UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

# SPECTRUM DEFRAGMENTATION IN ELASTIC OPTICAL NETWORKS

**A Degree Thesis**

**Submitted to the Faculty of the**

**Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona**

**Universitat Politècnica de Catalunya**

**by**

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**In partial fulfillment**

**of the requirements for the degree in**

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**ENGINEERING**

**Advisor: Jaume Comellas Colomé**

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## Abstract

In the present project we have studied the concept and several techniques for spectrum defragmentation in elastic optical networks.

The simulation tool used was the software named MATLAB, in which all the algorithms here described were designed and tested. An environment was created in order to simulate an optical network and see how the system behaves in relation to blocking probability and load of different network paths.

The results obtained have let us decide which algorithm designed was the best in terms of blocking probability at a given duration parameter.

## Resum

En aquesta tesis, s'ha estudiat el concepte i diverses tècniques de la desfragmentació espectral en les xarxes òptiques elàstiques.

L'eina de simulació que s'ha utilitzat és el software MATLAB, la qual tots els algoritmes descrits en aquesta tesis s'han dissenyat i testats. També s'ha creat un entorn de simulació d'una xarxa òptica per comprovar com es comporta el sistema en relació a la probabilitat de bloqueig en diversos camins de la xarxa.

Els resultats obtinguts ens han pogut fer decidir quin dels algoritmes dissenyats era el millor en termes de probabilitat de bloqueig en funció del paràmetre de duració donat.

# Resumen

En esta tesis, se ha estudiado el concepto y varias técnicas de la desfragmentación espectral en las redes ópticas elásticas.

La herramienta de simulación que se ha utilizado es el software MATLAB, la cual todos los algoritmos descritos en esta tesis se han diseñado y comprobado. También se ha creado un entorno a simulación de una red óptica para comprobar cómo se comporta el sistema en relación a la probabilidad de bloqueo en varios caminos de la red.

Los resultados obtenidos nos han podido decidir cuál de los algoritmos diseñados era el mejor en términos de probabilidad de bloqueo en función del parámetro de duración dado.

*I would like to dedicate to my family as they helped me so much during these university years despite all the difficulties and setbacks that have been appeared along the way.*

*To you, thank you.*

## Acknowledgements

I would like to give special thanks to my project supervisor Jaume Comellas. He has guided me through this project over the past six months.

I would also like to thank all those who supported and helped me throughout this project.

# Revision history and approval record

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| Position | Project Author | Position | Project Supervisor |

# Table of contents

## List of Figures

## List of Tables:

# 1. Introduction

## 1.1. Background

Throughout my studies in Telecommunications Engineering I developed an interest in optical communications, as I see them a huge milestone in the foreseen future. For this reason I went straight to the *Departament de Teoria del Senyal* to gather more information about the current ongoing projects related to optical communications.

All the topics presented to me, the one that professor Jaume Comellas was studying was the most interesting for me. At that time I didn't thought that there was a possibility of improving the already high efficiency of the optical networks, and that was the main motive for choosing this subject as my degree thesis.

## 1.2. Overview and goals

This project is carried out at the *Universitat Politècnica de Catalunya (UPC)* at the *Departament de Teoria del Senyal i Comunicacions*, focused in the field of the optical communications.

The purpose of this project is to design an advanced algorithm for the defragmentation of the spectrum in flex-grid elastic optical networks, and evaluation of its performance by means of extensive simulations.

Most optical networks deployed nowadays follow the EON architecture due to its high capacity and efficiency in massive deployments. Nevertheless, it presents some drawbacks that need to take into account. The most important of it is spectrum defragmentation, which decreases the efficiency of the optical network significantly.

For this reason the project's main goals are:

1. Design an algorithm that could implement the spectrum defragmentation in Elastic Optical Networks.

2. To improve the performance of the simulation given by implementing an advanced algorithm of defragmentation.

## 1.3. Requirements and specifications

Project requirements:

- To improve the already provided simulation code by implementing a defragmentation algorithm.

- Improve the overall performance of the simulation by implementing the defragmentation algorithm.

Project specifications:

- It has to improve the performance of the previous simulation implementation.
- It does not have to increase computational complexity.

## 1.4. Work plan

| **Documentation and Information Research** | WP ref: WP1 | |
|---|---|---|
| Major constituent: research and document making | | |
| Short description:<br>Obtain information about the project and redact all the needed documentation. | Planned start date: 08/02/2016<br>Planned end date: 30/06/2016<br><br>Start event: 08/02/2016<br>End event: | |
| Internal task T1: Information research<br>Internal task T2: Work plan<br>Internal task T3: Critical Design Review<br>Internal task T4: Final Report Review | Deliverables:<br>Report Files | |

Table 1: WP1

| **Algorithm design and implementation** | WP ref: WP2 | |
|---|---|---|
| Major constituent: Design and implementation | | |
| Short description:<br>Algorithm design, implementation and testing. | Planned start date: 22/02/2016<br>Planned end date: 24/05/2016<br><br>Start event: 23/02/2016<br>End event: 26/05/2016 | |
| Internal task T1: Algorithm design<br>Internal task T2: Algorithm implementation<br>Internal task T3: Algorithm testing | Deliverables:<br>Matlab files | |

