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RESEARCH ARTICLE

Optimization of Inter-Domain Routing and Resource Allocation in Elastic Multi-Domain Optical Networks

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Abstract – At the national level, Telecommunications systems are generally organized into several interconnected autonomous domains. When transmitting data between interconnected domains, the blocking probability of network can be high due to the complexity of management and management policies at the domain level. Therefore, the question it raises is how to optimize inter-domain routing between different autonomous systems? The optimization of the inter-domain routing can be realized from several criteria related to the interconnection links, namely: the fragmentation rate, the energy consumed, the link quality, the transmission delay, the blocking probability, and the service quality. In this work, we propose an interdomain routing algorithm for multi-domain elastic optical networks, and a model for managing fragmentation in the network to optimize resources utilization. The implementation of inter-domain routing requires the construction of sub-topologies from existing domain topologies and parameters such as fragmentation rate, link quality, energy consumption contrary to blocking probability which used in literature. These different contributions (CA-IL, CIL-TFM and CIL-CEM) based on parameters have allowed to optimize the use of the network resources, to reduce the consumed energy as well as the blocking probability of the network compared to existing model in the literature through the simulations that have been conducted. However, the CIL-TFM approach provides a better blocking probability than other approaches with less resources used, and more energy consumed. In the future, we intend to integrate an end-to-end delay management model to achieve optimal inter-domain routing with the parameters already used.

Index Terms – Multidomain, Elastic Optical Network, Inter-Domain Routing, Fragmentation, Energy Consumption, Sub-Topology, Inter-Link.

1. INTRODUCTION

Elastic optical networks, unlike WDM optical networks, are a promising solution for heterogeneous bandwidth connections thanks to the flexibility in managing optical resources and their high transmission capacities. Elastic optical networks support adaptive allocation of optical spectrum when allocating spectral resources to connections while respecting constraints such as continuity and contiguity of optical spectrum. This flexibility allows for optimal management of the optical spectrum. The advent of SDN (Software Defined Networking) has enabled Software Defined elastic Optical Network (SDON) emergence with flexible control and spectrum management functions [1, 2].

Generally, several telecommunication operators coexist and represent independent networks entities (domains). Generally, each entity is responsible for managing its own network. On a national scale, telecommunication systems are organized in several interconnected autonomous domains. However, a telecom operator can also subdivide its network into this way of doing things several autonomous domains interconnected via a central manager. This same idea is implemented with multi-domain SDONs where one controller manages a single domain and all domain controllers are managed by a central domain controller that coordinates the activities of all controllers in each domain of the network to account for inter-domain services throughout the network [3, 4, 5, 6].

Presently, the internet is a set of networks or domains where a domain or network is managed by a single network operator. Sharing specifics information on different domains allows the best routing decisions to be made. The goal of such collaboration is to improve the efficiency of interdomain routing by reducing transmission delay and optimizing link utilization. This requires an architecture that facilitates collaboration between domain controllers where each controller is responsible for an administrative domain. This collaboration usually involves a central controller which has several advantages, namely [7]: (i) allow each domain to decide the optimal routing considering the characteristics of the domains involved in the routing process in order to increase the flows between domains that consider the security criteria, (ii) establish an equitable relationship between operators of the involved domains by managing the internal resources in an optimal way (iii) use the shared data to build a virtual topology used to compute flow paths during inter-domain routing, (iv) pre-configure the domains involved in the flow routing process based on the path before the flow reaches them.

With the evolution of technologies, including the Internet of Things (IoT) and 5G [8], many connected objects and end users are easily connecting to the Internet. Therefore, the scale of the network grows exponentially, and the demands of network services users are gradually diversifying and becoming more personalized [9]. For better network management, dense networks are divided into several domains. Efficient deployment of service functions knowing that domain-specific information is managed locally, without information exchange is one of the major problems in multidomain networks [10]. Managers and service providers of such networks have internal management strategies for each domain [11 ,12].

1.1. Problem Statement

In this paper, we focus on the routing and resource allocation problem in multi-domain elastic optical networks. Specifically, we are interested in the optimization of inter-domain routing when a flow must transit through several domains from a source to a destination. This requires finding an optimal path considering the management of network resources to reduce blocking probability of network.

1.2. Organization of Paper

This part of the paper presents an introduction to SDN-based multi-domain optical networks; the problem addressed. The rest of this paper is organized in 7 sections. Section 2 presents related work on the problem of routing and resource allocation in elastic multi-domain optical networks. Section 3 presents our model of the multi-domain system, and Section 4 discusses the proposed fragmentation metric to evaluate the network fragmentation rate. Section 5 presents our different inter-domain routing approaches; section 6 presents the simulation results and our discussion. Finally, section 7 is dedicated to the conclusion of our work.

