Dynamic Routing and Spectrum Allocation with Traffic Differentiation to Reduce Fragmentation in Multifiber Elastic Optical Networks

Boris Stephane ZOUNEME[1†], Joel ADEPO[2††], Herve Gokou DIEDIE[3†††] and Souleymane OUMTANAGA[4††††]

Institut National Polytechnique Félix Houphouët-Boigny, Yamoussoukro, Côte d'Ivoire [1†,4††††]
Université Virtuelle de Côte d'Ivoire, Abidjan, Côte d'Ivoire[2††]
Université Peleforo-Gon-Coulibaly, Korhogo, Côte d'Ivoire[3†††]
Laboratoire de Recherche en Informatique et Télécommunication, Abidjan, Côte d'Ivoire[1†,2††,3†††,4††††]

Abstract
In recent decades, the heterogeneous and dynamic behavior of Internet traffic has placed new demands on the adaptive resource allocation of the optical network infrastructure. However, the advent of multifiber elastic optical networks has led to a higher degree of spectrum fragmentation than conventional flexible grid networks due to the dynamic and random establishment and removal of optical connections. In this paper, we propose heuristic routing and dynamic slot allocation algorithms to minimize spectrum fragmentation and reduce the probability of blocking future connection requests by considering the power consumption in elastic multifiber elastic optical networks.

Keywords:
Routing and spectrum allocation; fragmentation; multifiber elastic optical networks; allocation cost; energy-saving.

.1. Introduction

The growing demand for bandwidth in operator and corporate networks is mainly due to new Internet-related services, on-demand services such as video over IP, video-on-demand, distance learning, and the transport of large amounts of data between datacenters. This spectacular development has been accompanied by a correlative technological transformation of transport networks that is visible enough to support the transport of large quantities of data that are constantly growing. Optical elastic networks have been seen as a promising solution for managing service differentiation with heterogeneous bandwidth demands, since according to the International Telecommunication Union-Telecommunication ITU-T, this network tends to be more flexible in terms of the use of network resources than fixed-grid Wavelength Division Multiplexing (WDM) technology [1]. This new optical transport network technology is based on OFDM (Orthogonal Frequency Division Multiplexing) optical modulation in which frequency grids are flexible from one connection request to another [2]. Through its flexibility, elastic optical networks offer new features in terms of segmentation and aggregation of spectral resources (sub-wavelengths and super-wavelengths), efficient adaptation of multiple data rates, as well as elastic variation of allocated resources.

OFDM technology allows the channels of neighboring sub-carriers to overlap. This increases the spectral efficiency of the transmission. For this purpose, an optical signal is produced by a variable bandwidth OFDM transponder using the technology with just the right spectral resources to meet the customer's demand. The introduction of advanced modulation formats and Wavelength Cross-Connects (WXC) allows the increasing volume of traffic to be transported over long distances without opto-electronic-to-optical (OEO) conversion [3]. There are three transponder models: Mixed Line Rate (MLR), Multi Flow MF and Bandwidth Variable BV. The MLR model uses a few types of transponders, each with a different bit rate, e.g. 40, 100 and 400 Gb/s transponders to meet a wide range of traffic demands [4].

The MF model uses an MF transponder with several receiver sub-transmitters, which can be allocated to different traffic requests, each of which has a fixed throughput capacity. The BV model supports all types of traffic requests with a single BV transponder, which allocates as few spectrum resources as possible to traffic requests with a maximum bit rate of 400 Gbps.

The BV model provides better spectrum and the lowest consumption rate. It uses different modulation formats such as BPSK, QPSK, 4-QAM, 16-QAM, 32-QAM and 64-QAM. In addition, it offers a better balance between spectral efficiency and transmission range. Due to the reduction of active resources, a new generation of optical transponders (S-BVT) has been investigated in [5]. flexible grid optical networks thus enable efficient slot utilization by using the 12.5 GHz frequency (or even 6.25 GHz) instead of the traditional fixed 50 GHz spacing, and select different

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modulation formats depending on the transmission distance, thus considerably improving the use of spectrum resources in the optical layer [6].

However, it also reveals new technical challenges in addition to those already existing in traditional WDM networks, i.e. an end-to-end connection in elastic optical networks must occupy the same spectrum between its end nodes, i.e. ensure the spectrum continuity constraint. In addition, the entire spectrum allocated to connection requests must be contiguous, the so-called spectrum contiguity constraint. In addition, the available routing and wavelength assignment algorithms (RWA) proposed for WDM networks cannot be directly applicable in ROE. In this case, a new routing and resource allocation model must be developed, namely RSA (Routing and Spectrum Allocation). The RSA problem in the Optical Elastic Array can be considered as the RWA problem when the number of frequency slots in the spectrum is equivalent to the number of wavelengths. Therefore, the Routing and Spectrum Allocation problem is also a NP-difficult problem [7, 8].

