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Techniques and Benefits of Energy-Aware Load-Distribution in Multi-domain Translucent Wavelength Switched Optical Networks

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Abstract In this paper, we propose a novel inter-domain connection provisioning mechanism for multi-domain translucent Wavelength Switched Optical Networks. The mechanism can operate in hierarchical and non-hierarchical path computation element-based architectures. It is based on a novel approach to derive the domain abstract topologies jointly with an inter-domain routing algorithm. The overall objective is to perform end-to-end route computations for incoming connections. We do so by taking into account the current load of the physical links and some energy parameters of the optical network devices with the purpose of distributing the load (as much as possible) along the physical links and keeping the energy consumption low. The performance of the whole mechanism is highlighted through extensive and illustrative simulation results that benchmark it against shortest path-based techniques.

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1 Introduction

It is well known from consolidated literature that the ability of distributing a load in a dynamically-operated network is highly beneficial [1, 2]. An even distribution of traffic by the network elements (NEs) allows for the prevention of potential congestion conditions, thus increasing the capability of supporting a higher amount of demands by the users, i.e., lowering the blocking probability (BP).

Distributing the load generally implies the adoption of smart routing techniques that allow selecting a path for a connection on the basis of the occupancy state of the network. This also implies that routing will diverge from the shortest path ((SP), thus increasing the length of the connections, i.e., the higher the traffic intensity, the longer the connections will be in order to exploit all possible under-utilized NEs to accept more and more traffic.

This is a drawback in many situations, especially if we consider that the BP is not the only performance parameter to be relevant. For instance, in an IP network, a path elongation means a higher hop-count and thus, a relevant increase in the delay. Focusing on translucent Wavelength Switched Optical Networks (WSONs), where end-to-end path delay is not usually an issue, the length penalty translates into higher power consumption. Basically, due to the accumulation of physical layer impairments, which limit the transmission reach of the signal, longer physical paths require more optical amplifiers and optical regenerators in order to support the same number of connections. These considerations fall under the energy efficiency topic that is a very hot topic among the research community and is gaining interest in society in general.

In particular, the concept of energy efficiency has gained notoriety also in the information and communications technology (ICT) sector generating several industrial and academic initiatives, such as the GreenTouch [3]. The optical communications community has also been a subject of this interest and significant efforts have been (and are still being) devoted to making optical networks more energy efficient [4]. Basically, the research efforts are focused on the three main composing parts of current optical infrastructures. These are as follows: access networks [5], metro networks [6], and core networks [7].

If load distribution is easily achieved in a single-domain network, it becomes more difficult in a multi-domain scenario. In fact, end-to-end routing may not be totally computed by a single entity, especially when source and destination nodes are in different and distant domains. Also, the occupancy state of all the NEs may result as being unknown or unavailable outside the domains. These difficulties, generated by scalability and confidentiality issues, prevent classical load distribution routing algorithms to work properly in a multi-domain scenario.

Additionally, despite the numerous efforts targeting the problem of energy efficiency in optical networks and all its components, the vast majority of the related works are devoted to investigating the problem in single domain scenarios. Very few solutions have been studied for a dynamic translucent multi-domain optical networks scenario. For all these reasons, we present an end-to-end solution for computing inter-domain routes that benefit from the load-distribution concept while it also takes into account the power consumption to minimize the side-effects in a such scenario.

The presented mechanism is composed of two parts. First, there is a topology abstraction design model to perform the intra-domain routing. For this we present a mixed integer linear programming (MILP) formulation whose goal is to obtain optimal mapping between the physical paths and virtual links for a single domain in order to achieve a good trade-off between load-distribution and energy efficiency. Secondly, there is an inter-domain routing algorithm, which takes into account the costs associated to the virtual links obtained through the aforementioned MILP formulation (along with occupation and length parameters) in order to compute inter-domain routes that are both efficient in terms of energy consumption and connection establishment success. The algorithms we are proposing are compatible with the routing architectures usually adopted in a multi-domain WSON. In fact, one of the methods is suited for the hierarchical path computation element (H-PCE) architecture, while the other fits with the non-hierarchical path computation element (NH-PCE) architecture.

