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Contribution to the Defragmentation of the Frequency Spectrum of Elastic Optical Networks by Using Independent Sets in a Graph

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***Abstract*– This paper is about spectrum defragmentation in elastic optical network. Our proposal consists in creating independents sets with current connections in the network, so that they can easily be rerouted or reallocated to another position of frequency slots in the optical spectrum. We choose to reroute as much as possible connections to lowest slots indices in order to free more contiguous and continuous slots in the highest areas indices for future connections. In addition, we define a parameter for judging the need for the defragmentation operation. The simulation performed with Matlab has allowed us to observe a reduction in the rejection rate of connections in the order of 6% after defragmentation, especially for those with wide bandwidth.**

***Index Terms*– Elastic Optical Network, Fragmentation, Defragmentation, Frequency Slots and OFDM**

I. INTRODUCTION

THE rapid and sustained growth of Internet traffic and the bandwidth requirements of the new applications call for more flexibility in the usage of the huge potential of optical fiber. However the traditional fixed grid of ITUT-T based on wavelength division multiplexing (WDM) and its variations are struggling to meet these requirements. The fixed grid doesn't support the wide bandwidth connections and it doesn't offer either the flexibility necessary to meet those with smaller bandwidth. All these problems lead to an inefficient use of the optical fiber. To cope with these situations, a new generation of optical transport network has emerged. This new generation of optical transport network is based on the Optical Orthogonal Frequency Division Multiplexing (O-OFDM) modulation technique. In literature, we only have two type of transport network architecture based on O-OFDM modulation. The first one is called spectrum sliced elastic optical path (SLICE) which is described in [1].

This architecture uses the O-OFDM transmission technology and supports a variety of different granularities of services from the order of sub-wavelength to super wave-length. The second one proposed in [2], developed at that time, also uses the O-OFDM transmission, and is called programmable optical network. The interest of these optical networks based on the O-OFDM transmission, known as the elastic optical networks provides a resource and long reach that fits the customer's request. Supported capacities are not given in advance. Wavelengths are subdivided into sub-wavelengths; the frequency of a sub-wavelength is that of a frequency slot generally set at 12.5 GHz.

Also, in this kind of network, the central frequencies are not rigid, thereby providing flexibility in the usage of resources.

Notwithstanding all these qualities, in this type of network, it appears after some time a phenomenon of fragmentation of the frequency spectrum. This fragmentation results in a scattering of vacant slots between those already occupied. These isolated fragments become unusable by future connections, especially those with wide bandwidth. This is due to fact that in the process of Routing and Spectrum Allocation (RSA) in elastic optical network the frequency slots must comply with the requirements of continuity in overall optical path and adjacency in each optical link. So the expected effectiveness of elastic optical network decreases, thus leading to a number of increasingly high connections rejected for lack of contiguous and continuous resources. These rejections of connections that can be translated in terms of loss rate are an important parameter for assessing the quality of service perceived by the user. Therefore, it is necessary to set up effective defragmentation mechanism to overcome this problem by reducing the rejection rate.

This article deals with defragmentation of the frequency spectrum as a problem of research of independent sets in a graph .The remainder of this article will focus on the following points. In the second section, we will focus on the state of the works that exist in the literature, then in the third we will propose a new approach, in the fourth stage we will comment on the results of our simulation and finally, end with a conclusion and prospects.

II. STATE OF THE ART

A) Problem of spectrum fragmentation

The optical frequency spectrum is a concept that defines the frequencies range in which the optical technology is limited.

It is measured in gigahertz (GHz). As far as the elastic optical networks are concerned, the frequencies spectrum is subdivided into frequency slots. Each slot has a size of 12.5 GHz. A given connection needs a certain amount of slots on its path from its source node to its destination node under the following constraints:

-the constraint of continuity: the slots used, must be at the same position on all links of the path that means the same central frequency in each link.

-the constraint of contiguity: the slots used must be adjacent to each other on each link.

