



FLEXGRID OPTICAL NETWORK SIMULATOR IMPLEMENTATION

MASTERS' THESIS

REALIZED IN

**ESCOLA POLITÈCNICA D'ENGINYERIA DE
TELECOMUNICACIÓ DE BARCELONA**

UNIVERSITAT POLITÈCNICA DE CATALUNYA

BY

XAVIER CALZADA SALVIA

**MASTER'S DEGREE IN TELECOMMUNICATIONS
ENGINEERING**

TUTOR: Jaume Comellas Colome

BARCELONA, OCTUBER 2016

Acknowledgments

I would like to thank Professor Jaume Comellas, director of my thesis, for providing me with the topic of my project and for giving me so much help throughout its realization.

SUMARY

1. INTRODUCTION	6
2. STATE OF ART	8
2.1 WAVELENGTH DIVISION MULTIPLEXING NETWORKS	8
2.2 ELASTIC OPTICAL NETWORKS	8
2.2.1 <i>EON networks architecture</i>	9
2.3 ROUTING AND SPECTRUM ASSIGNMENT (RSA).....	10
2.4 SPECTRUM ALLOCATION.....	11
2.5 SPACE DIVISION MULTIPLEXING (SDM)	11
2.6 FEATURES OF THE EON NETWORKS	12
3. ROUTING AND NETWORK EMULATOR SOFTWARE.	13
3.1 NETWORK	14
3.2 FIBER.....	14
3.3 CONNECTIONS.....	14
3.3.1 <i>Modes of simulation</i>	15
3.4 STORAGE OF INFORMATION.....	18
3.5 GRAPHICAL USER INTERFACE.....	19
3.6 OPERATION OF THE GUI.....	20
3.7 PROGRAM STRUCTURE	23
4. SIMULATION RESULTS.	25
4.1 SIMULATION CHARACTERISTICS	25
4.1.1 <i>Network topologies</i>	25
4.2 TRAFFIC PROFILES (BW, TIME)	26
4.3 SIMULATED SCENARIOS	28
4.3.1 <i>Elastic Networks</i>	28
<i>Improving spectrum efficiency by allocating elastic demands into fixed size connections</i>	28
4.3.2 <i>Effects of transponders limitation vs. spectrum limitation</i>	30
4.3.3 <i>Combining static and dynamic traffic</i>	32
4.3.4 <i>Elastic and SDM Networks</i>	34
4.3.5 <i>Comparing different Sp-Ch spectrum allocation modes</i>	34
5. CONCLUSIONS	39
6. FUTURE LINES.....	40
7. ANNEX.....	41
7.1 REAL TIME MONITORING OF SPECTRUM STATUS.....	41
8. GLOSSARY	44
9. BIBLIOGRAPHY	45

LIST OF FIGURES.

FIGURE 1. CURRENT INFRASTRUCTURE TELECOMMUNICATION 6

FIGURE 2. EVOLUTION OF DATA CONSUMPTION..... 6

FIGURE 3. WDM NETWORK. PROBLEM OF CONNECTION WITH LOW DATA RATE. 8

FIGURE 4. SPECTRUM OF WDM AD EON 8

FIGURE 5. EON NETWORK USING OFDM. 9

FIGURE 6. EON NETWORK SCHEMATIC. 9

FIGURE 7. FIRST ALTERNATIVE TO THE PROBLEM OF FRAGMENTATION..... 10

FIGURE 8. SECOND ALTERNATIVE TO THE PROBLEM OF FRAGMENTATION. 10

FIGURE 9. SDM TECHNICS (PETER J. WINZER 2012)..... 11

FIGURE 10. CORE MULTIPLEXING MULTICORE FIBERS, MCF. 12

FIGURE 11. FRAGMENTATION PROBLEM. 12

FIGURE 12. NETWORK DESCRIPTION. 14

FIGURE 13. MODE 1 SPECTRUM..... 15

FIGURE 14. MODE 4 SPECTRUM..... 16

FIGURE 15. MODE 7 SPECTRUM..... 16

FIGURE 16. EXAMPLE OF DATA STORAGE..... 18

FIGURE 17. IMAGE OF NETWORK FRAGMENTATION. 18

FIGURE 18. TAB PROGRAM NETWORK..... 20

FIGURE 19. TAB PROGRAM FIBER. 21

FIGURE 20. TAB PROGRAM NODE..... 21

FIGURE 21. TAB PROGRAM STORAGE. 22

FIGURE 22. TAB PROGRAM RESULTS. 22

FIGURE 23. PROGRAM STRUCTURE. 24

FIGURE 24. NETWORK TOPOLOGIES. 25

FIGURE 25. NORMAL DISTRIBUTION TRUNCATED. 26

FIGURE 26. HT OF 100000 CONNECTIONS. 26

FIGURE 27. BANDWIDTH BLOCKING PROBABILITY (BBP) VS. NETWORK LOAD FOR ELASTIC CONNECTIONS AND CONSTANT . 29

FIGURE 28. SIMULATION RISING TRANSPONDERS IN NSF NETWORK 30

FIGURE 29. SIMULATION RISING TRANSPONDERS IN TELEFONICA CORE NETWORK. 31

FIGURE 30. DISTRIBUTION LIVE SLOTS IN THE NETWORK. 32

FIGURE 31. FS USAGE DURING THE SIMULATION..... 32

FIGURE 32. COMPARISON THE NODE LOAD BETWEEN MODE 1 AND MODE 2..... 34

FIGURE 33. BLOCKING PROBABILITY IN TPs AND NETWORK. 35

FIGURE 34. SIMULATION USING 140 TPs PER NODE. 36

FIGURE 35. SIMULATION 120 TPs PER NODE. 37

FIGURE 36. COMPARISON OF 4 MODES USING 120TP'S. 37

FIGURE 37. LOGARITHMIC COMPARISON OF 4 MODES USING 140TP'S. 38

FIGURE 38. LOGARITHMIC COMPARISON BETWEEN MODE 1, 2 AND 3..... 38

FIGURE 39. FRAGMENTATION AVL AND ENTROPY BASED..... 41

FIGURE 40. SPECTRUM NON FRAGMENTED..... 42

FIGURE 41. SPECTRUM FRAGMENTED..... 42

LIST OF TABLES.

TABLE 1. COMPARATIVE TABLE WITH THE BLOCKING PROBABILITY 11

TABLE 2. COMPARISON AMONG MODES. 17

TABLE 3. COMPARISON AMONG DIFFERENT TOPOLOGIES..... 25

TABLE 4. CONNECTIONS TO SPECTRUM MAPPING..... 28

TABLE 5. DETAILS OF MODE 3..... 35

TABLE 6. DETAILS MODE 4..... 36

1. Introduction

Currently, telecommunication networks are formed by different vertical infrastructures, such as Packet Switched Public Data Network, PSPDN, Public Land Mobile Network, PLMN, Public Switched Telephone Network, PSTN, and Broadcast/Community Antenna Television, CATV, and each one of them provides its own service. The trend in the next decade will be the unification of all of these infrastructures into a single horizontal infrastructure that will be able to unify all of these services.

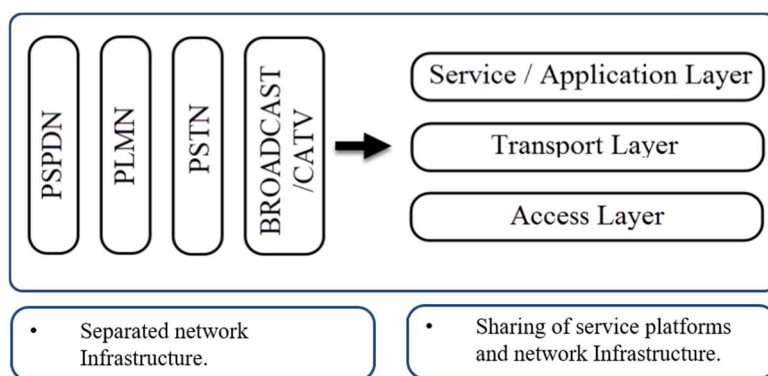


Figure 1. Current infrastructure telecommunication.

To unify all of these infrastructures it is necessary to create a new network able to absorb all the traffic generated by all of them. At the same time, new services like video streaming are appearing on the market. These new services are increasing the traffic generated in the network, as shown in the next figure.

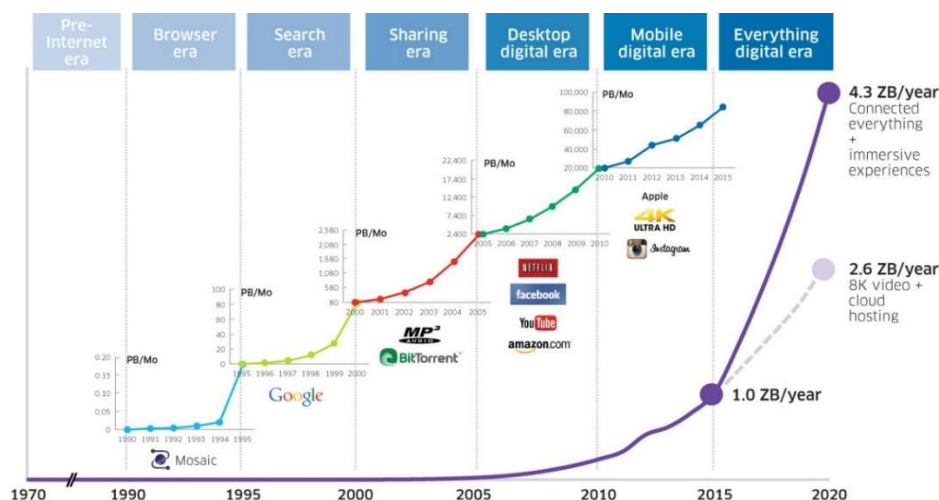


Figure 2. Evolution of data consumption¹

¹ (<https://insight.nokia.com/future-video-content-evolution-toward-2020> 2015)

According to the figure above, the traffic generated nowadays ascends to 1ZB/year and the forecast in 2020 will reach around 4.3ZB/year.

Presently, telecommunication infrastructures do not have sufficient capacity to meet both challenges mentioned before. Therefore, new paradigms are emerging with the goal of satisfying these necessities. This problem could be solved thanks to M. Jinno et al., (al. Nov. 2009.), who have launched a new kind of network called Elastic Optical Network, EON, which can considerably improve the efficiency and the performance of the present networks.

New research studies are emerging around these sorts of networks to study their viability and the possibility of establishing them in the society in the next decades. Hence, this project belongs in this context.

The aim of this work is create a tool capable of imitating the current and future optical fibers. The software developed will be used to contrast the network proposed by Jinno et al, EON, with the current network, WDM, and to verify the improvement in efficiency and its viability.

This software should be able to simulate any network distribution such as USBackbone, National Science Foundation, NSF or Telefonica Core Network and take into account the typical network limitations like the total number of fibers in the network and their capacity. Moreover, it should calculate the number of transceivers used by each node and their capacity. It should follow the patterns of realistic traffic using different probability functions to manage the traffic duration, manage the traffic creation or determine the bandwidth occupied by each connection. Finally, it should save all the information generated during the simulation in order to study and prevent network weaknesses and to discover whether this new kind of network really represents an improvement or not.

A programming language able to offer versatility and quickness is needed to build this tool. Hence, the language chosen was Java because it is a high level language, which is object oriented programming (OOP), and multithreading.

Once the program was developed, it was contrasted in simulation with the WDM networks. The comparison was done by matching the program data with values known from WDM networks.

We have proceeded to realize a study about EON. Firstly, the capacity and fragmentation of EON network has been studied; study published in (Jaume, Xavier y Gabriel, Efficient spectrum assignment in Elastic Optical Networks 2016). Then, a study about the measurement of transceivers of EON was done. Also, different configurations have been compared to establish the connections in the network in order to improve the spectral efficiency. Finally, how the connections are adapted better in the network when the bandwidth of each connection increases has been studied.

2. State of art

2.1 Wavelength Division Multiplexing Networks

Wavelength Division Multiplexing, WDM, is the technology employed to transmitting data via optical networks, which allows the multiplexing of several signals in the same optical fiber. Therefore, WDM networks divide the spectrum in different blocks or channels of 50 or 100 GHz. This kind of technology presents as main drawback the waste of the spectrum for transmissions with a low data rate. If there is established a communication among two points and the data rate is lower than 50 GHz this connection always will occupy the whole spectral bandwidth reserved for it, which will cause a low throughput. In Figure 1 is illustrated the problem of the spectral waste for the transmission of data with low data rates (Mukherjee 2006).

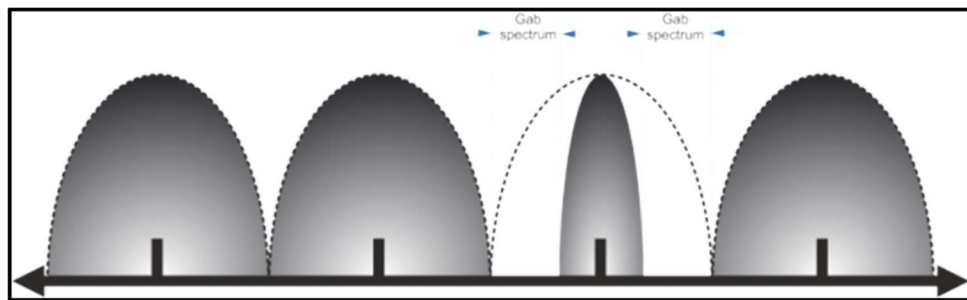


Figure 3. WDM network. Problem of connection with low data rate.

