



Spectrum management strategies for performance improvement in Elastic and Multi-Rate Optical Networks

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Abstract

Performance comparison between elastic optical networks and multi-rate optical networks, using different spectrum allocation algorithms to prevent fragmentation.

Keywords

Elastic optical networks, network optimization, spectrum fragmentation.

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To family for making me who I am, and for their never-ending support; without them, I probably would not have accomplished most of the things I have accomplished in my life.

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I.

Introduction

Elastic Optical Networks (hereinafter EONs) promise a potential solution to the growth and unpredictability of data traffic^{[1][2]}, but despite all the benefits new challenges arise, such as, the considerable fragmentation in routinary operation, which can ultimately degrade performance; moreover, EONs require cutting edge—and expensive—equipment that, at the time of this study, are in a very early state in terms of widespread deployment.

Some approaches using *Multi-rate Optical Networks*^[3] (hereinafter, MONs) with semi-elastic schemes, have been proposed in order to provide an alternative to EONs, while keeping the spectrum fragmentation restrained. The purpose of this study is to present a comparison between EONs and MONs, by means of simulating extensively each scenario using different spectrum management strategies to cope with fragmentation, and thus compare the performance.

This document consists of five chapters. The following chapter introduces the concepts and technologies that serve as a start point for this master thesis. A description about optical networks in general, and a comparison between the fixed and flexible grid technologies.

The third chapter will focus on the software OMNet++, and the methodology used for the simulations. An overall description about the environment used to simulate the scenarios, and a description about the spectrum management strategies used for each case.

The fourth chapter contains the results of the simulations, where four scenarios were considered. First, the evaluation of the performance of a MON using requests of 3 different sizes. The second and third scenario consist of simulating two different schemes which serve to translate incoming requests intended for an EON, into an equivalent for a MON, using only 3 traffic classes. Finally, the comparison between the two previous cases and an EON that uses 10 traffic classes.

The final chapter is dedicated to enunciate the conclusions of this study, product of the analysis of results, and the lessons learned via experimentation of the described scenarios.

The main objective of this study is to perform a comparison between EONs and MONs performance, considering different spectrum management strategies. It is a further objective to perform a simple cost analysis, considering EONs comprise cutting edge technologies that are expected to be expensive in the early stages of adoption.

II. Theoretical background

Optical networks at their simplest form comprise optical nodes intercommunicated by optical fibers. The data is converted from an electrical signal to an optical signal at the source node, then travels throughout the nodes in the network, whose in turn manipulate and route them in order to deliver them to the destination node, and finally they are once again converted into electrical signals for further processing.

Wavelength Division Multiplexing (hereinafter, WDM) is a straightforward multiplexing scheme that allows the transmission of multiple data carriers on the same fiber, by using different wavelengths. WDM systems generally use in the 1550nm band since it minimizes the signal attenuation. Current specifications for WDM comprise a fixed channel size in the range of 12.5GHz to 100GHz, hence the number data carriers being multiplexed are in the range of 50 to 400 channels^[4].

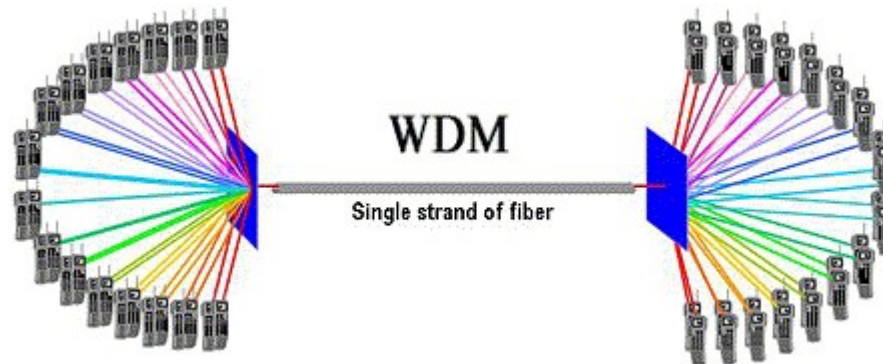


Figure 1: Illustration of a WDM system

Semi-conductor lasers—which conform the usual light source used in optical communications—serve as a translator to convert the signal from an electrical domain to a light signal, which can travel through fibers. In WDM, a multiplexer is set-up at the transmitter in order to pack the all the wavelengths together in a single light stream, and a demultiplexer to separate each one of them at the receiver.

II.1 Physical limitations and signal alteration

There is a plurality of effects that cause the degradation of the optical signal, thus making the detection less reliable at the end node. In order to cope with such deterioration, the inclusion of several devices along the path is often necessary, increasing the complexity and operative cost of the network. Said effects can be classified as linear and non-linear.

II.1.1 Linear optical effects

An optical signal can travel very long distances, nevertheless, the power of the signal decreases proportionally to it due to attenuation, which depends on the quality of the fiber, and is measured in dB/Km. Attenuation is mainly caused by the effects of scattering and absorption.

Light scattering: The imperfect internal surfaces of the optical fibers—mostly at the atomic scale—cause the light beams to bounce in slightly different directions, which over distance cause the dissemination of some of the photons of the pulse, which has the effect of reducing the power of the signal. The scattering is inversely proportional to the wavelength, and is the

primary cause of attenuation. This effect is also known as diffuse reflection, which is opposite to specular reflection thanks to a perfectly—yet practically impossible to achieve—flat surface.

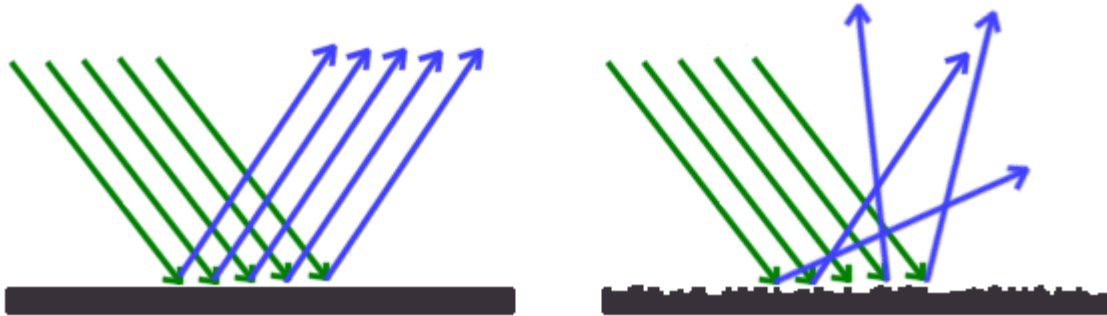


Figure 2: Representation of specular versus diffuse reflection

Absorption: Owing to quantum effects, the materials of the fiber can absorb specific wavelengths instead of reflecting them, causing signal loss. In contrast to scattering, absorption occurs at discrete wavelengths. As represented in Figure 3: The lowest attenuation is found in the 850nm, 1300nm and 1550nm bands. The 1550nm band provides the lowest absorption and scattering, thus being the one used the most as noted before.

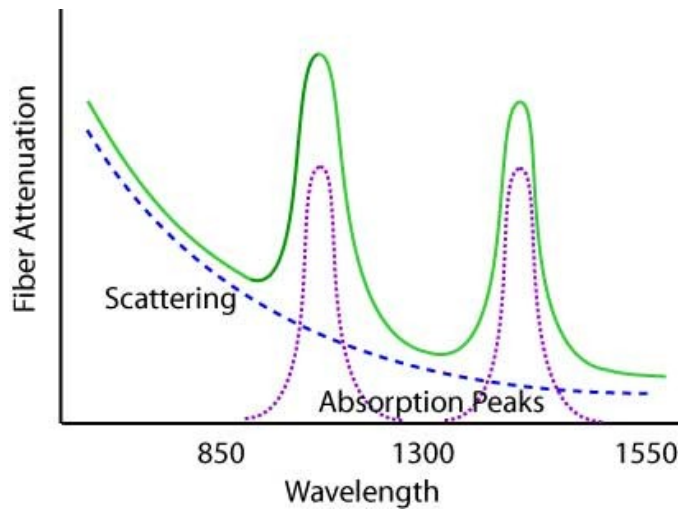


Figure 3: Representation of attenuation for different wavelengths

Owing to the attenuation effects described before, and depending on the distance, the signal has to go through one or more amplification phases in order to compensate the loss, typically with the aid of erbium-doped fiber amplifiers.

Amplified spontaneous emission noise: Optical amplifiers rely on the *stimulated emission* phenomenon. A doped fiber is made by adding a trace contaminant—usually erbium—to a regular fiber. The signal is multiplexed into the doped fiber along with secondary laser source, known as the pump, which excites the ions of the contaminant into a higher energy state.

When a photon of the signal collide with an excited ion a *stimulated emission* occurs, producing a second photon with the characteristics of the original. This increases the number of photons, augmenting the power of the signal. However, *spontaneous emission* causes the random decay of some of the excited ions producing non-coherent photons, that introduce noise into the transmission.

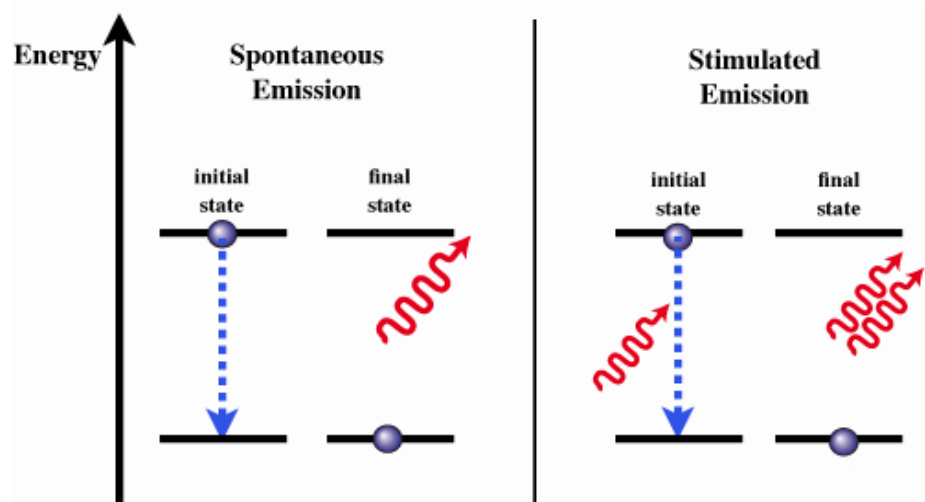


Figure 4: Representation of spontaneous versus stimulated emission

Additionally, the signal will be affected by dispersion—which consists of the alteration of the optical pulses, causing a distortion of the original signal at the destination node, in the form of inter-symbol interference.

Chromatic dispersion: Light sources cannot generate an isolated wavelength, thus the spectral width of the pulses is increased over distance, because longer wavelengths travel faster than shorter wavelengths. The pulses can become so wide that they start overlapping with each other.