We will prove (by simulations) that the proposed mechanism achieves relevant gains in terms of the BP when compared with simpler and more straightforward SP-based mechanisms. Specifically, the routing based on the least loaded (LL) algorithm (the one to be used in H-PCE) is superior in all (even non-uniform) traffic conditions, but tends to generate path-elongation impairments when the network is over-provisioned. The other method [based on the Round Robin (RR) algorithm], fits with a simpler NH-PCE architecture that under uniform traffic conditions does not generate elongation, and thus reveals itself to be even more energy-efficient than the LL routing. In any case, the RR routing is more efficient than the SP in all traffic conditions.

The rest of the paper is structured as follows. Section 2 summarizes the main traits of the multi-domain reference architectures. Section 3 reviews the available literature surrounding the multi-domain routing topic in optical networks. Section 4 details the main considerations that are taken in the design of our mechanism. Section 5 describes the MILP formulation used for the intra-domain abstract topology. Section 6 describes the proposed inter-domain routing algorithm. Section 7 shows the benefits of our proposal through illustrative results when compared to SP-based mechanisms along with a description of the test scenario and the main assumptions considered. Finally, Sect. 8 extracts the main conclusions of the presented work.

2 Multi-domain WSONs Reference Architectures

The H-PCE [8–10] architecture has arisen as the leading standard for inter-domain connection provisioning in WSONs. In this architecture, an entity called the parent PCE, which has visibility of the entire multi-domain topology, is responsible for the end-to-end domain sequences' computation from source to destination. A set of lower tier entities, one for each domain of the network, called the child PCE, is responsible for the computation of the intra-domain route inside the domain they belong. However, optimal multi-domain routing is a challenging task that poses some difficulties, in particular since the computation of the end-to-end domain sequence is related to the size of the multi-domain scenario.

In such a scenario, it is highly common to have a significant number of different domains connected between them through pairs of border nodes (BNs), resulting in quite a large network topology. Having a wide network topology, compromises the scalability of the H-PCE architectures, since the parent PCE must manage a huge amount of information to keep track of the multi-domain topology and of the available resources.

Moreover, and more commonly, domains are often managed by different administrators/operators. In such a context, confidentiality between domains plays an important role, because those entities do not want to disclose the details of their topology and available resources. For these reasons, it is not possible to provide the parent PCE with a fully detailed view of the multi-domain topology.

Focusing on the multi-operator/administrator scenario, one key point in the overall performance and management of the H-PCE architecture relates to which one of the involved entities has the ownership or management rights over the parent PCE. Looking at the literature, e.g., [10], and available standards, e.g, [9], there are no clear answers to this issue as it is still under discussion in the research community. One proposed approach is to have a third neutral entity responsible of the management of the parent PCE, but it has to be still defined how this entity would interact with the other operators/administrators. An alternative approach that totally avoids the issue is the simple NH-PCE architecture, where the PCEs of the domains exchange data directly communicating to each other. The information exchange is more limited than in the H-PCE case; in practice, we assume that only static topological data are transferred to neighborhood PCEs, and not real-time link-state updated.

For overcoming the confidentiality and scalability difficulties, in both the H- and NH-PCE architectures, domain topology aggregation was proposed in the literature [11]. The rationale behind this is to perform some transformations into the topology graphs of the domains to obtain smaller topologies that summarize the real topology of the domains. In this way, domain administrators are not obliged to provide the details of both the topology and occupation state of the domain. These aggregated topologies (also named virtual or abstract topologies) are then used by the source-domain or the parent PCE to compute the inter-domain routes.

Among all the topology aggregation schemes that the literature proposes, the one that presents better resource usage is the full-meshed abstract topology [12]. In such a full-meshed abstraction, the domain graph is summarized by the set of BNs of the domain connected in a full-mesh fashion through virtual links. Virtual links are usually associated to attributes that represent the cost of traversing the domain using a particular link. Using these costs along with the associated topologies, the parent PCE is able to compute the end-to-end sequence of domains with high efficiency, without compromising neither the scalability nor the confidentiality of the