2.2 Elastic Optical Networks

The Elastic Optical Networks, EON, can eliminate the problem mentioned previously, providing a variable bandwidth for each connection and consequently they can maximize the throughput in all the connections. This sort of network has a finer granularity than WDM, now each channel has 12.5 or 6.25 GHz. Therefore, EON can conform to the requirement of every connection without wasting so much spectrum. In the example of figure 2, we can observe that while in the EON network uses 100GHz to send the information, the WDM network needs twice this spectrum to send the same information.

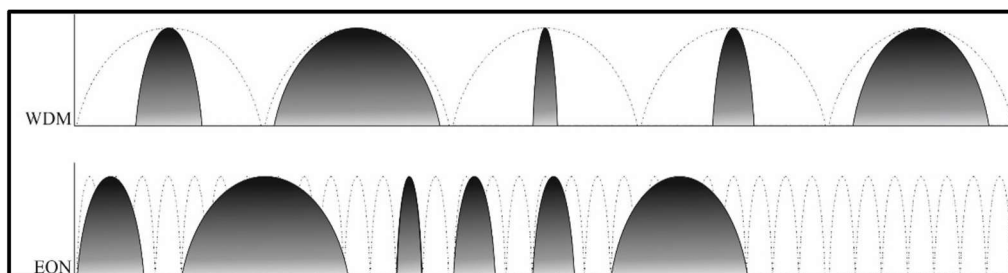


Figure 4. Spectrum of WDM ad EON.

Another important feature of the EON networks is the possibility of implementing OFDM technology, which allows adding data to several subcarriers that have low data rates. Hence, the spectral efficiency reached is higher, as shown Figure 2, due to the different channels avoid the overlapping of information because of the orthogonality between them. Thus, the EON networks are capable of adapting to the necessities of a user without wasting so much spectral space as in WDM, providing subcarriers with low bandwidth and with a high spectral capacity, which can be reached by using OFDM technology and the dynamic assignation of bandwidth.

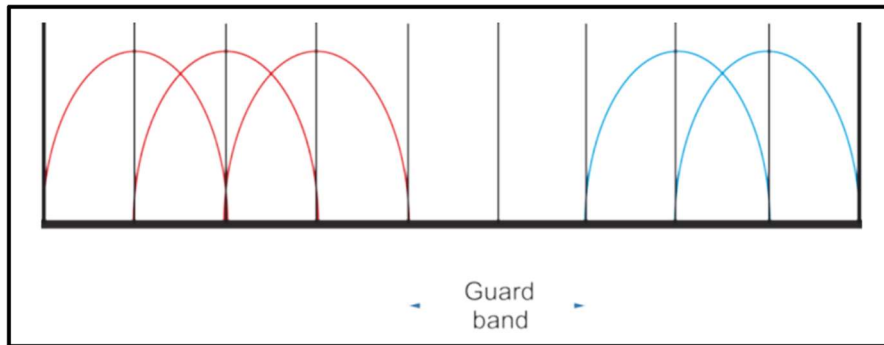


Figure 5. EON network using OFDM.

2.2.1 EON networks architecture

The architecture of the Elastic Optical Networks follows the same structure than the WDM networks but they incorporate two new elements: Bandwidth-Variable Transponder, BVT, and Bandwidth Variable Cross-Connect, BV-WXC, which add a higher flexibility and spectral use (Sarma 2015).

Bandwidth-Variable Transponder: This element allows fitting the modulation and change the bit-rate of our connections in every moment, using complex modulation formats such as 64QAM for short distances and less complex modulations, like QPSK or BPSK, for long distances while adjusting the bit-rate to cope with to the connection requirements.

Bandwidth Variable Cross-Connect: This element allows to optically switch at different bandwidth granularities, in line with the EON concept.

Figure 3 shows an example of interconnection between the different elements of an EON network.

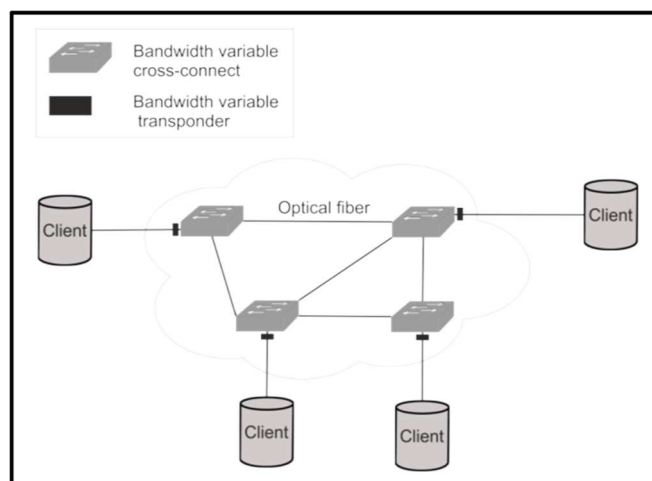


Figure 6. EON network schematic.

2.3 Routing and Spectrum Assignment (RSA)

The problem of the Routing and Spectrum Assignment, RSA, in EON networks is very similar to the problem of Routing and Wavelength Assignment, RWA, in WDM networks. RSA is employed to find the best route among the source and destination nodes. The main objective of the RSA is providing a route maintaining the same used spectrum along it. This problem is known as Wavelength Continuity Constraint, WCC (Sarma 2015).

The main difference between RSA and RWA appears due to the problem that has the Elastic Optical Networks, which are able to generate channels with a variable bandwidth. Another feature of the EON networks is that a connection is only established if two conditions are accomplished: Contiguity and Continuity. Otherwise, the communication is not established.

Contiguity: The transmissions must occupy contiguous slots in the spectrum.

Continuity: The route that the connection should trace must be always in the same frequency band.

In Figures 4 and 5 is shown an example of both conditions.

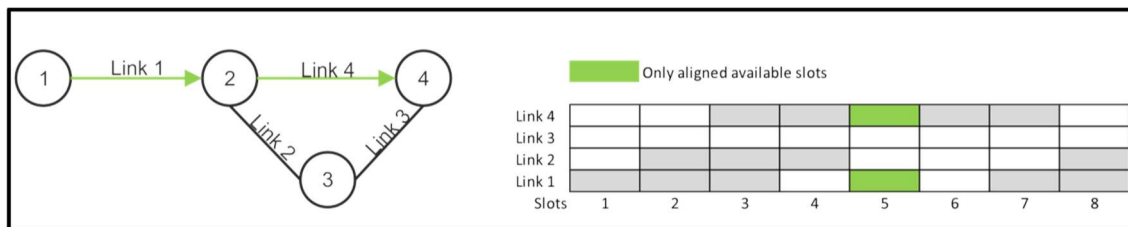


Figure 7. First alternative to the problem of fragmentation.

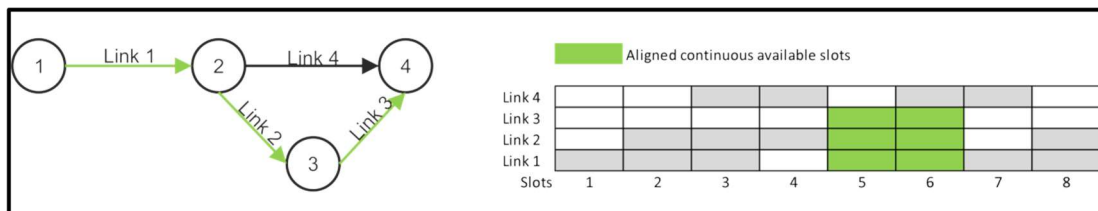


Figure 8. Second alternative to the problem of fragmentation.

In Figure 4, it is represented the connection establishment between node 1 and node 4 employing the shortest route, that is link 1 and link 4. As we can observe, the communication only can be established using a single hop. If the communication is bigger than one slot the contiguity condition is not accomplished and the communication will be rejected. However, in Figure 5 an alternative is proved among node 1 and node 4, using the links 1, 2 and 3. In this case the contiguity condition increases considerably because the 3 links share 2 slots, as is shown in Figure 5 in green, providing higher probability to allocate larger connections.

2.4 Spectrum Allocation

There are different techniques to allocate the spectrum to a connection: First Fit, Random Fit, Last Fit, First- Last Fit, Least Used, Most Used and Exact Fit. Among them, First Fit is the technique that has a low computational cost and offers a rather low blocking probability.

First Fit maintains an updated list containing all the spectral resources available in the network with their respective index. Thus, when a connection is attempted to be established, it will try to fill the slots with the lowest index, which represents a lower bandwidth than others. Consequently, when a connection is established the used resources are eliminated of this list and are not released until the connection is finished.

In the next table is presented a comparative study with the blocking probabilities for the different spectrum allocation policies in the EON networks.

Spectrum Allocation Policy	Blocking probability				
	20 [Erlang]	40 [Erlang]	60 [Erlang]	80 [Erlang]	100 [Erlang]
First-last fit	0,005	0,007	0,01	0,017	0,025
First-exact fit	0,006	0,008	0,012	0,02	0,027
First fit	0,006	0,009	0,014	0,021	0,029
Last fit	0,007	0,008	0,015	0,02	0,03
Random fit	0,017	0,022	0,031	0,043	0,055

Table 1. Comparative table with the blocking probability for the different spectrum allocation policies in the EON.

2.5 Space Division Multiplexing (SDM)

In the last years, the WDM technology has increased their capacity around 80%, because of new investigations in optoelectronic devices (Peter J. Winzer 2012). However, the advances have not been sufficient to satisfy the market necessities. The next step to get more capacity in the optical network has been integrating the SDM technology. SDM can be applied for several technics like TDM, FDM, changing the modulations, using horizontal and vertical polarizations and using the space.

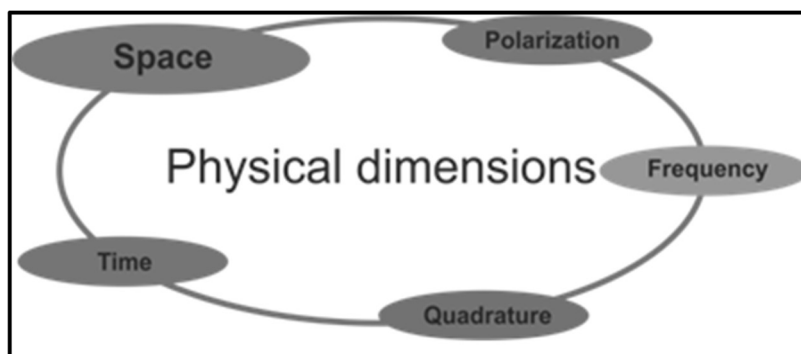


Figure 9. SDM Technics (Peter J. Winzer 2012).

SDM space can be implemented by 2 methods. The first method is named Multicore Fibers, MCF, in which just 1 fiber has multiple cores independently, as shown Figure 5. The second method is called Mode Division Multiplexing, MDM, and it is utilized for Multi-Mode Fibers, MMF.

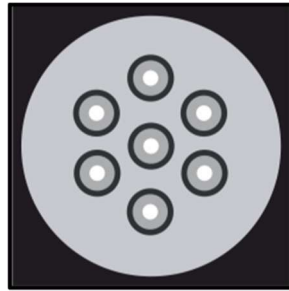


Figure 10. Core Multiplexing Multicore Fibers, MCF.

The main disadvantage of the Multi-Mode Fibers is the crosstalk effect or mode coupling, which is unavoidable in long distance transmissions. However, the Multicore Fibers remove this effect, containing multiple cores in a single fiber in which each core transmits in a single mode.

2.6 Features of the EON networks

The behavior of an EON network does not depend only on the physical elements but also on the way in which is managed. Thus, the RSA algorithm tries to obtain a better behavior, being aware of the physical limitations that present the network.

The main problem of this kind of networks is the fragmentation of the spectrum. When a connection is established, it only makes use of the spectrum that it needs in every moment. Then, when multiple parallel connections are established, each one of them occupies a different bandwidth and is active during a given time. It will cause after a while that the spectrum will be disordered and fragmented, causing the apparition of spectrum spaces that cannot be easily reused by new connections. In the next image is shown the fragmentation effect.

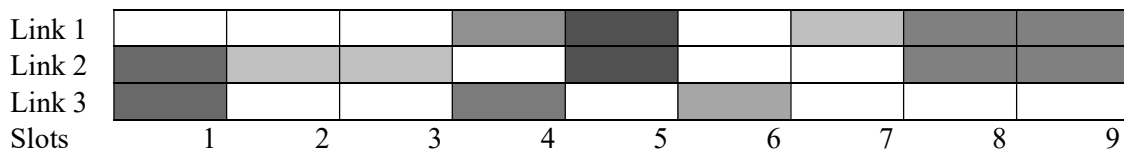


Figure 11. Fragmentation problem.

Another essential requirement to this sort of networks is its capacity to survive to failures. The survivability networks are networks that need to establish the continuity of the traffic when the network fails, for example by rerouting the traffic after the failure.

There are 2 different techniques to avoid the problem:

- **Protection:** In this technique alternative routes are provided to make use of them in case that the network fails. These back-up routes must accomplish the Link-Disjoint condition.
- **Restoration:** In this technique the back-up routes are calculated dynamically in the failure moment. Therefore, in terms of resources use is reached a higher efficiency than in the protection technique.

3. Routing and Network Emulator Software.

The main purpose of this work is the creation of an emulator of Elastic Optical Networks, in order to make later a study to prove the viability of this new kind of networks. Two important feature of this software are its versatility to accomplish with our specifications and the ease to make future improvements to adjust to new requirements.

First, to create the program we have chosen Java as programming language because it is a high level language and has a high processing speed, which allows running simulations with a big amount of data.