Table 2: WP2

| **Final simulations and conclusions** | WP ref: WP3 | |
|---|---|---|
| Major constituent: Tests and results | | |
| Short description:<br>Simulations with the implemented algorithm and performance evaluation. | Planned start date: 09/05/2016<br>Planned end date: 15/06/2016<br><br>Start event: 27/05/2016<br>End event: 08/05/2016 | |
| Internal task T1: Simulations with algorithm implementation<br>Internal task T2: Performance evaluation<br>Internal task T3: Results evaluation | Deliverables:<br>Results charts | |

Table 3: WP3

## 1.5. Gantt Diagram

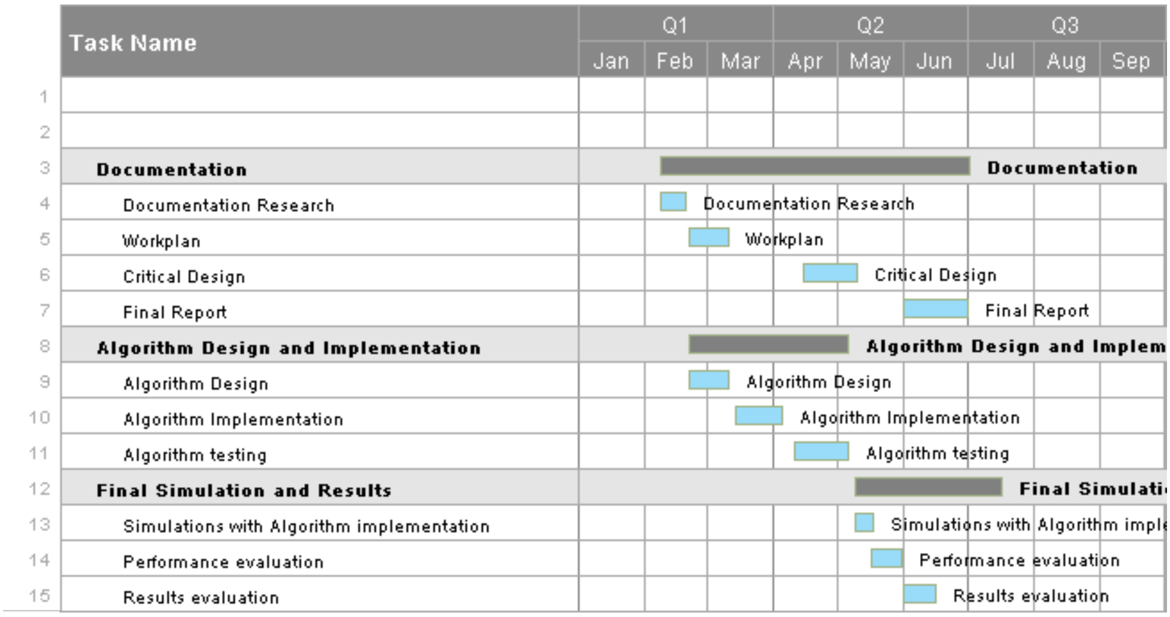


Figure 1: Gantt Diagram

## 1.6. Incidences

During the implementation of the algorithm there were some issues related to the design of the algorithm design, which has made increase the duration of the "Algorithm design" task and "Algorithm testing" task in WP2 for 2 extra weeks each task.

These incidences were associated with the method of managing the defragmentation, as this was not a trivial problem. Different approaches were proposed and tested some of them.

# 2. State of the art of the technology used or applied in this thesis:

Driven by the increasing growth of network traffic, efficient utilization of spectral resource has become a key milestone in elastic optical networks (EONs). Unlike traditional WDM networks, which make use of rigid spectral grid allocation, EONs have the potential to achieve higher spectrum utilization by assigning spectrum slices proportionally to the amount of traffic carried by each demand.

Achieving high spectrum utilization, however, is potentially hindered by the resulting fragmentation of the spectrum slices that remain available to accommodate future connection demands. Fragmentation refers to the occurrence of small and non-contiguous spectrum resources that cannot be used to accommodate large (in terms of contiguous spectrum slice requirements) connection requests and can thus prevent good spectrum utilization.

In recent times there is much research focused on this technology, as this could lead a huge impact on performance and boost the expansion of optical networks in a near future.

## 2.1. EON architecture

As has been commented before, the EON architecture has been proposed as a solution to the great demand and traffic diversity that is experiencing the Internet nowadays. This is due since their working method is different from the WDM system. The WDM system has a fixed limit for spectrum placement. This makes the network very rigid and inefficient.

The EON architecture, on the other hand, selects the appropriate size of the optical spectrum to place it on each connection depending on the traffic volume that the network is handling. The optical spectrum available is divided into different frequency slots (FS) of a fixed spectral width.

