\approx 6.6\%$ for 100 Gbps and 400 Gbps, and $\approx 66.7\%$ for 1 Tbps service. SS_SP in test T2 divides the spectrum in the same way as in test T0 (i.e., four partitions of 90 slots each), whereas SZB establishes its zones according to Tr, resulting in the following values: $K = 2$ (Equation (1)) and $Zc = \{18, 8, 14, 320\}$ (Equation (2)). None of the algorithms experience spectrum waste.

Figure 25 presents the results of test T2. As can be seen in Figure 25 (a) and (b) at

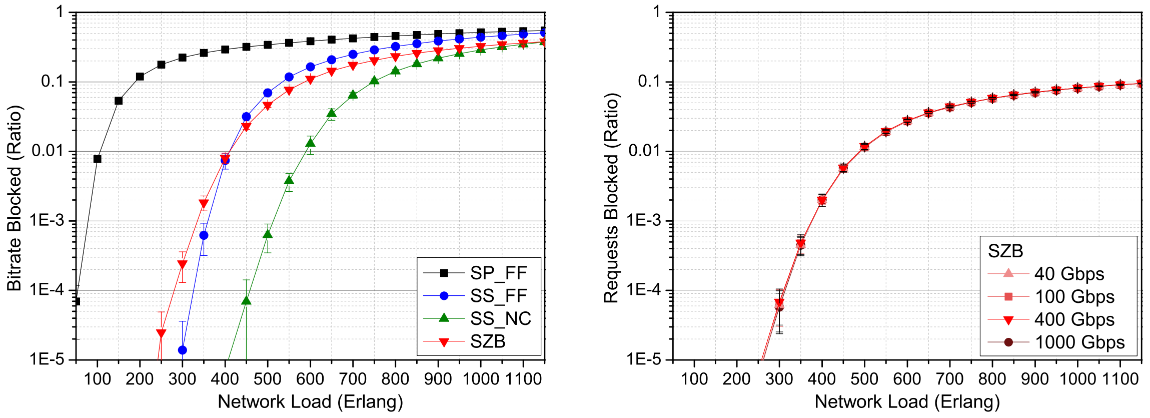


(a) (b)

(c) (d)

(e) (f)

Figure 23 – Test T0 results: (a) Requests blocked ratio. (b) Bitrate blocked ratio. Requests blocked ratio distinguish per Service Type: (c) Simple Partition First Fit (SP_FF) algorithm; (d) Spectrum Sharing First Fit (SS_FF); (e) Spectrum Sharing No Constraints (SS_NC); (f) Static Zone-Based (SZB).



(a) (b)

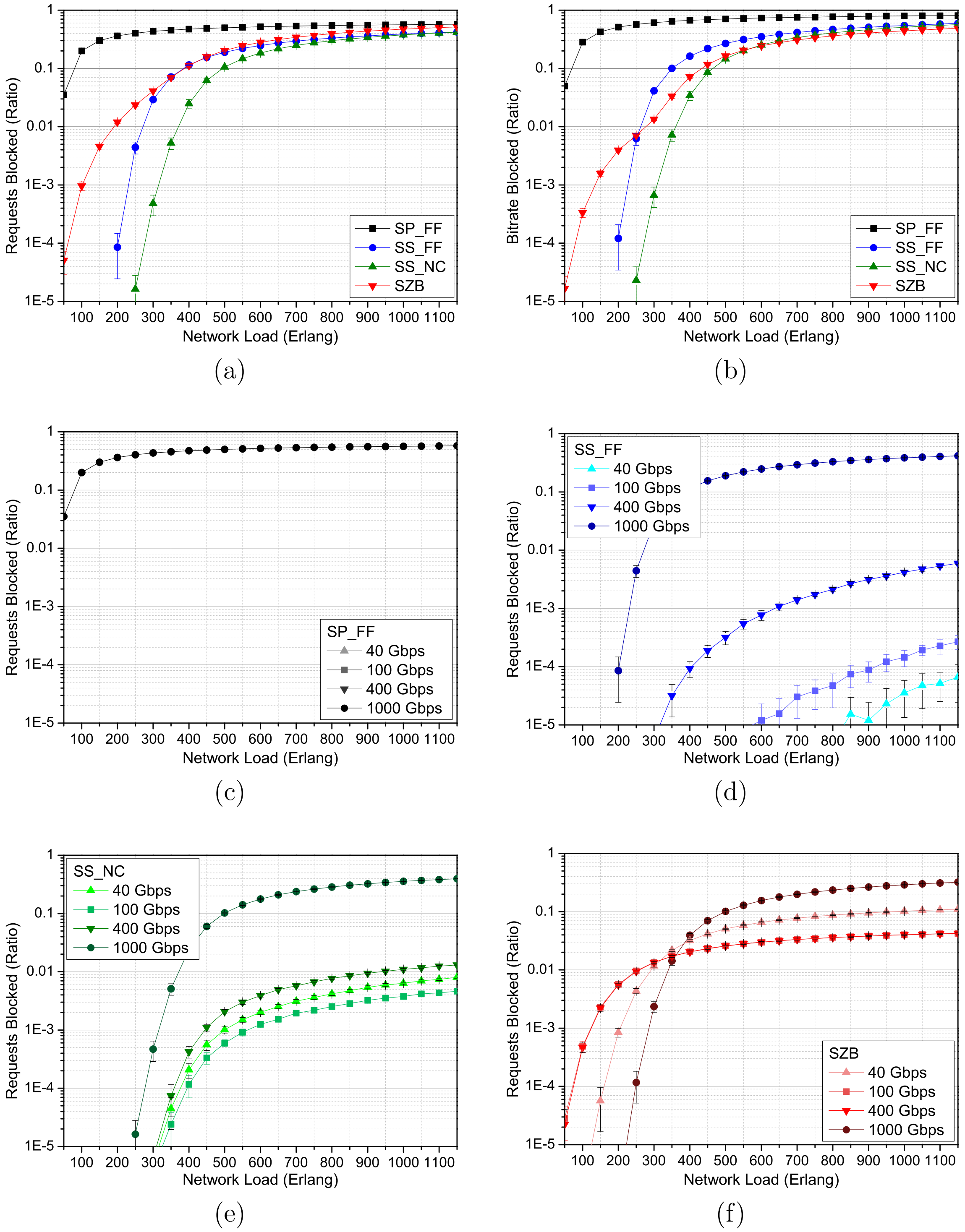
Figure 24 – Test T1 results: (a) Bitrate blocked ratio. (b) Requests blocked ratio of 40 Gbps, 100 Gbps, 400 Gbps, and 1 Tbps services for Static Zone-Based (SZB) algorithm.