The software is designed taking into account a list of requirements which has been updated continuously, including new requirements, to create a highly versatile simulator. Thus, new functionalities have been included in order to carry out different types of simulations and to obtain new conclusions that at the beginning were not expected. To design the software, we have make a class diagram, which has been updated whenever new functions have been included in the program. To make easier the use and accessibility of the program to the users a Graphical User Interface has been designed, as will be presented in this section.

The execution of the program is made using two threads. The first thread is in charge of the management and the simulation of the network, generating and eliminating connections. The second thread is in charge of the storage of the information generated during the simulation to avoid an overloading in the memory of the system and reach fluidity in the simulation.

In the next sections the different parts that compose the program are described in detail.

- **Network:** In the first section is described how must be introduced the data in the program to have a good connection between the different nodes and how the program recognizes these connections and the distances of the different routes among the nodes of the optical network.
- **Fiber:** In this part is explained in detail the versatility of the program and the different types of simulations that can be made by it, such as WDM, EON and SDM Multi Core EON.
- **Connections:** Here is exposed the different features of the several connections simulated the Probability Density Function, PDF, employed for the simulation and the behavior during the simulation.
- **Storage of information:** In this section is detailed how should be interpreted the data generated during the simulation.
- **Operation and behavior:** In the last section is described how must be introduced the different parameters of the program and the behavior of it during the simulation.

3.1 Network

The network is described by means of a matrix in which each column represents a node and each row represents a connection with another node of the same network. If there is a route between two nodes, in the matrix will be write a value different to zero. When the value written in the matrix is bigger than zero a connection between two nodes will be established. This value will indicate the distance among these two nodes, the value influence directly in the algorithm of search, as will be explained later.

Once that the connections are introduced will be described a list of generator and receptor nodes. Each one of the nodes that will not appear in this list will be interpreted as a transit node. These data will be storage in a “textfile” and will have the format shown in the next figure.

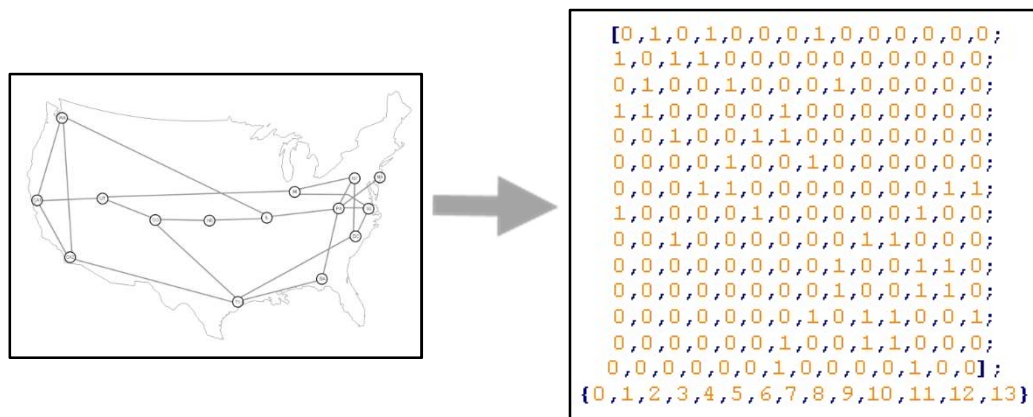


Figure 12. Network description.

How is represented in the above figure between the symbols “[“ and “]” is introduced the connection among nodes and the last array is introduced the nodes capable to receive and transmit information.

3.2 Fiber

Each one of the links which form the network can be configured basing on the requirements of the user, being able to choose the amount of input and output transceivers available for the different nodes and fit the bandwidth available for the different transceivers. On the other hand, the point to point connection can be configured with one or multiple optical fibers, varying the bandwidth of these fibers.

3.3 Connections

The inter arrival time, IAT, following a PDF, which is chosen by a user, and the holding time, HT, of each connection is determined by another PDF that the user must select. In each one of them the user must be informed about the PDF mean. The bandwidth employed for the different connections will depend mainly on the simulation mode, which is detailed later, and on the mode of spectral management chosen for the connections that could be manual or using a truncated PDF.

3.3.1 Modes of simulation

The criterions of the following modes of simulation are chosen with the goal of extract several conclusions for the project and to make future studies with this simulator. They can be modified easily or add new modes if is needed.

Mode 1

The first mode no implements the SDM. It has 12 possible configurations using like maximum 12 frequency slots. Therefore, in this mode each connection also can use one fiber. In the next figure is showed all the configuration of mode 1.

Spectrum 1	Slot 1 Fibra 1																		
Spectrum 2	Slot 1 Fibra 1	Slot 2 Fibra 1																	
Spectrum 3	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1																
Spectrum 4	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1	Slot 4 Fibra 1															
Spectrum 5	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1	Slot 4 Fibra 1	Slot 5 Fibra 1														
Spectrum 6	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1	Slot 4 Fibra 1	Slot 5 Fibra 1	Slot 6 Fibra 1													
Spectrum 7	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1	Slot 4 Fibra 1	Slot 5 Fibra 1	Slot 6 Fibra 1	Slot 7 Fibra 1												
Spectrum 8	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1	Slot 4 Fibra 1	Slot 5 Fibra 1	Slot 6 Fibra 1	Slot 7 Fibra 1	Slot 8 Fibra 1											
Spectrum 9	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1	Slot 4 Fibra 1	Slot 5 Fibra 1	Slot 6 Fibra 1	Slot 7 Fibra 1	Slot 8 Fibra 1	Slot 9 Fibra 1										
Spectrum 10	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1	Slot 4 Fibra 1	Slot 5 Fibra 1	Slot 6 Fibra 1	Slot 7 Fibra 1	Slot 8 Fibra 1	Slot 9 Fibra 1	Slot 10 Fibra 1									
Spectrum 11	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1	Slot 4 Fibra 1	Slot 5 Fibra 1	Slot 6 Fibra 1	Slot 7 Fibra 1	Slot 8 Fibra 1	Slot 9 Fibra 1	Slot 10 Fibra 1	Slot 11 Fibra 1								
Spectrum 12	Slot 1 Fibra 1	Slot 2 Fibra 1	Slot 3 Fibra 1	Slot 4 Fibra 1	Slot 5 Fibra 1	Slot 6 Fibra 1	Slot 7 Fibra 1	Slot 8 Fibra 1	Slot 9 Fibra 1	Slot 10 Fibra 1	Slot 11 Fibra 1	Slot 12 Fibra 1							

Figure 13. Mode 1 spectrum.

Mode 2

The idea of this mode is opposite of the mode 1. Now, SDM is always implanted, if the spectrum configuration before had the form of $1 \times N$, being the N the number of FS. Mode 2 has the spectrum configuration of the following form $N \times 1$ being, N the number of each fiber.

Mode 3

Here is used a rectangular spectrum configuration, but if the number of FS of the spectrum configuration is not even number, then is used the configuration of mode 1.

Mode 4

It was built in order to minimize the network fragmentation. To get it, these spectral figures are completely rectangular, but spectral space is wasted, in grey color. In this way is avoided holes in the spectrum.

Spectrum 1		Spectrum 7	
Spectrum 2		Spectrum 8	
Spectrum 3		Spectrum 9	
Spectrum 4		Spectrum 10	
Spectrum 5		Spectrum 11	
Spectrum 6		Spectrum 12	

Figure 14. Mode 4 spectrum.

Mode 5

This mode has the same structure that the figures in mode 4 but exchange the slots occupied between fiber and slots, like mode 2.

Mode 6

Here is followed the same slots structure in the mode 4, but if the network cannot find any place. Then the network will try to find a place for the connection using the mode 5. If the network cannot find any place using mode 4 or mode 5 the connection will be rejected.

Mode 7

This mode was created following a special pattern for the realization of simulations with the purpose of elaborating a paper presented in the conference of Fiber Optics of Trento in 2016.

Spectrum 1		Spectrum 7	
Spectrum 2		Spectrum 8	
Spectrum 3		Spectrum 9	
Spectrum 4		Spectrum 10	
Spectrum 5		Spectrum 11	
Spectrum 6		Spectrum 12	

Figure 15. Mode 7 spectrum.

Mode 8

This mode has the same structure that the figures in mode 7 but exchange the slots occupied between fiber and slots, like mode 5 and 2.

Mode 9

This does not allow the utilization of the PDFs to generate the spectral bandwidth. The probability weights of bandwidth are introduced manually, as will be explained later. The figures form is completely equal than in Mode 1 but in this case N does not has any limitation.

Summary of the modes

In the next table is shown a summary with the different modes of simulation.

BW	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5		Mode 7		Mode 8		Allocated		OVP	
	Fib	Spec	Fib	Spec	Fib	Spec	Fib	Spec	Fib	Spec	Fib	Spec	Fib	Spec	4, 5 y 6	7 y 8	4, 5 y 6	7 y 8
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
2	1	2	2	1	2	1	1	2	2	1	1	2	2	1	2	2	0	0
3	1	3	3	1	1	3	2	2	2	2	1	3	3	1	4	3	1	0
4	1	4	4	1	2	2	2	2	2	2	2	2	2	2	4	4	0	0
5	1	5	5	1	1	5	2	3	3	2	2	3	3	2	6	6	1	1
6	1	6	6	1	2	3	2	3	3	2	2	3	3	2	6	6	0	0
7	1	7	7	1	1	7	2	4	4	2	2	4	4	2	8	8	1	1
8	1	8	8	1	2	4	2	4	4	2	3	3	3	3	8	9	0	1
9	1	9	9	1	1	9	2	5	5	2	3	3	3	3	10	9	1	0
10	1	10	10	1	2	5	2	5	5	2	3	4	4	3	10	12	0	2
11	1	11	11	1	1	11	2	6	6	2	3	4	4	3	12	12	1	1
12	1	12	12	1	2	6	2	6	6	2	3	4	4	3	12	12	0	0

Table 2. Comparison among modes.

3.4 Storage of information

Each one of the generated connections during the simulation is saved in a file “xls” to avoid the overloading of the system. Therefore, in an Excel sheet is saved the following information about the generated connections: Initial Time, Final Time, Initial Node, Destination Node, Fiber Coord., Slot Coord., Transceiver Output Coord., Transceiver Output Slot Coord., Transceiver Input Coord., Transceiver Input Slot Coord., Number of used Slots, Amount of used useful Slots, Percentage of Blocking Connection for the node and Percentage of Blocking Connection for the network. In the following figure is presented an example of the data of a simulation.

Tiempo Inicio	Tiempo Final	Node Inicio	Nodo Destino	Fibra	Slot	Out Transiver	Out Slot	In Transiver	In Slot	Número slots usados	Número slots útiles	Bloqueo Slots Nodo	Bloqueo Slots Red
0	6	4	15	0	0	0	0	0	0	1	1	FALSE	FALSE
1	35	5	24	0	0	0	0	0	0	2	2	FALSE	FALSE
1	2	8	23	0	0	0	0	0	0	5	5	FALSE	FALSE
1	20	12	4	1	0	0	0	0	0	2	2	FALSE	FALSE
1	27	17	29	1	0	0	0	0	0	5	5	FALSE	FALSE
2	16	9	11	0	0	0	0	0	0	2	2	FALSE	FALSE
2	13	14	19	0	0	0	0	0	0	2	2	FALSE	FALSE
2	52	24	12	0	0	0	0	0	0	2	2	FALSE	FALSE
2	13	28	4	0	0	0	0	0	2	1	1	FALSE	FALSE
2	8	29	24	0	0	0	0	0	2	2	2	FALSE	FALSE
2	14	4	14	0	0	0	1	0	0	2	2	FALSE	FALSE
3	47	5	24	2	0	0	2	0	4	1	1	FALSE	FALSE
3	12	8	11	1	0	0	0	0	2	1	1	FALSE	FALSE
4	45	11	29	3	0	0	0	0	5	2	2	FALSE	FALSE
4	16	15	8	0	0	0	0	0	0	1	1	FALSE	FALSE
4	65	19	29	0	0	0	0	0	7	1	1	FALSE	FALSE
4	5	12	28	0	0	0	2	0	0	2	2	FALSE	TRUE

Figure 16. Example of data storage.

If a connection is rejected is showed through of the Colum “Bloqueo slots nodo” or “Bloqueo slots Red”. A connection is rejected per node, if it do not find space in the transceivers of a node and a connection is rejected per network, if it do not find sufficiently space in the network fibers.

On the other hand, another feature of this program is the capacity of capture images of the spectral state of a link during the simulation. This information is saved in the same “xls” file in which is storage the information about the state of the different links in a given time. In each spectral image is detailed the moment in which is taken the capture of the spectral state and the link in which is made the photography (top left cell). In the next figure is shown a spectral image of the link that goes from node 5 to node 9 in the moment in which were generated 200 connections. The amber cells indicate that the slot is occupied, with the numeric value 1, while the green cells with the value 0 represent the slots that are free.

200 5.9	Slot 0	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8	Slot 9	Slot 10
Fibra 0	0	0	0	0	0	1	1	1	1	0	0
Fibra 1	1	1	1	1	1	0	0	0	0	0	0
Fibra 2	0	1	1	1	1	0	0	1	1	1	1
Fibra 3	0	0	0	0	0	0	1	1	1	1	0
Fibra 4	1	1	0	0	0	0	0	0	0	0	0
Fibra 5	0	0	1	1	1	1	1	1	1	1	0
Fibra 6	0	0	0	0	0	0	0	0	0	0	0
Fibra 7	1	0	0	0	1	1	1	1	1	1	1
Fibra 8	0	1	1	1	1	0	0	0	0	0	1
Fibra 9	0	0	0	0	0	0	0	0	0	0	0

Figure 17. Image of network fragmentation.