2. RELATED WORK

Several works in the literature in the last five (5) years have focused on SDON. The authors in [13] proposed to extend the OpenFlow protocol to consider the characteristics of an elastic optical network to give birth to the OpenSlice protocol. The authors also proposed a resource allocation approach based on the OpenSlice protocol to solve the routing and resource allocation problem. In this second study [14], Given the scalability issues of OpenFlow's centralized architecture, and the fully dynamic and complex RSA routing, the authors implement a two-phase RSA algorithm at the controller level while considering Direct Detection OFDM (DDO-OFDM) as the optical transport technique. The authors of [15] propose a connection restoration procedure based on a restoration technique with a two-phase routing and resource allocation process, a path calculation phase, and a resource allocation phase. In this study, the OpenFlow protocol was updated to consider the breaking of an optical link and the dynamic restoration. In the study [16], the authors propose to reduce the protection overhead and improve the resource utilization rate through a shared data plane protection approach based on the use of the graph vertex coloring principle. They proposed a routing and resource allocation algorithm based on a multi-level network architecture. To consider inter-domain routing, a routing and resource allocation approach has been proposed in [17] considering QoS management, transmission quality and network energy consumption. In [18], the authors propose another approach to multi-domain routing and allocation by improving the approach proposed in [17]. An intelligent inter-domain routing algorithm, supported by a hierarchical control plane architecture, has been proposed by considering the notion of sub-topology to represent domains considering quality of service (QoS) and energy conservation. In this approach, intra-domain routing is managed by the domain controller and inter-domain routing is handled by the central controller who manages all the different domain controllers. To optimize inter-domain routing, the authors [19] proposed two methods: a routing resource optimization method based on the K shortest path algorithm and a spectral resource optimization method. In the context of spectral resource optimization, a spectrum defragmentation mechanism has been proposed considering the degree of fragmentation in software-defined elastic multi-domain optical networks through a hierarchical control architecture. The MEMETIC algorithm is proposed by [20] to resolve the problem of routing and resource allocation in multi-domain elastic optical network. The proposed approach based on a genetic algorithm whose objective is to minimize the used resources of the multi-domain network with minimal optical path computation time. To solve the routing problem in multi-domain WDM optical networks, a traffic scheduling strategy (TSSCF) based on traffic cost has been proposed [21] by the authors. The proposed inter-domain routing implements the K shortest path algorithm and takes the minimum number of domains as a parameter to select the best path. In [7], the authors propose an architecture that facilitates collaboration between multiple SDN domain controllers. This architecture addresses the lack of collaboration between network operators by proposing a new collaborative multi-domain routing framework capable of efficiently routing flows across multiple domains while considering performance criteria such as delay and, bandwidth. In this article, it is assumed that each controller shares its local data with a central element called a broker. And they believe that broker-based inter-domain routing allows for the benefits of collaboration without much security risk. In [22], the authors develop an approach to inter-domain routing between different autonomous systems managed by SDN domain controllers by improving the principle of routing with optimal throughput and delay between controllers unlike BGPv4 through the application of Artificial Intelligence. In [23], The authors believe that the use of a central controller is not applicable for latency-sensitive military applications because the central controller represents a point of failure for such applications. As a result, securing and dynamically managing traffic of different sensitivities and access policies, in an environment that includes legal applications at the SDN domain controllers becomes problematic. For the deployment of multi-domain services, the authors [24] propose an intelligent architecture based on software defined network (SDN) technologies and artificial intelligence.

When the source and destination nodes of a service belong to two different network domains, the data flow is directed to traverse several different network domains. The end-to-end delay of the network service can be prolonged, which seriously affects the user's quality of service.

When the source and destination nodes of a service belong to different domains, the flow passes through several different domains before reaching the destination. The flow transmission delay may be extended, which seriously affects the user's quality of service. As a result, managing the transmission delay of network services becomes problematic in the context of inter-domain routing. To ensure QoS, some attempts have been made to reduce the transmission delay by deploying services with multiple domains. Faced with a network-wide inter-domain service, the question arises as to how to coordinate multiple domains for efficient control and optimal allocation of routing spectrum resources? In most routing approaches in multi-domain elastic optical networks, all inter-links between the domains involved in the path computation process are considered. As a result, the load (computation time) of the central controller increases due to the density of information to be processed depending on the links of the topology. To reduce the computation time, the authors [18], propose to use sub-topologies with only one inter-link between the domains involved in the path computation. However, they choose the interlink with low blocking probability to build the sub-topologies. Assume that several interlinks have the same lowest blocking probability. How to choose an interlink? The fundamental question this choice raises is whether blocking probability is the ideal parameter for optimizing multi-domain routing? Another question that arises is what parameter would characterize the best inter-link between two domains? Table 1 presents a summary of inter-domain routing work in elastic optical networks through criteria such as: type of collaboration, inter-domain routing optimization parameters, and number of inter-links used between domains in the optical path calculation process.

Table 1 Summary of Inter-Domain Routing Work in Elastic Optical Networks

Ref	Type of collaboration	parameters	Interline used between domains
[7]	Hierarchical and controller to controller	Delay, bandwidth, path cost	All interlinks
[17]	Controller to controller	Energy, QoS	All interlinks
[18]	Hierarchical	Energy, QoS, blocking probability, sub-topology	One interlink
[19]	Hierarchical and controller to controller	Fragmentation rate	All interlinks
[20]	-	Computation time, fragmentation rate	All interlinks
[21]	-	Hop count, number of domains	All interlinks

3. MULTI-DOMAIN SYSTEM MODEL

We consider a multi-domain network is represented by an undirected graph G composed of several (n) sub-graphs (domains) defined as follows:

$$G=\left(D_i, L_{D_i \times D_j}, fs, cr\right): 1<i, j \leq n;\ n \in \mathbb{N} \ \ and \ \ n>1 \qquad (1)$$

where D_i represents domain number i and $L_{D_i \times D_j}$ represents the optical link(s) between the domains $D_i \ and \ D_j$ with $fs=\left\{fs_1, \ldots, fs_p : p \in \mathbb{N}^*\right\}$ the set of frequency slots of an optical link and $cr=\left\{cr_1, \ldots, cr_k : k \in \mathbb{N}^*\right\}$, the set of connection requests. $cr_k=\left(s_k, d_k, t_k\right)$ where s_k is the source node, d_k is the destination node and t_k is the time of connection *k*.