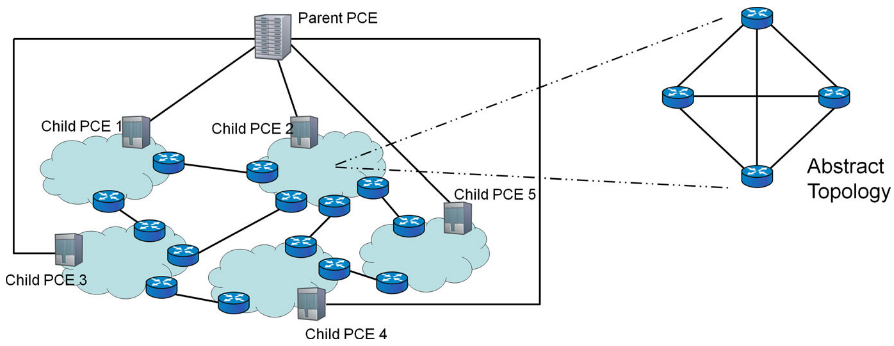

Fig. 1 H-PCE network architecture

multi-domain scenario. Figure 1 depicts the overall picture of the assumed H-PCE network architecture. The NH-PCE architecture (not represented for brevity) would be the same, but with no parent PCE and with local PCEs communicating with each other directly.

With this in mind, the present paper's goal, as mentioned before is to provide a mechanism to compute end-to-end routes in a multi-domain PCE-based translucent WSON. To this end, we propose an MILP formulation in order to obtain the full-meshed abstract topologies of the single domains. The goal of the MILP is to obtain optimal mapping between physical paths and virtual links in order to achieve a good trade off between load-balancing of the connections and power consumption of the domain. The corresponding mappings will be used by the child PCEs to establish the intra-domain route. Additionally, we also propose two inter-domain routing algorithms, whose goal is determining the best sequence of domains and inter-domain links, that is, the inter-domain route, again in both load-balancing and power consumption terms. Of these two routing methods, one is more suitable for an H-PCE architecture, while the other operates in an NH-PCE environment. The following sections review the literature about multi-domain routing and PCE in order to contextualize the presented work and state the main considerations that are taken into account for the design of the proposed solution.

3 Related Work

As commented previously, the ability to efficiently compute end-to-end paths across multiple optical domains is an essential requirement in today's optical transport networks. Due to their large scale, this route calculation becomes very challenging, as it requires the provision of mechanisms to ensure an optimal route from optical nodes belonging to distant domains while facing the particularities of each of the transit domains, such as their resource availability, different routing policies, etc.

One of the first works that relates to the virtual topology abstraction problem is [13], where the idea of employing aggregated topologies to deal with the scalability of multi-domain optical networks is presented. The authors present various abstraction models, namely the single node, star, and full-meshed model. In the single node model, the whole domain is summarized as a single node with degree equal to the number of inter-domain links incident to the domain. The star model is composed of all BNs of the domain connected in a star fashion to a central node in the domain. Finally, and as explained in the previous sections, the full-meshed abstraction is composed solely of all BNs of the domain connected through a full-meshed set of virtual links. Moreover, the authors provide simple mechanisms to obtain such abstractions given the physical topology of a domain.

Through a set of simulations, the authors prove that the full-meshed domain abstraction is the one that gives the best performance in terms of underlying physical resource usage, a conclusion that is corroborated by similar works of different authors, such as in [12].

Many other works have studied the impact on adopting different abstract topologies and the related techniques to obtain them in diverse scenarios. For example, in [14] authors face the issue of the delay between neighboring BNs, providing a mechanism that guarantees that any virtual link will have a delay below a certain threshold. Other works, as in [15], investigate the implications of topology abstraction on multi-layer networks. Here, the authors provide a full-meshed model in order to provide connection quality of service (QoS) in multi-layer multi-domain optical networks.

However, the vast majority of the works surrounding the virtual topology abstraction problem only provide ad-hoc heuristic mechanisms to obtain the virtual topology. Very few works deal with the issue of providing the optimal mapping between physical paths and virtual links in multi-domain optical networks. Moreover, and to the best of our knowledge, although there exists a plethora of work facing the energy-consumption issue in optical networks, most of them focus on single-domain networks, without any work addressing this issue in multi-domain optical networks. For these reasons, we present a novel MILP-based abstraction mechanism that combines the benefits of load balancing and energy-awareness in order to provide the optimal mapping between physical paths and virtual links.