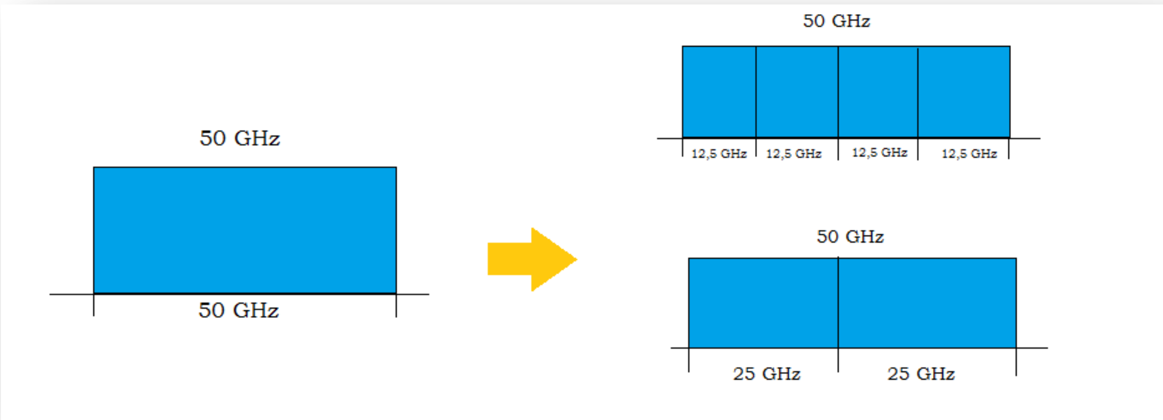


Figure 2: Flex-grid bandwidth division

Nonetheless, this type of architecture presents some problems, being the most important the phenomenon called spectral fragmentation. This happens when having different connections with durations and tour random makes that dividing the spectrum into smaller FS. Those near to completion of the spectrum, they present the spectrum available network become fragmented into small non-contiguous frequency bands. Hence, the probability of finding a large number of contiguous FS to allocate a large connection decreases significantly.

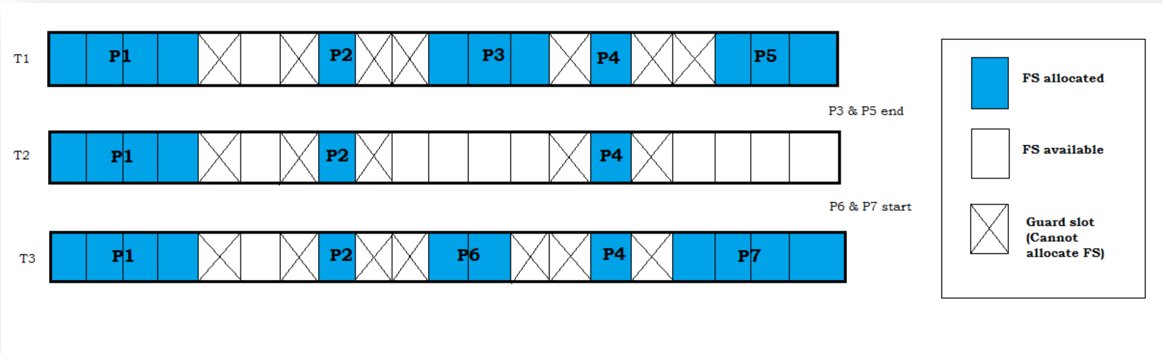


Figure 3: Spectrum fragmentation

As we can observe in the previous figure we have an example of a fraction of a possible connection in which we see how at the time t1 we found a spectrum divided into 30 FS in which we have allocated the packets P1 (4 FS), P2 (1 FS), P3 (3 FS), P4 (1 FS) and P5 (3 FS) with their respective guard slots (GS). These guard slots are needed in order to differentiate one connection from another. When we arrived at time T2, the packages P3 and P5 have completed their duration and let free a small part of the spectrum so new connections can be allocated. As occurs in the time t3, the packets P6 (2 FS) and P7 (4FS) pick up a portion of the available spectrum and place its connection.

It is clear that this method of connecting the packets is not completely the most efficient because the spectrum remains very fragmented and finding available gaps to allocate the following connections very complicated.

## 2.2. Spectrum assignment models

Due to the high bandwidth available in the optical networks, there is a need to predefine some bandwidths so that the spectrum stays tight in each connection. Because the heterogeneity of traffic offered by the network, the spectrum is divided in a set of frequency slots (FS). Each connection will occupy the number of FS needed for transmitting, depending the bandwidth needed. In this way, the traffic is fragmented in small sets of FS that tries to be as similar as possible to the traffic received.

The range of values of the bandwidth could take from 1 FS to 16 FS, depending on the bit rate connections. The speeds supported vary from 10 GB/s to 1TB/s.