A network domain can be represented by an undirected graph G_{D_i} composed of several (m) nodes and many links (l), defined by equation (2):

$$G_{D_i}=\left(Ni_{D_i}, Nb_{D_i}, L_{D_i}\right): 1<i \leq n \in \mathbb{N} \qquad (2)$$

where Ni_{D_i} represents the set of interior nodes and Nb_{D_i} denotes the set of edge nodes with L_{D_i} the set of optical links of the domain D_i. We have

$$L_{D_i}=\left\{\left(u_{D_i}, v_{D_i}\right): u_{D_i}, v_{D_i} \in Ni_{D_i} \cup Nb_{D_i}\right\} \qquad (3)$$

4. FRAGMENTATION METRICS

4.1. Existing Metrics

Frequency slot fragmentation caused by dynamic connection establishment and termination is a major problem in the routing and resource allocation process in elastic optical networks. Fragmentation can be reduced by appropriate spectrum management when allocating resources for connection requests. For this purpose, the authors of [25] present three methods of measuring spectrum fragmentation, namely the external fragmentation parameter, the entropy-based parameter, and the blocking probability-based parameter. According to the authors [26], spectrum fragmentation is more important when connections require more spectral resources, therefore the fragmentation rate is a function of the required slots number to meet the request. Similarly, to solve the fragmentation problem during dynamic routing and resource allocation in elastic optical networks, [27] propose a function that calculates the cost of fragmentation considering the amount free slots and is as follows.

$$FM=\sum_{i=1}^{n+1} e^{\left(\frac{1}{s_i}\right)} \qquad (4)$$

where s_i is the number of free slots in block *i*.

4.2. Proposed Fragmentation Metric

For the selection of the link/path that reduces the network fragmentation rate among several, we compute the forward fragmentation rate (TF) and the link/path quality (QL) after establishing a connection requiring c frequency slots. The fragmentation rate is a function of the number of frequency slots required for a connection request as specified by [26]. As a result, we propose to improve the model in [27] by incorporating the required slots (c) number for a connection request. We define the fragmentation rate before the resource c is allocated as follows:

$$TF=\sum_{i=1}^{n} e^{\left(-\frac{sb_i}{c}\right)} \qquad (5)$$

where sb_i is the amount free slots in block *i* before the allocation of c slots.

When a connection must traverse a domain before reaching its destination, it passes through inter-domain links. The question that arises is how to choose the most suitable inter-link among several? The least fragmented link/path is not necessarily the ideal link/path. Therefore, we assume that the resources (c) are allocated, and we estimate the quality of the link to choose through the definition of the quality of interlink/path through the following equation (6):

$$QL=\frac{La(c)}{Lb(c)} \times \sum_{i=1}^{n} e^{\left(-\frac{1}{sa_i}\right)} \qquad (6)$$

where (*Lb(c)*), (*La(c)*) is respectively the number of resource slot blocks available on the link/path before, after the c slot connection is established. sa_i is the number of free frequency slots in block *i* after c is allocated.

Among several links/paths that satisfy the demand for a connection with an acceptable fragmentation rate, the ideal link/path is the one with the lowest QL. We exploit our different proposals of fragmentation models on the examples given in [25] and [27], which gives us the following results:

4.2.1. Fragmentation Rate and Link Quality for Resource Allocation c=2 Slots: Case 1

In figure 1 below $b_i=k$ means that the free slot block number *i* contains *k* free slots. On a link, the slots are numbered from 1 to 10.

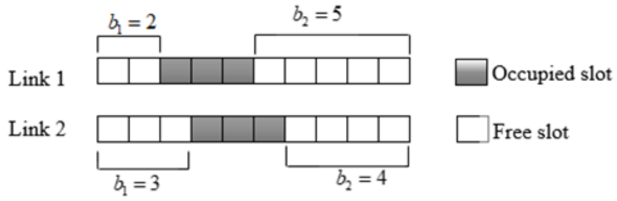

Figure 1 Free and Occupied Slots of Two Links

Table 2 Fragmentation Rate and Link Quality of 2 Links

Link	Fragmentation rate of link		Link quality
	FM : Bijoy et al en 2017 [27]	TF	QL
Link 1	$e^{-\frac{1}{2}}+e^{-\frac{1}{5}}=0,7$	$e^{-1}+e^{-\frac{5}{2}}=0,44$	$\frac{1}{2}e^{-\frac{1}{5}}=0,81$
Link 2	$e^{-\frac{1}{3}}+e^{-\frac{1}{4}}=0,58$	$e^{-\frac{3}{2}}+e^{-\frac{2}{1}}=0,35$	$\frac{2}{2}\left(e^{-1}+e^{-\frac{1}{4}}\right)=1,14$

Based on these results of Table 2, link 2 has the lowest fragmentation rate (TF) and is therefore the candidate link to allocate the connection request. However, with QL, the best link, the one with the lowest fragmentation rate is link 1. Indeed, on link 1, the number of isolated blocks decreases after the connection is established, whereas on link 2 this is not the case. As a result, we can say that the QL equation allows a better quantification of the fragmentation rate contrary to the model proposed by [27].

4.2.2. Fragmentation Rate and Link Quality for Resource Allocation c=2 Slots: Case 2

In figure 2 below means that the free slot block number i contains k free slots. On a link, the slots are numbered from 1 to 12.

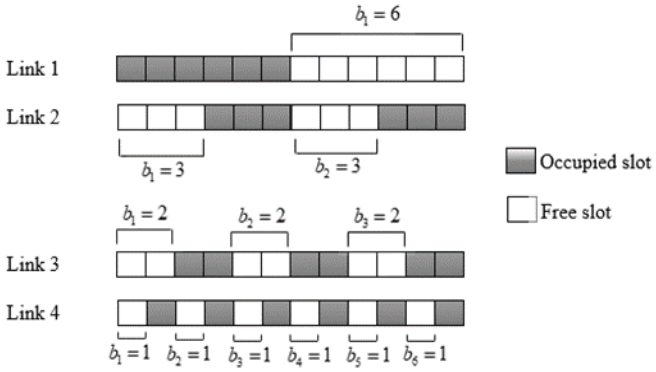

Figure 2 Free and Occupied Slots of Four Links

Table 3 Fragmentation Rate and Link Quality of 4 Links

Link	Fragmentation rate of link		Quality of link
	FM : Krishan et al en 2018	TF	QL
Link 1	$e^{-\frac{1}{6}}=0,8465$	$e^{-\frac{3}{1}}=0,04$	$\frac{1}{1}e^{-\frac{1}{4}}=0,7788$
Link 2	$2e^{-\frac{1}{3}}=1,4331$	$2e^{-\frac{3}{2}}=0,44$	$\frac{2}{2}\left(e^{-1}+e^{-\frac{1}{3}}\right)=1,0844$
Link 3	$3e^{-\frac{1}{2}}=1,8196$	$3e^{-1}=1,10$	$\frac{2}{3}\left(e^{-\frac{1}{2}}+e^{-\frac{1}{2}}\right)=0,8087$
Link 4	$6e^{-1}=2,2073$	$6e^{-\frac{1}{2}}=3,63$	$\frac{6}{6}\left(6e^{-1}\right)=2,2072$