As for the aspect of obtaining the inter-domain route on PCE-based multi-domain optical networks, the literature is full of works addressing different aspects of the problem. In [16], the authors propose a load-balancing mechanism in order to offer protection against link-failure. Their results show that balancing the load can reduce the disruption of services due to a physical link failure while also providing low blocking figures. A similar work is presented in [17], where the authors present a diverse lightpath protection scheme against multi-link failures in multi-domain optical networks.

Other aspects are investigated in the literature such as the presence of physical impairments [18] or the Service Level Agreements between the involved domains [19]. However, as in the case of topology abstraction, there is very little work concerning energy-aware routing in multi-domain optical networks. For this reason, we investigate the impact of adding energy-awareness into the route computation by proposing multiple algorithms that combine resource state and energy parameters in order to compute the inter-domain route.

4 Mechanism Design Considerations

Our method is intended to be applied to the dynamic management and design of long-distance high-capacity backbone networks that span multiple domains and that have a large geographical extension. In such networks, links are almost never composed of a single fiber. Rather, in order to save infrastructural costs (of the ducts), they are composed of several parallel fibers, each fiber equipped with a set of optical amplifiers and possibly other line equipment, such as dispersion compensators.

Therefore, we assume that all the inter- and intra-domain links are multifiber. Additionally, in our work we define the occupation of a link as the number of connections that are routed on that particular link with no regard to the fiber where a connection is allocated. Moreover, our mechanism intends to be used for establishing bidirectional connections between a source and a destination node, and therefore, the occupation of a link (i, j), connecting node i to node j, will be the same of the occupation of the link (j, i) according to the number of connections routed. This is due to the fact that we assume that the paths in both directions are exactly the same.

Furthermore, we assume that each physical link of the network has at least one fiber always in operation with all its amplifiers and related line equipment switched on, regardless of the traffic flowing through that link. This is to ensure connectivity for performance measurement and periodical testing (bit error rate, frame error rate, etc.), alarming, and control plane tasks. For example, the resource reservation protocol-traffic engineering (RSVP-TE) protocol is supported by a refresh procedure that implies periodically sending path messages once a connection is established [20]. Moreover, RSVP-TE based protection and restoration procedures also require connectivity during the network operation while the open shortest path first (OSPF)-TE protocol requires connectivity to disseminate topological and traffic engineering information [21]. In case the link management protocol (LMP) is also implemented, it requires Hello messages to be exchanged to monitor the health of the control channels [22].

Note that an always powered-on fiber does not entail that nodes have to also keep the local transceivers powered-on; in fact, the power state of all line equipment, such as amplifiers, is independent of the power state of the nodes equipment. That is, a node may switch-off unused transceivers without the need of switching-off all the equipment along the fiber. By keeping only a fiber switched-on, we guarantee still enough connectivity for monitoring reasons while the power consumption is kept minimal.

5 MILP Formulation for Intra-domain Routing

Let the optical network of a single domain be characterized by a graph $G = (N, E)$, where N denotes the set of nodes and $E = \{(i,j),(j,i) : i,j \in N, i \neq j\}$ the set of physical links. Moreover, let B denote the set of BNs of the domain with $B \subseteq N$ and E_v the set of virtual links of the domain abstraction, for which e_v^{sd} denotes the specific virtual link connecting BNs s and d. Additionally, let P denote the set of physical paths in the optical network of the domain, $P_{sd} \subseteq P$ the set of candidate paths between BNs s and d, and K the number of paths that will be associated to every virtual link.

Assuming a full-meshed domain abstraction, the objective of the model is to compute the optimal mapping between virtual links and physical paths that minimizes at the same time the BP (by means of load-balancing) and the power consumption of the domain. To this purpose, we define $Q_{sd}^{p} \subseteq P$ as the set of physical paths that share at least one physical link with the candidate path $p \in P_{sd}$ for connecting BNs s and d, l_{sd}^{p} as the physical length of $p \in P_{sd}$ and TR as the transparent reach of the lightpaths without needing regeneration. With this, the number of intra-domain regenerators needed for every candidate path, denoted as R_{sd}^{p}, is

$$R_{sd}^{p} = \left\lfloor \frac{l_{sd}^{p}}{TR} \right\rfloor \forall p \in P_{sd}; \quad s, d \in B, \quad s \neq d \tag{1}$$

where we will denote R_{max} as the maximum value among all R_{sd}^{p}.