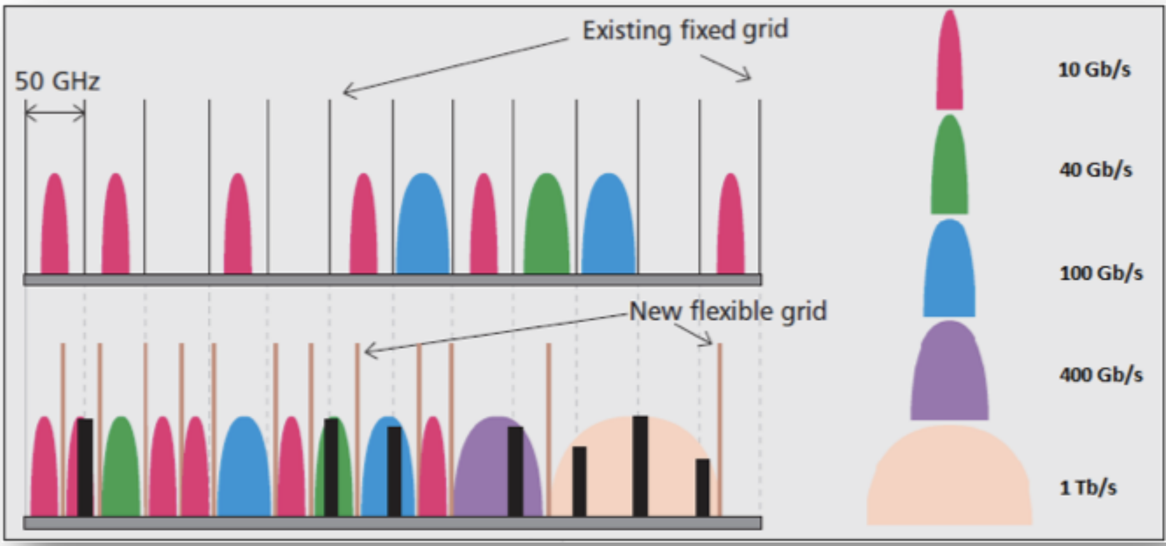


Figure 4: Spectrum assignment in fixed grid and flexgrid

From the image above it is clears the fixed grid of 50 GHz cannot transmit high-speed spectrum (400GB/s or 1 TB/s). That is because the traffic is fragmented into several connections, which reduces significantly the efficiency of the networks. On the other hand, with the new flexible grid it is possible to send data at high-speed thanks to the adaptation of the traffic received. This implies an increase in efficiency of network resources.

# 3. Methodology / project development:

This thesis we have developed new algorithms for Matlab code with the purpose of creating the spectrum defragmentation process and thereby see how the system behaves in relation to blocking probability of the different network paths. The simulation environment was already developed and provided by this project advisor.

## 3.1. Matlab simulator

The Matlab simulator recreated an optical network assuming an uniform model of traffic in which the simulation starts without network traffic and the connections are created one by one in random nodes of source and destination. It is possible to configure various parameters to simulate different traffic situations and test the different evaluation parameters, which are necessary to evaluate the performance of the network.

There are certain functions and parts that need to be explained in order to know which situation we depart from. The sequence of code that is executed in order to observe the behavior of the network is called *simul_totK*, which has the following key parameters:

- **Numconex:** Number of connections generated during the simulation. The predefined value used in this thesis is 1,000 but there has been other values tested.
- **Numslots:** Number of FS per link. The value used is 160.
- **Max_bandwith:** Maximum bandwidth connections. The maximum value has been 15.
- **Xarxa:** Network topology used. Two different topologies are possible to set here, NSF and EON topologies, which represent a different set of preconfigured nodes. The network used is NSF.
- **Temps_volta:** It corresponds to a unit of time. Due to the lack of time simulation in Matlab, this parameter is responsible to control the time. Each run of the main program iteration corresponds to 1 time unity. Hence, decreases the duration of each running connection one unit.
- **Duracio:** Creation of a random duration for each connection generated by an exponential function. This parameter range between 5 and 40.
- **Defrag_period:** This parameter is responsible to trigger the spectrum defragmentation each time this period is multiple of the number of connections created so far.
- **KSP:** This value has a relation with the Dijkstra algorithm used to find the shortest route available between the source and destination. This is the number of trials for different paths when the shortest path has not available bandwidth required for the connection created. The most loaded link is withdrawn from the topology and Dijkstra runs again without it. The value here used is 3.

These are all parameters that are needed to set before performing a simulation. Once these parameters are set, it is possible to perform various tests by varying one parameter to see how the network behaves.

In order to perform the defragmentation, the most important parameters are **Duracio** and **Defrag_period.** That is, when we perform the tests, the parameters we sweep in order to find the optimum point that the defragmentation achieves best performance.

In order to perform the simulation, it is also necessary to define a topology. This is a set of nodes interconnected that are able to send and receive traffic. The topology we have used is called NSFnet (National Science Foundation Network). It consists of 14 nodes and 21 links.