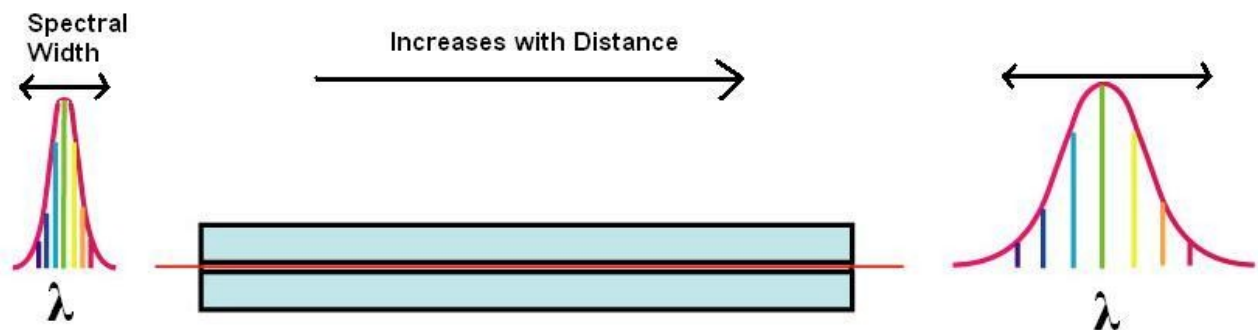


Figure 5: Representation of Chromatic dispersion in a pulse

Polarization mode dispersion: Is a consequence of the imperfections of the fiber. The light is polarized randomly, and each polarization travels through a slightly different path, which ultimately leads to an overlapping between the sets of pulses if the travel distance is great enough.

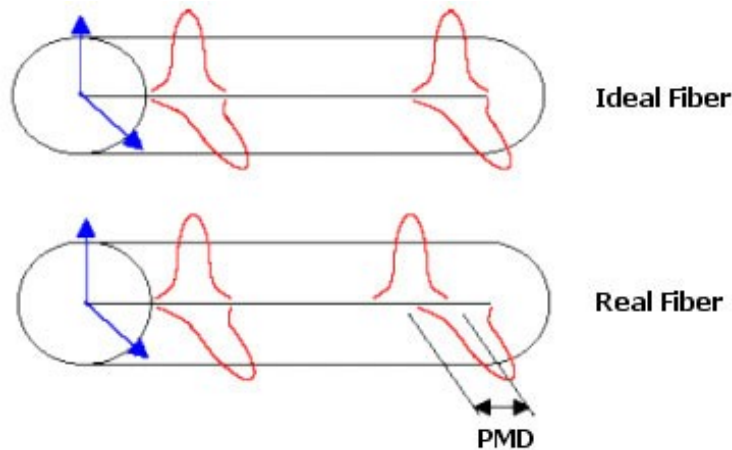


Figure 6: Representation of Polarization mode dispersion in a series of pulses

Depending on the distance, the signal has to go through one or more regeneration phases, which consists of converting the signal to an electrical analog and back to optical in order to counteract all the deterioration effects, however this is not particularly efficient. To get some perspective, nowadays a typical system with 40 channels at 10Gbps, can cover a distance of about 2000Km without the use of regenerators.

II.1.2 Non-linear optical effects

The main non-linear effects in optical fibers are a consequence of the Kerr effect. The Kerr effect describes a variation in the refractive index of a material, caused by the application of an electric field. In optics, this electrical field is generated by the signal itself. This is the case when the

duration of the light pulse is in the order of a pico second, also known as ultrashort pulses.

Ultrashort pulses have a broadband optical spectrum, and are characterized by a high intensity, which causes the induction of an electrical field responsible for the non-linear variation in the refraction index of the fiber, ultimately altering the signal.

The most relevant non-linear effects comprise *Self-phase modulation* (SPM), which causes a phase shift in the pulse and thus a change in its spectrum, *Cross-phase modulation* (XPM), in which the pulse of a wavelength affects the spectrum of a difference wavelength, and *Four-wave mixing* (FWM) which consists of the formation of additional wavelengths owing to the interaction of two initial wavelengths, and the scattering of the photons throughout the fiber.

Some of the non-linear effects can be used beneficially, applications such as spectral broadening^[5], ultra fast optical switching^[5], temporal and spectral pulse compression are achievable thanks to SPM and XPM. Nevertheless, in WDM systems they represent a liability as they lead to inter-channel crosstalk and jitter.

III. Simulation framework

III.1 Simulation methodology

The simulations were carried out by implementing an analog of the well-known NSFNET topology, using the OMNet++ framework. Each request selects a source and destination node randomly, and determines multiple routes between both using a k-shortest path algorithm, in order to provide alternatives in case of congestion; if all the paths are congested the request is dropped.

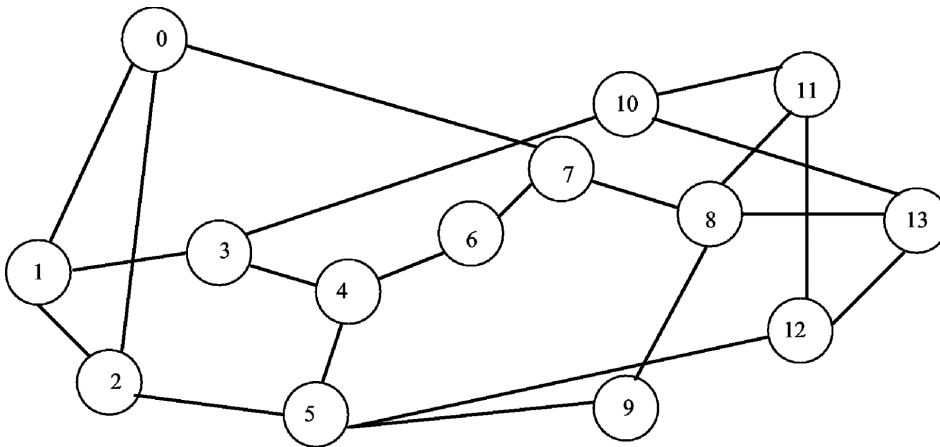


Figure 7: Representation of the NSFNET topology used in the simulations

Dynamic network operation was simulated employing traffic requests with a mean duration—or holding time (HT)—of 200s modeled by an exponential distribution, with a variable inter-arrival time (IAT) modeled by a Poisson distribution. Hence, the load in erlangs is defined by dividing the holding time by the inter-arrival time.

The whole spectrum size is 130 slots. In the EON simulations, the traffic classes consisted of connections with a bandwidth in the range of 1 to 10 slots. In the MON simulations, the traffic classes used consisted of connections with bandwidths of 1, 4, and 8 slots.

The value of the throughput per node—in Gbps—used in the simulations varied in order to generate a network blocking probability (hereinafter, NBP) in the range of 1% to 5% for every trial, thus providing useful results. This value can be calculated using the following equation:

$$T(l) = l * g * E[C]$$

T: Throughput per node in Gbps.

l: Load per node in erlangs.

g: Single slot bandwidth constant in GHz = 12,5.

E[C]: Mean connection size.

Thus, the methodology was to use a range of load values that provided a reasonable blocking probability for each scenario, and calculate the throughput afterwards.

III.2 Spectrum management strategies

There are two main categories of spectrum management strategies: single and multiple partition algorithms^{[6][7]}. In single partition algorithms, the connections can be allocated potentially anywhere in the spectrum; the algorithms may utilize a special sort of ordering that attempts to place the connections in a specific order, but fundamentally there is no restriction.

In multiple partition algorithms, the whole spectrum is divided into sections constrained to each traffic class. The constraints may be flexible in some cases, but there is a clear effort to keep connections of the same size in a specific part of the spectrum.

III.2.1 Single partition algorithms

Complete sharing: Connections are allocated in any part of the spectrum regardless of their size. This strategy proposes the most straightforward spectrum management, and for the purpose of this study, it is equivalent to the well-known *First Fit* algorithm in order to provide a basis for comparison with the rest of the strategies. Thus in this case, the spectrum reservation always starts from S_0 to S_N (hereinafter left-to-right direction), where N is the total number of slots in the spectrum, and S_i represents the position of a slot in the spectrum.



Figure 8: Representation of the Complete sharing strategy

Pseudo partitioning: It is a simple variation of the Complete sharing strategy. The difference is that depending on the size, the connections are allocated in either left-to-right direction or right-to-left direction (starting from S_N to S_0). For the purpose of this study, connections with size 1 were allocated in left-to-right direction, and connections with sizes 4 and 8 were allocated in right-to-left direction. The intent of this strategy is to prevent free slots segments with incompatible sizes from forming after slot release, hence, it is very desirable that connection sizes are multiple of each other.

The majority of the fragmentation is kept on one side of the spectrum by avoiding mixing 1 slot connections—which have the most entropy—with the 4 and 8 slots connections. However, this strategy does not explicitly enforce the aforementioned behavior; in cases of very high network traffic, the gap of free slots in-between the two groups of connections shrinks to zero, and both pseudo partitions start overlapping.

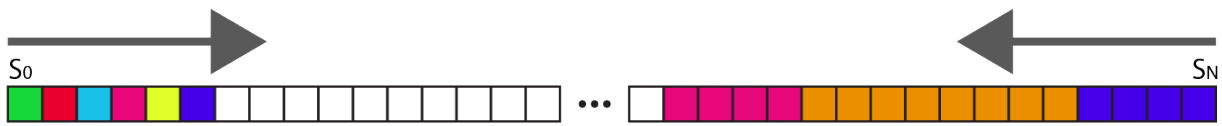


Figure 9: Representation of the Pseudo partitioning strategy

III.2.2 Multiple partition strategies

Dedicated partitioning: Connections are allocated in predefined segments of the spectrum—hence, partitions—depending on their size, thus defining different traffic classes. In the event that the partition of the target traffic class has not enough free slots to perform the allocation, the

connection will be automatically dropped, regardless of the availability in other partitions.

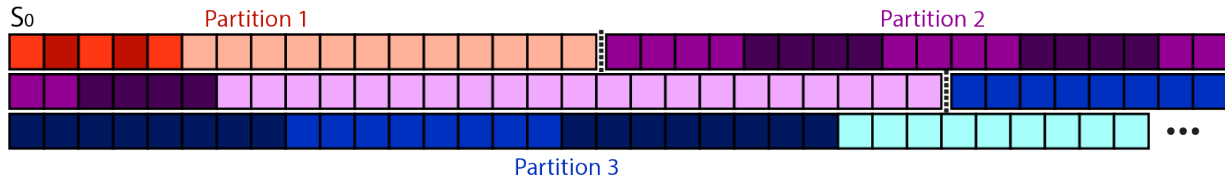


Figure 10: Representation of the Dedicated partitioning strategy

For the purpose of this study, partition sizes were calculated considering connection size and probability of each traffic class, in order to ensure an accurate proportional portion of the spectrum for each class:

$$Z_i(c_i, N) = \frac{N * c_i * P_C(c_i)}{E[C]}$$

Z_i: Partition size for traffic class i.

N: Whole spectrum size.

C: Traffic classes = {c₁: 1, c₂: 4, c₃: 8}.

E[C]: Mean connection size.

Shared partitioning: It is a variation of the Dedicated partitioning strategy. The difference is that once the partition of the target traffic class is full, instead of automatically dropping the connection, there will be an attempt to allocate it on the partition of any other traffic class whose connection size is inferior to the target traffic class, providing there is available space.

Bigger connections contribute less to fragmentation and it is safe to assume that they are more relevant because of the amount of information they carry, however, they are harder to allocate. This strategy, tries to balance this issue by giving priority proportionally to the size of each traffic class. As represented in Figure 11: Partition 3 is full, but Traffic Class 3 is allowed to allocate connections on Partition 2. Additionally, as Partition 1 is full all future connection attempts of size 1 will be dropped despite all the available space in Partition 2.

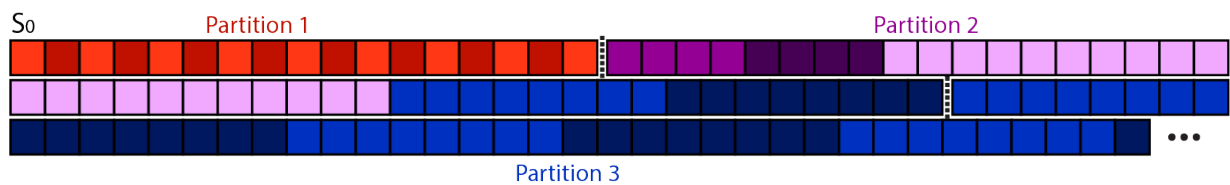


Figure 11: Representation of the Shared partitioning strategy

IV. Results and analysis

A total of 18 simulations were carried out for each spectrum management strategy over different scenarios, in order to provide a comprehensive comparison of performance. In each following section the experimentation results are shown.