Moreover, let us define M as the mean sharing of physical links between paths associated to virtual links, that is, the average number of virtual links that share at least one physical link with other virtual links. If this metric is minimized, that is, the number of virtual links that share physical resources between them is kept at minimum, the load in the domain becomes as balanced as possible among physical resources belonging to virtual links, potentially reducing the BP of the connections.

Finally, let us define T as the mean use of regenerators in the domain; that is, the average number of regenerators employed in the physical routes associated to the virtual links. If this metric is minimized, the paths that will be associated to the virtual links will entail a minimal use of regenerators and, hence, the power consumption of the domain will be kept at a minimum.

With all of these, let us discuss the details of the MILP formulations, for which the model variables are as stated below:

$x_{e_v^{sd}}^{p} = \{1$ if path p is used to map virtual link e_v^{sd}, 0 otherwise$\}$
$z_{e_v^{sd}}^{p} =$ positive integer variable indicating how many virtual links share some physical links with path p for virtual link e_v^{sd} if path p belongs to the solution, i.e., $x_{e_v^{sd}}^{p} = 1$, otherwise its value is equal to 0.
$Z =$ integer variable representing the maximum among all $z_{e_v^{sd}}^{p}$.

Now, with the presented variables, we can write M and T as:

$$M = \frac{1}{K|E_v|} \sum_{e_v^{sd} \in E_v} \sum_{p \in P_{sd}} z_{e_v^{sd}}^{p} \tag{2}$$

$$T = \frac{1}{K|E_v|R_{max}} \sum_{e_v^{sd} \in E_v} \sum_{p \in P_{sd}} R_{sd}^{p} x_{e_v^{sd}}^{p}. \tag{3}$$

As commented before, M, as defined in (2), takes the average value of all variables $z_{e_v^{sd}}^{p}$; that is, the average number of virtual links that share resources between them, and T, as defined in (3) takes the average value of all R^p_{sd} for all $x^p_{e^{sd}_v} = 1$; that is, the average number of regenerators employed in the physical routes associated to the virtual links.

With these definitions, the MILP formulation is as stated below:

$$min\, \alpha(\beta Z + (1-\beta)M) + (1-\alpha)T, s.t. \tag{4}$$

$$\sum_{p \in P_{sd}} x^p_{e^{sd}_v} = K, \quad \forall e^{sd}_v \in E_v \tag{5}$$

$$z^p_{e^{sd}_v} \geq \sum_{i \in B} \sum_{\substack{j \in B \\ i \neq j}} \sum_{k \in Q^p_{sd}} x^k_{e^{ij}_v} + \left(x^p_{e^{sd}_v} - 1\right) \sum_{i \in B} \sum_{\substack{j \in B \\ i \neq j}} \sum_{k \in Q^p_{sd}} 1, \quad \forall p \in P_{sd}, \quad e^{sd}_v \in E_v \tag{6}$$

$$Z \geq z^p_{e^{sd}_v}, \quad \forall p \in P_{sd}, \quad e^{sd}_v \in E_v \tag{7}$$

The objective function's (4) goal is twofold: (1) it minimizes the sharing of physical links between the paths associated to the virtual links that form the domain abstraction; (2) it also minimizes the average number of regenerators that are used by the intra-domain paths corresponding to the virtual links of the domain abstraction. Parameters α and β are real numbers in the range [0, 1] and are used to put more or less weight to the components of the objective function.

In minimizing the sharing of the physical links, we aim at reducing the BP of the connections, as they will potentially use different parts of the network and hence, balance the load among all the physical links. More in depth, the model minimizes at the same time the average sharing and the maximum sharing. The rationale behind this is to keep the mean sharing as low as possible and, at the same time, the deviation from this value for all virtual links; that is why the maximum sharing is also minimized (variable Z). In this way, we balance the load between virtual links in a fair way. Additionally, by minimizing the number of regenerators, we minimize the path-elongation effect mentioned before and hence, the power consumption of the associated virtual links.