The program will occupy the first excel sheets to save connection. In each tab can save until 65535 connections and in the last tab will be saved the spectrum images.

3.5 Graphical User Interface

A Graphical User Interface (GUI) has been developed to execute the program in order to facilitate the use of the program. This GUI is divided in the following tabs:

- **Network:** It allows to select and load the network that we want to simulate.
- **Fiber:** This menu allows to introduce the relevant features of the optical fiber, such as the maximum cost for the search algorithm, the choice of the simulation mode, the spectral configuration of the nodes and the introduction of the parameters of the spectral images.
- **Node:** In this tab are introduced the connection parameters, in which is allowed the configuration of the duration and generation of the traffic and the choice of the bandwidth generation employed for each connection.
- **Storage:** Here is set the options of data storage of all the information generated during the simulation.
- **Results:** This is the last tab and allows to deduce a fast conclusion about the data of the simulation. Print a summary of simulation like slots usage, %BP node and %BP network.

Finally, the operation of the fast menu is explained, which is in charge of the start and generation of data.

3.6 Operation of the GUI

Network

In the Network menu is allowed to choose the location of the directory where we have storage the network that will be simulated by the program. To choose one of the networks, we should click on the Browse button and select one of the directories. Once selected one directory, we should click on Load button and the program will be load all the networks that find in the directory. Later, the networks found in the directory will be showed in the field Combox called Available networks.



Figure 18. Tab program Network.

Fiber

The first section "Options" is used to specify the number of fibers and the bandwidth of each fiber, that will be used in the simulation, as well as the maximum cost that dijkstra's algorithm be able to establish a connection and finally it is possible to choose the simulation mode, detailed previously.

In the part of "Configuration Nodes" is introduced the maximum number of transceivers and the bandwidth that will have each transceiver. This process is carried out as much for output transceivers as for input transceivers.

Finally, in the section of "Spectrum Images" can be introduced the parameters to capture spectral images during the simulation. First, to capture spectral images the number of the initial and destination nodes will be indicated, separating both numbers by a dash. The different will be separated by a comma, as shown the next figure. In the last text box of this menu will be introduced the different moments in which will be captured the spectral images which are related with the number of simulations made.

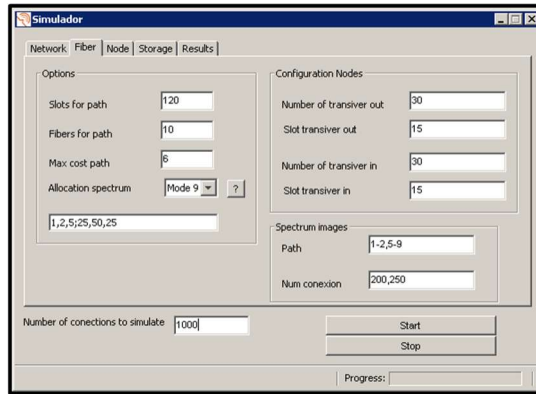


Figure 19. Tab program Fiber.

*Mode 9 has a special field that let introduce firstly the slots used by each connection separated by commas and later is put a semi-colon in order to introduce the respective probability percentage of each connection separated for commas too.

Node

In this tab are introduced the parameters to define the times of IAT, determining a PDF and its mean. Likewise, for each connection will be established a HT choosing a PDF and its mean. A minimum time of connection will be determined in the Offset text box to avoid the connections with a short duration. In the right of the tab we could choose how is generated the bandwidth for each connection. There are two options to generate the bandwidth which are available for all the modes except for Mode 9. These two options are named: Distribution, which allows choosing a PDF to generate the bandwidth for each connection, defining its mean, variance and maximum number of allowed slots (twelve slots as maximum), and Manual, which allows choosing among different bandwidths and indicating the weight of the different options.

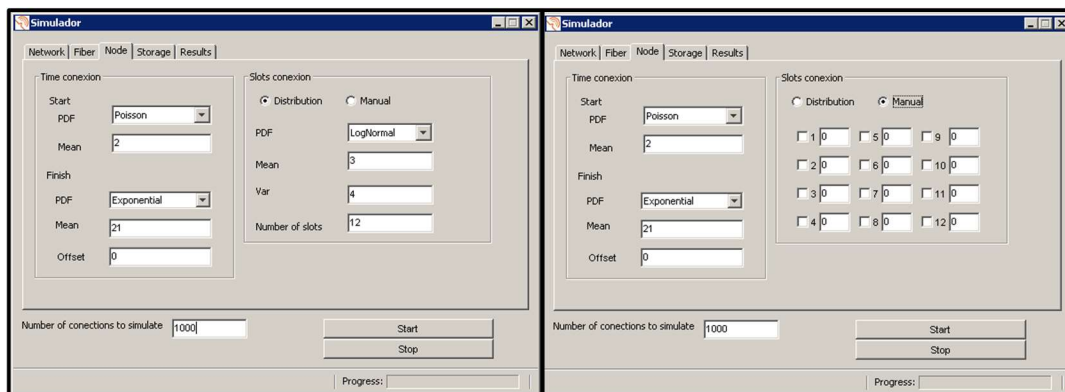


Figure 20. Tab program Node.

Storage

In this menu is indicated the location in the hard disk where all the data of the simulation will be storage. We click on the Browse button to select the destination route. Then, we should write the name of the file which will storage the data. An alternative option is click on the Overwrite button to overwrite the data in the same file when we will make a new simulation.

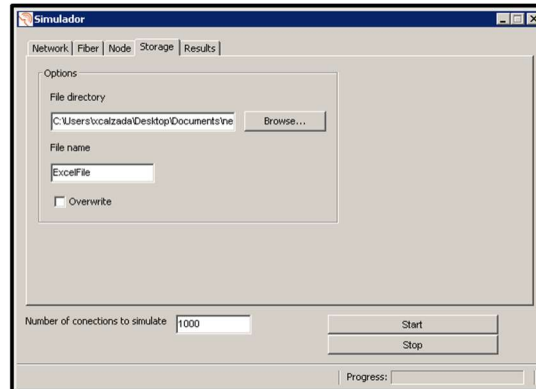


Figure 21. Tab program Storage.

Results

Once the simulation has been done, the program processes all the data to deduce a brief estimation of them, showing on the screen the following parameters: used slots, useful used slots, no blocked slots, blocked slots by the network, blocked slots by the node, time of the last connection, blocking probability caused by the network and blocking probability caused by the node.

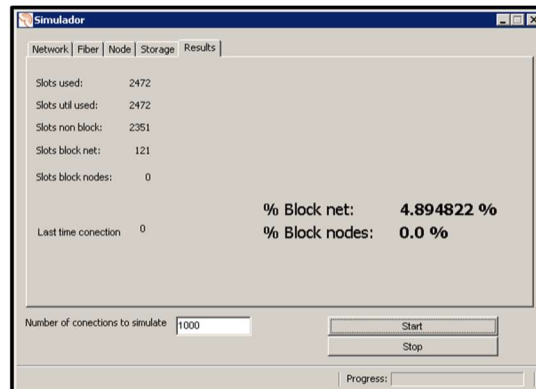


Figure 22. Tab program Results.

3.7 Program structure

Firstly, the program makes a checking of every parameter of the simulation to verify that have been introduced correctly. If some parameter has been introduced incorrectly, the program will indicate which this parameter is and we should reintroduce it again. Immediately, a checking of the matrix or simulation network will be done to determine if the requirements are accomplished. Once all the verifications have been done, we will check if the Overwrite option is selected. If this option is not selected, we will see if there is a conflict among different files. In the case in which there is some file in the destination folder with the same name we could stop the simulation or overwriting the simulated file.

To start the simulation, the program will create as many connections as generated nodes to initialize the simulation. Moreover, all the parameters introduced in the GUI will be load in the simulator. Once the precharge of the system is done, two threads will be executed. The first thread will be in charge of developing the simulation of the program by the generation of the connection and the management of the resources. Meanwhile, the second thread is in charge of the storage of information generated during the simulation.

The first thread has the behavior shown in the following state diagram, Figure 16. During its execution, when it is in the Connection Waiting state increases a time counter. When this time counter is equal to one or more connections which want establish communication with a node the thread changes its state in order to establish these communications.

The first step to establish a communication consist of verifying if there is spectral space enough in the input and output node transceivers. If there is not spectral space the connection is blocked and storage as a blocked connection by node. Otherwise, the connection will search space in the network using the Dijkstra's algorithm which will allow finding the shortest route to establish the communication. If there is not space in the network the algorithm will increase the weight of the used links to establish the communication. In addition, alternative routes will be searched until one of them will be bigger than the maximum allowed cost. In this case the connection will be blocked by the network and will be storage in the system. In the case in which the communication can be established all the used resources to the establishment are eliminated from the available resources list and are released once the connection is finished. In the moment in which the connection is established or blocked by the network or the node, this origin node could generate a new connection from that moment.

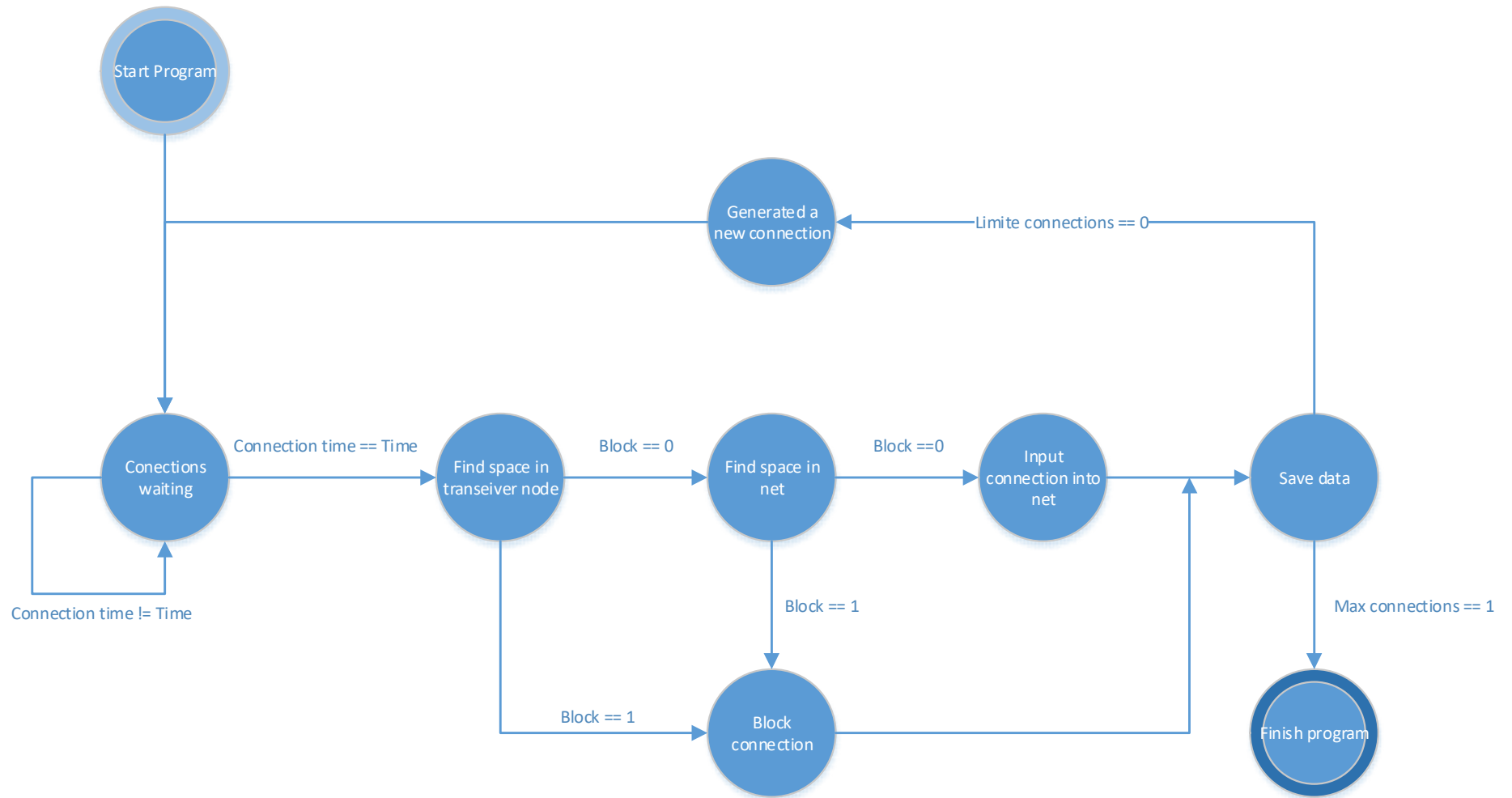


Figure 23. Program structure.

4. Simulation results.

4.1 Simulation characteristics

4.1.1 Network topologies

Three different topologies have been used during simulations “NSFnet (Ives, Bayvel and Savory 2014.), US Backbone (Fan Ji, et al. 2014) and Telefonica Core (project s.f.)”. These topologies are represented in Figure 17 and the main parameters are given in Table 7.