IV.1 Multi-rate optical network performance

The baseline simulation for the MON scenario consisted in testing the management strategies with connections of 1, 4 and 8 slots, being generated with a uniform probability distribution. Results are shown in Figure 12:

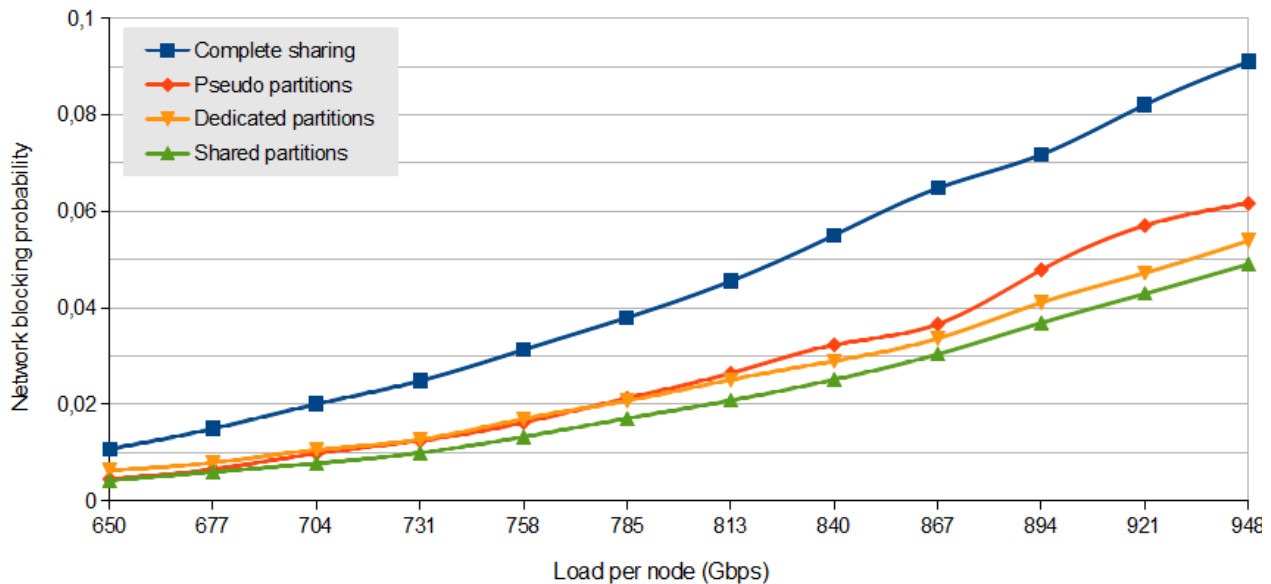
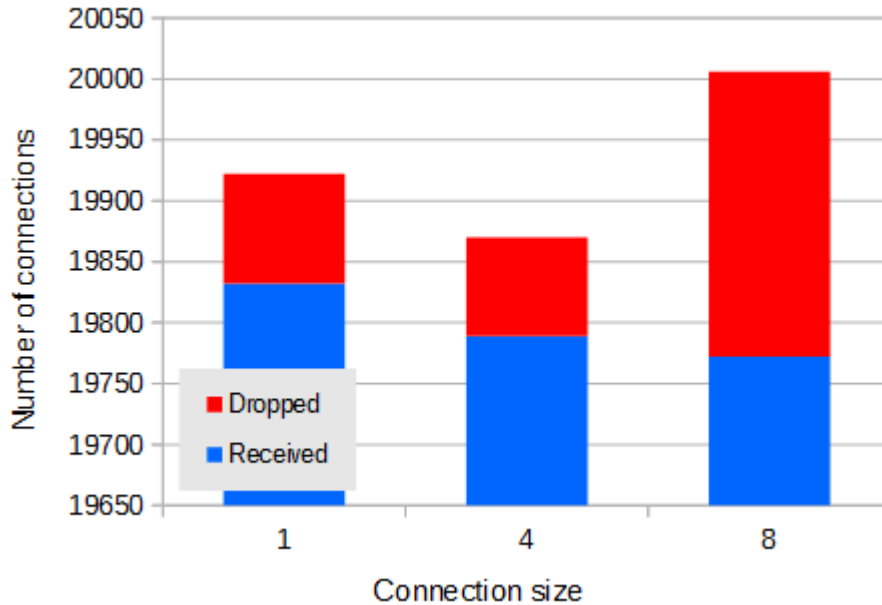


Figure 12: NBP of the MON baseline

Load	Complete sharing	Pseudo partitions	Dedicated partitions	Shared partitions
650	0.0019571891	0.0005549034	0.0009961828	0.0008360664
677	0.0029305633	0.0009882424	0.0020983483	0.0010845396
704	0.0052112057	0.0015390899	0.0031646439	0.0017825944
731	0.0077948499	0.0027909482	0.0046832923	0.0027103501
758	0.0107016455	0.0045442187	0.0062747458	0.0041785833
785	0.0149593098	0.0065153591	0.0079106861	0.0059624264
813	0.0200563888	0.00981378	0.0105359388	0.0077419945
840	0.0248769011	0.0124409404	0.012694284	0.0099257874
867	0.0313216571	0.0162328659	0.0169964223	0.01326588
894	0.0379960915	0.0212717592	0.0207425268	0.017068292
921	0.0455440046	0.0264503536	0.0250969021	0.0207963657
948	0.0550736625	0.0323269858	0.0289905209	0.0251324383
975	0.0647971837	0.0366408352	0.0336691977	0.030389194
1002	0.0717706236	0.0478762336	0.0410889357	0.0368824763
1029	0.0820846546	0.0570627457	0.0472503277	0.0429274643
1056	0.0910370044	0.0616659637	0.0539181079	0.0490538906
1083	0.1021235216	0.0700221032	0.0599461687	0.0550478711
1110	0.1110182224	0.0783236004	0.0671065559	0.0608467791

Table 1: NBP values of the MON baseline

Figure 13: Request distribution at NBP $\approx 1\%$ and load 785Gbps in MON baseline

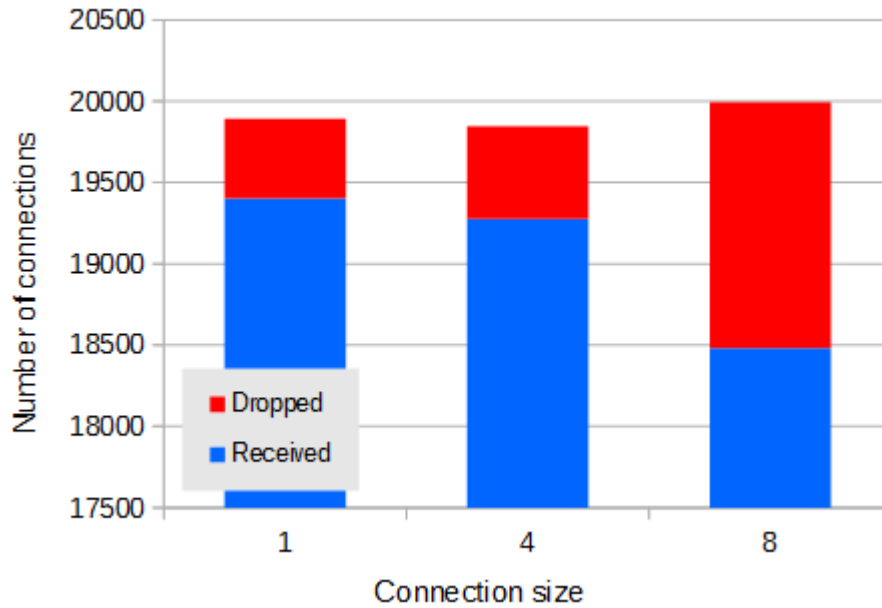


Figure 14: Request distribution at NBP \approx 5% and load 1029Gbps in MON baseline

Load: 785Gbps

Size	Sent	Received	Dropped
1	19922	19832	90
4	19870	19789	81
8	20006	19772	234

Load: 1029Gbps

Size	Sent	Received	Dropped
1	19894	19403	491
4	19845	19276	569
8	19994	18482	1512

Table 2: Number of requests at NBP in the range of \approx 1%-5% in MON baseline

The differences in performance are attributed to the efficacy of the allocation algorithms. In this case, the worst performer was the complete sharing, which is a synonym of the standard first fit algorithm. Also is worth

noting that the number of dropped connections is proportional to its size, which is perfectly logical considering that the greater the size, the harder it is to allocate.

In order to fairly compete with an EON, a MON has to be capable of processing the same set of connections an EON would. The proposed manner to achieve this goal is to split the non-native connections into traffic classes the MON can handle. In this case the whole set of connections are between 1 to 10 slots, which are translated in connections of sizes 1, 4 and 8 slots, using two different schemes.

IV.1.1 Fit splitting

With fit splitting, the mapping into the MON is done using the exact number of slots of the original connection, in order to avoid spectrum wasting. The disadvantage of this method is the increased number transceivers as a result of splitting the connections so minutely. The fit splitting scheme used is shown in Table 3:

Original connection size	MON equivalent
1	1
2	1,1
3	1,1,1
4	4
5	4,1
6	4,1,1
7	4,1,1,1
8	8
9	8,1
10	8,1,1

Table 3: Fit splitting scheme

The results are shown in Figure 15:

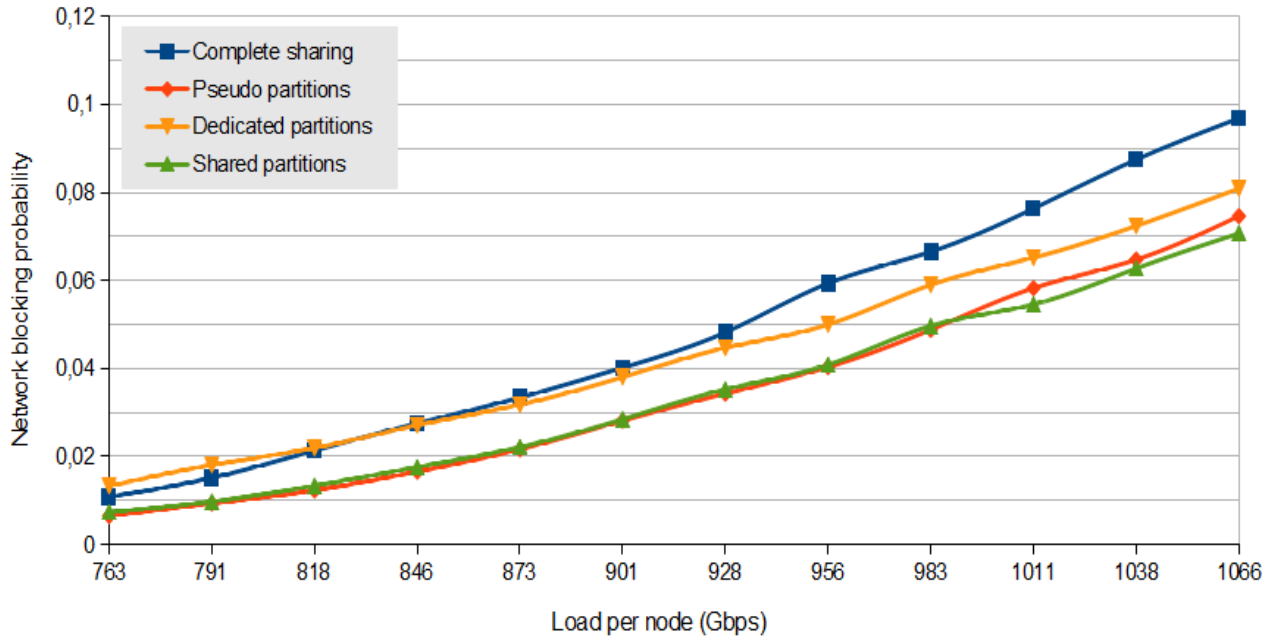


Figure 15: NBP of the MON with fit splitting

Load	Complete sharing	Pseudo partitions	Dedicated partitions	Shared partitions
653	0.0016433612	0.0008358333	0.0046996874	0.0007179196
681	0.0022304763	0.0015588943	0.006482094	0.0018073528
708	0.0044295492	0.0025422	0.0087408101	0.0028767541
736	0.0072885883	0.0041969352	0.0108437392	0.0049691986
763	0.0108001548	0.0065264702	0.0132883441	0.0073541444
791	0.0151691938	0.0093273307	0.0180853164	0.0097531943
818	0.0213659576	0.0123233499	0.0219322554	0.0133760339
846	0.0275425757	0.0165881035	0.0271102982	0.0175868135
873	0.0334112059	0.0216519728	0.0317907447	0.0221687865
901	0.0401948337	0.0281489471	0.038063311	0.0284823539
928	0.048226845	0.0343154599	0.044689658	0.0352716919
956	0.0593571297	0.0403434289	0.0499943698	0.0408622098
983	0.0665525365	0.0488107594	0.0590111041	0.0496914608
1011	0.0763565017	0.058265621	0.0651946303	0.0545849043
1038	0.0874642008	0.0647517941	0.0724140733	0.0627282542
1066	0.096879279	0.074633943	0.0808972296	0.0706994663
1093	0.10485338	0.0836247455	0.0896686682	0.0785893636
1121	0.1168849213	0.0918367073	0.0981199527	0.08605959

Table 4: NBP values of the MON with fit splitting

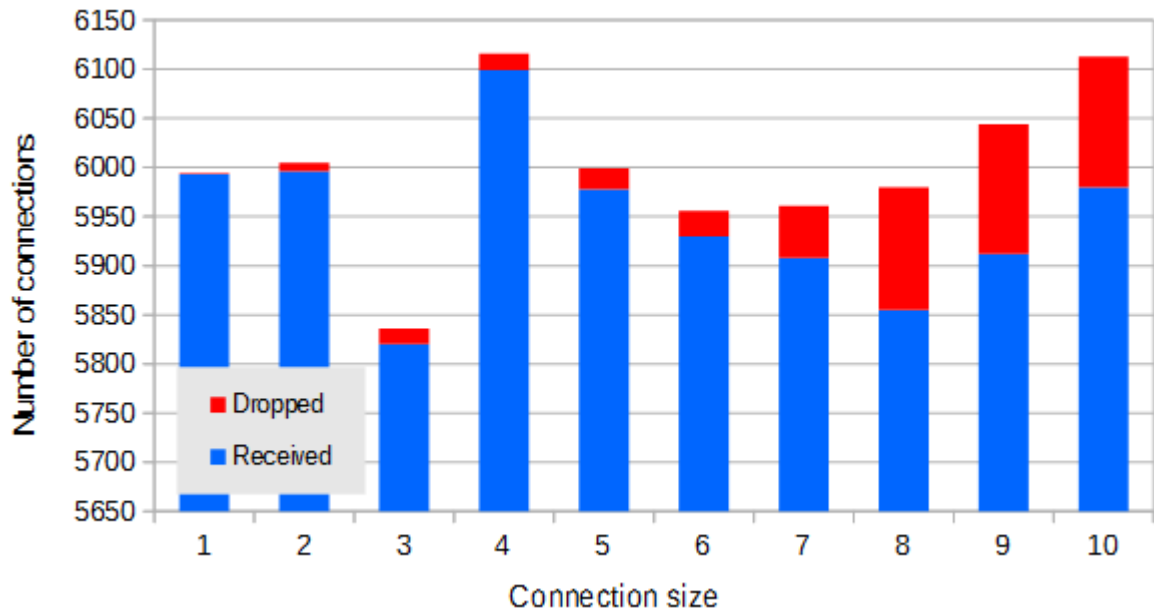


Figure 16: Request distribution at NBP \approx 1% and load 791Gbps in MON with fit splitting

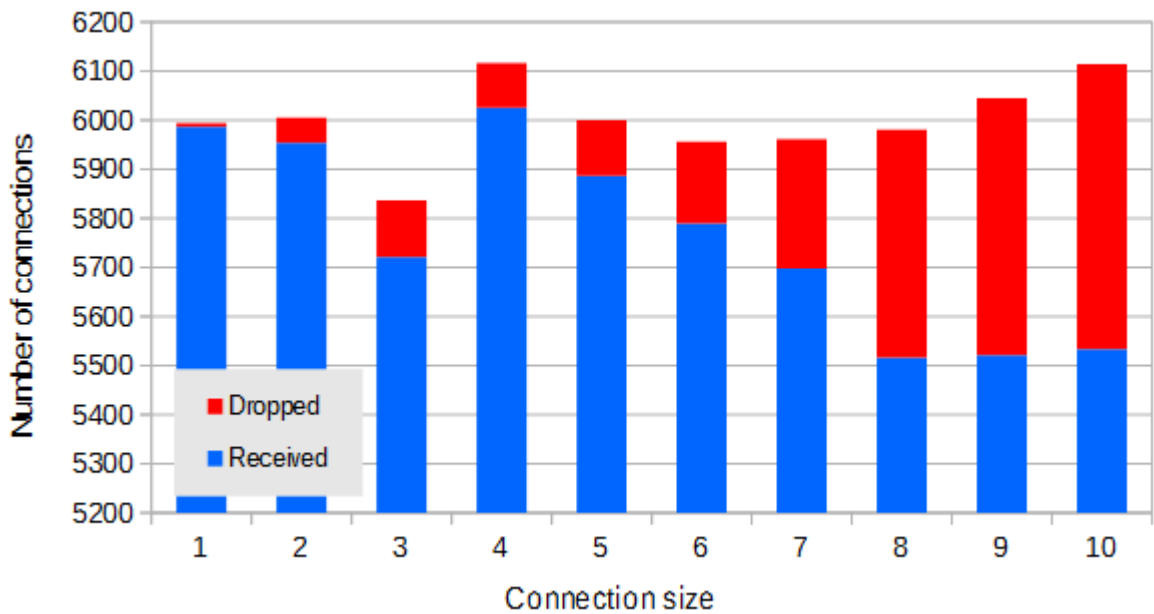


Figure 17: Request distribution at NBP \approx 5% and load 983Gbps in MON with fit splitting

Owing to the splitting scheme, the real amount of allocated connections does not longer match the sum of received requests and the only values fall into the 1, 4, and 8 slot categories, as shown in Table 5:

Load: 791Gbps

Size	Sent	Received	Dropped	Real
1	5994	5993	1	88640
2	6005	5996	9	0
3	5836	5820	16	0
4	6116	6099	17	23839
5	5999	5978	21	0
6	5956	5930	26	0
7	5961	5908	53	0
8	5980	5855	125	17700
9	6044	5912	132	0
10	6113	5980	133	0

Load: 983Gbps

Size	Sent	Received	Dropped	Real
1	5994	5986	8	85921
2	6005	5954	51	0
3	5836	5721	115	0
4	6116	6025	91	23310
5	6000	5886	114	0
6	5956	5789	167	0
7	5961	5698	263	0
8	5980	5516	464	16514
9	6044	5521	523	0
10	6114	5533	581	0

Table 5: Number of requests at NBP in the range of $\approx 1\%$ - 5% in MON with fit splitting

It is important to notice the performance similarity between the pseudo partitioning and shared partitioning strategies, which deviates from the baseline case. The reason for this incident relies on the fact that multiple partition strategies depend on specific partition sizes in order to perform adequately, thus it is critical that these sizes are multiples of the number of slots of the traffic classes they contain—which coincidentally was the case in the baseline.

The problem then is merely numerical: the calculation of the partition sizes—in both multiple partition strategies—depends on the exact probability of each connection class, which is assumed to be known beforehand, and the whole spectrum size, therefore it is very unlikely to obtain optimal sizes.

Consequently, several adjustments were made over the original partition sizes in order to find the combination that yielded the best results for the fit splitting scenario. The aforementioned changes are summarize in Table 6:

Traffic class	Original partition size	Ajusted partition size
1	35.4545454545	34
4	37.8181818182	40
8	56.7272727273	56

Table 6: Manual adjustment of partition sizes for the fit splitting

In contrast to the baseline scenario, the distribution of the allocated connections is no longer uniform due to the splitting process. The new distribution can be seen in Figure 18:

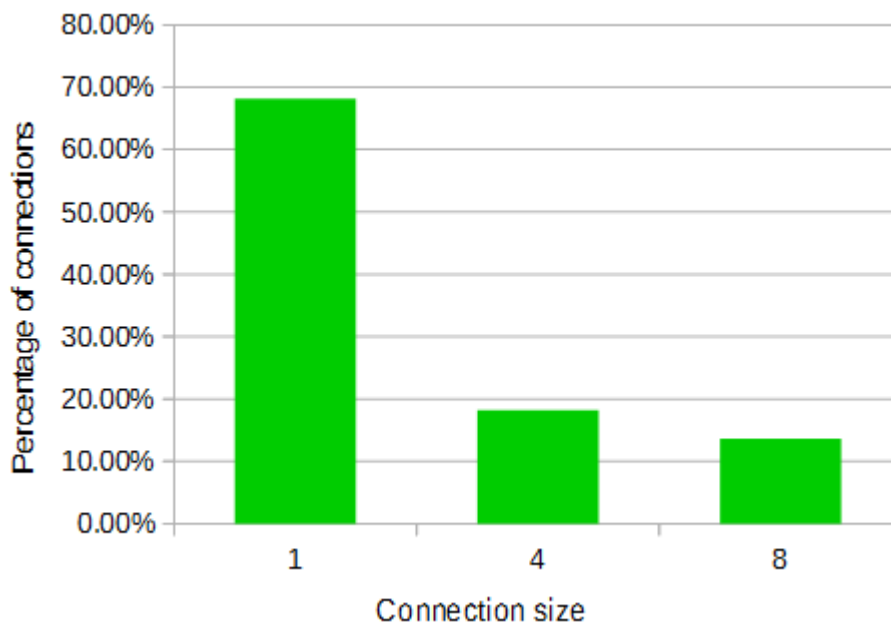


Figure 18: Real connection distribution for the MON with fit splitting

IV.1.2 Loose splitting

With loose splitting, the mapping into the MON attempts to keep a balance between reducing the number of transceivers used in comparison with fit splitting, without wasting too much spectrum. The caveat of this method is that the allocation of non-used extra slots will degrade performance. However, it is worth noting that time-varying connections could take advantage of the unused slots in this method to grow in case they needed it, nonetheless that such considerations are beyond the scope of this study. The loose splitting scheme used is shown in Table 7:

Original connection size	MON equivalent
1	1
2	1,1
3	4
4	4
5	4,1
6	8
7	8
8	8
9	8,1
10	8,4

Table 7: Loose splitting scheme

The results are shown in Figure 19:

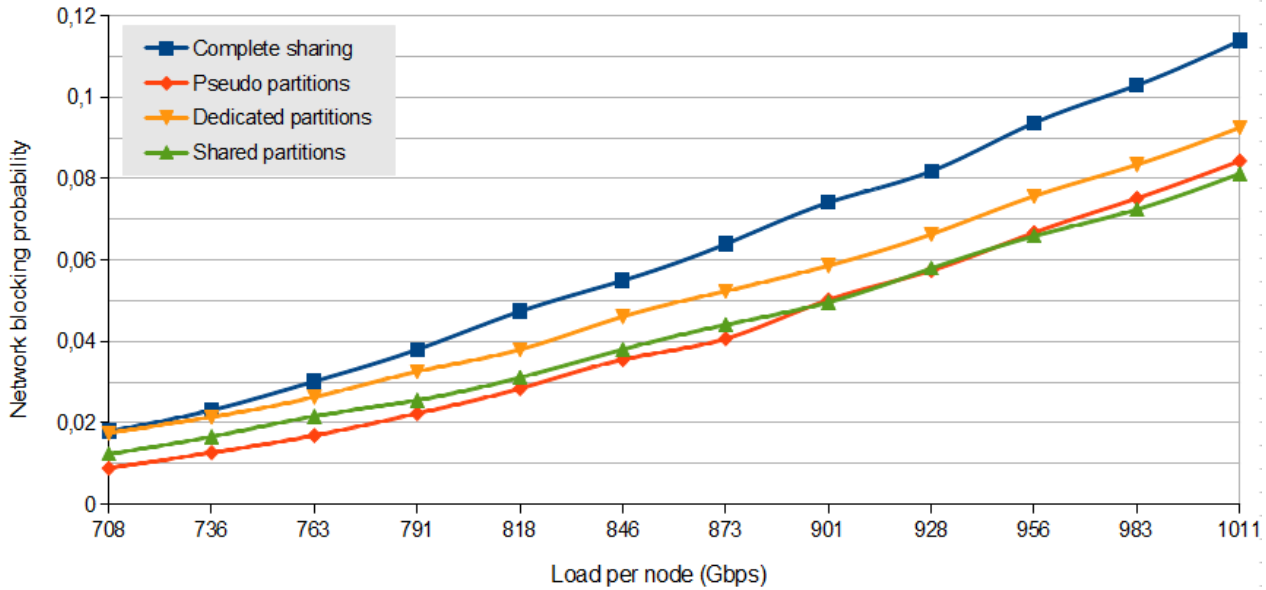


Figure 19: NBP values of the MON with loose splitting

Load	Complete sharing	Pseudo partitions	Dedicated partitions	Shared partitions
653	0.0092740229	0.0036201745	0.0098035158	0.0078253771
681	0.0132580837	0.0058067919	0.0133396333	0.0095281797
708	0.0179484655	0.0088743356	0.0175002344	0.0123570677
736	0.0231358443	0.0127022029	0.0214769886	0.0166280563
763	0.0302102147	0.0169079514	0.0263589484	0.0216450504
791	0.0380404573	0.0223312863	0.032624175	0.025601264
818	0.0474198683	0.0284687648	0.0380444533	0.0311699279
846	0.0550041183	0.0355593906	0.0461357056	0.0380550629
873	0.0639554166	0.0407058715	0.0523980344	0.0441280168
901	0.0741621028	0.0502519728	0.0586566207	0.0496566742
928	0.0818662643	0.0574491242	0.0663713144	0.0579721614
956	0.0937235711	0.0667738936	0.0757344826	0.0658978331
983	0.1029824279	0.0752007186	0.0834689699	0.0724769983
1011	0.1139180961	0.0843901361	0.0925763579	0.081263338
1038	0.1219796312	0.0931709385	0.0996378439	0.0895684856
1066	0.1322229507	0.104754492	0.1076641282	0.0971048814
1093	0.1417349513	0.1126943115	0.1175137466	0.1047401363
1121	0.1491075802	0.1199926419	0.1237920192	0.1128449876

Table 8: NBP values of the MON with loose splitting

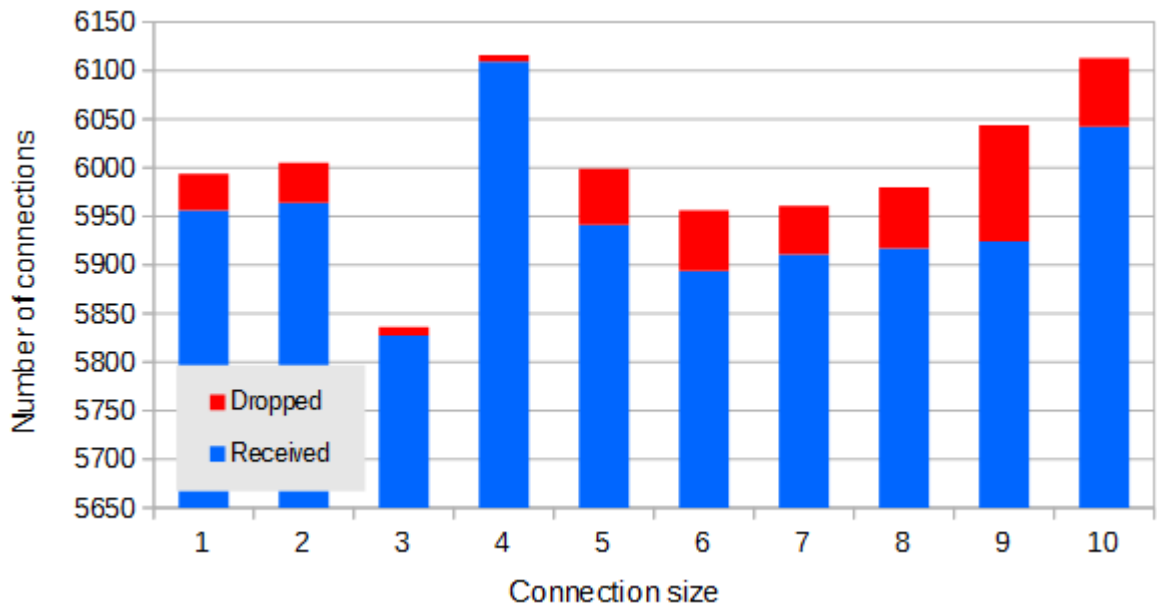


Figure 20: Request distribution at NBP \approx 1% and load 681Gbps in MON with loose splitting

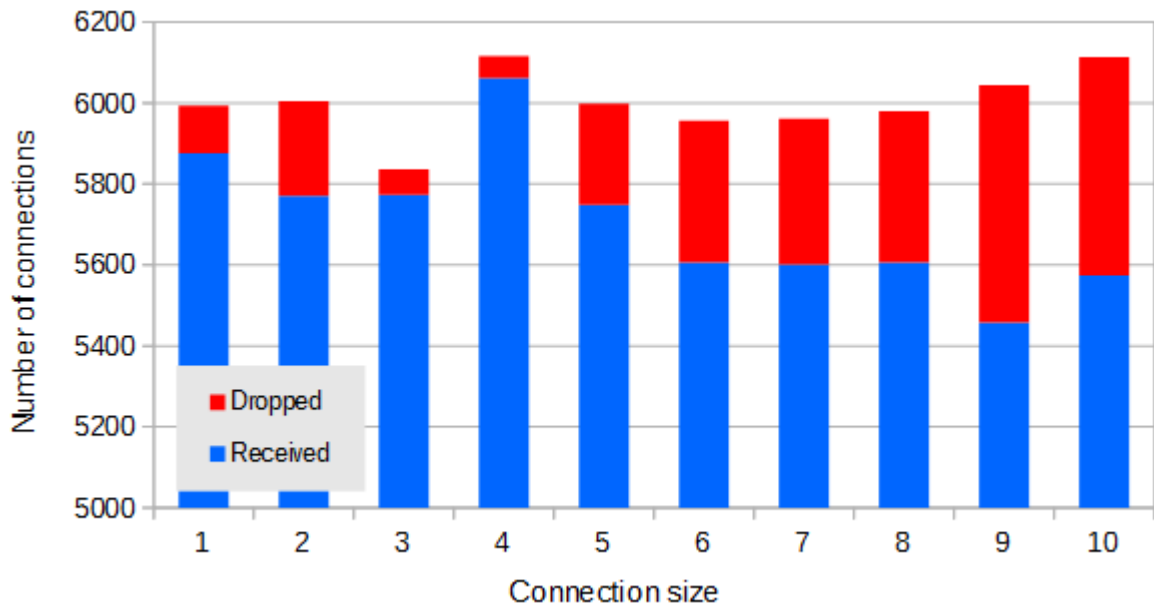


Figure 21: Request distribution at NBP \approx 5% and load 901Gbps in MON with loose splitting

Load: 681Gbps

Size	Sent	Received	Dropped	Real
1	5994	5956	38	29338
2	6005	5964	41	0
3	5836	5827	9	0
4	6116	6109	7	23855
5	5999	5941	58	0
6	5956	5894	62	0
7	5961	5911	50	0
8	5980	5917	63	29620
9	6044	5924	120	0
10	6113	6042	71	0

Load: 901Gbps

Size	Sent	Received	Dropped	Real
1	5994	5876	118	27930
2	6005	5771	234	0
3	5836	5773	63	0
4	6116	6062	54	23079
5	5999	5748	251	0
6	5956	5606	350	0
7	5961	5601	360	0
8	5980	5606	374	27760
9	6044	5458	586	0
10	6113	5574	539	0

Table 9: Number of requests at NBP in the range of $\approx 1\%$ - 5% in MON with loose splitting

Loose splitting and fit splitting results show the same trend. The worst performer was the complete sharing strategy, followed by the dedicated partitioning strategy. The pseudo partitioning and shared partitioning strategies, perform similarly and constitute the best results in terms of NBP.

As in the fit splitting case, partitions had to be manually adjusted to improve performance. The changes are summarized in Table 10:

Traffic class	Original partition size	Adjusted partition size
1	10.6557377049	10
4	34.098360655	40
8	85.245901639	80

Table 10: Manual adjustment of partition sizes for the loose splitting

The distribution of the allocated connections in the loose splitting scenario is almost uniform—even comparable to the baseline—however, and despite the slight change, the results are worse than the baseline in terms of NBP; this is a consequence of the wasted spectrum, as more bandwidth is used for the same throughput when compared to the previous scenarios. The new distribution can be seen in Figure 22:

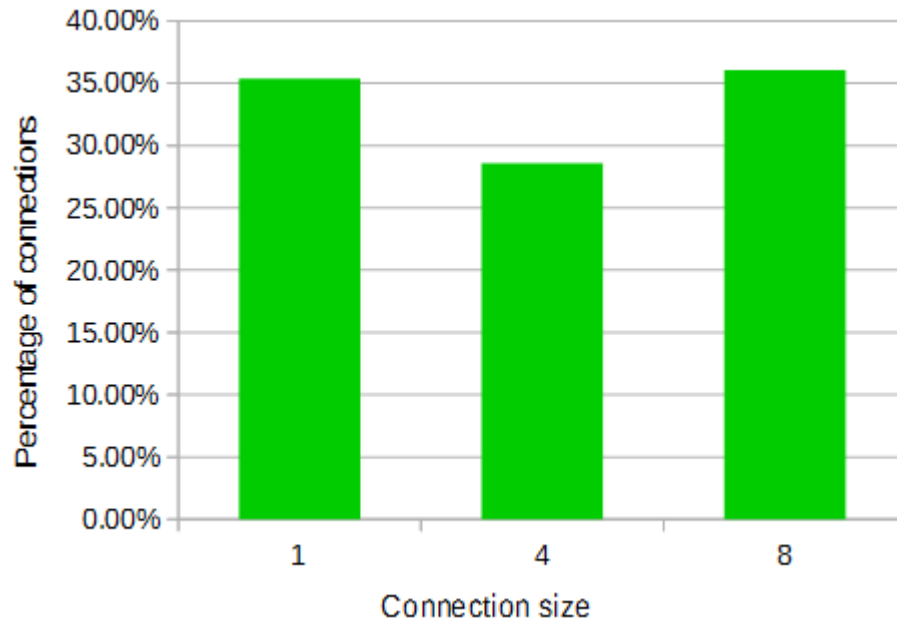


Figure 22: Real connection distribution for the MON with loose splitting

IV.2 Elastic optical network performance and comparison

For the EON scenario, the first fit algorithm was used for the comparison, because of its widespread usage. Another reason was that, implementing any of the other strategies used for the previous scenarios would have been non practical, mainly because the high number of traffic classes, and the relatively small spectrum size. For instance, using multiple partition strategies in this case causes each partition to be too small to be useful.