lower loads, it is observed a similar behavior from Figure 23 (a) and (b), with the SS_FF algorithm performing better than SZB regarding RBR and BBR. When comparing the SZB and SS_FF curves in Figure 25 (b) it is observed that SZB starts to perform better than FF earlier, about 250 Erlang against the 350 Erlang load from test T0. We believe two reasons justify this behavior: the heavier traffic pattern, and again, the fairness. As the strongest point of the SZB is to prevent unfairness, it enables a higher number of more demanding services to be allocated, thus reducing the total bitrate blocked.

Observing Figure 25 (f) it is interesting to see how the non-uniform traffic impacts the fairness results. In lower loads, the 100 Gbps and 400 Gbps services experience much higher RBR than 40 Gbps and 1 Tbps services. This behavior is inverted under higher loads. Figure 25 (f) also shows that SZB reaches its best fairness performance between 300-450 Erlang (peaking in 350 Erlang). In fact, after analyzing (a) in 300-450 Erlang range, it is visible how the SZB curve reaches the same level of performance of the SS_FF algorithm. Although achieved fairness is not good as the fairness observed in previous tests, it is still the best between the compared algorithms. After comparing Figure 25 (c), (d), (e), and (f) against Figure 23 (c), (d), (e), and (f), it is noticeable that the heavier traffic pattern increases the unfairness among all algorithms, not only to SZB. The difference is evident in SS_NC results (e).

The test T2 is the worst scenario for SP_FF algorithm as its division can not keep up with the massive number of 1 Tbps requests. SP_FF results illustrate how devastating a bad choice while partitioning can be to the network performance.

It is also valuable to point that there is an opportunity cost involved with the SS_NC algorithm. At extremely high levels of network occupation, there is a possibility that after accepting a small request (e.g., three slots) the total remainder spectrum is not



(a) (b) (c) (d) (e) (f)

Figure 25 – Test T2 results: (a) Requests blocked ratio. (b) Bitrate blocked ratio. Requests blocked ratio distinguish per Service Type: (c) Simple Partition First Fit (SP_FF) algorithm; (d) Spectrum Sharing First Fit (SS_FF); (e) Spectrum Sharing No Constraints (SS_NC); (f) Static Zone-Based (SZB).

enough to support a bigger request (e.g., 16 slots) that may arrive next. This situation is observed throughout all tests presented, and it is more evident in Figure 25 (b). It is important to highlight that this situation may never happen in a realistic network operation scenario, given the magnitude of the blocking rates involved ($\approx 40\% RBR$). Table 5 shows some values of bitrate blocking rates extracted from Figure 25 and correlate it with 1 Tbps service blocked rates (RBR_{1Tbps}).

Table 5 – Correlation between bitrate blocked rates (BBR) and requests blocked rates of 1 Tbps service (RBR_{1Tbps}) in three different network loads in test T2.

	350 Erlang Load (BBR / RBR_{1Tbps})	550 Erlang Load (BBR / RBR_{1Tbps})	750 Erlang Load (BBR / RBR_{1Tbps})
SS_NC	0.58% / 0.41%	19.72% / 13.85%	37.83% / 26.52%
SZB	3.31% / 1.44%	20.88% / 13.21%	33.64% / 21.86%