The results in Table 3 of the different calculations on each link show us that link 1 is the link with the lowest fragmentation rate (TF), is therefore the candidate link to allocate the connection request. Applying the link quality metric shows us that link 1 is the best quality link. However, using Link 2 would reduce the number of isolated slots blocks in the network.

To choose an interlink between two different domains, we calculate the fragmentation rate of each interlink. Then, the interlinks are arranged in the increasing order of their fragmentation rate. The interlink that satisfy the connection request requirements is chosen. Among these links, we find the best quality link.

The question is whether the lowest quality link is exactly the best link. Not exactly because beyond the value of the link quality in terms of fragmentation, you must see the impact on the number of slots blocks available in the network. This leads us to improve equation (6) by integrating a parameter α, which tends to 0 when the number of slot blocks decreases after establishing a connection on a link, to this equation (7) as follows:

$$QL=\alpha\times\frac{La(c)}{Lb(c)}\times\sum_{i=1}^{n}e^{\left(-\frac{1}{sa_i}\right)} \tag{7}$$

$$\begin{cases}\alpha=1 & if\ La=Lb\\ \alpha\in\left]0,1\right[& if\ La<Lb\end{cases} \tag{8}$$

5. ALGORITHMS FOR CHOOSING INTER-LINKS BETWEEN TWO DOMAINS TO BUILD SUB-TOPOLOGIES

From this work, we consider the basic NSFnet topology used in [8] that we adopt for our simulation is organized into several domains (Figure 3).

In Figure 4 [18], we have three domains. These three domains are used to create the sub-topologies of the global topology.

In Figure 4 the sub-topologies of the global topology are the domain12, domain13 and domain23 topologies. These sub-topologies are built from the topologies of domain 1, domain 2 and domain 3. In our proposal, we propose different approaches to select the inter-links to build the sub-topologies (inter-domain topology) on which we will perform the routing. It is assumed that the parameter for selecting the inter-links between two distinct domains (e.g., domain 1 and domain 2) for building the inter-domain topology from the sub-topologies is that of the link blocking probability as in [18]. However, when there are several inter-links with the same blocking probability, several possibilities emerge, namely choosing an inter-link at random or choosing an inter-link that has the best quality in terms of reducing the network fragmentation rate.

From the base topology, the domains are created, and the inter-links are already defined from the links of the base topology. However, in the creation of the sub-topology, according to the routing approach, the inter-links are selected randomly with algorithm 1 (CA-IL), considering the fragmentation rate with CIL-TFM, considering the energy with algorithm 2 (CIL-CEM).