The Routing and Spectrum Allocation (RSA) algorithm in elastic optical networks allocates a physical path and frequency slots between two optical nodes. The lightpath should allocate the same spectrum along its routing path, while the allocated sub-carriers along this path should be contiguous. The first is known as the spectrum continuity constraint, while the second is known as the spectrum contiguity constraint. In addition, where two optical paths share one or more common fibers, the corresponding allocated sub-carriers should be separated by guard bands [9].

The RSA problem can be formulated in several ways, with different objectives and different assumptions. In general, the RSA problem in elastic optical networks can be classified into two versions: RSA outline, where the network topology and traffic demands are known in advance, and RSA online, where the network topology is known in advance but traffic demands arrive in a random order. Since RSA is the key to efficient spectrum allocation in elastic optical networks. The problem of routing and static spectrum allocation is a well-known problem in the literature. The problem of routing and spectrum allocation in elastic optical networks is similar to the problem of routing and wavelength allocation (RWA) in WDM networks [10].

The complexity of the offline spectrum allocation problem has been calculated in [11]. Using the results of the graph coloring theory, it has been shown that the spectrum allocation problem is NP-difficult. Since the RSA problem is NP-difficult, a variety of Integer Linear Program (ILP) formulations have been proposed for offline RSA in elastic optical networks, each dedicated to solving a specific problem. However, these ILPs cannot be solved within a reasonable delay for problem cases involving much larger network topologies. Therefore, several heuristic algorithms have also been proposed to solve the problem of static RSA in large networks.

Dynamic RSA in elastic optical networks is even more difficult due to the random arrival and departure of traffic and fluctuating connection demands over time. Depending on the state of the network, the available spectrum resources may or may not be enough to establish a connection. As the network evolves, a current optimal routing algorithm may no longer be optimal over time. Thus, each time a new connection request arrives, an algorithm must be run in real time to determine whether it is possible to accept the new connection request. If a new connection request cannot be satisfied, it is blocked. Thus, the probability of blocking connection requests appears as the key objective in a dynamic RSA algorithm. The study in [12] examined the optimal slot width for elastic optical networks by measuring the blocking probability under dynamic traffic using Monte Carlo simulations. Each request was routed on its shortest path and the first policy was used for spectrum allocation. While in [13] the authors proposed an improvement in the functioning of the First-Fit allocation strategy. This study proposed an evolutionary algorithm to search for the most feasible spectrum order to minimize the probability of blocking.

During network operation, connection requests require spectrum slices consisting of slots that must be available on each link along the optical path from the source node to the destination node, this results in the continuity constraint. The dynamic nature of incoming and outgoing connections, as well as contiguity and continuity constraints, cause a phenomenon known as spectrum fragmentation, leaving unused gaps along the spectrum. As a result, spectrum occupation is not organized and the available resources become more fragmented, negatively affecting the efficiency and degrading performance of the network. This is detrimental when taking into account the constraints of continuity and contiguity of the spectrum for all connection requests that arrive randomly on the network. Internet traffic continues to grow dramatically due to the emergence of applications such as live streams and social networks. To satisfy the growing demand for traffic, it is necessary to deploy multiple fibers over a physical link. Multifiber links offer greater flexibility in frequency slot switching than previous systems are designed to make full use of [14]. With the advent of multifiber, this rate of fragmentation has become more pronounced, resulting in a high blocking rate in multifiber elastic optical networks.