The performance of the EON is compared with the performance of both schemes—fit and loose splitting—used for the MON in Figure 23:

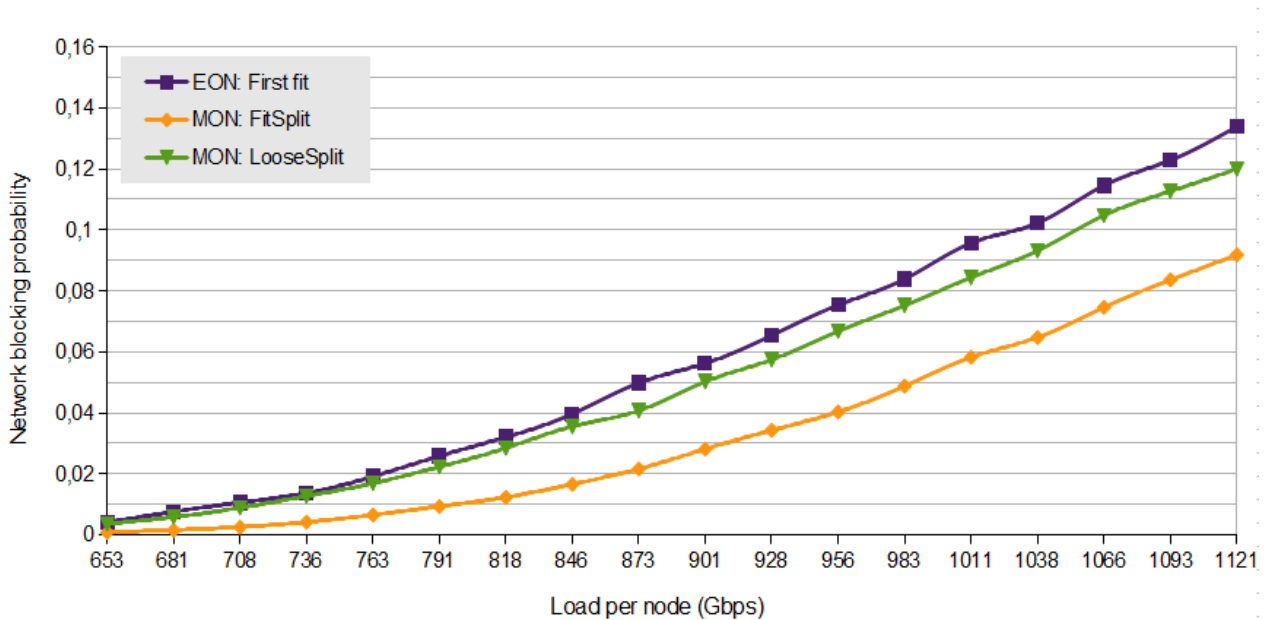


Figure 23: Comparison between EON and MON NBP

In both fit and loose splitting cases, the pseudo partitioning strategy was chosen for the comparison due to several reasons: its performance is comparable to the shared partitioning strategy—especially 1% to 5% network blocking probability, which is the region of interest of this study—and it does not require partitioning, which requires precision and the investment of computational resources. Exploiting the full potential of shared partitioning would require a much bigger spectrum in order to minimize the numerical errors and make it feasible. Both MON strategies outperformed the fully flexible scenario, as shown in Table 11:

Load	EON First fit	MON FitSplit	MON LooseSplit
653	0.00409356	0.0008358333	0.0036201745
681	0.007564043	0.0015588943	0.0058067919
708	0.010610729	0.0025422	0.0088743356
736	0.013661066	0.0041969352	0.0127022029
763	0.019125268	0.0065264702	0.0169079514
791	0.025836474	0.0093273307	0.0223312863
818	0.032035723	0.0123233499	0.0284687648
846	0.039686327	0.0165881035	0.0355593906
873	0.049838555	0.0216519728	0.0407058715
901	0.056256135	0.0281489471	0.0502519728
928	0.065423311	0.0343154599	0.0574491242
956	0.075346016	0.0403434289	0.0667738936
983	0.083879392	0.0488107594	0.0752007186
1011	0.095689919	0.058265621	0.0843901361
1038	0.102254599	0.0647517941	0.0931709385
1066	0.114583638	0.074633943	0.104754492
1093	0.12283023	0.0836247455	0.1126943115
1121	0.133903285	0.0918367073	0.1199926419

Table 11: Comparison between EON and MON NBP values

However, it's important to notice the difference in the number of transponders used. In EONs, a single transponder can generate signals with a great variation in bandwidth, on demand, in contrast to a MON where each

transponder can only generate a signal with a fixed bandwidth. Based on the *Real* number of connections shown in the sections before, the differences in transponder usage relative to the EON scenario are shown in Figure 24:

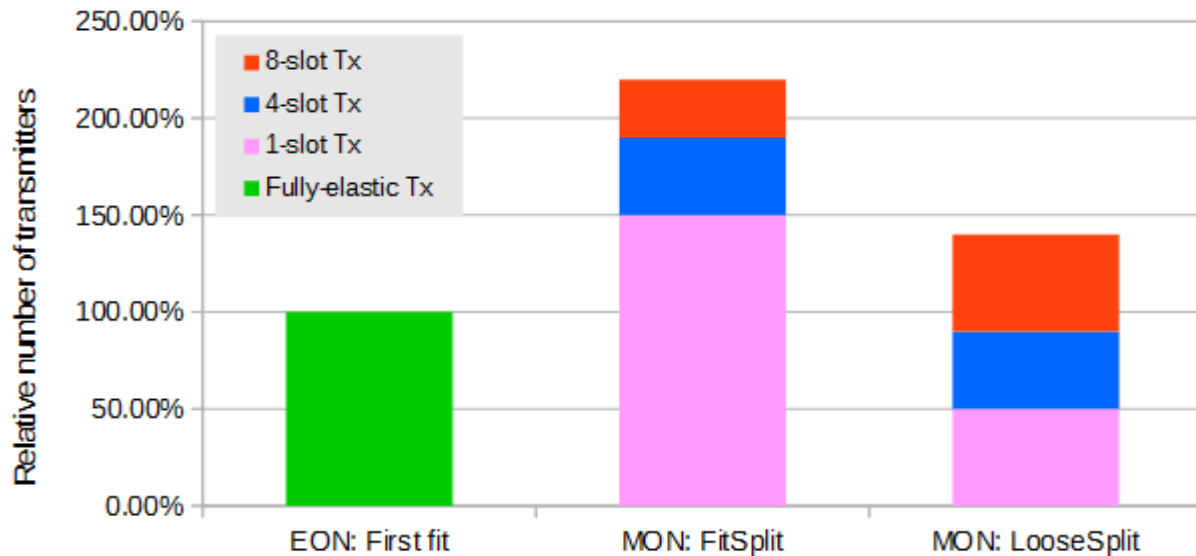


Figure 24: Relative use of transponders required in the experimentation scenarios

So far, a surplus of transponders has been assumed for every scenario, but this will not be the usual case in real-world applications. The MON with a fit splitting strategy uses around 120% more devices than an EON, while the MON with a loose splitting strategy uses around 40% more devices, both values are considerable in terms of infrastructure.

Furthermore, the relative number of transponders of each class not only varies according to the splitting strategy, also to the distribution of the initial set of requests—which are assumed to be uniform in this study—ultimately adding another layer of complexity in terms of network planning and provisioning.

At this point, a new simulation was done in order to study the effects of a finite number of transponders. In this case, the throughput was fixed at 736Gbps—which yields a NBP in the vicinity of 1%—while progressively reducing the available number of transponders for each scenario. The results are shown in Figure 25:

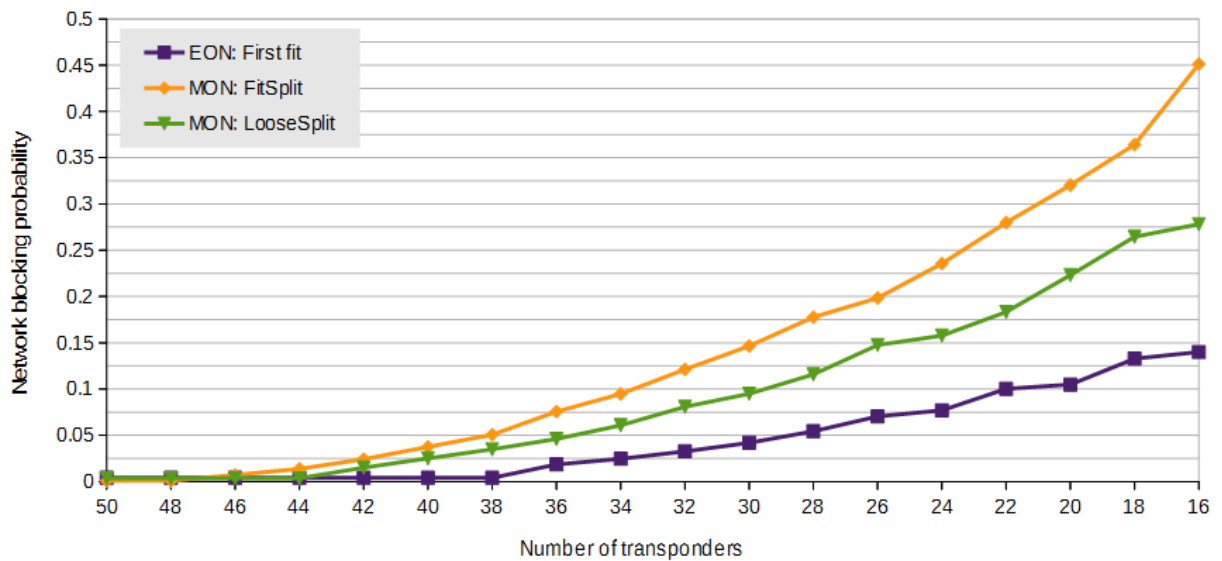


Figure 25: Comparison between EON and MON NBP with finite transponders

As illustrated, the NBP increases rapidly with the reduction of transponders. The MON with fit splitting is the most susceptible, as it requires the greater number of transmitters, followed by the MON with loose splitting. However, the EON performance does not decrease as rapidly thanks to the adaptability of its transponders.