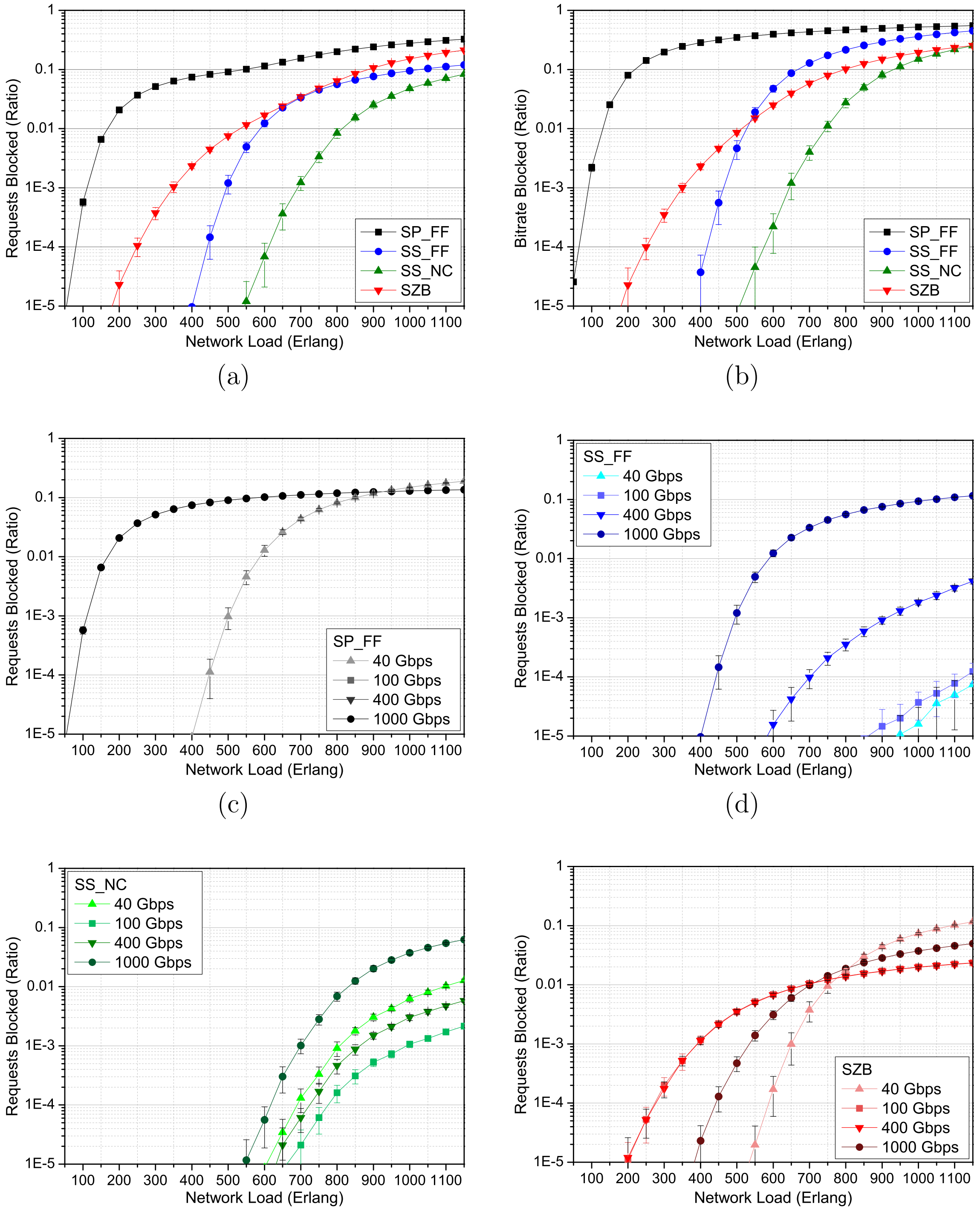
Test T3 is set to use a non-uniform traffic ratio between service types, prioritizing the arrival of heavier demands. The ratio used is $Tr = 10, 1, 1, 3$, implying in the following proportion between services: $\approx$ 66.7% for 40 Gbps, $\approx$ 6.6% for 100 Gbps and 400 Gbps, and 20% for 1 Tbps service. As a result of this configuration, the SZB algorithm experiences a minor spectrum waste of four slots ($\approx$ 1.1%).

Since the most abundant service type in the network is the smallest one, it is expected this test to be the worst for the algorithm SZB regarding both blocking rates. For the same reason, this is presumed to be the best scenario to SP_FF algorithm. Indeed, Figure 26 (a) and (b) confirm it and shows that SZB and SS_FF curves touch point is pushed to 650 Erlang in (a), and to 550 Erlang in (b).

Interestingly, a similar pattern from Figure 25 (f) appears in Figure 26 (f), at a higher 750 Erlang load, but with an inversion between the 1 Tbps and the 40 Gbps RBR curves. This result confirms the result from test T2, thus indicating that the relation between the traffic pattern and the partitioning required to maintain optimum fairness is non-linear. This subject deserves further investigation in future works.

Finally, test T4 aims to investigate if using a defragmentation technique improves or not the Static Zone-Based (SZB) performance. An in-house implementation of the Make-Before-Break (MBB) (5) algorithm is used.