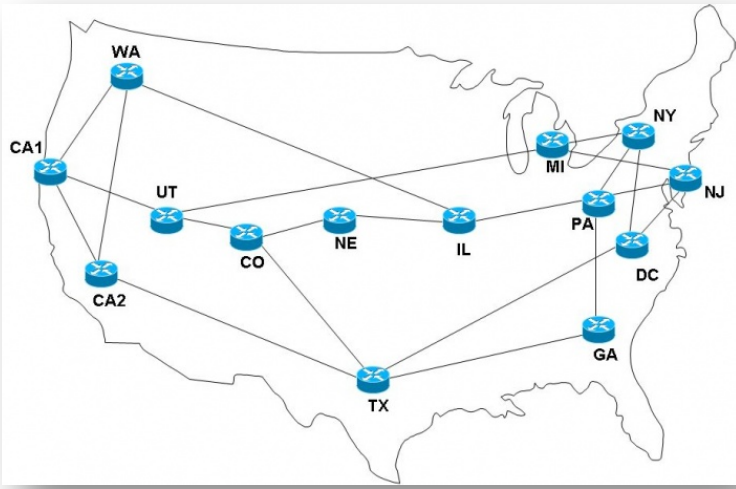


Figure 5: NSFnet Topology

There is another topology available in this simulator, called EONet, which consist of 19 nodes and 37 links. Given that our project focuses on the performance of the network, network topology would not affect much our results. Since NSF network has fewer nodes it would make easier to check on our results.

## 3.2. Defragmentation procedure

As connections are created during the simulation, they are allocated in the gaps the simulator finds best suited for them. However, this may lead to the fragmentation of the spectrum, as previously explained. To improve the effectiveness and efficiency of the network, there should be a process of compacting the spectrum so that future connections should not be rejected for not being able to allocate in the spectrum.

One possible method of compacting the spectrum is to localize the gaps of the spectrum and try to reallocate already established connections in these gaps. If the connections succeed one after the other, only leaving a GS between them, the spectrum keeps compacted and, therefore, the efficiency increases.

The problem that arises from this proposed solution is the procedure of moving the connections in the same link. The importance here revolves around the position of the gap in the spectrum and the procedure of filling the gaps by another connections already present in the link.

The position of the gaps is really important. It is obvious that the spectrum is compacted if the lowest FS are occupied by connections and the highest FS are kept empty, if possible, for future connections could be allocated just after the last connection established. Hence, the defragmentation procedure should reallocate connections that are located in higher band of the spectrum to possible gaps that are situated in the lower band of the spectrum.

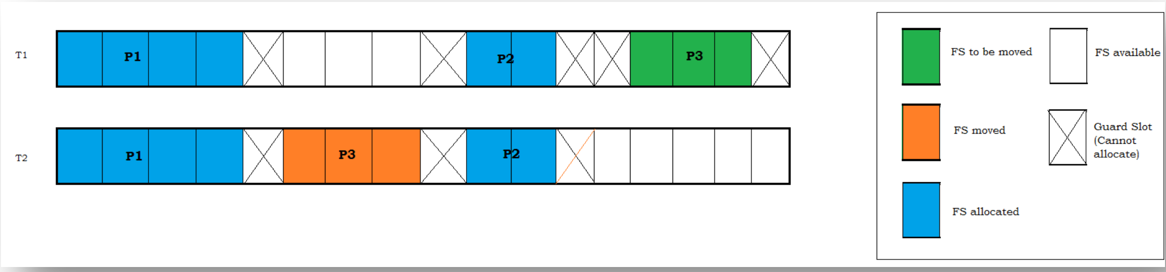


Figure 6: Defragmentation procedure

The other issue to take into consideration is how the gaps are filled. This procedure, however, is not trivial. At a glance, there is no proof that whether filling the gaps completely or partially would perform better. The common sense tells us that it should perform better by filling completely the gaps wherever possible than only partially. That is, finding a connection with the same number of FS that would fit perfectly in the gap between two connections so that all the connections succeeds one after another in all links.

Another concern arises when considering the order of filling the gaps. This refers on how to begin the defragmentation process. It is not known if filling first the largest gaps would be better than filling the smallest ones first.

It has been decided that two processes should be tested in order to know which one performs better, best fit filling first the largest gaps (called *Defragmentation Major*) and best fit filling first the smallest ones first (called *Defragmentation Minor*).

Not all of connections are going to be eligible for the defragmentation. This is because those connections that are near to conclude are not worthy of changing their position because it is better to liberate FS available for further connections than adding computational cost for moving these connections that may not improve the effectiveness.

### 3.3. Evaluating Performance

Once all the connections have been established and concluded, the next step is to prepare the results obtained. In this part we need to focus on the objectives we have settled, being the decrease of network congestion and diminish the connections that are rejected.