Speaking about the combined objective function, let us discuss a little bit about the implications of setting the values for the tunable parameters α and β. First, for the parameter α, a value equal to 0 would imply that the model is only minimizing the energy consumption of the model, choosing the paths that involve a lesser number of regenerators; that is, the paths with minimal length, but will condense all the traffic in a small set of physical paths, potentially increasing the BP of the connections. On the other hand, a value equal to 1 means that the model is only minimizing the aforementioned sharing of resources between virtual links; that is, it is only performing load-balancing. Although this setting will lead to the lowest BP possible, it also increases the energy consumption of the domain, as longer paths are needed to perform the load-balancing, and hence, more regenerators are employed. Any value between 0 and 1 combines the effects of both extremes. The same reasoning applies to β parameter in regards to the average and maximum sharing of physical resources between virtual links (variables M and Z, respectively).

As for the constraints and their meaning, constraints (5) is needed to map every virtual link to K different paths in the physical network. The role of variable K is to provide a more flexible mapping mechanism if more sophisticated routing schemes were adopted, e.g., K candidate physical paths may be employed for connections traversing a particular virtual link. Constraints (6) set the value of variables $z^{p}_{e^{sd}_{v}}$, which account for the sharing of physical links among virtual links. As we commented before, $z^{p}_{e^{sd}_{v}}$ only takes a value >0 if the corresponding $x^{p}_{e^{sd}_{v}} = 1$; that is, the path belongs to the solution. For this reason, the second term is added to the constraint, which will drag to 0 variable $z^{p}_{e^{sd}_{v}}$ if $x^{p}_{e^{sd}_{v}} = 0$, as all variables z are defined as positive integers (greater or equal to 0). Finally, constraints (7) allow the minimization of the maximum sharing of physical links.

6 Inter-domain Routing

In this section, we present the inter-domain routing algorithms that we consider in our work. We assume that only BNs can be the source or destination of the traffic. Moreover, we compute only an inter-domain path specified in terms of a sequence of inter-domain physical links, BNs and intra-domain virtual links. The translation of this path into a fully-detailed path, i.e., a sequence of physical links and nodes, is not done at the inter-domain level. In fact, the intra-domain virtual links are automatically translated into physical paths within each crossed domain because of the fixed correspondence between virtual links and physical paths connecting the BNs. We assume that mapping of virtual links to physical paths remains static (no re-optimization of the abstract topologies is performed) due to the computational complexity of the MILP formulation described in Sect. 5. We will show that, although for some values of α and sizes of the domains, the MILP formulation produces results in the order of a few seconds, for other values of α and larger domains it takes much more time, e.g., in the order of 1,000s of seconds.

This is the reason why the model cannot be applied to actualize the mapping of the virtual links in a periodic basis (re-optimization). In fact, the MILP model is executed off-line, since it is essentially traffic independent; in this way, the model execution times do not affect the performance of the dynamic inter-domain connection provisioning. In order to be capable of re-optimizing the virtual topologies for the domains, fast heuristics (to obtain near-optimal results) should be applied. However, since the goal of the paper is to provide an optimal mapping for the intra-domain aggregated topologies, the design and evaluation of these heuristics is left for future work. In this regard, in order to perform a fair comparison, the static SP is also being considered as the benchmark for the intra-domain virtual link mapping mechanism.

As for the inter-domain routing calculation, we have considered three different procedures to compute the inter-domain path: SP routing, LL routing, and RR routing. In the following sections, they are described in detail.

6.1 Shortest Path Routing Algorithm

In the SP routing algorithm, the path chosen is the shortest one in terms of the physical length, between the source and destination nodes. Thus, the cost related to the length of the path is computed in the same manner for both inter- and intra-domain links by directly assigning to each link a cost proportional to its physical length and then summing over all the links crossed by the path. The state of the links (both virtual and inter-domain) is not taken into account at all: if a link on a computed path is fully occupied, then the connection is blocked. Thus, this algorithm requires only a limited amount of information exchanged between domains; in particular link-state information updates are not required in real time.