Defragmentation algorithms like MBB work moving existing connections in the network towards an end of the spectrum (e.g., moving connections to lowest frequencies available when possible). This spectrum reorganization reduces the number of unused (and possibly unusable) spectrum fragments (i.e., intra-fragmentation). Since MBB improves network performance by mitigating the intra-fragmentation occurrence, we believe that after applying the MBB algorithm a fragmented network would get better results whereas



(a) (b)

(c) (d)

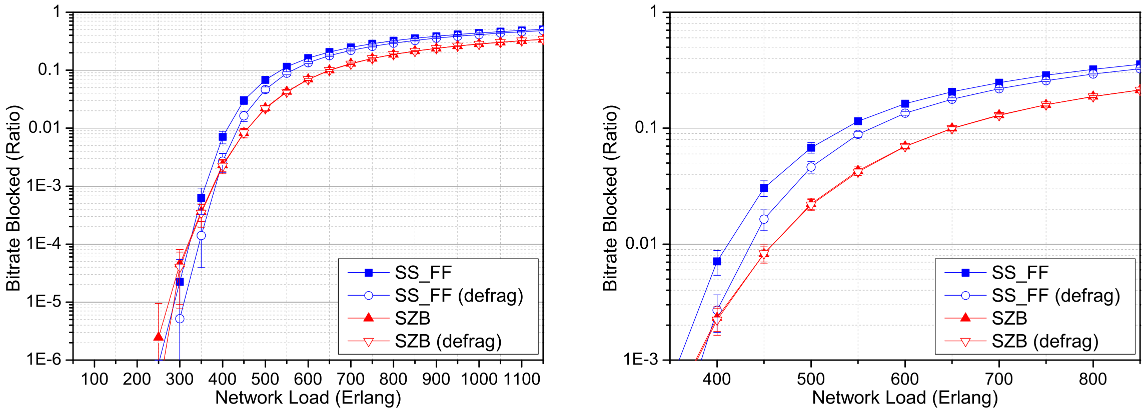
(e) (f)

Figure 26 – Test T3 results: (a) Requests blocked ratio. (b) Bitrate blocked ratio. Requests blocked ratio distinguish per Service Type: (c) Simple Partition First Fit (SP_FF) algorithm; (d) Spectrum Sharing First Fit (SS_FF); (e) Spectrum Sharing No Constraints (SS_NC); (f) Static Zone-Based (SZB).

a non-fragmented network would not.

Therefore, the premise of this test is that by running the MBB algorithm in conjunction with the SZB and confirming that the MBB does not reduce the RBR nor the BBR, provides evidence that SZB avoids the "problematic" intra-link fragmentation. Of course, there will be empty spaces within the links, however, as long those fragments are multiple of the zone designed connection size, that fragmentation does not impact the performance.

Figure 27 presents the results of the SZB algorithm and also the SS_FF algorithm, used as a "control test". The improved performance of SS_FF in BBR (a) metric proves that the MBB does work. Figure 27 (b) shows a zoomed version of (a). On the other hand, the results show that the SZB does not benefit from the MBB defragmentation algorithm. Although this result alone is not sufficient to prove that the SZB solves inter-fragmentation problem, it is evidence that SZB is indeed helping mitigate the problem.



(a) (b)

Figure 27 – Test T4 results: Bitrate blocked ratio. (a) Full range. (b) Curves zoomed for more detail.

4.3 Dynamic Zone-Based Spectrum Assignment Algorithm

Section 4.2 describes how the Static Zone-Based spectrum assignment algorithm works and how the spectrum is partitioned according to Equation (1) and Equation (2). The partitioning is *highly dependent* on the traffic pattern in the network. In cases where the nature of the network traffic is known beforehand, and the traffic does not change, the static version can perform well, as results in Section 4.2.1 show.

The question that naturally comes next is "What if the traffic pattern is unknown and/or varies over time?" In both cases, the static version of the algorithm would not be capable of establishing proper zones boundaries and/or would not perform according the expected.

In this context, we present the Dynamic Zone-Based Spectrum Assignment Algorithm (DZB). The proposed technique is capable of monitoring the traffic, infer a compatible distribution that fits the received traffic, and then use this calculated traffic distribution to adjust the zones boundaries dynamically.

At first, it is assumed that no information regarding the network traffic is known during the algorithm initialization. The first step of the proposed algorithm is to acquire data regarding traffic received. However, the network can not afford to reject requisitions while waiting for the algorithms calibration, thus needing to attend the arriving requests. Consequently, the use of an auxiliary algorithm is necessary during this calibration phase.

After dozens of simulations performed during this Doctoral work, empirical results induce to the conclusion that the first fit algorithm is a good all-around solution. The first fit algorithm is easy to implement, and it is light in matters of complexity and computational power needed to be executed. Suppose that a network is starting its operation, and there are plenty of resources available. If the service demand is low, there is no need to use complex algorithms, and the first fit should be enough. Therefore it makes sense to use the first fit algorithm as the auxiliary algorithm throughout the setup of the DZB algorithm. Figure 28 shows how the algorithm works.