In the literature, spectrum fragmentation is considered to be a crucial and major problem in optical multifiber elastic networks, especially in the context of dynamic traffic. Several mechanisms have been investigated to solve this problem, but their limitations have been revealed in the face of the parameter of increasing size for a given operational network. [15] In fixed-grid WDM networks, spectrum fragmentation is also a problem, but it is called spatial or horizontal fragmentation because of continuity constraint and routing distribution [16, 17]. The understanding of routing distribution is as follows, for a given topology each link may have paths with different lengths. In this scenario, a connection request may be denied if the resource required for that request is not available simultaneously on all links in the path, even if there are resources available on each link separately [18]. Therefore, the spatial or horizontal fragmentation resulting from the continuity constraint depends on the routing definitions, and more particularly on the network topology. The overall network fragmentation, taking into account the contiguity and continuity constraints, is a key parameter for determining the performance of elastic optical networks that has been widely studied in the literature [19, 20]. In the context of dynamic routing and allocation, the fragmentation of bandwidth and spectrum mismatch caused by dynamic configuration and suppression of traffic demands is detrimental to network performance. Many RSA systems have been proposed to reduce the problem of bandwidth fragmentation [21, 22]. The authors of [23] propose a new approach to the dynamic RSA problem in multifiber elastic optical networks. Given a dynamic stochastic network and connection requests with known traffic loads, the problem is to assign a route and slot to each request, so that the probability of blocking is minimized. Each link in the network contains several fibers. A network planning formulation based on topology information is proposed so that candidate routes for each source-destination node pair can be selected based on some of the predetermined probabilities. In [24], the authors develop defragmentation algorithms that redirect connections. Thus, another strategy to eliminate bandwidth fragmentation without re-routing connections is to partition the spectrum for heterogeneous bandwidth demands. In [25, 26], different partitioning methods are investigated using the first-fit allocation strategy. In [27] the spectrum is partitioned by classifying group connections. By proposing some simple measures to assess fragmentation and by testing some routing and spectrum allocation algorithms, the authors concluded that some fragmentation criteria can reduce the probability of blocking, which is the ratio of the number of blocked connections to the total number of connection requests in the network. To eliminate fragmentation caused by heterogeneous bandwidth mismatch when dynamically configuring and removing requests, [28] uses a dedicated partitioning technique. In which the spectrum is divided into different segments, each of which is dedicated to traffic requests with the same bandwidth. Blocking probability has been used in [29] to evaluate RSA algorithms considering fragmentation, based on traffic distribution, making more efficient use of spectrum gaps and better adapting to incoming traffic. In addition, [30] presented a new measure of fragmentation that can consider both unused free slots available on the network and proposed efficient algorithms that take into account the probability of blocking and network usage. In [31], it was shown that new systems acting on the different steps of an RSA algorithm can more effectively reduce spectrum fragmentation and adapt to incoming traffic while improving network performance in terms of blocking probability and spectrum utilization.

In [32], the authors proposed a technique to make more efficient use of fragmented frequency slots by dividing traffic into several paths, thereby improving network performance.

According to [33], spectrum loss can be used to measure spectrum fragmentation.

On the other hand, spectrum loss can be measured by the probability of blocking, which depends on the service. This is because services with a higher bandwidth demand are likely to be blocked. Therefore, this parameter cannot be considered solely for estimating spectrum fragmentation. But the most commonly used measure for estimating fragmentation is the blocking rate. The assumption is that if the blocking rate is lower, the fragmentation effect is also lower. However, the blocking rate is not a complete measure of fragmentation because the blocking rate is also impacted by several system parameters, such as lack of resources, transmission quality and waiting time. Therefore, it is necessary to identify other key parameters to measure spectrum fragmentation. This leads us to define significantly in what follows a new fragmentation parameter as a criterion for choosing the best optimal path. Minimizing this parameter leads to a significant reduction in the blocking probability rate in the whole elastic optical network with several fibers per link.

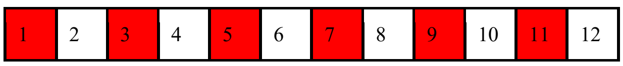
In order to minimize fragmentation, we consider a fragmentation parameter which we will define as a criterion for choosing the best path with a view to minimizing fragmentation. We will name this parameter AC Allocation Cost which depends on the presence of the total number of frequency slots available on the path and the number of slot blocks. This parameter is defined through Eq. 1.

$$AC = \sum_{i=1}^{n} \exp\left(\frac{1}{S_i}\right) \qquad (1)$$

Where Si is the number of frequency slots in the i-block available on the path.

We illustrate this parameter as follows with four links L_1, L_2, L_3 and L_4 for a connection request requiring 4 contiguous frequency slots:

L_1



AC(L_1) = $6\boldsymbol{e}^{\mathbf{1}}$ = 16.309

L_2

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

AC(L_2) $= \boldsymbol{e}^{\frac{1}{3}} + \boldsymbol{e}^{\frac{1}{2}} + \boldsymbol{e}^{1}$ = 5.763

L_3

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

AC(L_3) $= 2e^{\frac{1}{2}} + e^{1}$ = 6.016

L_4

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

AC(L_4) $= e^{\frac{1}{6}}$ = 2.363

The allocation costs of the L_1, L_2, L_3 and L_4 links show that:

CA(L_1) > CA(L_3) > CA(L_2) > CA(L_4)

When the cost of allocating a link is high, this causes the creation of small blocks of slots with a low probability of being used for future connection requests and increases the fragmentation of the network.

On the other hand, when the cost of allocating a link of this parameter is as low as possible, it reduces the rate of fragmentation of spectrum resources in the network.

In this paper, we propose routing and frequency slot allocation algorithms that reduce the impact of this phenomenon in elastic optical networks with multiple fibers per link for random and dynamic increasing connection demands in the network. The rest of the paper is organized as follows. Section II presents the mathematical modelling of the multifiber elastic optical network. Section III presents the dynamic routing and resource allocation algorithms for reducing fragmentation (RSA-RF) in multifiber elastic optical networks taking into account power consumption. Simulation results and discussions on the performance evaluation of our routing and spectrum allocation strategy are presented in section IV. Section V concludes the paper and provides perspectives on our approach.