The multiple and random access to the frequencies spectrum of the connections of various granularities inevitably lead to the fragmentation of the frequencies spectrum. The frequency slots become isolated and unusable for future connections because they are not able to meet the requirements constraints of any connections. Defragmentation is the reconfiguration at a certain period of the running connections so that the scattered slots can be usable. It is either a reallocation on other slots in the same path or rerouting current connections to new shortest path with slots required on all links [3]. The defragmentation process can be illustrated by Fig. 1, which reflects the resource usage status (frequency slots) of a network of three nodes and three links (Fig. 1(a): M, N, P and {M, N}, {N, P}, {M, P}). It is assumed that the optical links are bidirectional. Fig. 1(b) shows the frequency slots usage by current connections: A, B, C, D, E, G and F. Fig. 1(c) and Fig. 1(d) give two possible defragmentation solutions. On the Fig. 1(c), the connection G

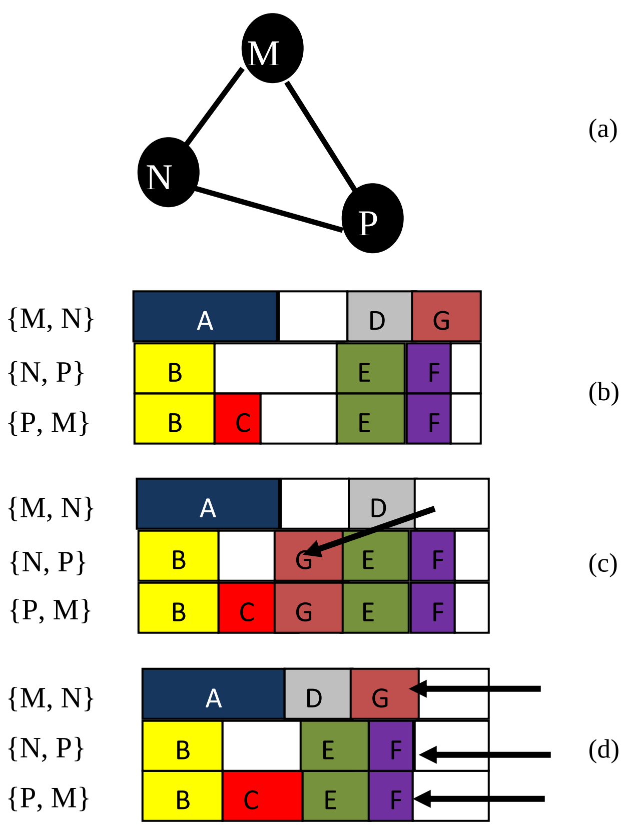

Fig. 1: Illustrative example of defragmentation

that initially, was on the M-N path is rerouted on the path M -P -N because there are enough resources on the links (M, P) and (P, N). Fig. 1(d) describes another solution where connections D, G, E and F are reallocated on slots with small indices without changing their paths. The solution (c) results in the disruption of a single connection but releases less contiguous slots ,while the solution (d) causes the disruption of four connections ,but releases more contiguous slots. The defragmentation process will therefore consist in maximizing the number of slots made available while minimizing connections disrupted by this process.

The other essential element in the process of defragmentation is the fact of detect active connections at a given time. For this reason, we can define the following model. Given a physical network G (V, E) in which V is a set of nodes and E a set of optical links that bind together the nodes of network. If we assume that the network supports a set of L connections, every one represented by its bandwidth defined as a certain amount of slots L = {2Fs, 4Fs, 8Fs, 16FS} here Fs denotes the size of a slot which value is 12.5 GHz. For each connection $l \in L$ having n_l amount of slots, information on the current configuration of the optical spectrum can be defined by:

$E_{p_l n_l}^{sd} \epsilon \{1,0\}$, thus $E_{p_l n_l}^{sd} = 1$ reflects the existence of a connection between the source node *s* and destination node *d* which bandwidth is n_l, this connection is established in the spectrum slots that start with index p_l. On the other hand, if $E_{p_l n_l}^{sd} = 0$, this means that there is no such active connection between the source node *s* and destination node *d*. It should be noted that an optical link is divided into frequency slots. Each slot is defined by an index whose value is between 1 and the maximum index slots. For example for a 400GHz spectrum, the maximum index is 400GHz / 12,5GHz or 32. This means that the indices will vary from 1 to 32.