As requests arrive in the network, the DZB algorithm stores data regarding the number of slots demanded. After X requisitions (X is configurable), the algorithm reads obtained data of last X requisitions and estimates the ratio between the number of slots held ($\_num\_slots\_$ in Figure 28). The estimation is done by accounting how many times each $\_num\_slots\_$ was requested; then it normalizes by the lowest value, rounding down the results. This estimated traffic ratio is stored for later use. Next, an internal counter is checked against another configurable parameter (Y in Figure 28) and if both values match the counter is reset, and the flow continues. Y parameter is based on the Central Limit Theorem which states that given a sufficiently large sample size from a population with a finite level of variance, the mean of all samples from the same population will be approximately equal to the mean of the population. After the estimation of the traffic ratio, the algorithm verifies if the network rejected any of the latest $X\,Y$ requests. If not, nothing happens since supposedly current boundaries are good enough, and/or traffic load is low. If at least one request was rejected, the algorithm uses the estimated traffic ratio and delimits the new boundaries of the zones, according to Equation (1) and Equation (2).

The higher the X and Y values are, the better are the results, but the controller takes more time to adapt the zones to the new detected traffic pattern. There is an opportunity cost involved, a trade-off between precision and requests missed because of a wrong zone delimitation.

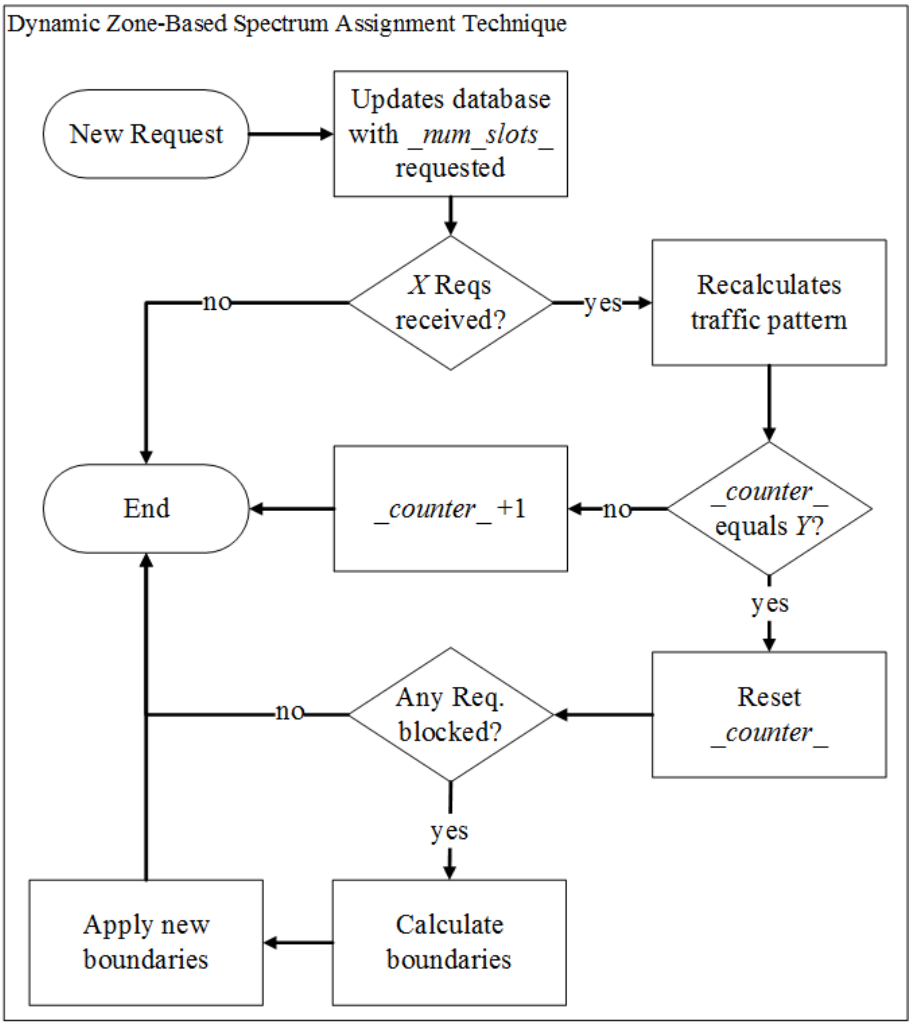


Figure 28 – Dynamic Zone-Based Spectrum Assignment Algorithm.

4.3.1 Simulations

This section presents some simulations of the Dynamic Zone-Based Spectrum Assignment algorithm (DZB). Two tests are presented, the first with no change in the traffic pattern during the simulation and the second with two traffic changes. The following Figures 29 and 30 are created by the ongoing development *Simulation Progression Monitoring* feature of ElasticO++, and plotted automatically by the framework, using the Matplotlib library (55).

This feature allows monitoring the behavior of the chosen metrics throughout the simulation. At the current version of the framework, the resulting chart represents only one simulation run, and, as a consequence can not be used to infer any quantitative conclusion.

In the charts of Figures 29 and 30, the X-axis represents the simulation evolution, using the number of requests (Req #) as the unit. Y-axis represents the monitored metric. The "resolution" of the chart can be increased by configuring the X-axis, decreasing the number of requests between each "snapshot" of the simulation, at a cost of bigger logs and more memory consumption.

The results in Figures 29 and 30 are divided as follows: (a) shows the periodic data. After each step (i.e., X requests in the simulation) monitored data is reset. (b) the bottom part shows the “absolute” values accumulated up to that point in the simulation. (c) shows bitrate blocked ratio and (d) shows requests blocked ratio.