2. Mathematical modeling of network components

2.1 Modeling of the network topology

We define the topology of the multifiber elastic optical grating by a graph G (V, E Rs, C) in which:

- V represents all optical nodes (OXC).
- $E = \{(i,j)$; i ≠ j , i and j are the vertices of the graph } represents the set of links in the network where each link contains several fibers, assuming that the number of fibers on each link is identical.
- $R_s = \{R_{s_1}^k, R_{s_2,\dots,}^k R_{s_m}^k\}_{m \in \mathbb{N}}$, F denotes the number of fibers per link and m the number of slots such that $1 \leq m$ and $1 \leq k \leq F$.
- $C = \{c_1, c_2, \dots, c_m\}$ Indicates all requests for network connections.

$c_{sd} = (s_c, d_c, \omega_c)$ represents a request for connection c between a source s and a destination d for a rate ω expressed in Gb/s.

For a connection request c_{sd} on a p path, the number of NRs frequency slots is calculated according to Eq. 2.

$$NR_s\big(p(c_{sd})\big) = \frac{\omega_{c_{sd}}}{M(p(c_{sd}).\omega_{c_{sd}}} + GB \qquad (2)$$

With :

- $\omega_{c_{sd}}$ indicates the speed of the optical signal for a frequency slot expressed in GHz.
- $M\big(p(c_{sd})\big) = Mdft(\sum_{(i,j)\in p} l(i,j)$ (3)

with $Mdft(.)$ is a function that returns the coefficient of the appropriate modulation format.

- l represents the length of the link from the source to the destination on the path p
- GB designates the protective guard band.

2.2 Energy cost of network components

The optical transport revolution is one of the most promising technologies for achieving more than the performance previously offered by conventional networks. However, one of the main challenges of this technology is the energy consumption of the various optical components required for its implementation. Therefore, for a connection request c_{sd}, the energy cost of an optical path is calculated according to the essential elements: the energy consumption of an Erbium Doped Fiber Amplifier (EFDA), the energy consumption of an optical node (OXC) and the energy consumption of a frequency slot according to Eq.4 presented as follows:

$$EC(p(c_{sd})) = C_{slot} \times PC_{slot} \times (NR_s(p(c_{sd}) - GB) + \left(\sum_{(i,j) \in c_{sd}} C_{OXC} \times PC_{OXC} + \sum_{(i,j) \in c_{sd}} C_{AMP} \times PC_{AMP} \times (\sigma(i,j) + 2) \right) \times \frac{NR_s(p(c_{sd}))}{\sum_{(i,j) \in l} slot} \quad (4)$$

with

- $\sigma(i,j) = \begin{cases} 0, & \text{if } \frac{l(i,j)}{d_{Amp}} \le 1 \\ \left\lceil \frac{l(i,j)}{d_{Amp}} \right\rceil & \text{otherwise} \end{cases}$;

- GB represents the number of guard bands per connection ;
- C_{slot} represents the cost of the power consumed by a slot ;
- PC_{slot} indicates the power consumed by a slot;
- C_{Amp} refers to the cost of the power consumed by an EFDA amplifier ;
- PC_{Amp} represents the power consumed by an EFDA amplifier ;
- C_{OXC} represents the cost of the power consumed by an OXC optical node ;
- PC_{OXC} refers to the power consumed by an OXC optical node ;
- and $\sum_{(i,j)\in l} slot$ represents the total number of slots per link.

The number of slots increases with the distance of the path that a connection from a source to a destination has to cover, depending on the bit rate and modulation format. Therefore, for a given connection request, the number of amplifiers involved in the establishment is a function of the path distance, i.e. the greater the path distance, the greater the number of amplifiers, and the smaller the path length of the connection request, the smaller the number of amplifiers. It can be deduced from this that a connection demand established over a long distance will then require more amplifiers and optical nodes with higher power consumption than a connection established over a shorter distance with a smaller number of amplifiers and optical nodes. In this case, the distance a connection must cover, the number of EDFA amplifiers and the number of OXC optical nodes are essential parameters in the energy consumption of a link.

For a given connection, the capacity of a slot and the signal range depends on the modulation format chosen in the case of adaptive routing. In elastic optical networks, the use of optical transponders with heterogeneous bit rates based on the orthogonal frequency division multiplexing technique without dispersion makes it possible to use several modulation formats for different subcarriers to ensure flexibility in connection requirements.

The maximum reach of the optical signal and the energy consumed by a slot according to the modulation format are shown in Table 1.