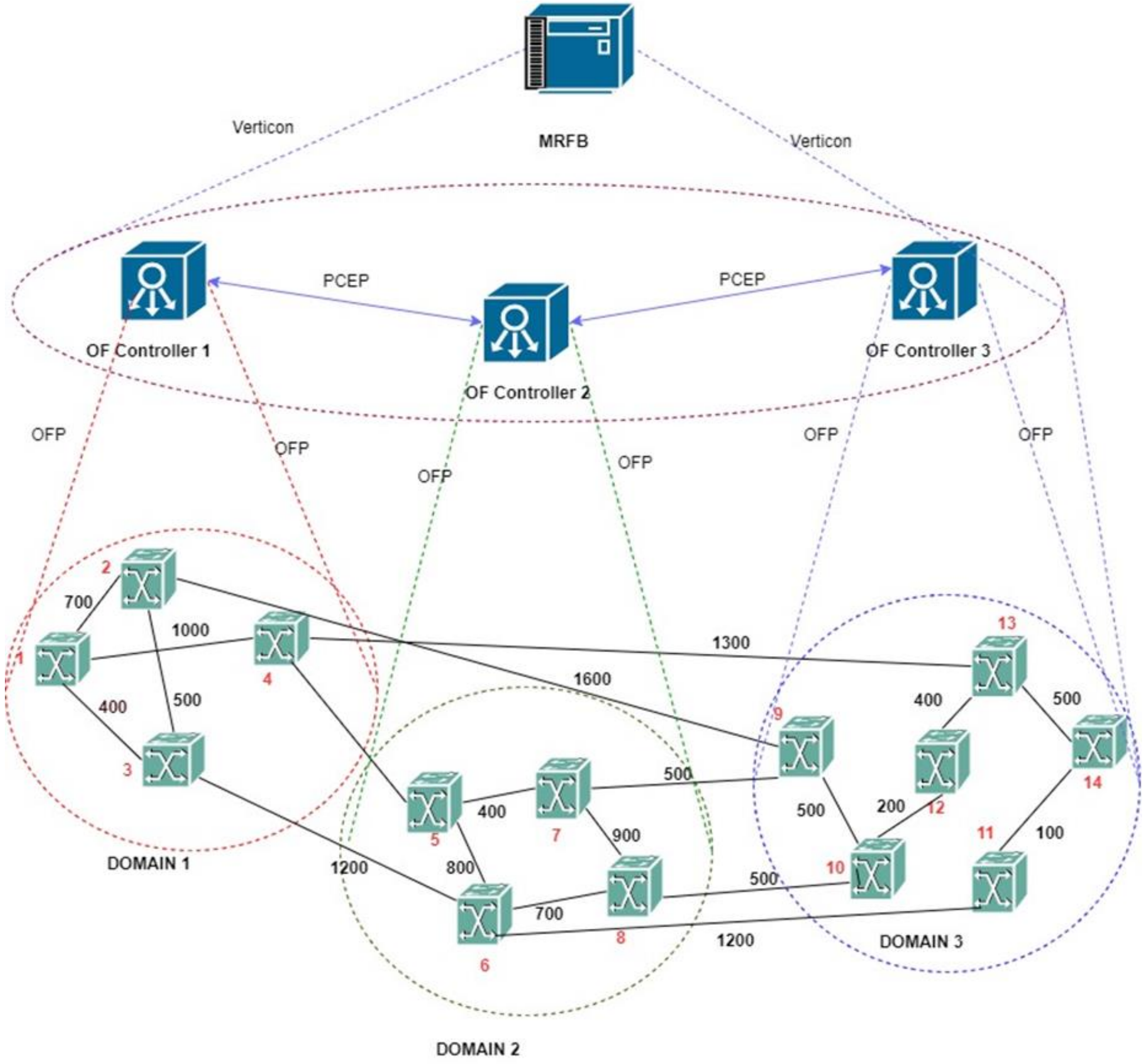

Figure 3 NSFnet Topology of 3 Domains

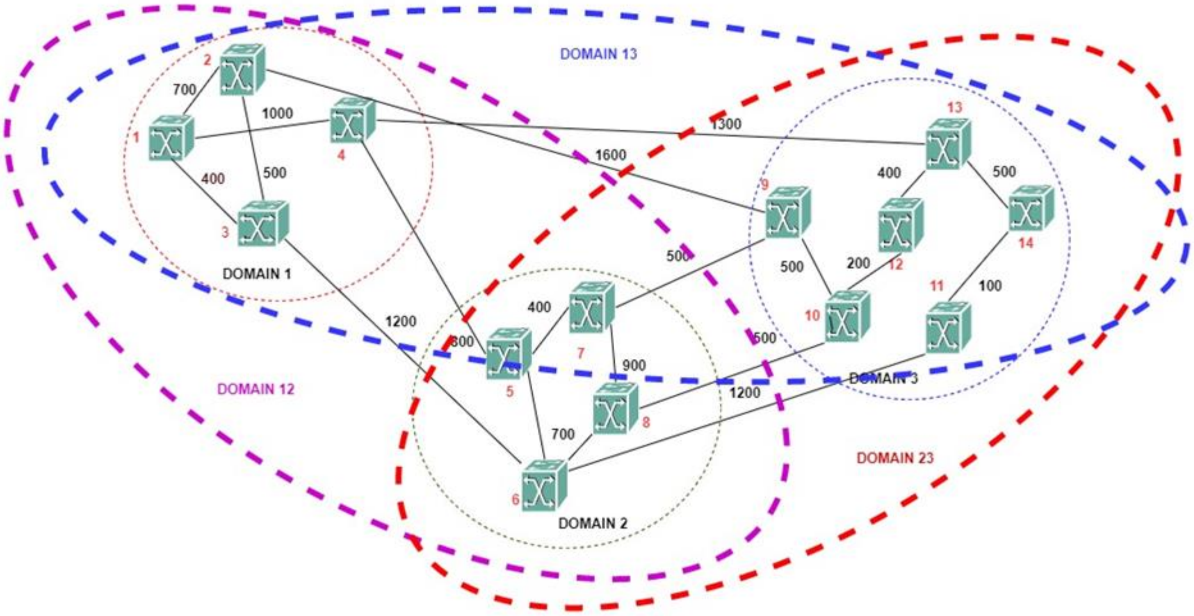

Figure 4 Sub-Topology of 3 Domains

Here we assume that all the links have the same blocking probability. The choice of the link is then made at random.

```
Input: List of interlinks
Output: Interlink
Begin
    Choose a link randomly
    Save the selected interlink
End
```

Algorithm 1 Random Selection of Links (CA-IL)

5.2. Algorithm of the Best Inter-Link Selection

```
Input: List of interlinks
Output: best fragmentation rate link
Begin
For each interlink
    Calculate the fragmentation rate with (5)
    Save fragmentation rate
End
    Select the link with the minimum fragmentation rate
End
```

Algorithm 2 Cross-Link Selection based on Fragmentation Rate (CIL-TFM)

For each element of the interlink list, we compute the fragmentation rate using equation (5). The interlink with the lowest fragmentation rate is selected.

The link with the lowest fragmentation rate may not be the one with the best quality in terms of reducing the network fragmentation rate. As a result, we define algorithm 3 to determine the best quality inter-link.

```
Input: List of interlinks
Output: best quality link
Begin
For each interlink
    Calculate the quality of the inter-link with (7)
    Select the link with the smallest value
End
End
```

Algorithm 3 Selection of a Link based on the Quality of the Link

5.3. Algorithm of the Inter-Link that Consumes Less Energy

Components such as nodes and controllers consume a lot of energy during their activities in elastic optical networks. In view of this observation, [28] propose a model for calculating energy consumed in the network considering the energy consumed by a transponder, an optical switch, and optical amplifier from [29, 30]. In the following, we define the equation for the energy consumed by the different components.