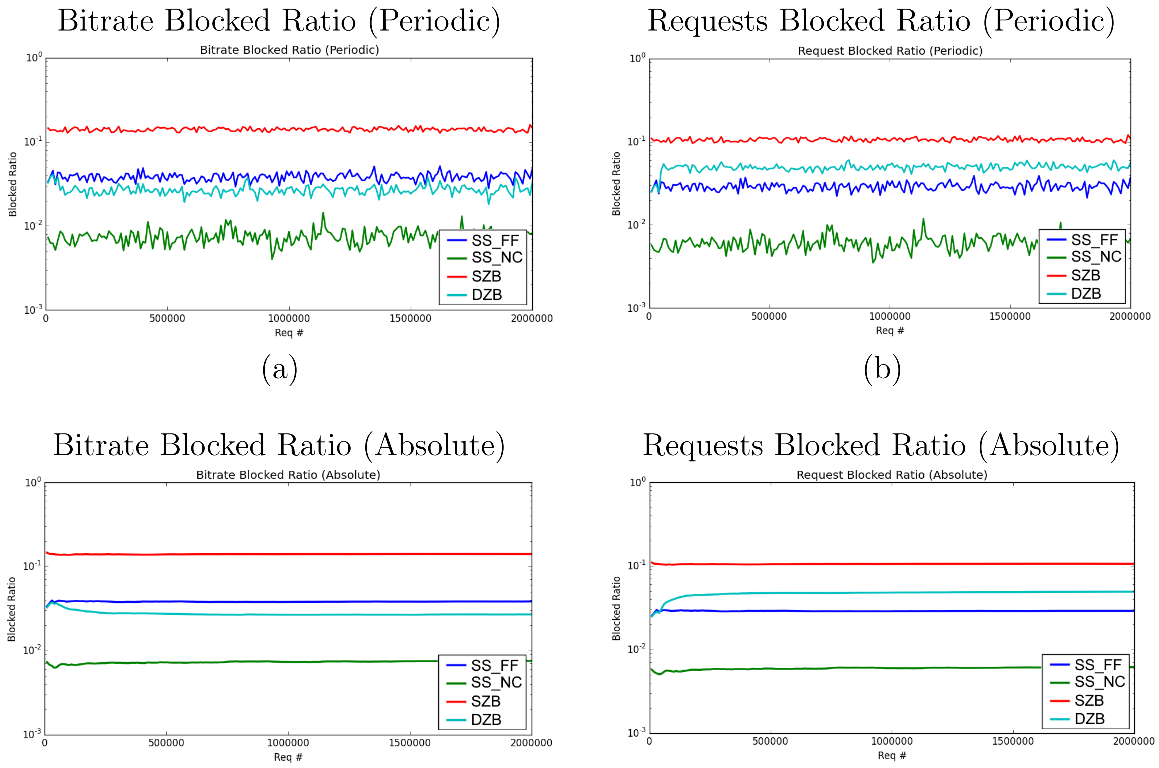
It is important to emphasize at this point that it is not the intent of this section insinuating any conclusion regarding the performance of the simulated algorithms. The performance is not important at the following results, as they are deeply related to simulation parameters, and given the characteristics of the following charts, it would be nearly impossible to display all the situations discussed in Section 4.2.1. What is important is verifying the overall behavior of the DZB algorithm during traffic pattern changes. The other algorithms should be used as guidelines, helping the reader to localize themselves during their analysis.

The four algorithms present in the tests are Spectrum Sharing First Fit (SS_FF), Spectrum Sharing No Constraints (SS_NC), Static Zone-Based (SZB) and Dynamic Zone- Based (DZB). SS_FF and SS_NC are the same of Section 4.2.1. SZB algorithm is calibrated expecting a uniform traffic pattern whereas DZB algorithm parameters X and Y (Figure 28) are configured as of $X = 10000$ and $Y = 3$. Those values are by no means the best to be used. They were select through empirical tray-and-error tests. In fact, there is a whole research field on the topic of traffic/pattern recognition, thus out of the scope of this Doctoral Thesis. Figure 29 shows the results of a simulation of $2 \cdot 10^6$ requests and a fixed traffic ratio of $Tr = \{3, 1, 1, 10\}$.

Figure 30 presents the results of the second scenario simulated, in which the traffic pattern changes over the time. It starts as uniform traffic $Tr = \{1, 1, 1, 1\}$. It is noticeable that DZB starts as a Spectrum Sharing First Fit algorithm as in the leftmost corner of all figures the DZB curve (light blue color) is close to the SS_FF curve (dark blue color). Then, after the first request is blocked the algorithm changes the zones to fit the uniform traffic, approximating to the SZB curve (in red). After one-third of the total requests, the traffic pattern changes to more a demanding proportion $Tr = \{3, 1, 1, 7\}$, increasing overall network load. As a consequence of this increased load, all algorithms suffers from higher blocking rates. After two-thirds of the simulation, the traffic changes again, this time to a ratio of $Tr = \{6, 1, 1, 1\}$. This higher proportion of less demanding services decreases overall blocking rates.