Table 1: Characteristics of modulation formats and energy consumed by a slot as a function of optical reach

MF	Index	Slot capacity	Optical reach	Power Consumption/ Transponder
BPSK	1	12.5 Gb/s	4000 Km	112.374 W
QPSK	2	25 Gb/s	2000 Km	133.416 W
8QAM	3	37.5 Gb/s	1000 Km	154.457 W
16QAM	4	50 Gb/s	500 Km	175.498 W
32QAM	5	62.5 Gb/s	250 Km	196.539 W
64QAM	6	75 Gb/s	125 Km	217.581 W

3. Dynamic RSA Algorithm for Reducing Fragmentation in Multifiber Elastic Optical Networks (RSA-RF)

In this approach, we consider that a connection request can be established on different fibers on a given path while respecting the constraints of continuity and contiguity of the spectrum. Thus, we assume the physical topology below:

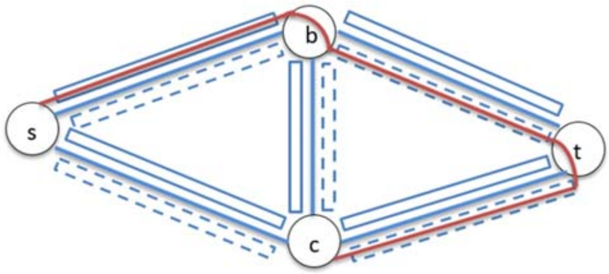


Fig. 1 Multifiber network topology

Thus, an optical path is characterized by the source, the destination and the optical fiber as follows:
$\boldsymbol{p(s,d,f_i)}$ where s is the source node, d the destination node and i represents the fiber.
Let $\boldsymbol{B_{l_i}}$ the set of slots of the link $\boldsymbol{l_i}$ such as:

$$\boldsymbol{B_{l_i}} = \left\{ \boldsymbol{b^f_{l_i}} : \boldsymbol{f} \in \boldsymbol{F(l_i)} \right\} \quad (5)$$

where F($\boldsymbol{l_i}$) is the set of fibers of the link $\boldsymbol{l_i}$
$\boldsymbol{b^f_{li}}$ is a partition of the set $\boldsymbol{B_{li}}$, the slot block of the link on the fiber f.
Be $\boldsymbol{F(p(i,j)} = \{\boldsymbol{f_k} : \boldsymbol{f_k} \in \boldsymbol{p(i,j}\}$ (6)
the set of fibers from path p from the source i to the destination j.
Be $\boldsymbol{L(p(i,j)} = \{\boldsymbol{l_k} : \boldsymbol{l_k} \in \boldsymbol{p(i,j)}\}$ (7)

the set of links in path p between source i and destination j.
Each link $\boldsymbol{l_k}$ has a set of disjointed and distinct blocks of fibers.
In the process of determination of the set of slot blocks of a path, we create intersection combinations between the blocks of each set $\boldsymbol{B_{li}}$where $\boldsymbol{l_i} \in \boldsymbol{p}$; which makes it possible to obtain all the blocks of slots of the path.

Be $\boldsymbol{B(p(i,j)} = \left\{\boldsymbol{b_{f_i,f_g,\dots,f_q}}: \boldsymbol{f_i, f_g, \dots, f_q} \in \boldsymbol{p(i,j)}\right\}$ (8)

where $b_{f_i,f_g,\dots,f_q} = \cap\, b_{l_k}^{f_k}, \forall\, l_k \in l(p(i,j))$ (9)

$f_k \in \{f_i, f_g, \dots, f_q\}$

$f_k \in F(l_k)$

where $BC(i,j) = \left\{b_{f_i,f_g,\dots,f_q}: \left|b_{f_{i,\dots,f_q}}\right| \geq NR_s\right\}$ (10)

such as $f_i, f_g, \dots, f_q \in p(i,j)$.

We can illustrate our resource allocation process through this approach in the following example:
Consider three nodes s, b and t connected by six fibers numbered from 1 to 6 and having respectively 3 slots f_1(1,2,3), 4 slots f_2(1,2,3,4), 5 slots f_3(1,2,3,4,5), 4 slots f_4(2,3,4,5), 4 slots f_5(1,2,3,4) et 4 slots f_6(2,3,4,5).

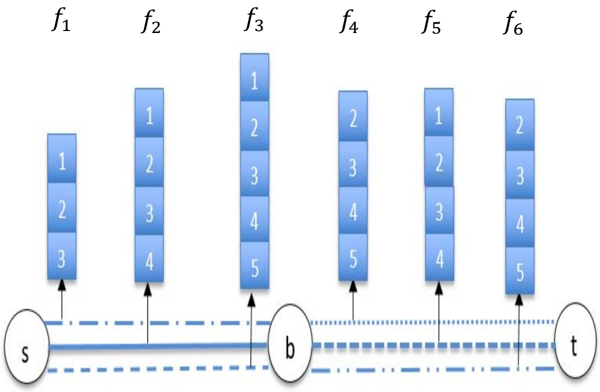


Fig. 2 Resource allocation process for 6 fibers

A connection request arrives on the network requiring 4 continuous and contiguous resources from the source to the destination.