One of the metrics that we need to define is Blocking Probability (BP). It consists on the probability that has a connection to be blocked at the moment that is sent to the network due to the path being very saturated and there is not enough FS to fit this connection. This BP is calculated from the sum of all blocked connections, in this case the bandwidth of the blocked connections, divided by the entire offered load to the network, that is the sum of all bandwidths of all connections completed successfully.

$$BP = \frac{Blocked\ connections}{Offered\ Load}$$

Once defined the metrics that are needed we will represent this BP in function of the two variables previously mentioned that affect more the defragmentation process, which are the **Duracio** and **Defrag_Period.**

# 4. Results

Once defined all the parameters established and the functioning of the Matlab Simulator, the next step is testing different situations through the variables explained previously. We will evaluate different settings of **Duracio** and **Defrag_Period** to see how behaves the network using the two different defragmentation methods that have been developed. All this will help us to reach different conclusions.

For all tests, **Numconex** has a constant value of 1,000.

## 4.1. Variable duration of connections

In this section we will analyze how the network behaves when there is no defragmentation implemented and the two different methods of defragmentation that have been developed. For the defragmentation methods, the **Defrag_Period** has been set only two time, so in this case, **Defrag_Period**=500. That means that the defragmentation processes are executed every 500 connections established. Because we have established that are 1,000 connections in this network, they would only execute two times.

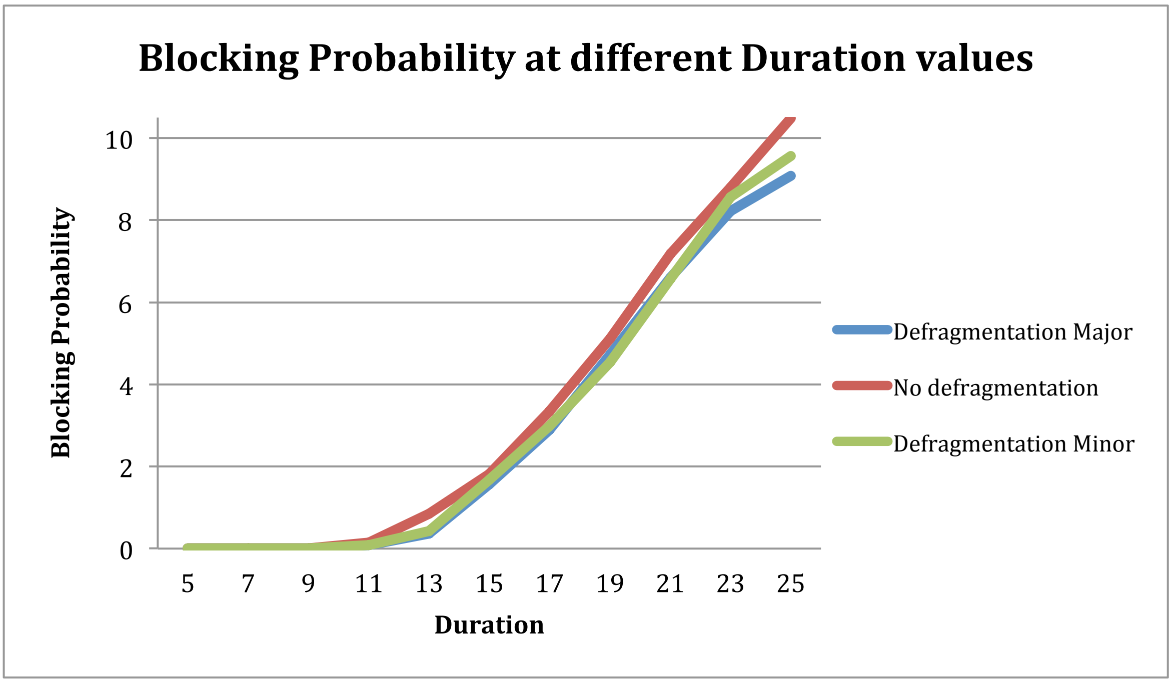


Figure 7: Comparison Blocking Probability at different Duration values

This graphic shows the difference between the three states of the network in different durations of the connections. This is a typical behavior of the EON networks. As the connections increase their durations, they stay more time in the network, increasing the congestion of the network. Hence, when a new connection is made under these circumstances, it is more probable that the new connection gets rejected because there is not FS available for them.

At a glance, there is not a significant difference between the two developed methods and the network without defragmentation. There is a small improvement between a network with a defragmentation applied and one with no defragmentation applied, merely a 1% difference in performance in the best case. Nevertheless, it seems that both methods perform more or less the same.

Because there is not a significant performance improvement in the current setting, it is going to find the optimum point where the defragmentation can perform the best performance for the network. To do this, it is going to evaluate the **Defrag_period** parameter at a fixed **Duracio**.

## 4.2. Variable defragmentation period of appliance

Another important parameter that affects directly to the defragmentation process is the period elapsed between each defragmentation process is triggered; in this case the number of connections determines it.

Because previous measurements the defragmentation period was large, it is now proposed to study the impact of the variable **Defrag_period** at a fixed duration, set at 25. The reason why the **Duracio** parameter is set at 25 is because it is considered that a BP of 10% is considered high and not desired. Thus, it is going to perform an analysis on this parameter to observe the improvement.