Several studies have already been carried out on the problems posed by the fragmentation of the frequencies spectrum. Guocheng Wu *et al.* in [4] proposal are based on the assumption that running connections at a given time, are not on their optimal paths due to the dynamics of access to bandwidth and the Routing and Spectrum Allocation (RSA) algorithm used. To this end, on the expiry of an existing connection, one must look among the rest running which can be reconfigured on the path of the connection expired with a maximum gain of frequency slots? Therefore they define a mathematical model that estimates the cost of a connection in terms of resource usage (frequency slots). From this model they calculate the gain obtained by deciding to reconfigure a connection on a vacant path instead of another. Ankitkumar et *al.* [5] suggest two defragmentation algorithms, a greedy algorithm and another one based on the shortest path. The main objective of these algorithms is to maximize the number of slots made available, in other words minimizing the space occupied by running connections and disrupted connections. Other articles are based on concepts taken from graph theory to complete defragmentation in order to reduce the inconvenience associated with this process on current connections. This is the case of the author in [6]; who uses the theory of connectivity of graphs in his defragmentation process, the concept of independent sets of graphs is also used. As our study is focused on the use of independent sets to solve the problem of fragmentation; in the section below, we will do literary review of existing works on the use of independent sets in a graph in the defragmentation of elastic optical network frequencies spectrum.

B) Defragmentation based on independent set in graph

Given a graph G (V, E) where V is a set of edges and E a set of vertices. An independent set is a subset of E such that any two vertices of this subset have no edges between them. Among these independent sets, the search for the one which has the greater cardinality called Maximum Independent Set (MIS) is an NP-hard optimization problem [7].

Yawei Yin *et al.* [8] formalize the problem of fragmentation described above as a problem of research of an independent set with maximum cardinality in a graph. They establish a correspondence between a series of potential connections to reconfiguration and a series of blocks free frequency slots. To avoid the overlap of potential connections to reconfiguration, their new locations are independent sets obtained from an auxiliary graph which vertices are the connections to move from one area to another with the purpose to let the old area for a new connection. This defragmentation is made to satisfy a particular connection. This is called defragmentation on-demand. In addition, the authors assume the existence of wavelength converters in the intermediate nodes in order to resolve the problem of the continuity constraint. So to avoid conflicts, the wavelength of a connection to be moved can be converted to another wavelength available on the same link. As far as Sunny Shakya *et al.* are concerned in [9], they propose defragmentation of the entire frequency spectrum. In this approach, after the construction of the auxiliary graph, they search an independent set with maximum cardinality. Every time, such a set is found, relative connections are grouped, and then, the process attempts to reconfigure them on their more optimal path. They are then removed from the graph and the graph is reorganized. This process continues until the degree of the graph is zero. The algorithm used to search for independent sets has exponential complexity. Beyond a certain number of active connections in the network, connections partitioning into disjoint independent sets can be lost over in time.

III. NEW DEFRAGMENTATION APPROACH

We propose a defragmentation mechanism using independent sets in a graph. Furthermore we define a parameter that allows as to assess the state of fragmentation of spectrum. Our method assumes no wavelength converters in the intermediate nodes.

A) Parameter defining the state of fragmentation

The author of the article [10] defines the state of fragmentation of a link through formula (1):

$$F_{link} = \left(1 - \frac{\sum_{i=1}^{N} Si}{\lambda_{max} - \lambda_{min} + 1}\right) \times K \qquad (1)$$

along with:

$\boldsymbol{\lambda}_{max}$: Maximum index number of occupied slots

$\boldsymbol{\lambda}_{min}$: Minimum index number of occupied slots

N: number of slots on a link

K: number of gaps between the blocks of slots be occupied on a link

F_{link} : the state of the slots fragmentation of a link

In this formula (1) that describes what can be called the spectral disorder, K is the number of blocks of empty slots between two blocks of slots that are already used. On the illustrative example of Figure 2, for the case of the link L1, K = 2. Whereas the number of vacant slots between the index maximal λ_{max} = 11 and the minimum index λ_{min} =1 in this illustration is 8 slots. By replacing 2 with 8, it better reflects the gap between λ_{max} and λ_{min}, that is to say, we express much the fact that there remains more free slots on this link. Thus, if the small number of occupied slots can be released by reconfiguring the connections to the homogeneous frequency slots which have the smaller index that may contain them, then, we hope to have many more homogeneous frequency slots. This allows us to have enough slots that meet the constraints of contiguity and continuity in the highest indices. We find it suitable to replace K with a new formula that takes account of the number of empty slots over a link rather than empty blocs. We can therefore replace K by $\sum_{i=\lambda_{min}}^{\lambda_{max}} \overline{\boldsymbol{S}_i}$ that expresses more the number of empty slots. Indeed, for every index i, if the λ_i frequency slot is unoccupied, $\overline{S_i}$ =1 otherwise $\overline{S_i}$ =0 so $\sum_{i=\lambda_{min}}^{\lambda_{max}} \overline{S_i}$ denotes the number of unoccupied slots on each link then new formula that describes the state of fragmentation of a network link is expressed as follows:

$$\boldsymbol{F_{link}} = \left(1 - \frac{\sum_{i=1}^{N} \boldsymbol{Si}}{\boldsymbol{\lambda_{max} - \lambda_{min} + 1}}\right) \times \sum_{i=\lambda_{min}}^{\lambda_{max}} \overline{\boldsymbol{S}_i} \qquad (2)$$

From this formula (2), we can determine the state of total network fragmentation, by doing a sum. So let us assume a network of M links, the state of total fragmentation of the network is:

$$F_{network} = \sum_{j=1}^{M} F_{link} \qquad (3)$$

By applying this new approach to the occupation of slots in Fig. 2. We have the following results:

$$F_{L1} = \left(1 - \frac{6}{11 - 1 + 1}\right) \times 5 = 2{,}28$$

$$F_{L2} = 3{,}28$$

$$F_{L3} = 1{,}78$$

$$F_{network} = F_{L_1} + F_{L_2} + F_{L_3} = 7{,}34$$

L1	A			C	C	C				G	G	…
L2	H			B	B					G	G	…
L3	H	I			E			D	F			…
	λ 1	λ 2	λ 3	λ 4	λ 5	λ 6	λ 7	λ 8	λ 9	λ 10	λ 11	…

Fig. 2: occupation of the slots of the frequency Spectrum of three consecutive links

The value of $F_{network}$ in our defragmentation process determines the threshold at which it is estimated that defragmentation is needed. The threshold value must be defined empirically by the network administrator. By having a thorough knowledge of the type of traffic and an indication of the rejection rate that can be tolerated.

B) Search for Independent Sets

Our defragmentation mechanism is based on the research of independent sets in a graph. Indeed, from the current connections in the physical network, we construct an auxiliary graph whose nodes are these connections. Every independent set is made up of the current connections with the same bandwidth, because it is more advantageous to reconfigure connections with identical bandwidths before moving on to other connections. The use of independent sets theory will help us to partition off the running connections in disjoint sets and allow us to ensure their reallocation or rerouting without any overlapping between them. After the determination of independent sets, we establish a correspondence between each connection of a given independent set and block of free slots of frequencies that can receive it. We ensure compliance with the requirements of contiguity and continuity constraints, plus the assumption of the absence of wavelength converters. However, as we mentioned above, finding independent sets in a graph is an NP-hard optimization problem, so we must use algorithm with a better time complexity in order to reduce duration of defragmentation, to mitigate the risk that the defragmentation may not be transparent to the user level and that he can feels the inconvenience caused by this process.