# Tx	EON: First fit	MON: FitSplit	MON: LooseSplit
50	0.00409356	0.0008358333	0.0036201745
48	0.00409356	0.0008358333	0.0036201745
46	0.00409356	0.0072680246	0.0036201745
44	0.00409356	0.013845929	0.0036201745
42	0.00409356	0.0242748254	0.0150761499
40	0.00409356	0.037601101	0.0251258624
38	0.00409356	0.0507040732	0.0349078718
36	0.018556606	0.0756257256	0.0460567841
34	0.0246573328	0.0947404453	0.0608022527
32	0.0326598795	0.1212568205	0.0808649585
30	0.041915961	0.1465488782	0.0948996824
28	0.0544359422	0.1777404743	0.1158151991
26	0.0704009991	0.1984197281	0.147565398
24	0.0769557783	0.2356259005	0.1577222908
22	0.100289072	0.2799040488	0.1833184575
20	0.1048481562	0.3204224854	0.2231909485
18	0.1328819503	0.3641698213	0.2645119094
16	0.1400260119	0.4511857075	0.2782127806

Table 12: NBP values for EON and MON with finite transponders

IV.2.1 Cost approximation

Given the fact that EONs comprise cutting edge technologies that are expected to be expensive in the early stages of adoption, and that MON equivalents require an increased number of transponders, there are several considerations to be taken into account when determining the best choice for the design of a network. The following equation is a good starting point for the estimation, assuming both scenarios perform similarly:

$$Investment_{EON} = Tx_{EON} \times Ptx_{EON}$$

$$Investment_{EON} = (\alpha \cdot Tx_{MON}) \times (\beta \cdot \overline{Ptx_{MON}})$$

$$Investment_{EON} = \alpha \cdot \beta \times Investment_{MON}$$

$$\alpha \geq 1 \cup \beta \leq 1$$

T_x: Number of transponders.

P_{tx}: Price per transponder.

α: Transponder quantity factor.

β: Transponder price factor.

For an EON to be economically viable in terms of initial investment, $\alpha \cdot \beta$ has to be equal or higher than 1. In other words, the relative increase in the number of transponders has to be greater than the fraction each MON transponder costs.

For the fit splitting scenario in the MON $\alpha=2.2$ —which represents the 220% increase in number of transponders—thus the EON solution would be cheaper if each transponder costs at most 2.2 times the price of MON transponder counterpart ($\beta \leq 0.454545$), in other words, if the MON transponders are at most around 54% cheaper.

For the loose splitting scenario in the MON—which still yields a better performance than the EON—the transponder price gap closes as $\alpha=1.4$ ($\beta \leq 0.714285$), which means the MON transponders have to be at most around 28% cheaper, in order to have an economic benefit by using an EON.

V.**Conclusions**

- At present time it is more cost-effective to implement a MON with a performance of an EON over an EON itself, the cost of the equipment of the latter is high enough to make it more profitable to acquire as much MON equipment as needed to fully replace the EON scenario.
- The decision of whether opting for a MON with either fit or loose splitting strategies, is based on choosing a compromise between performance, complexity and costs.
- Fit splitting MONs have the best performance as they take full advantage of every free spectrum slot, however, they are also more complex due to increased number of equipment and therefore more costly.
- Even when loose splitting MONs perform worse than the fit splitting scenario, they still have a slightly better performance than the EON baseline. Loose splitting uses around half the equipment of fit splitting which have the potential of reducing costs greatly, and also simplify the implementation.
- Even when the EONs are more flexible in the sense that they can adapt on demand to an specific bandwidth request, the overall performance is degraded owing to fragmentation. Also, it is much more difficult to implement a better allocation algorithm in this case due to the large number of traffic classes.

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A Comparison of Elastic and Multi-rate Optical Networks Performance

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ABSTRACT

While Elastic Optical Networks (EONs) have recently emerged as a promising solution to cope with the growth and heterogeneity of data traffic, there are some drawbacks that have attracted the researchers' attention. One of such flaws is spectrum fragmentation, which has generated many controversial as it imposes huge number of extra actions during network operation. Some intermediate proposals have been disclosed, such as semi-elastic schemes that approach the performance of EONs while keeping the spectral entropy restrained. The purpose of this paper is to present a comparison between EONs and semi-elastic networks, where all the offered connections are allocated using only three different channel rate options. Different spectrum management strategies are introduced and evaluated by means of simulation considering both scenarios.

Keywords: Elastic optical networks, Network optimization, Spectrum Fragmentation.

1. INTRODUCTION

Owing to emerging services such as high-definition video distribution or social networking, the IP traffic volume has shown an exponential increase in the recent years. Furthermore, the traffic growth rate will not stop here thanks to the continuous technology advances [1]. The predictable consequence is that network operators will require a new generation of optical transport networks in the near future, so as to serve this huge and heterogeneous volume of traffic in a cost-effective and scalable manner. In response to these large capacity and diverse traffic granularity needs of the future Internet, the Elastic Optical Network (EON) architecture has been proposed [2].

By breaking the fixed-grid spectrum allocation limit of conventional wavelength division multiplexing (WDM) networks, such elastic optical networks increase the flexibility in terms of connection provisioning. To do so, depending on the traffic volume, an appropriate-sized optical spectrum is allocated to each connection in EON. In this way, incoming network connection requests can be served in a spectrum efficient manner. Nevertheless, this EONs spectrum tailored model has some functional drawbacks, being the most important the so called spectrum fragmentation [3]. The randomness in the connection setup and tear down processes leads to fragmentation of the spectral resources in the network. As the number of spectrum slots

assigned to each connection can take random values (ranging from 1 to 10 in our model), the available spectrum in the network links is fragmented into small non-contiguous spectral bands. As a result, the probability of finding enough contiguous spectrum resources for serving incoming traffic demands, especially those traversing multi-hop paths and/or requesting large amounts of bandwidth, significantly decreases.

To mitigate this problem a pseudo-elastic network is considered in this work. The traditional EON scenario is compared to a semi-flexible multi-rate network (MON) model where connections are adapted to a kind of fixed rate transmitters with different bit rate values (only 1, 4 or 8 transmitted spectrum slots are allowed in our model). By losing some flexibility (the incoming traffic demands are yet asking for a random number of slots between 1 and 10), some spectral entropy reduction is achieved. Both, EON and MON models are compared by means of simulation and some conclusions about their performance are obtained.

2. MON NETWORK MODEL

As stated in the previous section, the main purpose of this work consists in reducing the fragmentation problem introduced by EONs. To do so, instead of employing fully bandwidth variable transponders at network ingress nodes (able to support arbitrary number of slots), a set of transmitters able to generate 1, 4 or 8 slots are utilized in MONs. It is worth to note that, as stated previously, incoming traffic demands may ask for any number of slots from 1 to 10. Therefore, in order to solve the mismatch problem between the requested bandwidth and the transponders' capacity a mapping scheme has to be introduced. As shown in Table 1, we proposed two different mapping strategies:

Incoming traffic demand	Down mapping	Up mapping
1	1	1
2	1,1	1,1
3	1,1,1	4
4	4	4
5	4,1	4,1
6	4,1,1	8
7	4,1,1,1	8
8	8	8
9	8,1	8,1
10	8,1,1	8,4

Table 1. Connections splitting used for the MON scenario. Two different cases are considered: fit splitting (Down mapping) and loose splitting (Up mapping).

1) *fit splitting* (down mapping) where the incoming traffic demand is split into smaller sub-demands that adjust the available transponders capacity; and 2) *loose splitting* (up mapping) which has the objective of reducing the number of transponders used even at the cost of wasting some bandwidth. As a matter of fact, since down mapping slices an incoming traffic demand into smaller pieces, it may need more transmitters to allocate it comparing to the Up mapping case, which sacrifices some spectrum to achieve transponders savings. This can be observed in Table 1 where an incoming traffic demand of 7 slots uses 4 transmitters for down mapping while and only 1 for up mapping, at the cost of wasting 1 slot. It is important to note that, in order to guarantee the QoS of network, all the sliced sub-demands have to be accommodated in the same path between connection's end nodes.

3. SPECTRUM ALLOCATION POLICIES

To improve the performance of both EON and MON networks, it is possible to consider different spectrum allocation policies. Authors in [4] proposed the following policies:

- **First Fit:** Connections are established over the lowest available part of spectrum, so this strategy would result in a perfectly compacted spectrum in case of static traffic. This policy is widely used in EONs.
- **Pseudo partitioning:** It is a simple variation of the First Fit policy. The difference is that depending on their size, connections are allocated in either left-to-right direction or right-to-left direction over the whole available spectrum. To do so, small connections (with size of 1 slot) are allocated in left-to-right direction, while big connections (with size of bigger than 1 slot) are allocated in right-to-left direction. In this sense, the Pseudo partitioning policy provides two separate spectrum segments, reserved only for the small or big connections, which can be functionally considered as different traffic classes. It is worth to note that for high network load values, the gap between both segments shrinks to zero, and they start to overlap.
- **Dedicated partitioning:** Connections are allocated in predefined segments of the spectrum (partitions). The size of each partition is calculated respecting to the size of connections in terms of number of slots and the total offered load to the network. In the event that the partition of the target traffic class has not enough free slots to perform the allocation, the connection is dropped, regardless of having spectrum availability in other partitions.
- **Shared partitioning:** It is a variation of the previous policy. The difference is that once the partition of the target traffic class is full, instead of dropping the connection, there will be an attempt to allocate it on the partition assigned to any other traffic class whose occupation is inferior to the target traffic class.

Simulations about the performance of both network models (EON and MON) as well as the different spectrum management strategies considered are given in next section.

4. SIMULATION RESULTS

The performance of EON and MON networks are evaluated through extensive discrete event simulation studies. Both cases use a k-Shortest Path routing algorithm with spectrum assignment, starting with the shortest computed path. In addition, the different explained spectrum allocation policies in the previous section have been considered for both cases. The well-known 14-node NSFnet topology has been selected for the simulation purposes. A total optical spectrum of 1.5 THz per link and a spectrum slot size of 12.5 GHz are assumed. For the sake of simplicity, the modulation format selected yields a spectrum efficiency of 1 bit/s/Hz, so each spectrum slot has a bit rate capacity of 12.5 Gb/s. As for the traffic characteristics and according to the asymmetric nature of today's Internet traffic, unidirectional connections between end nodes are considered. The traffic generation follows a Poisson distribution process, so that different offered load values are obtained by keeping the mean Holding Time (HT) of the connections constant to 200s, while modifying their mean Inter-Arrival Time (IAT) accordingly (i.e., offered load = HT/IAT). Traffic demands for each source-destination pair are randomly generated by normal distribution ranging from 12.5 Gb/s (1 frequency slot) to 125 Gb/s (10 frequency slots). The average traffic demand is used to study the relationship between aggregation policy efficiency and service granularity.

A traffic load in the range of 13 up to 16 Erlang per node (which provides a total offered network traffic ranging from 182 to 224 Erlang) has been used in the simulations. The average demand of each connection request is assumed to be 55 Gb/s. Hence, the total traffic generated per node ranges from 715 Gb/s to 880 Gb/s in this study. In addition, an initially unlimited number of transmitters per node has been considered; the effect of the number of transmitters on the performance of each case is investigated later.

First results obtained (which are related to the different spectrum management strategies utilized) concluded that the *shared partitioning* scheme outperforms the rest when MONs are considered. For example, when the load per node is around 800 Gbit/s, the blocking probability value for *First Fit* is 0.04 while it is below 0.02 for *shared partitioning*. So, taking that into account, this strategy has been chosen for the remaining MON model simulations.

Next results, once selected the spectrum management strategy, are related to the mapping of the flexible connections to the semi-flexible (1, 4 or 8 slots) transponders of MON networks. As it is shown in Fig 1, the MON case with down mapping outperforms both other cases in the whole range of study. The reason is that, when compared to the EON case, it reduces the level of fragmentation over the network links. However, the high number of transponders needed in this scenario is a clear drawback when compared to the other cases as it is shown later. It has to be taken into account that in the worst case (MON with Up mapping), there is some overprovisioning of bandwidth that could be useful in case of time varying connections. Some allocated spectrum slots (e.g. 8 are allocated when the connection bandwidth is 6) would be really useful if the connection bandwidth is increased during its HT.