6.2 Least Loaded Routing Algorithm

In the LL routing procedure, two different weights with different priorities are used to compute the minimum-cost path. In particular, since we aim at sharing the load over different alternative paths, the weights that we consider in our work are (1) the occupation weight, and (2) a cost related to the length of the links.

In general, we define the occupation weight of a physical link as the number of wavelength channels currently in use on that link. The occupation weight of an inter-domain link is straightforward. Instead, the occupation weight assigned to an intra-domain link is the occupation weight of the most used physical link that composes the corresponding intra-domain path. Conversely, the cost related to the length of the path is computed in the same manner for both inter-domain and intra-domain links by directly assigning to each link a cost proportional to its physical length and then summing over all the links crossed by the path.

To route a connection between the source BN and the destination BN, our procedure first runs the Dijkstra algorithm considering the occupation cost of the (intra- and inter-domain) links. During this operation, the algorithm also computes the total physical length of the end-to-end paths. In such a way, at the end of this operation both occupation and length costs are assigned to each route. The routing decision, i.e., the selection of the end-to-end path to assign to the connection, is primarily based on the total occupation cost: the connection will be routed on the path with the minimum occupation cost in terms of the maximum link ocupation. This means that the occupation cost of an end-to-end path is the occupation of the most charged link which belongs to the end-to-end route. It may happen that more than one end-to-end path has the same occupation cost. In this case, the route selected is the one having the minimum end-to-end physical length among all the paths with the same occupation cost.

Additionally, we added a constraint to the routing algorithm to avoid that a particular domain is crossed more than once by the same end-to-end connection. Such a fact would not make sense, both in terms of occupation and power consumption. The normal behavior of the Dijkstra algorithm is thus modified preventing a path to comprise more than one virtual link belonging to the same domain.

LL needs dissemination of real-time link-state information between domains, for both inter-domain links and intra-domain virtual links. Moreover, it requires a supervisor agent able to run the Dijkstra algorithm as described. LL is therefore suitable for an H-PCE architecture.

6.3 Round Robin Routing Algorithm

In the RR routing solution, the path is chosen in a RR fashion. This means that when a connection has to be routed from BN s to BN d, the parent PCE chooses, as a first path, the SP. Then, for the following connection starting at BN s, it will choose (in a RR way) the other possible routes, e.g., if the last route used was route k, the following route to be used will be route $k + 1$. When all the possible routes originating from BN s have been used at least once to establish a connection, then the algorithm will start the same procedure from the beginning. The RR algorithm is performed independently for each source BN, meaning that the choice of the path made for BN s_1 does not affect the decision to route a new connection starting in BN s_2.

By using the RR policy, it is possible to route connections across the network without the need of exchanging link-state information among the nodes, as it does not make use of any state parameter of the links (virtual and physical). RR enjoys the load-distribution properties of the LL. On the other hand, as in the SP case, if a link of a chosen path is fully occupied, then the connection will be blocked. Since a parent PCE is not needed, RR is suitable for an NH-PCE architecture. Being link-state blind, the RR algorithm is expected to mimic the LL algorithm's load-balancing property under uniform traffic conditions, while it may be outperformed by LL when traffic is not uniform. This conjecture will be tested later on commenting the simulation results.

6.4 Illustrative Example

In this subsection, we show a practical example of how the three routing policies, namely the SP routing algorithm, the LL routing algorithm, and the RR routing algorithm, behave in a translucent WSON multi-domain network. In Fig. 2 we show a multi-domain network composed of eight domains in which, for simplicity, only the relevant BNs of each domain are shown.

We assume that each link is composed of two fibers, each one supporting $W = 3$ wavelengths. For simplicity, we also assume that each virtual link is mapped to a single intra-domain physical link. In the network, links MN and DE are already used by other previously-established connections. In particular, link MN is already supporting three connections while on link DE one connection is already established. Finally, each link, both physical and virtual, is supposed to have length equal to 1. Four connections are requested from s to d:

1. Being totally unaware of the link state, SP will route all four connections on Path 1, which is the shortest one, causing two extra fibers on the virtual link MN to be switched on.
2. LL will use the sequence of paths: 2, 2, 3, 2; no extra fibers are required.
3. RR will use the sequence of paths: 1, 2, 3, 1; one extra fiber on link MN is required.