Let be $BC(s,b) = \left\{b_{(s,b)}^{f_i}: f_i \in F(s,t)\right\}$

the set of continuous and contiguous frequency slot blocks on the link (s,b)

and $BC(b,t) = \left\{b_{(b,t)}^{f_i}: f_i \in F(s,t)\right\}$

the set of continuous and contiguous frequency slot blocks on the link (b,t).
Soc we have:
$BC(s,b) = \{b_{(s,b)}^1, b_{(s,b)}^2, b_{(s,b)}^3\}$
and $BC(b,t) = \{b_{(b,t)}^4, b_{(b,t)}^5, b_{(b,t)}^6\}$

To determine the set of slot blocks in the path from s to t, we create the intersection combinations between the blocks in each set B(s,b) and B(b,t);
Thus, we obtain the set of candidate slot blocks of the path from s to t verifying the Eq.8,
BC(s,t) = {(1,2,3,4); (2,3,4,5)}.

In our ASCP algorithm, for each connection request that arrives in the network; we determine the shortest paths from the source to the destination among all the links in the G graph and for each shortest path we determine the path that has resources for the connection. When a path in the network has sufficient resources for the connection then this optical path is saved. Then the optimal path with minimal energy cost is chosen to serve the connection. If this is not possible, the connection is blocked.

Physical path selection algorithm (ASCP)
Input: Graph G (V, E Rs, C)
Output: Physical paths and resources
1: For each connection request that arrives in the network from a source s to a destination d do
2. Determine the k-shortest paths
3: For each path found do
4: Determine the resources for the connection according to Eq. 2.
5: If Resource found then
6 : Save the path and its resources
7: End If
8: End for
9: If optical path found then
10: Select the optimal path according to the *ASMC algorithm*
11: Establishing the connection
12: Otherwise
13: The connection request is blocked
14 : Go to step 2
15 : End if
16 : End for

In the process of determination of spectral resources by our ASBR algorithm, for each optimal physical path found, we determine the resource blocks of each link. When blocks of resources are available in the network, we create intersection blocks between the blocks of each set. Then we determine the eligible resource blocks for a given connection request, from source s to destination d. Then we calculate the AC allocation cost according to Eq. 1 and the smallest block of eligible slots with a minimum allocation cost is extracted to serve the connection.

Algorithm for resource block selection (ASBR)
Input: Optimal physical path
Output: Spectral resource blocks to be used
1: Determine the blocks of resources for each link
2: If resource blocks found then
3: Create the blocks of intersections between the blocks of each set B_{li} using Eq. 5 to Eq. 10
4: Determine which blocks are eligible for connection c_{sd}
5: Calculate the cost of AC allocation for each block of eligible slots from Eq. 1.
6: Extract the smallest block of slots eligible for connection c_{sd} with the minimum allocation cost AC_{min}
7: End if

In the principle of selection of the best optical path by our ASMC algorithm in this approach, for each connection request that arrives on the network, we calculate the energy cost of each path in order to determine the optical path with a minimum energy cost. In the case where several paths have the same minimum energy cost, the optical path that has the minimum allocation cost is chosen in order to minimize fragmentation.

Algorithm for selection of the best optical path (ASMC)
Input: The connection request and the set of optical paths
Output: Optimal optical path for a connection request
1: Calculate the energy cost of each path using Eq. 4
2. Determine the light path with the minimum energy cost EC_{min}
3: If two lightpaths have the same minimum energy cost then
5: select the optical path that has a minimum allocation cost AC_{min}
6: End if

Dynamic routing and spectrum allocation algorithm for reducing fragmentation in multifiber elastic optical networks (RSA-RF)
Input: Graph G (V, E Rs, C)
Output: Physical paths and resources
1: For each connection request that comes into the network Do
2. Determine the k-shortest paths using the *ASCP algorithm*
3: For each shortest path found do
4: Determine the resources for the connection according to the *ASBR algorithm*
5: If Resource found then
6: Save the physical path and its resources
7: End if
8: End for
9: If optical path found then
10: Select the optimal path according to the *ASMC algorithm*
11: Save the optimal optical path
12: If two paths have the same allocation cost then
13: Choose the optimal path that has the minimum energy cost EC_{min}
14: Save optimal path (p(i,j), AC_{min}, EC_{min})
15: End if
16: If optimal paths found then
17: Select the best optimal path that has a minimum allocation cost AC_{min}
18: End if
19: End for

4. Performance evaluation

To demonstrate the efficiency and performance of the proposed algorithms, several experiments are implemented, and the experimental results are presented in this section. In section 4.1, the simulation parameters are presented. Analyses of the simulation results are presented in section 4.2.