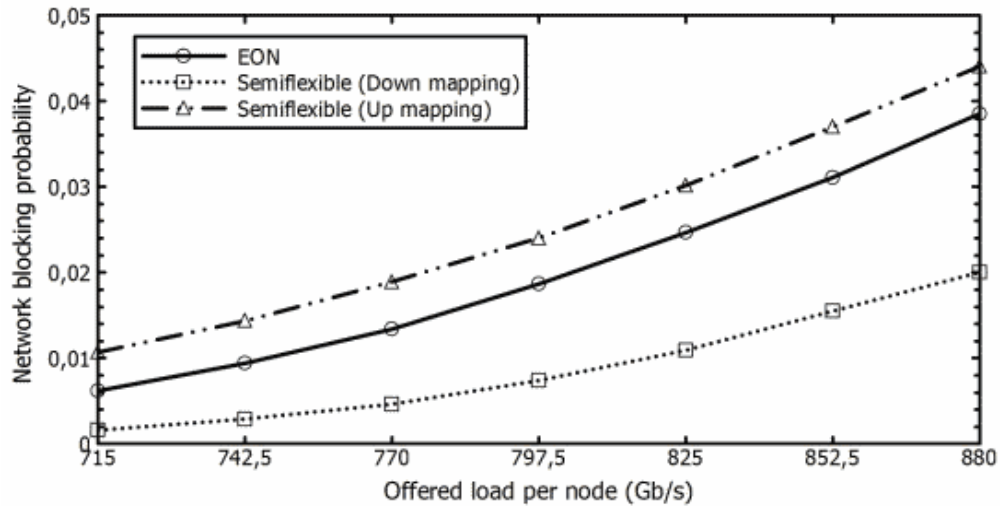


Figure 1. Blocking probability vs. offered load per node for EON and MON (with up and down mapping) networks.

The effect of traffic granularity on the performance of the aforementioned scenarios for a fixed offered load per node is shown in Fig. 2. In this case the average number of active optical connections from each source node is kept to 14.5 Erlang, but the average number of slots per connection is increased from 3.5 to 5.5. It can be observed that again the MON with down mapping outperforms the other cases. It is worth to note that the effectiveness of down mapping proposal is more significant comparing to the up mapping case when moving towards higher connections' bandwidth. The reason is that the possibility of accommodating smaller connections in a fragmented spectrum (due to an increased network load), is higher.

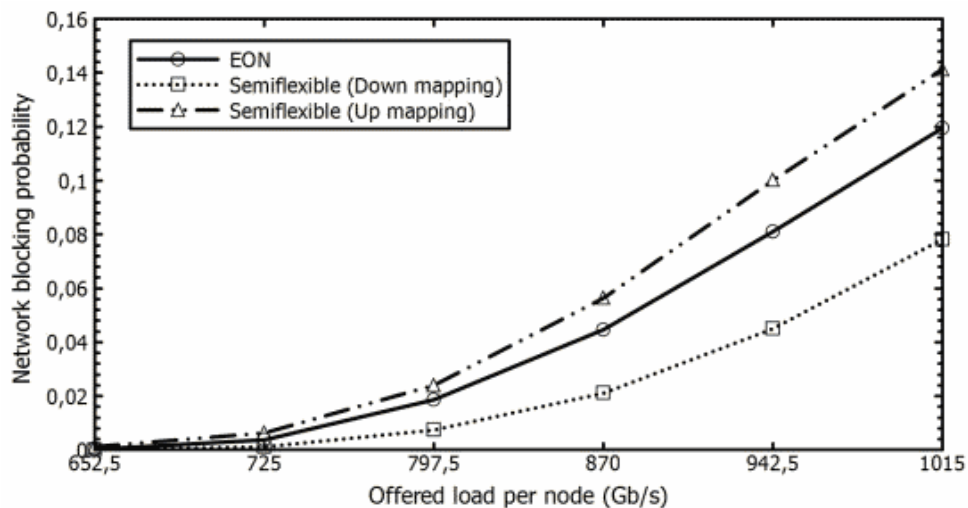


Figure 2. Effect of connections' bandwidth on the blocking probability. The average number of connections in the network is kept constant while their bandwidth grows (from 3.5 to 5.5 slots).

Once we have concluded, not surprisingly, that the MON with down mapping offers the best performance in terms of blocking probability, the number of available transponders per node has been limited. The effect of this limitation on the performance of the network is shown in Fig. 3. In this study, the fixed load of 14.5 Erlang with an average bit rate value per connection of 55 Gb/s (or 4.4 spectrum slots) is assumed. From the previous results, the corresponding blocking probability under this load value was lower than 0.01 for all the scenarios considered. As it is illustrated, all cases perform almost equally while the number of transmitters per node is higher than 40. When this number is reduced, MON with up mapping approaches the performance of EON for 30 transmitters per node, while the MON with down mapping blocking probability is already higher than the acceptable values.

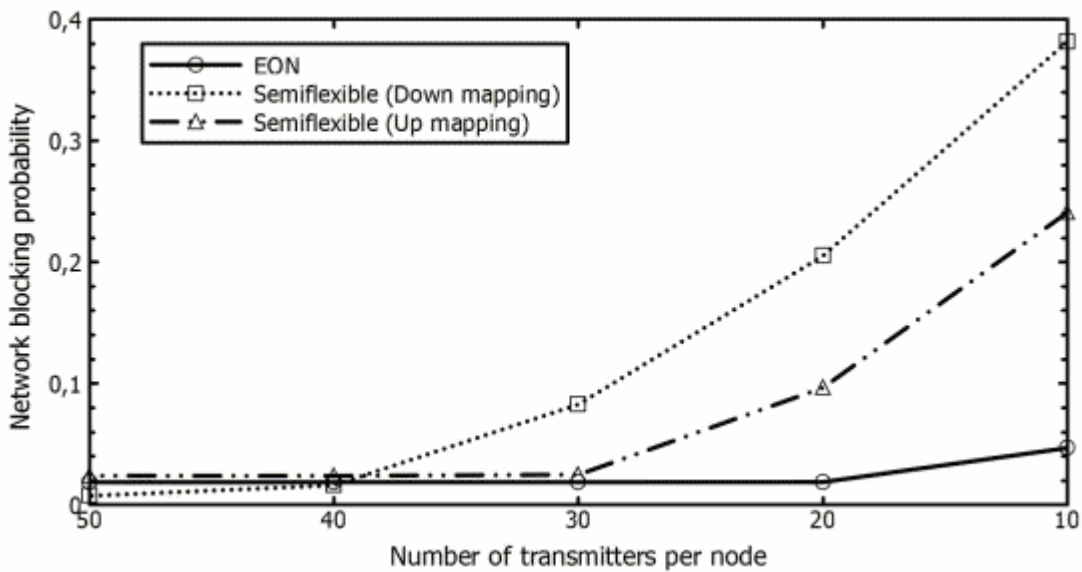


Figure 3. Effect of limiting the number of transponders per node on the network blocking probability.

It can be seen that, if this number is further reduced, only the EON network performs appropriately. The relative cost of flexible transponders in front of fixed ones would therefore give us light about the worthiness of EON networks. Preliminary results show that with current values (cost of 20 flexible transponders is today higher than cost of 30 fixed ones) EON is not yet cost effective. In addition, cost of switching nodes is higher if they have to adapt to fully flexible transponders. However, if future technology allows that the cost of flexible transponders [5] reduces to less than 1.5 times the cost of fixed ones, EON will be the most effective solution.

5. CONCLUSION

In this paper, a comparison between EON (transponders can use any number of spectrum slots) and semi-flexible (transponders can allocate only 1, 4 or 8 slots) networks performance has been done. Different strategies for spectrum occupation in this kind of networks have been evaluated by means of simulation. The obtained results show that semi-flexible can perform better in terms of blocking, due to the fact that spectrum fragmentation is reduced and more connections can be allocated for medium to high offered load values. However, when the number of transponders per node is limited, the EON networks show some advantages.

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Allocation algorithms for OMNet++ in C++

```

/**
Selects the allocation algorithm, and attempts to perform the allocation.

Sets all the parameters necessary to call the LRFit function, in order to
match the allocation algorithm set up in the .ini files. If LRFit is
successful, then proceeds to allocate the connection in the spectrum.

@param *msg Connection object.
@param &spectrum Contains the spectrum allocation status for the calculated
path.
@return True if the allocation was successful, or False otherwise.
*/
bool ChannelFinder(Request *msg, std::vector<long> &spectrum) {
    Start = msg->getStart();
    End = msg->getEnd();

    bool outst;

    unsigned int begining = 0;
    unsigned int end = spectrum.size();
    int th = end;

    //Calculate boundaries for multi partition algorithms
    double p1 = par("prob1");
    double p2 = par("prob4");
    double e = SIZE1*p1 + SIZE2*p2 + SIZE3*(1-p1-p2);
    int b1 = round((SIZE1*p1/e)*end);
    int b2 = b1 + round((SIZE2*p2/e)*end);

    //Forces the boundaries in case the options part1 and part4 are set in the
.ini
    int part1 = par("part1");
    int part4 = par("part4");

    if (part1 != 0 || part4 != 0) {
        b1 = part1;
        b2 = b1 + part4;
    }

    //Select algorithm
    int alg = par("alg");
    switch(alg) {

```

```

case 1: //First Fit
    //Do nothing
    break;

case 2: //Pseudo partition
    th = par("ppthr");
    break;

case 3: //Dedicated partition
    if(msg->getBandwidth() == SIZE1)
        begining = 0;
    else if(msg->getBandwidth() == SIZE2)
        begining = b1;
    else
        begining = b2;

case 4:
    if(msg->getBandwidth() == SIZE1)
        end = b1;
    else if(msg->getBandwidth() == SIZE2)
        end = b2;

    if(alg == 4) {
        begining = 0;
        th = SIZE2;
    }
}

//Perform search
outst = LRFit(msg, th, begining, end, spectrum);

//Update spectrum on success
if(outst) {
    msg->setStart(Start);
    msg->setEnd(End);

    for(int i=Start; i<End; i++)
        spectrum[i] = msg->getId();
}

return outst;
}

```

```

/**
Attempts to find a place in the spectrum for the connection.

Once all the parameters are set, the ChannelFinder function calls LRFit to
determine if the allocation is possible. The function attempts to find
available space in the spectrum, if successful the result of the search is
stored in the global variables Start and End.

@param *msg Connection object.
@param thres Threshold, if it's lower than the connection size the search is
performed from left-to-right, otherwise from right-to-left.
@param begining Defines the start point of the search.
@param end Defines the end point of the search.
@param &spectrum Vector containing the spectrum allocation status for the
calculated path.
@return True if there is place in the spectrum, or False if the allocation is
impossible.
*/
bool LRFit(Request *msg, int thres, unsigned int begining, unsigned int end,
std::vector<long> &spectrum) {
    unsigned int i;
    int run = 0;
    Start = -1;

    for(unsigned int j=begining; j<end; j++) {

        //Reverse search if connection size is greater or equal than the
threshold
        if(msg->getBandwidth() >= thres) {
            i = end - j - 1;
        } else {
            i = j;
        }

        //Check for availability
        if(spectrum.at(i) == 0) {
            run++;

            if(Start == -1) {
                Start = i;
            }

            //Break if the space for the connection was found
            if(run == msg->getBandwidth()) {
                break;
            }
        } else {

            //Clean variables in case no space is available
            run = 0;

```

```
        Start = -1;
    }
}

//Translate results if the order was reversed
if(Start != -1 && run == msg->getBandwidth()) {
    if(msg->getBandwidth() >= thres) {
        End = Start + 1;
        Start = End - run;
    } else {
        End = Start + run;
    }

    return true;
}

return false;
}
```