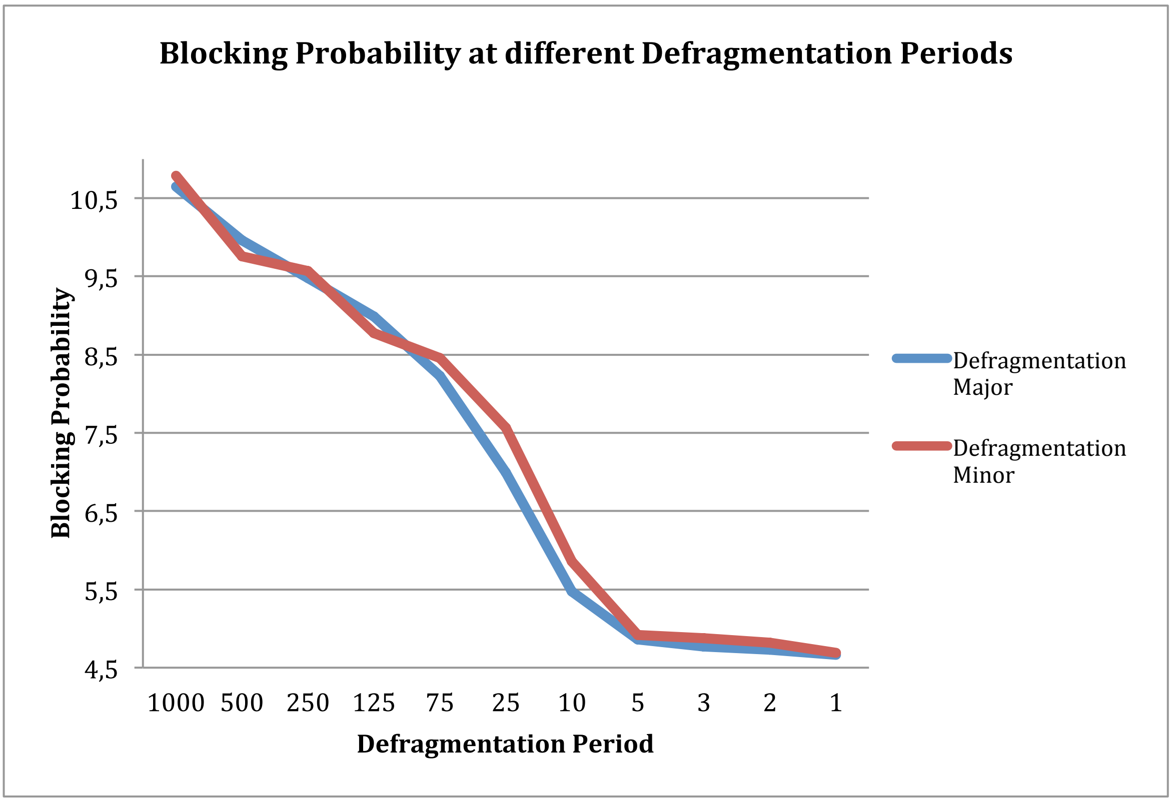


Figure 8: Comparison Blocking Probability at different Defragmentation Periods

The two processes maintain a similar structure. As we decrease the defragmentation period, it is clear that the blocking probability lowers because the spectrum keeps more compacted, thus decreasing the blocking probability. At a glance, there are some important factors we can extract from this graphic. First of all, there is a steady decrease of blocking probability as we decrease until at a defragmentation period of 5. After that value, there is a tiny decrease of the blocking probability, but not as accentuated in greater values of defragmentation period.

Another factor important appreciated during this analysis is that as the defragmentation period decreases, the computational cost increases also. Thus, the range [5,1] of defragmentation period offers little improvement but greater computational cost. This range of values has little to offer at a great cost so it would be correct to take 5 as the optimum value for the defragmentation period. It offers the best blocking probability at a reasonable computational cost.

Another important fact is that both defragmentation processes differ little in terms of performance. It is observed that the defragmentation major process is having a tiny better performance on some values of defragmentation period (best case differs only 0.60%) but not enough to state that performs better than the other process.

### 4.3. Final simulation

After the previous analysis, it is going to perform the final simulation taking the optimum value of defragmentation period and see how performs the network in terms of connection durations.