4.1 Simulation parameters

Our simulations were performed on two network topologies to evaluate the performance of our approach, namely NSFNET and US-backbone. The NSFNET topology has 14 nodes and 22 bi-directional links while the US-backbone topology has 24 nodes and 43 bi-directional links shown in Figs. 3 and 4 respectively. Each link includes F the same number of fibers with F = 10. We estimate the capacity of a 4400 Gb/s fiber link. Each slot has a bandwidth of 12.5 GHz, which means that there are 352 slots per optical fiber.

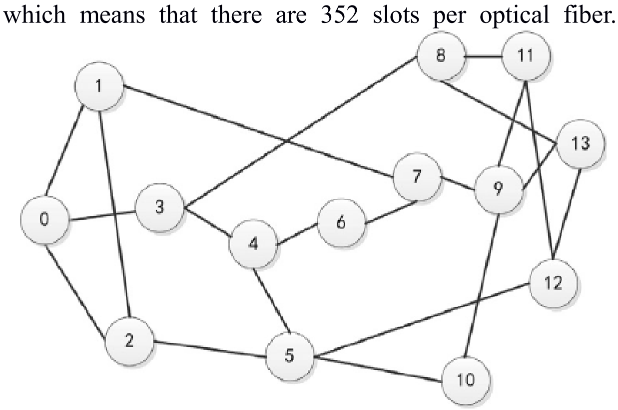


Fig. 3 NSFNET topology

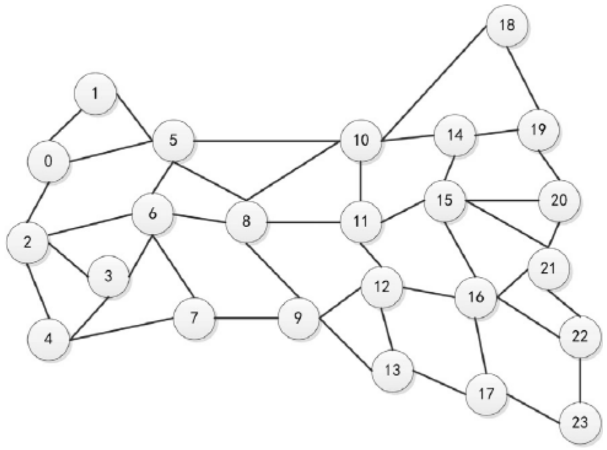


Fig. 4 US-backbone topology

Each source-destination node pair is selected randomly. Connection requests arrive as dynamic traffic in a sequential, random process in the network. The modulation formats and the energy consumed per slot as a function of optical reach used in our simulations are shown in Table 1.

4.2 Analysis of simulation results

We evaluate the performance of the proposed RSA-RF algorithm as a function of two network parameters, namely the blocking probability and the spectral resource utilization rate. It should be noted that for a better network performance, the blocking probability and the spectral resource utilization rate must be minimum. We compare our approach with the approach presented in [21].

Figs. 5 and 6 show the simulation results of the blocking probability of the RSA-RF and NSA algorithms in the NSFNET and US-backbone topologies respectively. In both figures, we observe that the curves follow the same trends. When we compare the results between the RSA-RF and NSA approaches, we notice that between 300 and 350 Erlangs, the blocking probability is approximately the same and that from 350 Erlangs onwards, the RSA-RF algorithm reaches a significantly lower blocking probability than the NSA algorithm in both topologies. This performance shows that the RSA-RF algorithm reduces the fragmentation of the spectrum caused by the increasing establishment and removal of connection requests at heterogeneous data rates. This is due to the fact that for the selection of the best optical path for each connection request, the RSA-RF algorithm takes into account the lowest possible allocation cost in determining the blocks of spectrum resources eligible to serve the connection. However, we can see that the probability of blocking in the US-backbone topology is better than that of the NSFNET topology. This is because the US-backbone topology offers more possibilities for establishing connection requests from a source to a destination in both approaches.

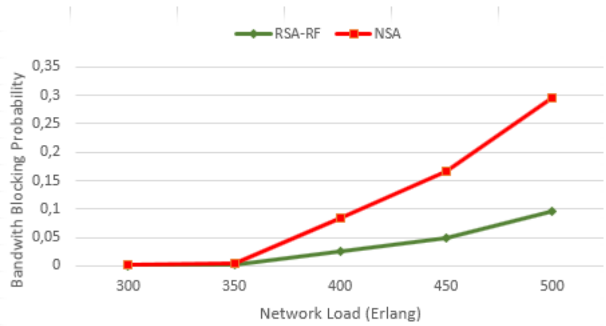


Fig. 5 Blocking Probability (NSFNET)

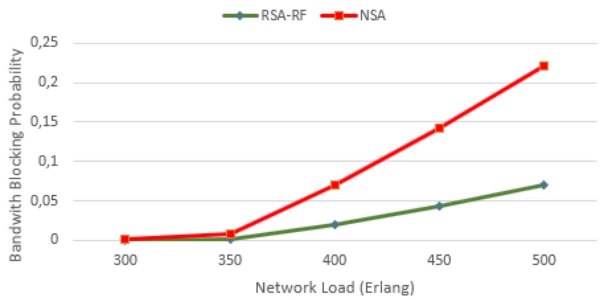


Fig. 6 Blocking Probability (US-backbone)