This is why, we have used polynomial complexity algorithm ($O(n^2)$)developed by H. Almara and *al* in [9], that provides a search time of independent sets better than the algorithm already used in the literature for finding independent sets whose complexity is exponential ($O(2^{0,0076n})$ as part of defragmentation. The main function of this algorithm is to find the Maximum Independent Set of any graph. If we want to find all Independent Set's (MIS), after finding the first MIS, we eliminate the nodes that are in MIS and their edges from the graph, and call the procedure again. This procedure, called Min-Max by the author selects a node with minimum and maximum degree consecutively. The procedure ends when the degree of the graph takes the value zero. The time complexity of both two algorithms depends on number of running connections in the network, which is represented by variable n. As we choose to use polynomial complexity algorithm, the main reason of this choice is that beyond a certain number of running connections, it consumes less time than using the exponential algorithm. Figure 3 shows a representation in semi-logarithmic scale because of the orders of magnitude. We can see that beyond 3000 active connections, the independent sets search time is preferable with polynomial complexity algorithm represented in blue than that used by the author of the article [10], which is represented in red and which increases rapidly beyond this threshold. Obviously, we may easily reach the number of 3000 connections in a network, considering the increasing number of users.

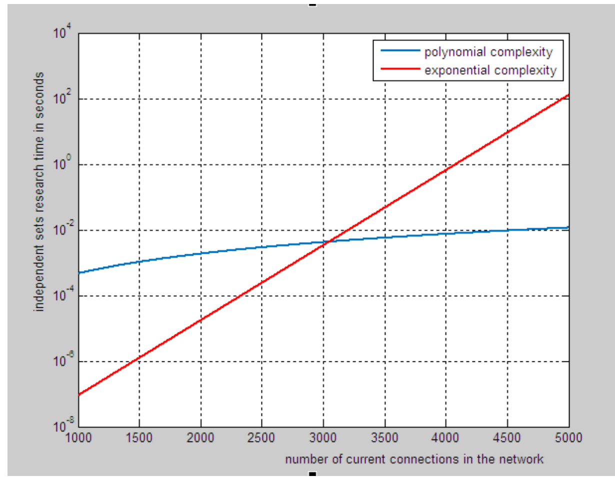

Fig. 3: Semi-logarithmic scale representation of polynomial and exponential complexities

C) Defragmentation algorithm using the Min-Max procedure for searching the independent sets

In this section, we first present how the auxiliary graph is constructed and then we present the overall defragmentation process in which the auxiliary graph is used.

- *Construction of the auxiliary graph*

The construction of the auxiliary graph consists to create nodes with the running connections at the moment the defragmentation process begin. We make the assumption that every independent set is made up of connections that can be allocated on slots of the same indices, that is, the connections with the same bandwidth. Here are the steps of auxiliary graph construction:

Step 1: Transform each current connection in to a node of the auxiliary graph.

Step 2: Create a link between two nodes if they do not have the same bandwidth.

- *Overall defragmentation process*

Step 1: Periodically, calculate the network fragmentation state using the formula (3).

Step 2: Compare the network fragmentation state to the threshold. If the state of fragmentation is greater than the threshold, go to step 3. Otherwise defragmentation is not necessary.

Step 3: Create the auxiliary graph.

Step 4: Create a partition with the nodes of the auxiliary graph into Independent Sets (IS). The number of independent sets is the number of subsets forming the partition. Each subset of the partition is composed of connections with the same bandwidth. Then arrange them in ascending order according to their bandwidth.

Step 5: For each IS, starting with the one with the connections of smaller bandwidth. Determine a path for each connection favouring connections with a higher hop Count. If there is no path, block the connection. If the path exists and that there are available of frequency slots that are continuous and contiguous on this path, reconfigure the connection by using on frequency slots that have the smallest index. If there are not enough free slots, block the connection and go to the next.

Step 6: Repeat step 5 until there is no more IS.