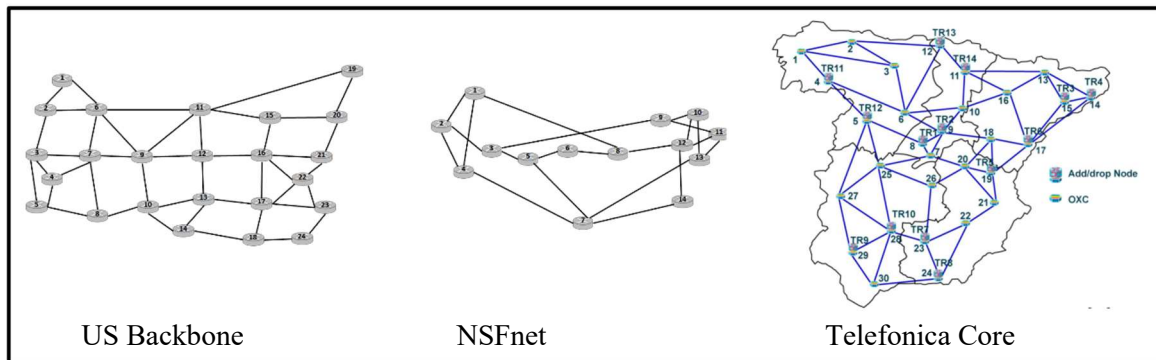


Figure 24. Network topologies.

	Nodes	Links	ND	NHops
NSFnet	14	21	3	2.14
US Backbone	24	86	3.58	2.99
Telefonica ²	30 (14)	112	3.73	(3.45)

Table 3. Comparison among different topologies.

It is worth noting that some of the links are usually much more crowded than others. As an example, link 9-10 in the US Backbone topology is used by 20 of the possible 182 shortest paths. Therefore, more than 10% of the total average traffic generated crosses this link. This implies that the most loaded links will be the most likely contributors to blocking situations.

² Only 14 of the nodes are considered as source-destination nodes. Values inside brackets correspond to these nodes.

4.2 Traffic profiles (BW, time)

As has been stated in previous sections, the developed simulator allows the user to choose the appropriate traffic profile. In addition to manually adjusted traffic, some typical statistical distributions are allowed concerning both, the connections' bandwidth as well as their time characteristics. With respect to bandwidth three different distributions are implemented: Normal, LogNormal and Uniform. As there is a maximum allowed size for connections, these distributions are actually truncated (a maximum number of Frequency Slots is chosen by the user). The main parameters chosen for every simulation are Average Size and Variance.

Figure 18 shows the real values obtained in a single simulation for Normal distribution (truncated >0 and <13 FS) with maximum size 12 FS, average 7 FS and Variance 3.

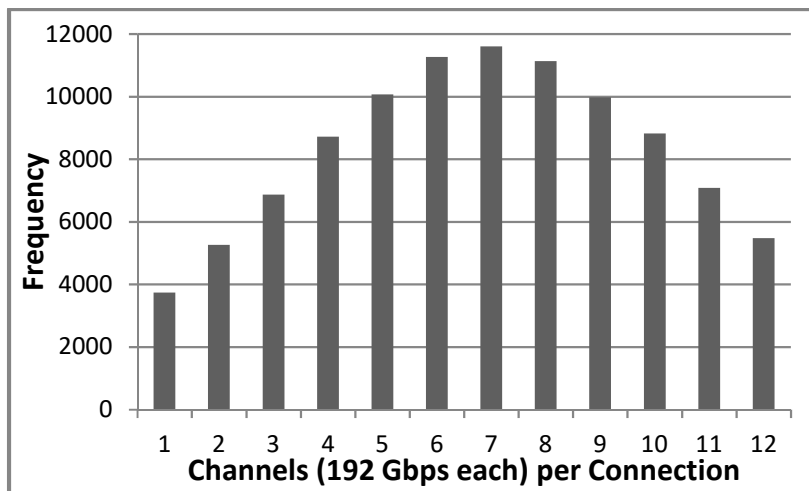


Figure 25. Normal distribution truncated.

Concerning time distributions, two parameters are selected: Inter Arrival Time (IAT) and Holding Time (HT). The time distributions used are Poisson for IAT and negative Exponential for HT. Figure 19 shows a concrete capture of the HT distribution obtained in a 10000 connections simulation (Average HT in this case is 330 u.t.).

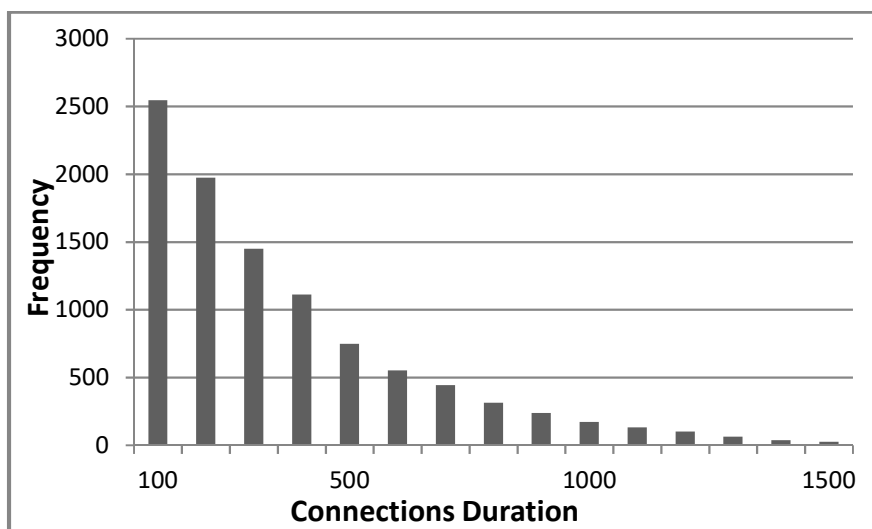


Figure 26. HT of 10000 connections.

Real network capacity can be easily inferred from the parameters used during simulations. Assuming that each FS corresponds to X GHz and that the modulation format used allows a spectral efficiency of $Y \cdot b/s \cdot Hz$, the network load is calculated as follows:

$$\frac{\text{Average HT}}{\text{Average IAT}} = \text{Average Number of live Connections during simulatio}$$

$$\text{Network Load} = \frac{\text{AVG HT}}{\text{AVG IAT}} \cdot \text{AVG FS / Connection} \cdot X \cdot Y [b/s]$$

Obviously, this is the average load values and, due to the dynamic conditions of the offered load (random fluctuations), the actual load can be quite higher during some simulation periods. These dynamic effects have been also studied as simulator results convey details about each one of the 100000 connections generated during one simulation run. Some conclusions extracted from the instantaneous load study are given in next section (Combining static and dynamic traffic).

4.3 Simulated scenarios

4.3.1 Elastic Networks

In this case, no SDM is considered (so only one fiber between nodes is available).

Improving spectrum efficiency by allocating elastic demands into fixed size connections

Finding ways to alleviate fragmentation in EONs has become a really crowded research topic during last years. Most of the works concerning routing and spectrum assignment (RSA) in EONs must appropriately tackle this issue. A lot of efforts have been directed to de-fragmentation strategies (R. Wang 2013), but using RSA algorithms that prevent fragmentation (Khodashenas, et al. 2014) can also help in alleviating its effects. Spectrum partitioning was introduced in (Wang and Mukherjee 2014) as a simple way to efficiently manage some problems arising in EONs, which are there classified as,

1. Fairness issues, due to the fact that small size connection requests have higher probability of finding enough contiguous FS than larger ones.
2. Fragmentation, already defined above, which is worsened as more heterogeneous traffic is offered.

An alternative solution to the fragmentation problem consists in proactively avoiding it. If spectrum is allocated using constant sized blocks, all of the spectrum voids found in the links will have the same size. Therefore, the blocks allocated will perfectly fit with the voids available. This idea was previously introduced in (Comellas y Junyent 2015) and is extended in this work. A model where connections can take any BW value from 1 to N FS has been considered. A fixed number of FS per connection (N) is used to avoid fragmentation. In case that the required number of FS is larger than N, more than one of these spectrum blocks will be assigned to it (see Table 8). Different N values have been tested during simulations and N=4 FS has been demonstrated to be the best option when generated connections sizes range from 1 to 12 FS.

Connection Size (FS)	Assigned Spectrum (FS)	Wasted Spectrum (FS)	Connection Size (FS)	Assigned Spectrum (FS)	Wasted Spectrum (FS)
1	4	3	7	8	1
2	4	2	8	8	0
3	4	1	9	12	3
4	4	0	10	12	2
5	8	3	11	12	1
6	8	2	12	12	0

Table 4. Connections to spectrum mapping.

It has to be highlighted than in many cases (9 out of the 12 right column values in Table 8), the spectrum assignment process implies leaving free FS inside the allocated blocks. This can be seen from two different points of view: 1. Spectrum is being wasted, as blocks of 4 FS are used while the connection required a lower spectrum band. 2. There is available spectrum in case of time varying connections (Comellas y Junyent 2015), or even the same 4 FS block could be re-used by future incoming connections whose required BW is less than the number of free slots. A final constraint which has been avoided up to now comes from the modulation level chosen. Although traffic carried is related to spectrum used, the relationship between them is not a constant.

Depending on the modulation format used, each FS can transport from $1 \text{ } b/s.Hz$ to higher values. This point is not considered in this study whose focus is just on spectrum consumption.

The simulation main characteristics considered in this case are:

- Maximum number of FS per link equal to 320. Assuming that every FS corresponds to 12.5 GHz, the available bandwidth per fiber link corresponds to 4 THz.
- Number of FS per connection (BW) ranging from 1 to 12, with uniformly distributed probability, so each connection can take any of the allowed BW values. Some simulations avoiding specific sizes have also been carried out.
- Connections inter-arrival time follows a Poisson process with average value equal to 1. Connections holding time follows a negative exponential distribution. The average value is adjusted to obtain the appropriate Offered Load values (those that led the network Blocking Probability to the desired values).
- Network topology. The well-known 14-nodes 21-links NSFnet topology has been selected. Source-Destination pairs are uniformly distributed among all the networks' nodes. Connections (10^5 are generated in each simulation run) are considered unidirectional.
- Regarding the routing and spectrum allocation algorithm for allocating new connections, simulations run a typical k-Shortest Path (with $k = 3$) routing and First-Fit spectrum allocation (Wang, Cao and Pan 2011).

It has to be highlighted that the network load values shown in the results Figures are given as average number of live connections per node during simulation. As connections sizes are uniformly distributed from 1 to 12 FS, the average bandwidth of connections is 6.5 FS. When constant size connections are used, each generated connection requires two 4 FS connections. Therefore, there is some excess capacity allocated in this case which has not been taken into account. Results are summarized in Figure 20, where two different simulated scenarios are described. In the first one, elastic allocation (assigned spectrum fits the required one) is compared with constant size ($N = 4 \text{ FS}$, as described in Table 8) allocation of connections.

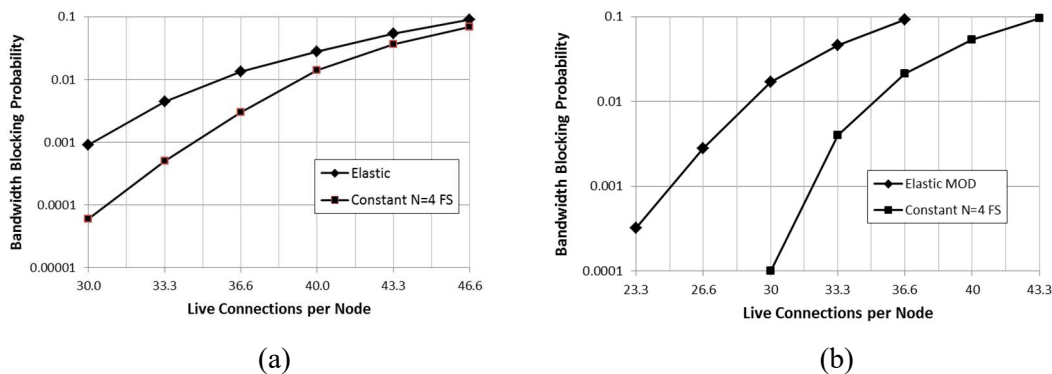


Figure 27. Bandwidth Blocking Probability (BBP) vs. Network Load for Elastic connections and Constant (N=4 FS) sized connections. (a) Elastic traffic uniform for 1 to 12 FS. (b) Some sizes are avoided (1 FS, 5 FS and 9 FS) so probability of appearance of 2, 6 and 10 FS connections is doubled.

It can be seen how the supported load per node at BBP=0.01 is around 36 connections in the elastic case while it approaches 39 in the constant size case. Taking into account that the average connection size is about 6.5 FS and there are 14 nodes in the network, the throughput is increased, assuming 1 b/s.Hz spectral efficiency; in 3.4 Tb/s (an 8.3% of extra capacity is conveyed). In the second scenario, connections with sizes 1, 5 and 9 FS are avoided and fractions for 2, 6 and 10 FS sizes are doubled. As these were the less efficiently mapped to 4 FS blocks, the additional load supported at BBP=0.01 is notably increased reaching up to 20%. As was explained in Section 2, these changes have no great impact on the traffic profile. These results have been validated by using different network topologies and generated traffic profiles.

The results obtained were reported in (Jaume, Xavier and Junyent 2016)

4.3.2 Effects of transponders limitation vs. spectrum limitation

In the previous scenario, the only factor limiting connections allocation was the finite (320 FS) spectrum per link. In this section, the effects of the limitation in the number of transponders as well as the effects of the spectrum limitation have been compared. The main objective of these simulations was to figure out when network blocking is due to each of these causes.

The features of simulation this case is:

- Each link has 320 FS and a unique fiber per path in each direction. The previous considerations represent that if a link is 12.5 GHz the maximum available bandwidth per fiber is 4 THz.
- Connections are bounded from 1 until 8 FS (12.5GHz to 100GHz). The simulation is realized by Normal distribution and the variance is 3.
- The IAT is simulated by Poisson distribution and the mean is 1. On the other hand, the HT is simulated by Exponential distribution and the average is 96. These parameters are choosing to get the Blocking Probability to the desired values.
- Network topology. The topology is NSFNet, it has 14-nodes and 21-links.