Fig. 7 Spectrum Utilization (NSFNET)

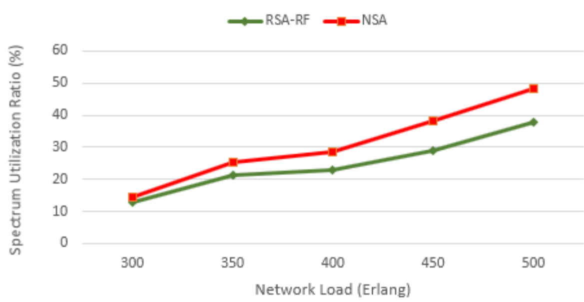


Fig. 8 Spectrum Utilization (US-backbone)

Figs. 7 and 8 show the performance in terms of spectrum utilization ratio as a function of network load in the NSFNET and Us-backbone topologies respectively.

We note that in both topologies, the FS-RSA approach has better performance in terms of spectrum resource utilization for all network loads. This shows that the NSA algorithm has a low impact on the dynamic allocation of spectrum resources for connection requests with heterogeneous data rates. Since the NSA algorithm calculates the set of paths and the probability of path selection in offline mode. This demonstrates the performance of both routing and dynamic allocation of our algorithm.

5. Conclusion

In this paper, in order to reduce fragmentation in multifiber elastic optical networks, we proposed heuristic algorithms for energy-saving routing and spectral resource allocation in a dynamic traffic context in multifiber elastic optical networks. Four algorithms and a new parameter AC allocation cost were implemented, namely the ASCP physical path selection algorithm, the ASMC best optical path selection algorithm and the ASBR resource block selection algorithm for dynamic traffic demands in elastic optical networks with multiple fibers per link. Our approach thus brings more flexibility and robustness to the management and allocation of optical network infrastructure resources. The proposed algorithms are evaluated by simulating NSFNET and US-Backbone topologies for random and sequential dynamic traffic. Simulation results show that our RSA-RF approach achieves better performance than existing algorithms in the literature in terms of blocking probability and network resource utilization ratio.

In recent years, the development of software-defined networks and their integration process in optical networks has led to a new generation of networks, the software-defined elastic optical networks (SDON). The most relevant feature in software-defined elastic optical networks are SDN-based controllers and the development of routing algorithms for optical spectrum allocation. The objective of this other line of research would be to optimize bandwidth management by increasing network capacity while reducing the complexity of network elements and improving network reconfiguration with SDON in a multifiber context.

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Boris Stephane Zouneme received his master's degree in Computer Science from the Faculty of Applied Basic Sciences of the Computer Engineering Department of Nangui Abrogoua Univ. (Côte d'Ivoire) in 2016. He is currently a PhD student at the Mixed Unit of Research and Innovation in Electronics and Applied Electricity at the Polytechnic Doctoral School of the INP-HB in Yamoussoukro (Ivory Coast). He is interested in elastic optical networks and machine learning. He is a member of the research team Innovation in Networks of the Future (IReF) of the Computer and Telecommunication Research Laboratory (LARIT), ISOC and OPENLAB.

Joël Christian Adepo received his PhD in Computer Science at Nangui Abrogoua Univ. (Côte d'Ivoire) in 2016. Currently, he is an assistant professor in Computer Science at Virtual Univ. (Côte d'Ivoire). His research interests include routing reconfiguration. He is also member of the Computer and Telecommunication Research Laboratory (LARIT) and the responsible of IReF.

Herve Gokou Diedie received his PhD in Computer Science at Nangui Abrogoua Univ. (Côte d'Ivoire) in 2018. Currently, he is working an assistant professor in the Dept. of Agricultural and Pastoral Management Institute from Peleforo-Gon-Coulibaly Univ. (Côte d'Ivoire). His research interest includes sensor networks. He is a member of Computer and Telecommunication Research Laboratory (LARIT) and IReF.

Souleymane Oumtanaga received his PhD from the Paul Sabatier Univ. (France) in 1994. He is a Full Professor of Universities and a lecturer-researcher at the National Polytechnic Institute Felix Houphouet-Boigny (INP-HB) in Yamoussoukro (Ivory Coast). He is the founder of the Computer and Telecommunication Research Laboratory (LARIT) and the Laboratory of Information and Communication Technologies (LABTIC) of the INP-HB. He is also the founder of the .ci registry and one of the pioneers of the Internet in Côte d'Ivoire. He is a member of IReF, AFNIC, ICANN, AFRINIC, NIC-CI, ISOC and OPENLAB.