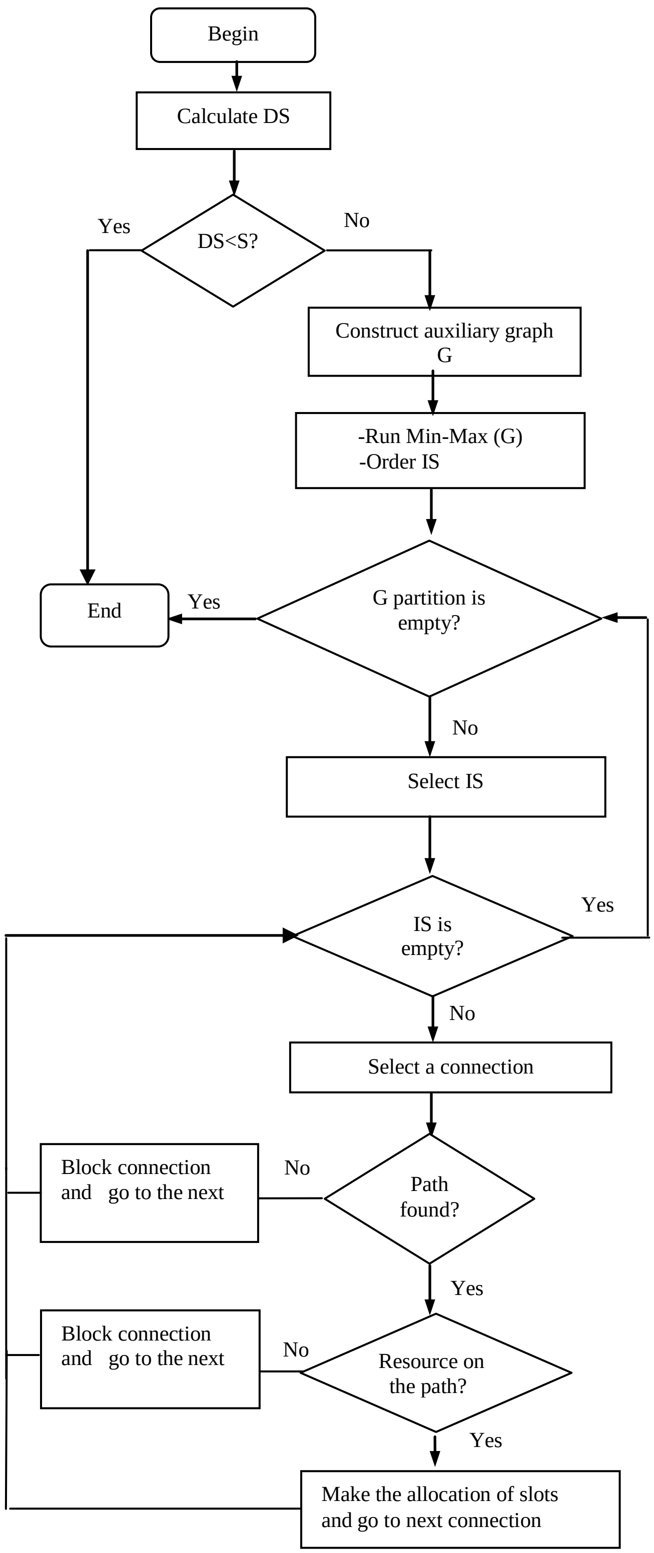

Fig. 4: Defragmentation algorithm flowchart

Here:

DS: the network fragmentation status

S: threshold at which it triggers the defragmentation

IS: Independent Set

Min-Max: Procedure used to create independent sets

These different steps are shown schematically by the flowchart in Fig. 4.

IV. SIMULATION

To assess the performance of our proposal, we conducted a simulation on the experimental network NSFNetwork (14 knots-21 links). We have assumed that every optical fiber has a spectral capacity of 5 THz frequencies and each slot has a 12,5GHz size. We have considered connections of which bandwidths correspond at 2, 4, 8, 16, 32, 64 and 128 slots.