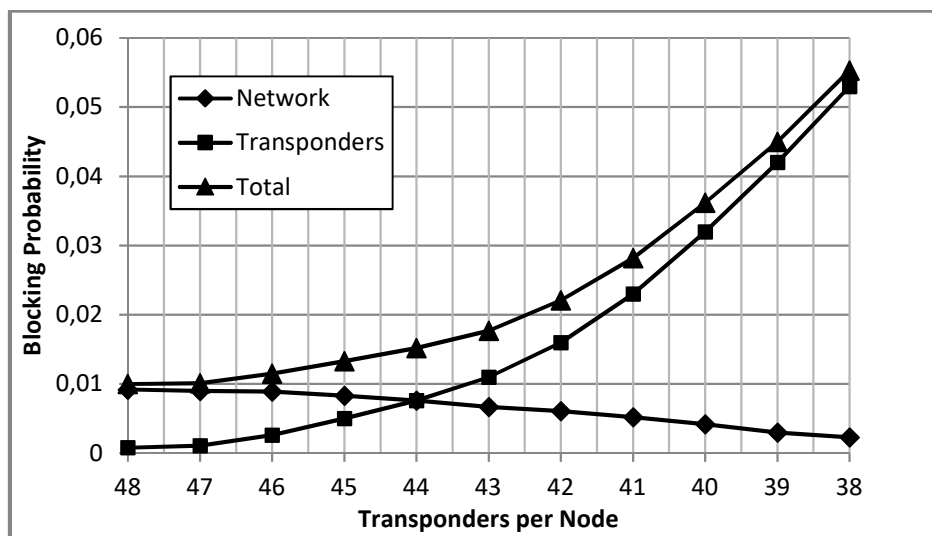


Figure 28. Simulation rising transponders in NSF network

Connections from 1 to 8 FS with Normal distribution (AVG=4.5 FS, Variance=3 FS)

Average traffic per Node 216.4 FS. It can be seen how to ensure BBP=1% 44 Transponders per Node are necessary (avoiding the spectrum effects).

The features of simulation this case are (We only do mention in the changing parameters, regarding the previous case):

- The HT simulation is realized by Exponential distribution with an average of 107.
- Network topology. The topology is Telefonica Core Network, it has 30-nodes, but only 14 nodes are sources-destination and 110-links.

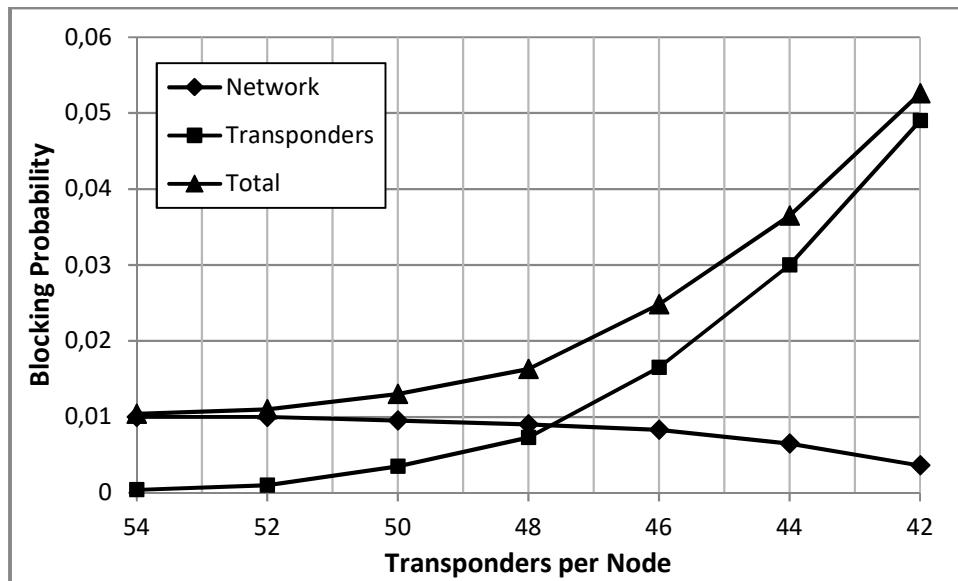


Figure 29. Simulation rising transponders in Telefonica Core Network.

In this case, 48 Transponders per node are required to guarantee BBP=1%. The average traffic supported per node is 241.2 FS.

As every transponder can send 8 FS, the theoretical maximum traffic which can be sent per node is $48 \cdot 8 = 384$ FS. Therefore, the load supported at BBP=1% is $241.2/384 = 63\%$ of the maximum theoretical capacity.

4.3.3 Combining static and dynamic traffic

Taking into account the previously reported results, some doubts about the worthiness of switched optical networks arose. It is concluded that keeping the bandwidth blocking probability at recommendable low values (around 1%) implies that the maximum load supported by the networks is around 60% of the theoretical maximum capacity. A real-time analysis of the load occupation has also been done during this study. Next Figure shows the CDF of the Number of live connections during a whole simulation (65000 Connections are randomly generated). US Backbone topology has been considered in this case even the obtained results can be leveraged to other topologies.

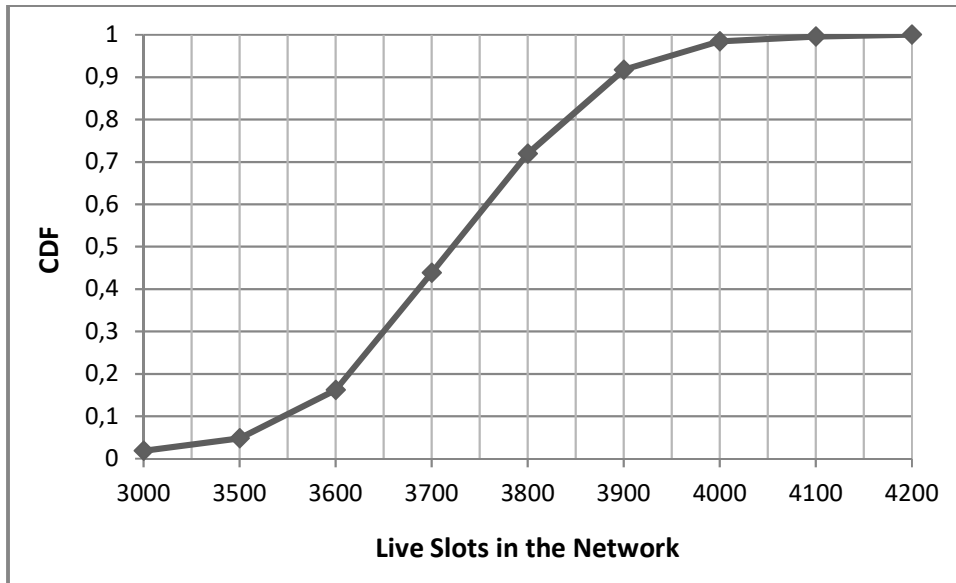


Figure 30. Distribution live slots in the Network.

Live slots in the network are more than 3900 only during less than 10% of the time. Actually, the network load is less than 3800 FS for more than 70% of time. Instantaneous load during simulation is shown in next figure.

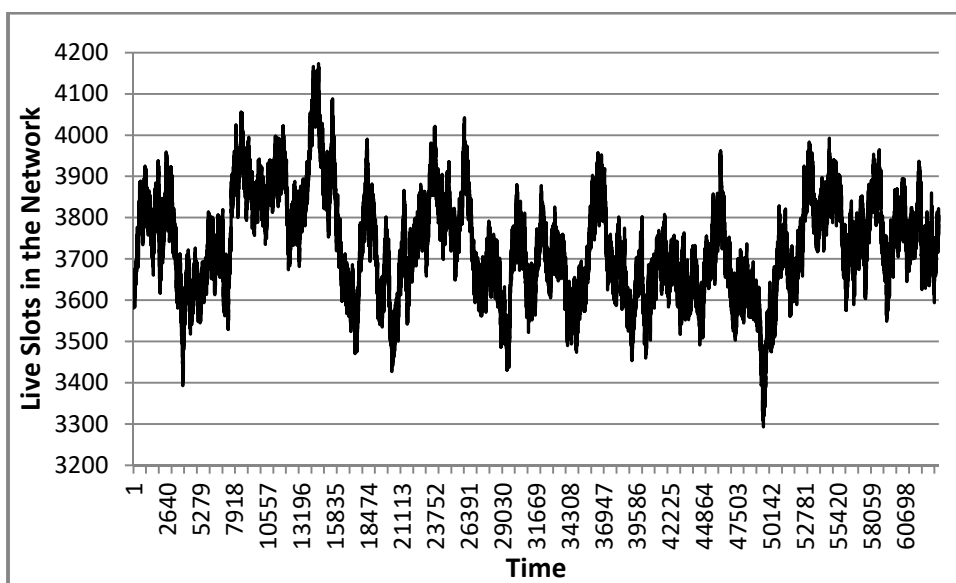


Figure 31. FS usage during the simulation.

The average load after the initial transition phase is 3711 FS. As 40 transponders per node (with 8 FS of capacity each) have been considered in this simulation, the theoretical maximum load in the network is $40 \text{ TPs} \cdot 8 \text{ FS} \cdot 24 \text{ Nodes} = 7680 \text{ FS}$. Therefore, the average supported load at $BBP = 1\%$ is $3711/7680 = 48.3\%$. This result suggests us the possibility of considering a hybrid approach where static traffic is allocated from any to any nodes while some transponders are reserved per node to absorb random fluctuations of traffic. Further simulations are being carried out to assess the feasibility of this scenario.

In previous simulations is observed that the average usage of transponders is around 50% with BP 1%. It represents that in the USBackbone in average with a BP 1% is used 3700 FS, when the maximum capacity of each node of all network is of 7680 FS. To solve the previous spectral inefficiency usage in the transponders, we have dedicated a transponder for each node, then each node has a transponder for every node and the others transponders are dynamic. In this way the results are improved, now the average usage of the transponders is around 5428 FS, it is 70% of usage. Yet the main drawback is that the network has lost dynamism.

4.3.4 Elastic and SDM Networks

In this Section SDM is considered. Each link corresponds to 12 parallel fibers (FMF, MCF or Multi-fiber are undistinguishable from the networking point of view).

The next simulations are making following the next parameters:

Each link is modeled as 12 *parallel links* · 96 FS. Each FS in this case is supposed to correspond to 50 GHz so 4.8 THz per fiber is considered as the usable spectrum. Assuming 4 $b/(s \cdot Hz)$ (for example using DP-QPSK), 192 Gb/s per FS are transported (4% overhead for FEC purposes).

4.3.5 Comparing different Sp-Ch spectrum allocation modes

A simulation between Mode 1 and Mode 2 is realized in the figure 25 following the next parameters:

- The maximum bandwidth per connection is 600GHz using a using a Uniform Distribution of mean 7 and variance 4.
- The inter-arrival time for each connection has a Poisson distribution (7 connections are offered per time unit t.u IAT(node)=2 s IAT(network)=1/7s) and duration exponential negative (the average duration is changed to adjust the network load).
- In this case the topology selected is Telefonica Core Network.
- The total number of connections generated is equal 100.000.

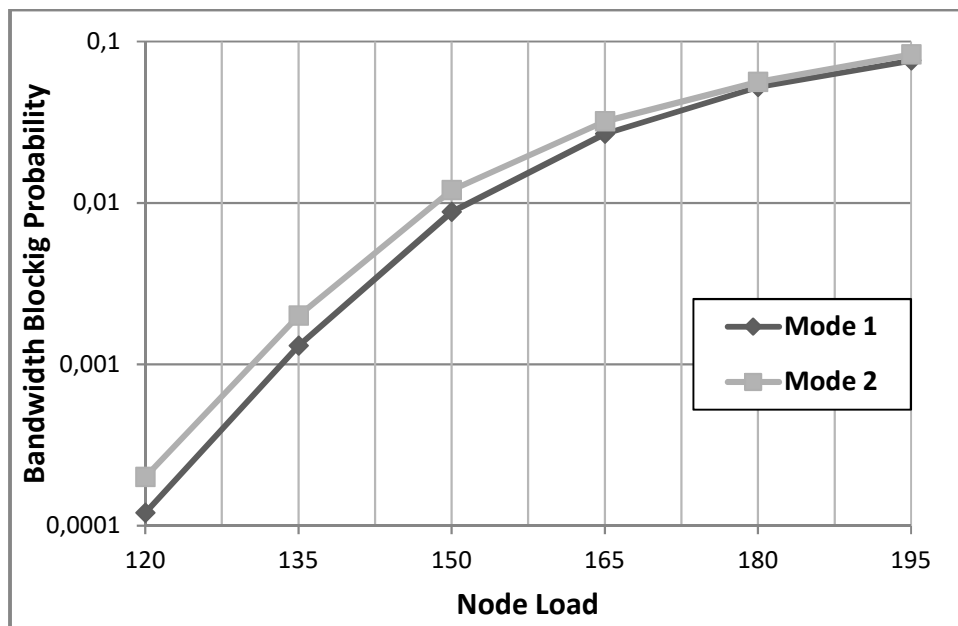


Figure 32. Comparison the node load between Mode 1 and Mode 2.

As shown in the figure 25, results for Mode 1 are slightly better than for Mode 2 (probably due to the fact that you have 96 “containers” instead of 12 and you cannot use 2 different containers for any connection). In this case there is no limitation in the number of transponders per node. The network load is shown in terms of average offered connections per node. Therefore 150 Node

Load means $150 \text{ connections} \cdot 6.78 \frac{\text{channels}}{\text{connections}} \cdot 192 \frac{\text{Gbps}}{\text{chann}} = 195 \text{ Tbps}$ per node transmitted.