5.3.1. Energy Consumed by a Transponder

Energy consumed by a transponder for a connection is calculated according to an equation (9):

$$P_{trans}(c_r) = \left(N_{FS}(c_r) - N_{GB}\right) \times P_{subc} \qquad (9)$$

Where N_{FS} is the number of contiguous slots required for a connection c_r and N_{GB} is the guard band. N_{FS} is defined by equation (10):

$$N_{FS}(c_r) = \left\lceil \frac{B(c_r)}{M(c_r) \times w_{slot}} \right\rceil + N_{GB} \qquad (10)$$

Where $B(c_r)$ is the connection rate, $M(c_r)$ is the modulation format corresponding to the connection, and w_{slot} is the capacity of a frequency slot (12,5 GHz or 6,25 GHz). Energy consumed by a CO-OFDM transponder during subcarrier transmission is defined according to Table 4 below.

Table 4 Energy Consumed by a CO-OFDM Transponder with Modulation Format [30]

Modulation format	Size of one slot (GHz)	Energy consumed by a transponder (W)
BP-SK	12,5	112,374
QP-SK	25	133,416
8-QAM	37,5	154,457
16-QAM	50	175,498
32-QAM	62,5	196,539
64-QAM	75	217,581

5.3.2. Energy Consumed by an Optical Switch

Energy consumed by a variable bandwidth optical switch depends on the number of optical links adjacent to the switch and the selective add/drop switches embedded in it. It is defined by the following equation (11):

$$P_{oxc} = 85 \times N + 100 \times \mu + 150 \qquad (11)$$

Where, N is the degree of the node. μ is the number of selective add and remove switches for the node.

5.3.3. Energy Consumed by an Optical Amplifier

On each optical link, an optical amplifier is placed at a regular distance (d_{Amp}) of 80 or 100 km. The number of optical amplifiers required on an optical link depends of the link length (L_{Fiber}), the power consumed by an amplifier (PC_{In-Amp}), the pre-amplification power $(PC_{pre-Amp})$ and post-amplification power $(PC_{post-Amp})$. The energy consumed by an optical amplifier is given by the equation (12):

$$P_{edfa} = \left\lfloor \frac{L_{Fiber}}{d_{Amp}} \right\rfloor \times PC_{In-Amp} + PC_{pre-Amp} + PC_{post-Amp} \qquad (12)$$

According to [31], at the arrival of any connection request, the duration of its hold on the optical link is known. As a result, it is possible to know the lifetime of a lightpath, which is a function of the longest duration of all connection requests. We deduce that the longer the maximum time connection demand lasts, the more energy the optical link consumes. We then propose the model (13) for calculating energy consumption over an optical link as follows:

$$P_{link} = (P_{trans} + P_{oxc} + P_{edfa}) \times T \qquad (13)$$

Where T is the maximum holding time of a connection on the optical link.

However, the energy consumed by a link depends not only on the maximum duration of a connection on the link but also on the number of connections that use the link. Considering the proposed model for calculating the energy consumed by an optical path from [29] and [32], the weight of an optical link is a key factor in routing and allocation problems. The routing and resource allocation decision on the optical link is based on the link weight. Indeed, when a connection request arrives, the appropriate link weight is based on the resource state of the link. The optical link weight factor α at a time t can be obtained by the ratio of the amount slots (n) available at that instant to the total number of slots N (available or not) along the entire optical link as defined by the following equation (14):

$$\alpha^{(t)} = \frac{n^{(t)}}{N} \qquad (14)$$

One should note that along the active optical link, there can be several connections. The duration of the use of the link can be determined by the following equation (15):

$$T = Max\{t_i : 1 \le i \le k\} \qquad (15)$$

Where *k* is the total number of connections on the link and t_i is the remaining time of a connection *i* on the link. From the previous equations, we propose the following model (16) for the calculation of the energy consumption on an optical link at any time:

$$P_l^{(t)} = \left(P_{trans} + P_{oxc} + P_{edfa}\right) \times Cost_l^{(t)} \tag{16}$$

Where the cost of the link is defined by $Cost_l^{(t)} = \alpha^{(t)} \times \left(1 - \frac{\Delta t^{(t)}}{T}\right)$ and t is any time different from the time at which the connection was established, noted t' and $\Delta t^{(t)} = t - t' \; where \; t > t'$ is the connection runtime and *T* is the maximum connection time on link l.

For example, we assume that a link (1,2) has 6 frequency slots. a connection cr1(1,2,2) is established on the link and uses 4 frequency slots. the cost of the link at time t=t'=0, T=2, is Cost=4/6(1-1/2)=0.33. At time t=1, a connection cr2(1,2,3) is also established on the link with 2 frequency slots. the link cost at this time with t=1, t'=0, T=max{3, 2}=3, is cost=6/6(1-1/3)=0.66. At another time t=2, the connection cr1(1,2,2) is terminated so the link resources are released. the link cost at this time with t=2, t'=1, T≈2<3, is cost =2/6(1-1/2)=0.16. At another time t=3, a cr3(1,2,2) connection is also established on the link with 2 frequency slots. the link cost at this time with t=3, t'=2, T=max{2, 2}=2, is cost =4/6(1-1/2)=0.33. These different values of the link cost applied to the energy consumed by the link, allow to find the value of the energy consumed by a link at each time. For a given path *p*, the power consumed will be defined by the equation (17):

$$P^{(t)}(p) = \sum_{l \in p} P_l^{(t)} \tag{17}$$

The algorithm that determines the inter-link that consumes less energy is defined by algorithm 4 as follows:

```
Input: List of interlinks
Output: minimum energy link
Begin
For each interlink
    Calculate power consumption with (16)
    Select the link with the lowest power consumption
End
End
```

Algorithm 4 Selection of the Link that Minimizes Energy Consumption (CIL-CEM)