4.4 Conclusions

This Chapter presented the second contribution of this Doctoral Thesis. Related works are described in Section 4.1, the Static Zone-Based spectrum assignment algorithm (SZB)



(a) (b)

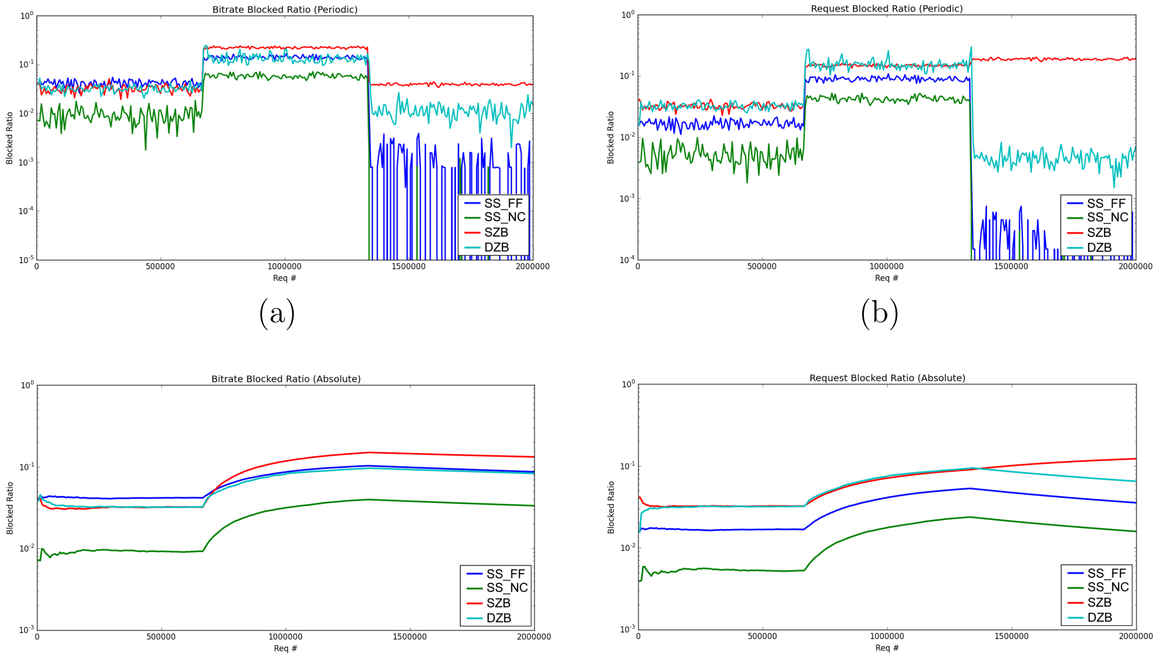
(c) (d)

Figure 29 – Results of a simulation of a fixed traffic ratio $Tr = \{3, 1, 1, 10\}$. Periodic values: (a) bitrate blocked ratio, and (b) requests blocked ratio. Absolute values: (c) bitrate blocked ratio, and (b) requests blocked ratio.

in Section 4.2, and the Dynamic Zone-Based spectrum assignment algorithm (DZB) in Section 4.3.

The SZB algorithm is a technique to be employed in specifics scenarios. It is meant to be used in heterogeneous dynamic network scenarios under heavy load, where the fairness is an important metric and needs to be ensured. All tests conducted indicate a significant improvement on fairness. Although test T4 shows a reduced intra-fragmentation effect, it is still not sufficient evidence that the SZB algorithm should be used exclusively to that end. More investigation is still needed on the subject. From the results shown in Section 4.2.2, it is possible to conclude that Zone-based solutions require some degree of stability to run in a useful way. If the traffic is not stable, then this technique should not be used, as it would not be effective.

By looking at Figure 24 (b), it can be seen that the fairness persists even when a mismatch of between the network and the SZB algorithm parameters is experienced. The increased fairness comes as a consequence of the K parameter from Equation (1) being rounded down, instead of rounding the Zone Sizes. The trade-off is a possible spectrum waste. In test T1, roughly 8% of the total spectrum was wasted, but with different combinations of the parameters St, Tr, and B_{max}, the waste can be increased. This raises



(a) (b)

(c) (d)

Figure 30 – Three different traffic patterns are explored in this test. Periodic values: (a) bitrate blocked ratio, and (b) requests blocked ratio. Absolute values: (c) bitrate blocked ratio, and (b) requests blocked ratio.

a flag that is important to analyze if the SZB algorithm fits the network characteristics before using it.

The DZB algorithm and the tests presented are a concept proof that the SZB technique can be adapted to be utilized in scenarios with no previous information about the network traffic. The results obtained in Section 4.3.1 and the parameters chosen are by no means the best possible, but, again, an evidence that the idea is viable. Further studies are suggested to keep improving the technique performance and usefulness.

Concluding, if the traffic characteristic is known beforehand, and if it does not change over time, the static version should be used. Otherwise, if the traffic pattern is unknown or changes over time, the dynamic version is more suitable. If the traffic is completely random (e.g., never stabilizes, or change very often) it is better to utilize other solution, or even the classic spectrum sharing first-fit.