Then, we have limited the number of channels per node to 1200 (this is $1200/6.78=177$ connections is the maximum instantaneous traffic that any node can send). Therefore, now this limitation has effect for high load points (only Mode 1 case is shown as performance is very similar for Mode 2):

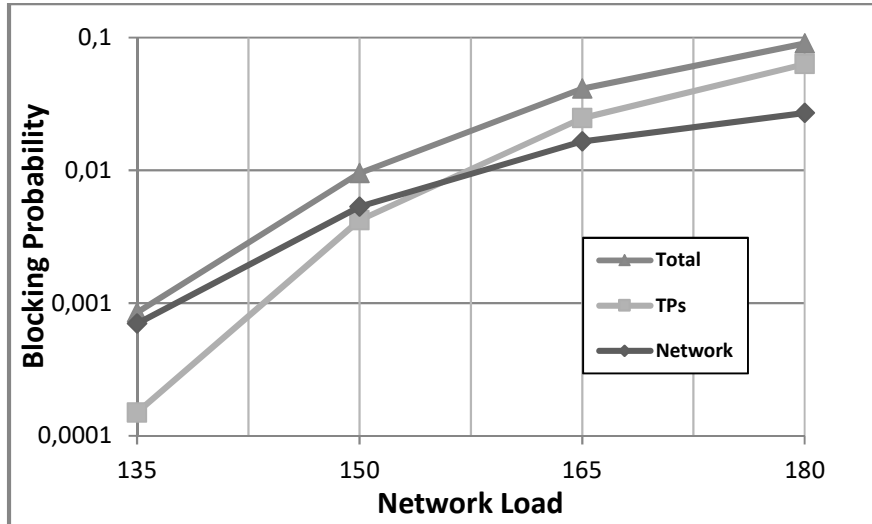


Figure 33. Blocking probability in TPs and Network.

For a load more than 155 $\text{Connections}/\text{Node}$ TPs limitation effect dominates on blocking performance.

A transponder is only used by a new connection if its residual capacity is higher than the number of required channels.

We have implemented the combined case and we have some interesting results.

Mode 3 case: if the number of channels is divisible by 2 we use 2 fibers, if it is prime we use 1 fiber.

Connection size (channels)	Assigned spectral (channel)	Assigned space (fibers)
1	1	1
2	2	1
3	3	1
4	2	2
5	5	1
6	3	2
7	7	1
8	4	2
9	9	1
10	5	2
11	11	1
12	6	2

Table 5. Details of mode 3.

Mode 4 case: we overprovision some channels for the non-divisible connections.

Connection size (channels)	Assigned spe (channel)	Assigned spa (fibers)
1	1	1
2	2	1
3	2	2
4	2	2
5	3	2
6	3	2
7	4	2
8	4	2
9	5	2
10	5	2
11	6	2
12	6	2

Table 6. Details Mode 4.

Two different scenarios have been simulated.

1. 140 TPs per node (so the transponders effect is negligible and the blocking is only due to the network limitations).
2. 120 TPs per node (in this case, when load increases the lack of TPs becomes the main cause of blocking)

It is found that combined case with overprovisioning performs better than combined case when there are enough transponders, so spectrum allocation is more efficient for Mode 4. In addition, there are “extra channels” allocated which have not been requested (1 extra channel is allocated for connections requesting 3, 5, 7 or 11 channels). This could be sold as extra capacity in the network (which has not been considered in the results plotted where the carried load corresponds to the requested one). So, if “actual load” (adding this extra traffic which corresponds to 6.8%) is plotted, Mode 4 would be better than any of the schemes.

For example, at BP=0.01 Mode 4 supports around 147 connections per node. If 6.8% is added it supports more than 152 which is the best value (mode 1).

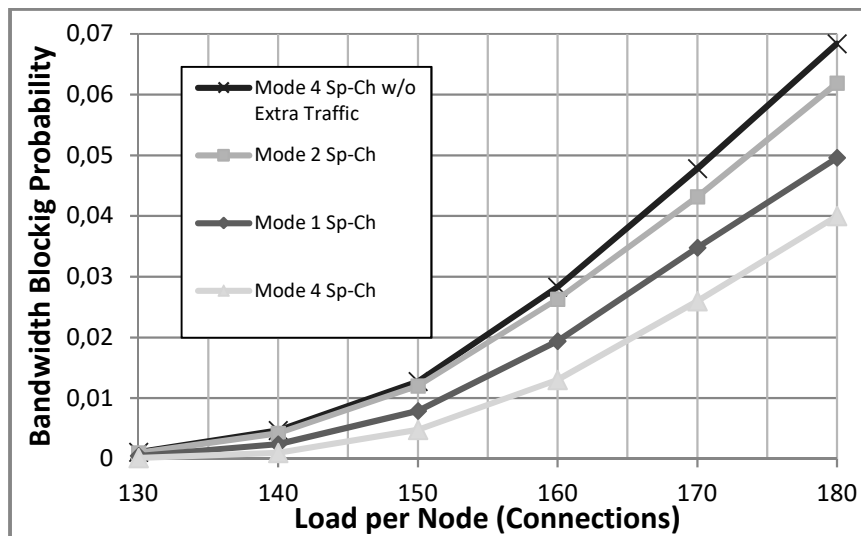


Figure 34. Simulation using 140 TPs per node.

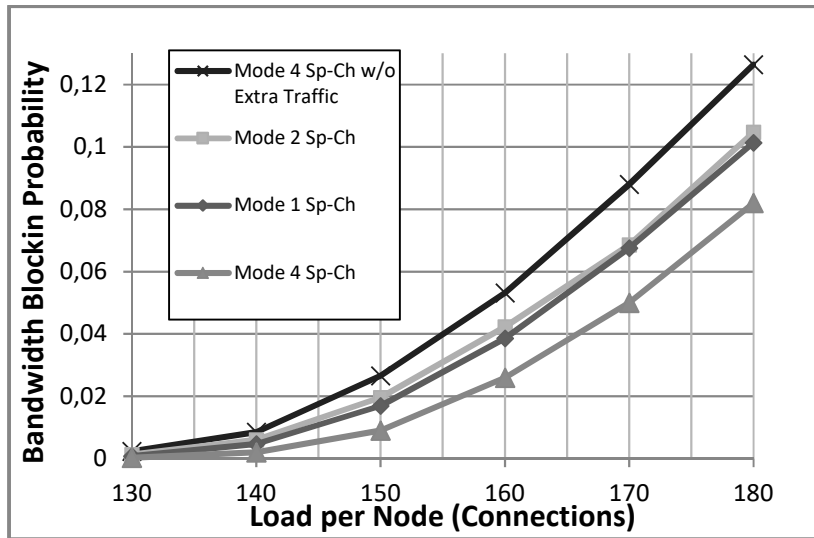


Figure 35. Simulation 120 TPs per node.

Finally, it was concluded that Mode 4 with Extra Traffic case was better than Mode 4 for hybrid Spe-Spa allocation. Next Figures show results obtained comparing Mode 1, Mode 2 and Mode 4 without and with taking into account the extra capacity allocated as real conveyed traffic.

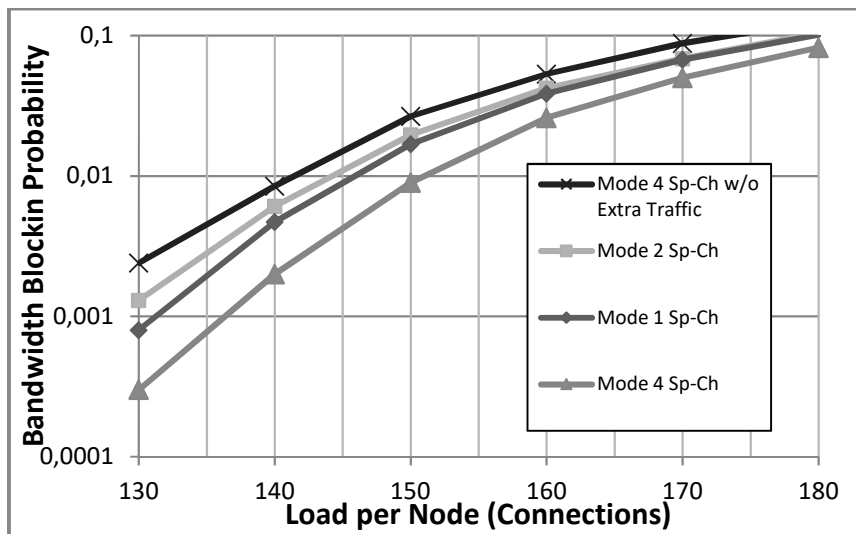


Figure 36. Comparison of 4 Modes using 120TP's.

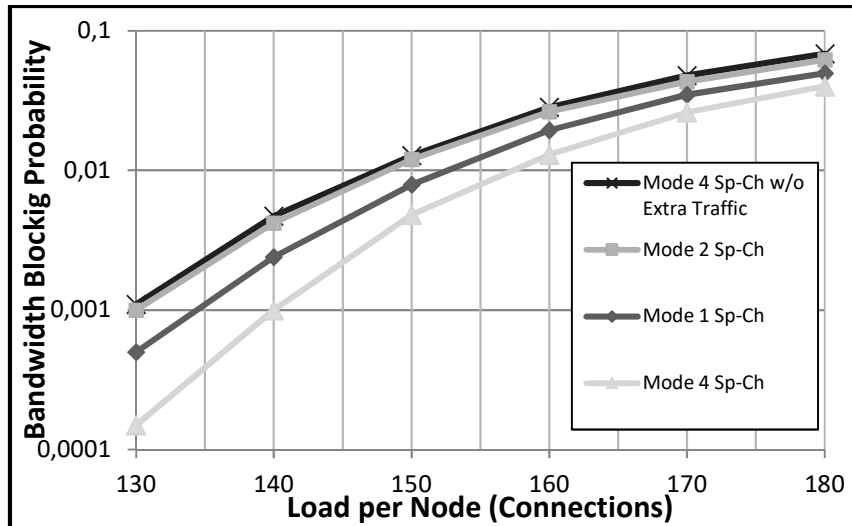


Figure 37. Logarithmic comparison of 4 Modes using 140TP's.

Finally, the effect of the increase in the connections bandwidth has been studied. While Mode 1 allocation overcomes Mode 2 when average bandwidth is 7 FS (previous results) it is seen how Mode 2 gives better results as connections bandwidth increases. This effect is shown in next Figure.

140 TPs per node have been considered so the main effect is lack of spectral resources. The results are plausible as increasing connections size implies that the number of 12 FS connections (the Normal distribution is truncated at this value) grows, and these connections fit perfectly to the Spa containers (12 spatial positions are considered throughout this work).

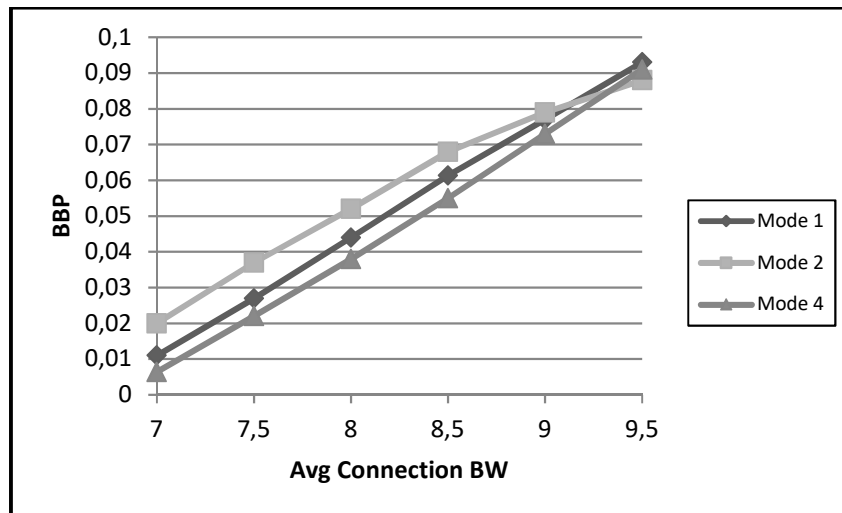


Figure 38. Logarithmic comparison between Mode 1, 2 and 3.

The average BW value has been moved from 7 to 9.5 FS while the variance is kept at 3 FS. For values higher than 9 FS the Spa scheme becomes the best one in terms of bandwidth blocking probability (BBP).

Obtained results show that supported load at BBP=1 % is 5% higher (191.8 Tb/s/node vs. 182.2 Tb/s/node) using Mode 2 than Mode 1 when average connections size is 10 FS.

5. Conclusions

The aim of this work has been to develop a software capable of emulating an elastic optical network with the purpose of studying its characteristics before their deployment. Hence, we have done this work with the intention of reproducing conventional networks like WDM and future networks such as EON to obtain some insight on their performance differences.