5.3.4. Algorithm of the Sub-Topology Construction based on Two Domains

Algorithm 5 below, allows us to determine sub topologies from the topologies of different domains of the global topology. The algorithm for constructing the inter-domain sub-topologies is defined as follows:

```
Input: topology G, Domain 1, Domain 2, Domain 3, source, destination
Output: inter-domain topology
Begin
    $if (source \in Domain1) and (destination \in Domain2) then$
        Determine the inter-link between Domain1 and Domain2 from the algorithm 1, 2, 3 or 4
        Delete in G all the links different from the links of the domains Domain1, Domain2 and the selected interlink to give the topology Domain12
    Else
        $if (source \in Domain1) and (destination \in Domain3) then$
            Determine the inter-link between Domain1 and Domain3 from the algorithm 1, 2, 3 or 4
            Delete in G all the links different from the links of the domains Domain1, Domain3 and the selected interlink to give the topology Domain13
        Else
            $if (source \in Domain2) et (destination \in Domain3) then$
                Determine the inter-link between Domain2 and Domain3 from the algorithm 1, 2, 3 or 4
                Delete in G all the links different from the links of the domains Domain2, Domain3 and the selected interlink to give the topology Domain23
            End
        End
    End
End
```

Algorithm 5 Construction of Sub-Topology based on Two Domains

5.4. Multi-Domain Routing and Resource Allocation Algorithm

The proposed algorithm in Figure 5 is based on the one in

[18]. In the routing and resource allocation process, it is assumed that requests may require different service requests. As a result, the service requests are grouped into two classes according to the request characteristics. When the request arrives in the network, if it is one that requires inter-domain routing, the request is classified according to these characteristics in terms of transmission quality. Then, in the process of updating the inter-domain topology, the ideal inter-link is determined according to the criteria defined by algorithms 1, 2, 3 and 4. When the inter-link is determined, we use Algorithm 5 for the implementation of the inter-domain topology specific to the chosen inter-link. Based on this new topology, the k shortest path algorithm based on Dijkstra's algorithm is used to determine the possible paths. In the case where routing is done at the local domain level, the k plus path algorithm is executed from the local topology.

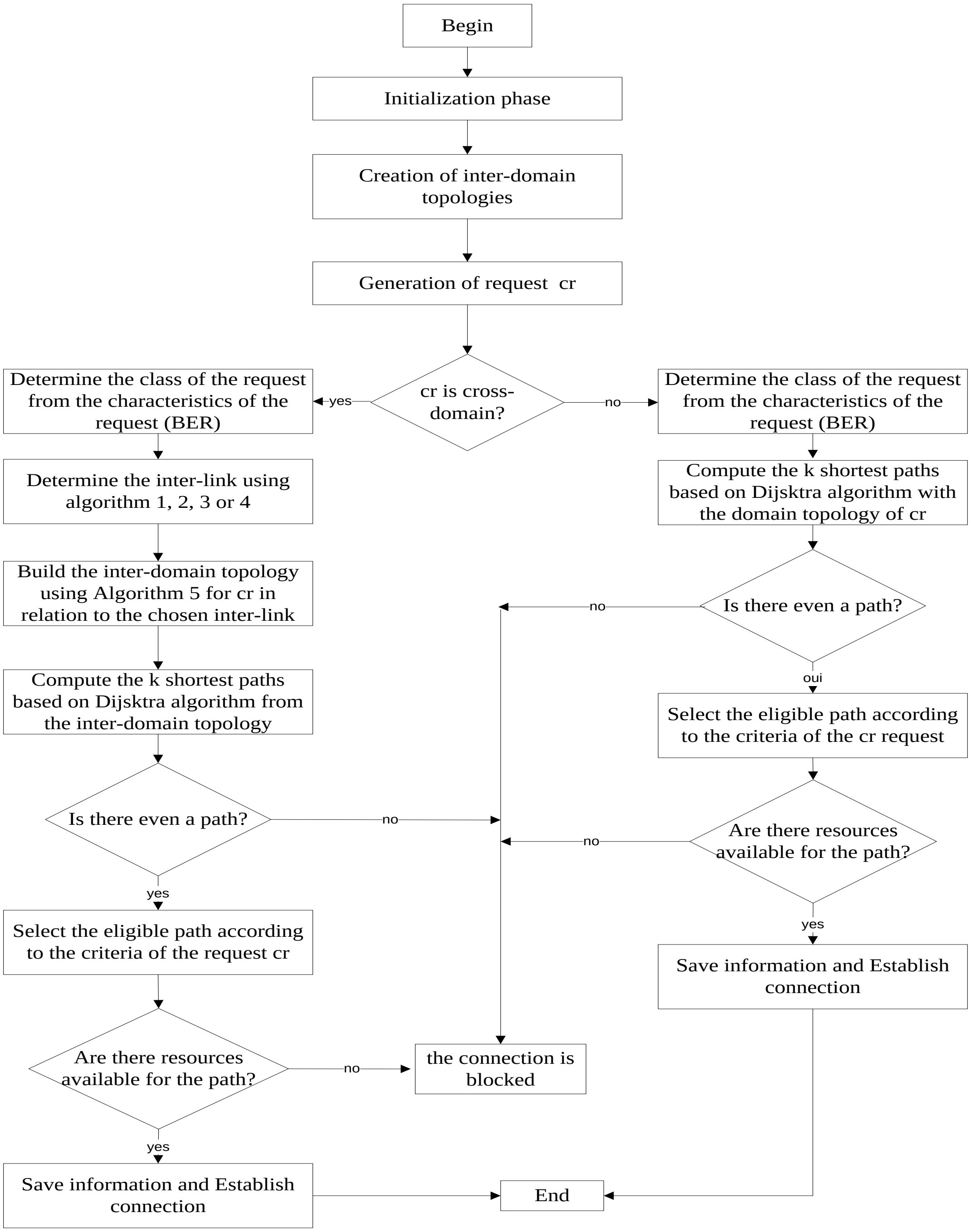

Figure 5 Proposed Multi-Domain Routing Flowchart

6. SIMULATION AND DISCUSSION

In this section, we make a simulation of our contribution. The simulation environment consists of a corei7 PC with 16GB of RAM and the Java programming language. The connections are randomly generated and processed sequentially. We assumed that an optical link contains 100 slots, and each slot bandwidth is 12.5, and the connection rates are randomly generated between 40 and 100 Gb/s. The topology used for the simulations is the one shown in Figure 4. The simulation parameters are summarized in Table 5.