Our simulation performed on MATLAB consists in the assessing of the impact that defragmentation has on the reducing of failure of the connections. For routing and spectrum allocation (RSA), we used the algorithm proposed in [11]. After a first implementation of RSA, we have found a failure rate of different connections. Then we have executed our defragmentation process in the same conditions of the use of network resources that when we began the running RSA. This defragmentation, has allowed us to have a new configuration in the usage of the optical spectrum by current connections. Then, we have carried out again the RSA on this new configuration obtained after defragmentation; we have also noted the different failure rates. In Figure 5, the failure rates before defragmentation is represented with red colour and the failure rates after defragmentation in blue. We can see that beyond the connections with more than 4 slots in terms of bandwidth, defragmentation has contributed on the decrease in the failure rate. This decrease is of the order of 6%.

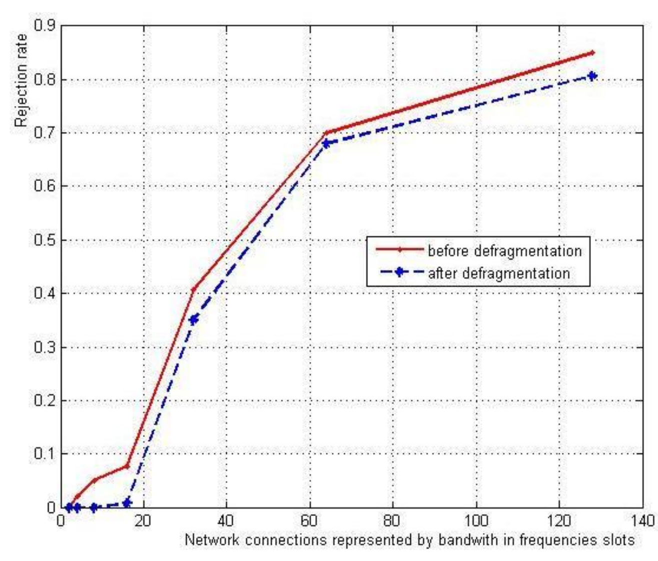

Fig. 5: Evaluation of failure rates before and after defragmentation

Also the histogram of Fig. 6 shows that the gain is sharper for connections of wide granularity. The number of connections established after defragmentation is higher than before the defragmentation.

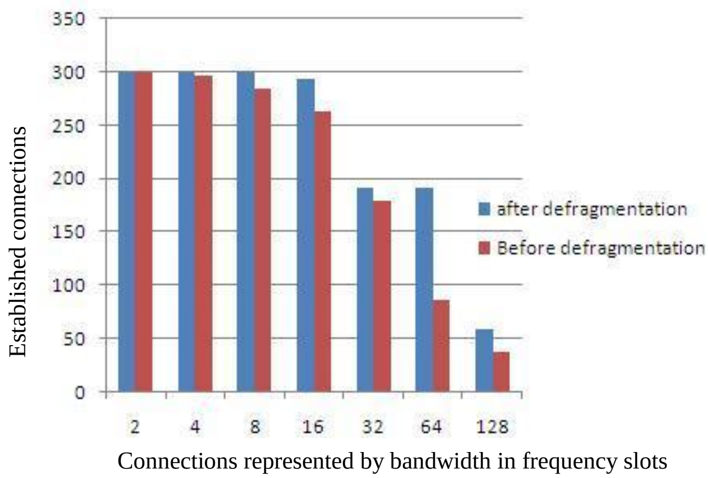

Fig. 6: Assessment of established applications before and after defragmenting

V. CONCLUSION

In this work, we have proceeded to the establishment of a defragmentation mechanism that takes into account the state of fragmentation of spectrum before carrying out. In addition, we have used a partitioning algorithm of the graph into independent sets. Every independent set represents a class of connections with the same bandwidth. That is to say connections that can be assigned to the same index slots. Moreover, our approach is to use the lowest slots index available first before going to the highest slots index. In doing so, running connections are confined to the lowest part of the spectrum. The highest part will be used to perform future connections. Note also that the algorithm we use to search for independent sets in the auxiliary graph obtained from connections is a polynomial time complexity algorithm in the worst case. It brings a greater reduction in the duration of defragmentation, and appears more useful in the present state of growth of network traffic.

Certainly this work has allowed us to maximize the use of resources, but the other problem of defragmentation is that connections can be disrupted. A future study could be conducted on minimizing the number of disrupted connections.

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