1. The software has been made using Java as the programming language. It was chosen because it is a high level language, has high processing speed and allows the use of multithreading.
2. Thanks to the use of multithreading, the software is able to emulate optical networks at the same time that it saves all the information generated. Therefore, while the simulation is done, the program saves all the information generated in real time and processes it to extract basic parameters that allow us to determine not only the network performance but also the assessment of the appropriateness of the parameters used.
3. The software is able to generate up to one hundred thousand (100.000) *connections/run*, allowing quite realistic simulations.
4. The program can manage many different parameters. It permits the user to adjust the simulations to the realistic behaviour of an optical network. For instance, the user can configure the number of optical fibers and their spectral capacity, the number of transceivers available at each network node and their capacity, introduce any network topology configuration, as well as adjusting the statistical characteristics of generated connections, such as connection duration, spectrum size, implemented SDM scheme, etc.
5. Accordingly, it is possible to simulate any network configuration without any restriction in the number of source and destination nodes.
6. In parallel with the traffic generation process, the program saves the information of each connection generated and starts the process of computing the percentage of network blocking, adds the number of used slots and unused slots, etc. These values are very useful to determine if the simulation was satisfactory.
7. When the simulation is over, all the data is stored in a file “.xls”. This file allows the user to deeply study the behaviour of the network. The information saved in this file comprises for example the initial and final time values of each connection, the spectrum usage, the position of the spectrum occupied, the blocking type if applicable, etc.
8. In addition, the software is able to take spectrum images at any moment during the simulation. This allows us to study the behaviour of spectrum fragmentation during the simulations.
9. Traditional WDM networks can also be simulated, allowing to get information about performance of EON compared to them.
10. During the simulation of EON some important results were extracted.
 - a. A comparative study between the EON and WDM networks was done, in which it was proven that, when no defragmentation algorithm is applied, the spectral efficiency and the capacity of an EON network are identical to those of a WDM network. Therefore, if a defragmentation algorithm and improved RSA techniques are implemented, higher efficiency networks will be obtained. From these results, a scientific contribution was presented during the IEEE 16th ICTON

conference(Jaume, Xavier y Gabriel, Efficient spectrum assignment in Elastic Optical Networks 2016).

- b. A study about the measurement and the utility of the transceivers available at each node was developed. In this study, it has been proved that to achieve a blocking probability of connections of 1%, the actual use of transceivers is around 50%. To increase the efficiency of the transceivers, the flexibility of the network was eliminated and 60% of the transceivers were fixed to the pairs and the remaining 40% of the transceivers remained elastic. The use of a buffer was also proposed to avoid the peaks of connection. From this study, it can be concluded that the efficiency of the transceivers increases around 70% and consequently the costs are reduced considerably.
- c. Finally, a study was done proving that as the size of the connections increased, the spectral efficiency improved if the mode of simulation chosen was 1, while it would get worse if the mode of simulation chosen was 2, when the SDM structure is utilized.

6. Future lines

In the final annex of this work, the creation of a new parameter that considers the capacity to accept a new connection and the fragmentation of an optical fiber at any instant is explained. If a consistent improvement in the calculation of this new parameter for each one of the fibers that form the network is introduced in the software, this will allow for the reconfiguration of the network and consequently the efficiency could be significantly improved. Further studies are being carried out to assess this idea.

7. Annex

7.1 Real time monitoring of spectrum status

Some functionality about real time monitoring of the spectrum usage on each link was also included in the simulator as explained in Section 3.3

The spectrum entropy of each link, introduced in [9], is an important parameter determining the potential capacity of the links to allocate future requests. But the entropy parameter has some flaws. It just measures fragmentation and gives not much info about potential acceptance of new incoming connections. Next figure shows obtained values for a link going from completely empty to completely full:

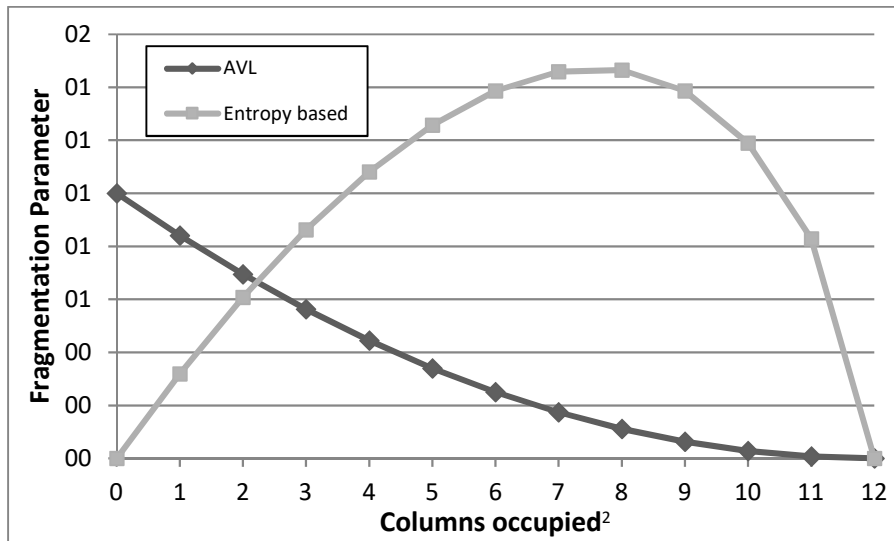


Figure 39. Fragmentation AVL and Entropy based.

The detailed study of spectrum used during network operation should provide ways to improve the whole network performance. As an example, a spectrum occupation parameter has been defined which could be used to adjust the routing function cost during simulation. This parameter should reflect both, the link load as well as the fragmentation of each network link.

Values in vertical axis correspond to fragmentation (AVL, from Availability Link, is explained later). Horizontal axis represents a 4 fibres · 12 slots link where 0 means (all slots on all fibers empty) and 1 to 12 means that one more column (from left to right) has been occupied (e.g. 4 means that the 4 first slots of all fibers are occupied).

Fragmentation approaches 0 at both extremes (empty and full link). For each one of the link fibers fragmentation is calculated in that paper as:

$$Frag = - \sum_{i=1}^{Nvoids} \frac{VoidSize}{Slots} * \ln\left(\frac{VoidSize}{Slots}\right)$$

To better capture the link status is proposed like AVL (from “availability”). It is calculated per each link fiber as:

$$AVL_{Fiber} = \sum_{i=1}^{N_{voids}} \frac{VoidSize^2}{Slots * MaxBW}$$

Where maximum bandwidth is the maximum connections size.

This way big void sizes are prioritized (squared) and its ratio to the maximum connection size is taken into account.

Examples:

If the fiber is completely empty:

$$AVL_{Fiber} = \frac{Slots}{MaxBW}$$

When the voids are the half of all slots, $Void = \frac{Slots}{2}$:

$$AVL_{Fiber} = \frac{Slots}{4 * Maximum\ Bandwidth}$$

And if the fiber is completely filled:

$$AVL_{Fiber} = 0$$

Then, for the SDM case, AVL is obtained as

$$AVL = \sum_i AVL_{fiber_i} \cdot \frac{MaxBW}{NumberFibers \cdot Slots}$$

reaching 1 only for a totally empty link and high values when some of the parallel fibers are completely empty.

Example with 96 slots and 12 fibers:

Compact occupation (902 used slots)

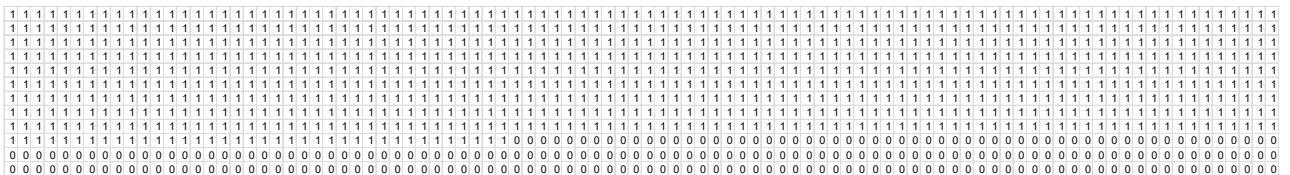


Figure 40. Spectrum non fragmented.

The value of AVL is 0.1971.

Fragmented occupation (902 used slots)

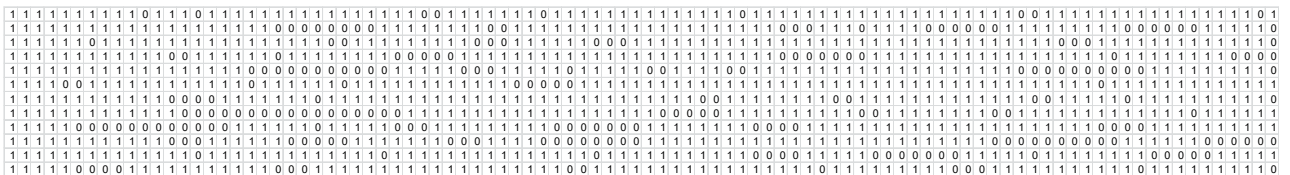


Figure 41. Spectrum fragmented.

The parameter has the value of 0.014.

So, even the number of free slots in the link is the same, availability is 14 times greater in the upper case.

I've been testing different situations and it seems to reflect quite well "link availability". By monitoring the AVL values during simulations we can have reliable info about network status.

On the other hand, for uniform source-destination distribution, blocking is concentrated at few crowded links (for low blocking values). Therefore, some way to predict network performance by just monitoring few links should be feasible.

8. Glossary

A

AVL: Availability Link, 39, 41

B

BBP: Bandwidth Blocking Probability, 28, 29, 31, 36

BP: And, if the fiber is completely filled:, 17, 31, 34;
Blocking probability, 17

BPSK: Binary phase-shift keying, 7

BVT: Bandwidth-Variable Transponder, 7

BV-WXC: Bandwidth Variable Cross-Connect, 7

C

CATV: Cable Television, 4; Community Antenna
Television, 4

CDF: Cumulative Distribution Function, 30

D

DP-QPSK: Dual Polarization Quadrature Phase Shift
Keying, 32

E

EON: Elastic Optical Network, 2, 3, 5, 6, 7, 9, 37;
Elastic Optical Networks, 6, 7, 8, 9, 10, 11, 26

F

FDM: Frequency-division multiplexing, 9

FS: Frequency Slots, 3, 13, 24, 25, 26, 27, 28, 29, 30,
31, 32, 36

G

GHz: Gigahertz, 6, 25, 27, 28, 32

GUI: Graphical User Interface, 2, 17, 18, 21

H

HT: Holding Time, 12, 19, 24, 28, 29

I

IAT: Inter Arrival Time, 12, 19, 24, 28, 32

M

MCF: Multi-Core Fiber, 10, 32

MDM: Mode Division Multiplexing, 10

MMF: Multi-Mode Fibbers, 10

O

OFDM: Orthogonal Frequency Division Multiplexing,
7

OOP: Object Oriented Programming, 5

P

PDF: Probability Density Function, 11, 12, 15, 19

Q

QAM: Quadrature amplitude modulation, 7

QPSK: Quadrature Phase Shift Keying, 7

R

RSA: Routing and Spectrum Assignment, 8, 10

RWA: Routing and Wavelength Assignment, 8

S

SDM: Space Domain Multiplexing, 9, 10, 11, 13, 26,
32, 37, 40

Sp-Ch: Super Chanel, 32

T

Tb: Terabits, 28, 36

TDM: Time-division multiplexing, 9

TPs: Transponders, 33, 34

W

WCC: Wavelength Continuity Constraint, 8

WDM: Wavelength Division Multiplexing 3,5, 6, 7, 8,
9, 11, 37, 43;

X

xls: file extension for a spreadsheet, 15, 16, 37

Z

ZB: Zettabyte, 5

9. Bibliography

- al., M. Jinno et. «Spectrum-efficient and scalable elastic optical path network: Architecture, benefits, and enabling technologies.» *IEEE Commun* 47, n° 11 (Nov. 2009.): pp. 66–73.
- Comellas, J., y G. Junyent. «On the Worthiness of Flexible Grid in Elastic Optical Networks.» in *Proc. ECOC*, 2015: 6.2.
- Fan Ji, Xiaoliang Chen, Wei Lu, Joel J. P. C. Rodrigues, and Zuqing Zhu. "Dynamic p-Cycle Protection in Spectrum-Sliced Elastic Optical Networks." *Journal of Lightwave Technology* 32, no. 6 (2014): 1190-1199.
- <https://insight.nokia.com/future-video-content-evolution-toward-2020>. November de 2015.
- Ives, D. J., P. Bayvel, and S. J. Savory. "Adapting Transmitter Power and Modulation Format to Improve Optical Network Performance Utilizing the Gaussian Noise Model of Nonlinear Impairments." *Journal of Lightwave Technology* 32, , no. 21 (2014.): 3485-3494.
- Jaume, Comellas, Calzada Xavier, and Gabriel Junyent. "Efficient spectrum assignment in Elastic Optical Networks." *International Conference on Transparent Optical Networks*. Trento: IEEE, 2016. 1-4.
- Khodashenas, P. S., J. Comellas, S. Spadaro, J. Perelló, and G. Junyent. "Using Spectrum Fragmentation to Better Allocate Time-Varying Connections in Elastic Optical Networks." *Journal of Optical Communications and Networking* 6, no. 5 (2014): 433-440.
- Mukherjee, B. «Optical WDM Networks.» *Bussines: SpringerVerlag*. Berlin, Germany, 2006.
- Peter J. Winzer. «Optical Networking Beyond WDM.» *IEEE*, 2012.
- project, FP7-STRONGEST. «Efficient and optimized network architecture: Requirements and reference scenarios.» s.f.
- R. Wang, B.Mukherjee. «Provisioning in elastic optical networks with non-disruptive defragmentation.» *IEEE Journal of Lightwave Technology* 31, n° 15 (2013): 2491-2500.
- Sarma, Nityananda and Oki, Eiji. «Routing and Spectrum Allocation in Elastic Optical Networks.» *IEEE*, 2015: 1776 - 1800.
- Wang, R., and B. Mukherjee. "Spectrum management in heterogeneous bandwidth optical networks." *Optical Switching and Networking* 11 (2014): 83-91.
- Wang, Y., X. Cao, and Y. Pan. "A Study of the Routing and Spectrum Allocation in Spectrum-sliced Elastic Optical Path Networks." in *Proc. INFOCOM*, 2011: 1503-1511.
-