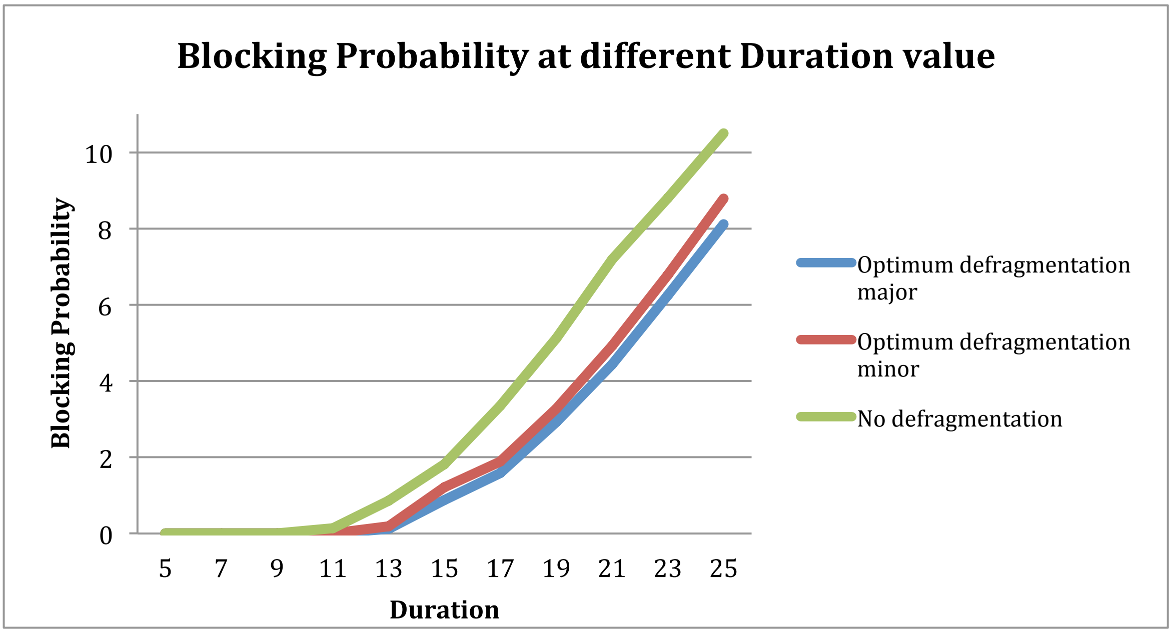


Figure 9: Comparison blocking probability at different Duration values with optimum Defragmentation period value

Now there is an evident improvement over the overall blocking probability. Nevertheless, this comes with a computational cost, which has increased it, but has not affected the overall performance of the network. In this graphic, it is clear to appreciate the difference between a network without defragmentation and one with defragmentation applied. At the highest values of the duration parameter the improvement of blocking probability is, in average, 2%. This means that the network is more efficient and therefore the spectrum more compacted.

There is also an improvement of capacity. This means that the network can handle more connections with a defragmentation process applied than one without defragmentation. For example, at a value of 6% blocking probability, a network without defragmentation can handle connection of a duration parameter value of 19. To obtain the same blocking probability value in a network with defragmentation applied, there is the possibility to add more stress to the network because it can handle connections with a duration parameter value of 21 to obtain the same blocking probability value.

# 5. Budget

All work done on this thesis has consisted in performing various algorithms for Matlab software in a simulator. The economic impact found in this thesis has been an estimation of hours dedicated to the realization of this project, evaluated at a price of junior engineer (10€ / hour) and the license of the software used, in that case, Matlab.

| Task | Hours (estimated) | Cost |
|---|---|---|
| Documentation and Information Research | 45 | 450 € |
| Algorithm design and Implementation | 140 | 1.400 € |
| Final simulations and conclusions | 120 | 1.200 € |
| Matlab License (software) | - | 500 € |
| **Total** | **305** | **3.550 €** |

Table 4: Budget

## 6. Conclusions and future development:

After all the work done, it is right to say that spectrum defragmentation is a non-trivial topic that needs to take further research because of its variability.

First of all, the EON networks are still in a research state and its development still presents some issues that need to be resolved before its commercial launch. However, it does present new exciting features that could lead to an improvement over the traditional spectrum management of optical networks.

As services offered increment and the demands of the users increase over time, it is logical the change of WDM system of spectrum allocation to EON architecture because of its flexibility and scalability necessary for the more demanding growth of network traffic. By using the flexible use of bandwidth and appropriate spectrum allocation of the different sizes of connections, this technology is the best appropriate for the future necessities of the optical networks.

The necessity of spectrum defragmentation in EON networks is a must if this technology is implemented, as this makes the network reliable. The two different methods developed in this thesis of defragmentation gives an approach on how to solve this problem. It is clear that improves the reliability of the network and overall performance. However, this needs to be improved and more efficient if the EON networks come as a reality. The randomness and variability of this kind of networks make these networks more difficult to manage.

From the results, the two methods proposed does not differ from each other in terms of efficiency, as these two methods present similar blocking probabilities at different states of the network. It seems that the way of filling the gaps does not affect much in the overall performance.

To sum up, some proposed future developments could perform better algorithms for the spectrum defragmentation. The overall performance may be improved if considered filling the gaps not only in best fit but also a gap large enough to be fitted the connection in case of not finding a gap with exactly the same space available.

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[2] Bijoy Chand Chatterjee, Nityananda Sarma, Eiji Oki. "Routing and Spectrum Allocation in Elastic Optical Networks: A Tutorial". *IEEE Communication Surveys & Tutorials*, vol. 17, no.3, third quarter 2015.

## Glossary

WDM: Wavelength Division Multiplexing

EON: Elastic Optical Networks

FS: Frequency Slot

GS: Guard Slot

BP: Blocking Probability

NSFnet: National Science Foundation Network topology