5 Conclusion

In the past few years, Elastic Optical Networking (EON) emerged as the “next generation” core network technology, intended to surpass Wavelength-Division Multiplex (WDM) weaknesses and limitations. To keep pace with the always greater demand for bandwidth in core networks, EON relies on Optical Orthogonal Frequency Division Multiplexing (OOFDM) and advanced modulation technologies that enhance spectral efficiency and flexibility. OOFDM allows the aggregation of multiple sub-carriers to form super-channels, thus changing the paradigm of the network, from fixed-size WDM channels to variable-sized EON channels that can reduce spectrum waste.

Although several works have pointed EON benefits, there is no perfect technology, and the added efficiency and flexibility comes at the price of increased complexity and new problems, such as spectrum fragmentation and service unfairness. A myriad of works have been done trying to mitigate those questions, but with such richness of results, it is not always possible to choose and test the most suitable solution for each particular scenario.

In this context, Chapter 3 presented the first contribution of this Doctoral Thesis, ElasticO++: an Elastic Optical Network Simulation Framework for OMNeT++. ElasticO++ is a simulation framework that enables rapidly testing of Allocation and Defragmentation Algorithms using a different set of parameters and topologies. To the best of our knowledge, ElasticO++ is the first software available capable of handling fragmentation and defragmentation scenarios.

Since the beginning of the studies on Elastic Optical Networks in January 2014, roughly 70% of the time was invested in its development. It is believed the framework has the potential to grow and become a useful tool to help other fellow researchers in their research projects, providing a set of instruments to implement rapidly, to test, and to analyze results for new algorithms, as presented in Chapter 3.

The second contribution of this Doctoral Thesis is the Zone-Based Spectrum Assignment algorithm, presented in Chapter 4. The technique is presented in two versions. The Static Zone-Based (SZB) version main objective is to mitigate the unfairness problem, by dividing the spectrum into zones and ensuring a strict assignment policy to them. The Dynamic Zone-Based (DZB) version goal is monitoring the requests received by the network, and from those infer a suitable traffic pattern that is used to calibrate delimitation of the mentioned zones, following the SZB algorithms. In this sense, the static version is intended to be used in cases where information regarding the nature of the network traffic is known beforehand, whereas the dynamic version was developed as a solution in cases in which absolutely no information relating to the network traffic characteristic is known.

5.1 Contributions

This Doctoral Thesis presents the following contributions:

- Two new spectrum assignment algorithms, one for when the traffic pattern is known (Static Zone-Based Spectrum Assignment algorithm), and another one for more broad and dynamic scenarios, usable even when no information regarding the traffic pattern is available (Dynamic Zone-Based Spectrum Assignment algorithm).
- A new simulation framework for elastic optical networks, the first of its kind, capable of working with fragmentation and defragmentation in dynamic network scenarios (ElasticO++).

Following publications were obtained from those contributions:

- *Zone Based Spectrum Assignment in Elastic Optical Networks: A Fairness Approach* - Opto-Electronics and Communications Conference (OECC) 2015 (15).
- *ElasticO++: An Elastic Optical Network Simulation Framework for OMNeT++* - Optical Switching and Networking [*Qualis A2*] (34).
- *A Defragmentation-Ready Simulation Framework For Elastic Optical Networks* - Journal of Communication and Information Systems [*Qualis B1*] - Accepted for publication.

Other related publication obtained during this Ph.D. period:

- *"Arquiteturas de Plano de Controle para Redes Ópticas de Nova Geração Utilizando LSPs Hierarquicos"* - Book Chapter of "Telecomunicações: Teoria, Avanços e Aplicações" - Simpósio Brasileiro de Telecomunicaçoes (SBRT) 2013 (35).
- *"Proposta de Arquitetura OTN Switch Segundo as Recomendações ITU-T"* - Simpósio Brasileiro de Telecomunicações (SBRT) 2013 (36).
- *Proposal for Automatic Initialization and Configuration of the Control Channel for Optical Control Plane* - International Workshop on ADVANCEs in ICT Infrastructures and Services (ADVANCE) 2013 (37).

5.2 Future works

This section presents some of the opportunities available to keep improving the results obtained by this Doctoral work. Those possibilities are described below, divided into two subjects:

1. ElasticO++ evolution:
    - Implementation of more algorithms.
    - Implementation of new simulation metrics and new chart types.
    - Improvement of the defragmentation algorithms classes, thus creating new forms to control it, defining, for example, specific parts to perform the defragmentation.
    - Including physical layer impairments, thus increasing the legitimacy of the encountered results.
    - Integration of ElasticO++ with other software developed by other members of Labtel research group (e.g., the planning tool (56) created by Ph.D. Fabio Lima).
2. Zone-Based Spectrum Assignment improvement:
    - Investigation of the relationship between the network parameters and fairness level in non-uniform traffic scenarios, as discussed in Section 4.2.1 test T3.
    - Improvement of the traffic pattern detection method.
    - Creation of a specific defragmentation algorithm to move connections from the wrong to the correct zones. That algorithm would be used to reduce the convergence time between traffic pattern changes.

    - A lot has been said about adaptive modulation schemes, but not about adaptive spectrum allocation schemes. It sounds promising to evaluate better ways to monitor the network status and react to it changing algorithms as the environment changes.

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