Table 5 Simulation Parameters

Parameters	Values
Domaine ID	{1 ,2,3}
Number of slots per optical link	100
Bandwidth of frequency slot	12.5 GHz
connection rates	40 - 100 Gb/s
Number of simulations	1500
Topology	NSFnet
Number of nodes	14
Number of links	25
amplification distance	80

The different results obtained with CA-IL, CIL-TFM and CIL-CEM have been compared to MD-STG-RSA approach of zaho et al. as our different approaches have been based on this contribution. Figure 6 below shows the performance of the different approaches. As the number of connections increases, the results obtained with CA-IL, CIL-TFM and CIL-CEM show better performance compared to the approach of [18].

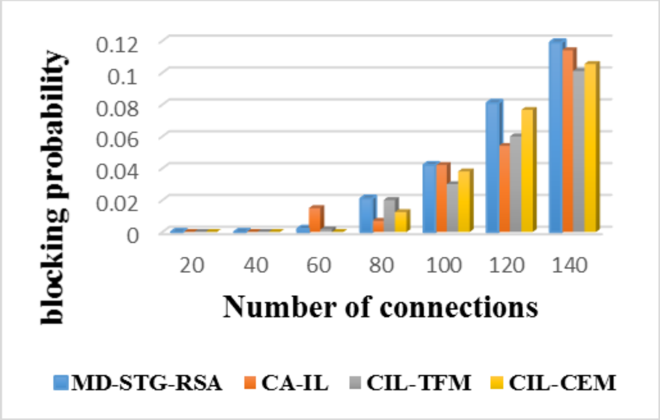

Figure 6 Blocking Probability

Figure 7 below shows that the results obtained with CA-IL, CIL-TFM and CIL-CEM consume more energy contrary to the approach of MD-STG-RSA. Indeed, the approaches we proposed have the lowest blocking probabilities. As a result, they favor the establishment of more connections that consume more energy.

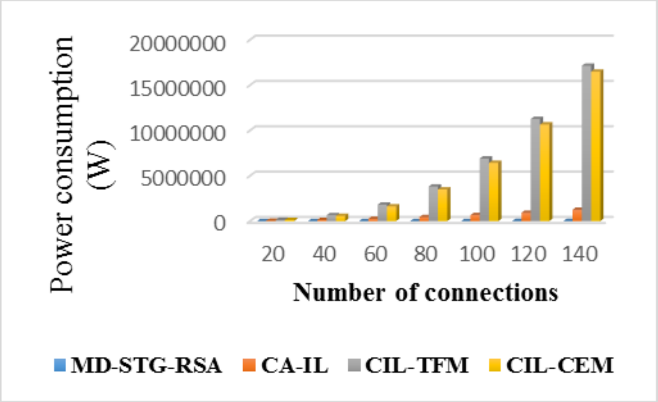

Figure 7 Power Consumption

The results in Figure 8 show that CA-IL, CIL-TFM and CIL-CEM consume less resources than that of MD-STG-RSA. This is because the resources used to establish a connection is an appropriate number that considers the connection characteristics.

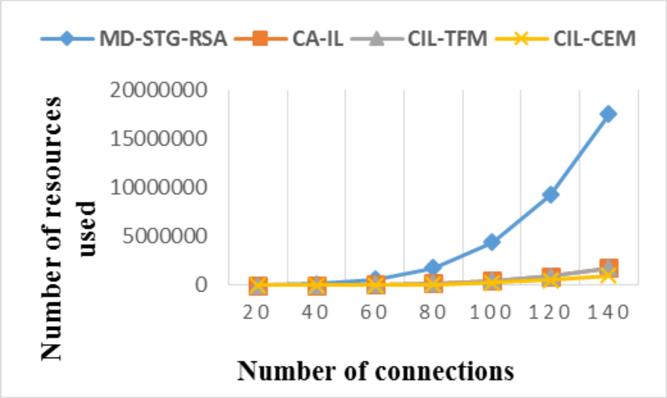

Figure 8 Number of Resources Used

In the CA-IL routing approach, the choices of inter-links are made randomly. This does not guarantee that the ideal inter-link is chosen for the construction of the sub-topology in terms of spectral resource optimization. With the CIL-TFM approach, the optimization of the spectral resources management is considered thanks to the fragmentation model that is proposed. Indeed, this approach allows to reduce the slots blocks of the link during the resource's allocation to a path since in the choice of the optical paths, the links that do not provide additional blocks of slots and/or that reduce the number of existing slots blocks are chosen to establish a connection. This explains the fact that CIL-TFM provides a lower blocking probability compared to other approaches that do not implement the fragmentation model such as that of J. Zaho et al. This is one of the reasons why this approach consumes more energy and uses more spectral resources compared to other proposed approaches (CA-IL, CIL-CEM).

7. CONCLUSION

In this work, we proposed a new multi-domain routing approach to optimize routing in multi-domain elastic optical networks. We have defined a new model to better characterize the fragmentation rate in the network. Then, we proposed different routing approaches to optimize multi-domain routing by defining an algorithm to build sub-topologies from existing domain topologies. The first approach (CA-IL) is applied to a sub-topology obtained from a randomly chosen inter-link. The second approach (CIL-TFM) considers a sub-topology obtained from the inter-link with the lowest fragmentation rate. In the third approach (CIL-CEM), we implement a sub-topology obtained from the inter-link that consumes less energy. However, the CIL-TFM approach provides a better blocking probability than other approaches with less resources used, and more energy consumed. Simulation results show that our proposal optimizes multi-domain routing. In the future, we intend to integrate an end-to-end delay management model to achieve a complete optimization of inter-domain routing in addition to the parameters already used.

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