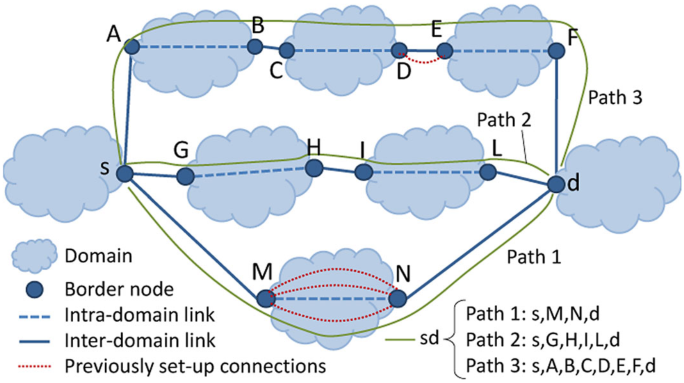

Fig. 2 Multi-domain topology used to exemplify the behavior of the proposed routing algorithms

7 Results and Discussion

7.1 Assumptions and Scenario Description

Before presenting the results, this section will explain which has been the network scenario used to test the proposed solution, along with the major assumptions concerning the physical equipment. The presented model and routing mechanism have been tested through simulations, considering one topology composed of nine domains, with a total of 75 optical nodes (48 BNs and 27 non-BNs) and a total of 146 bidirectional physical links (26 inter-domain and 120 intra-domain). In order to investigate the impact of the energy consumption due to extra-fibers, we have assumed a multi-fiber scenario in which each physical link is composed of two fibers per direction. Each one of these fibers carries 32 wavelength channels. Figure 3 depicts the mentioned topology. The length of each link, although not shown, is normalized to the transparent reach of the connections, i.e., to the maximum length the optical signals can travel without regeneration; for instance, a link distance of 0.6 means that the link length is 60 % of the transparent reach.

Two different scenarios have been tested, the single-carrier (SC) scenario, where all the domains belong to the same administrator, and the multi-carrier (MC) scenario, where domains are managed by different administrators. For both scenarios, we consider that every fiber has a set of in-line bidirectional amplifiers that amplify the whole bundle of wavelengths. If the fiber is the first one of the link, then its amplifiers are always powered up, regardless of the actual traffic. If the fiber is an extra fiber (second, third, etc.) its amplifiers are only powered up when there are connections using that particular fiber. The distance between amplifiers (amplification span) is constant. In order to calculate the necessary number of amplifiers in one fiber, we use the expression reported in Eq. 8, where l_{link} is the length of the physical link and AR the length of the amplification span [23]. For the calculation of the number of amplifiers, we consider that the distance between amplifiers is equal to a normalized length of 0.07. To obtain this value, we assume a

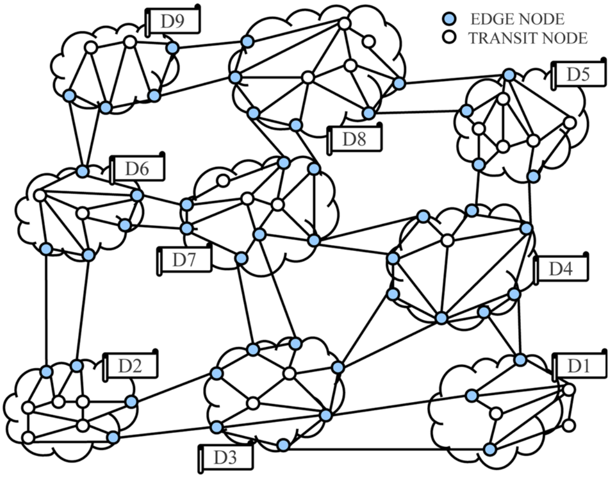

Fig. 3 Network topology of the multi-domain scenario

100 Gb/s network scenario with a transparent reach of 1,200 km [24] and a distance of 80 km between amplifiers as in [23] (80/1200 $\approx$ 0.07).

$$N_{amp} = \left\lceil \frac{l_{link}}{AR} - 1 \right\rceil + 2. \tag{8}$$

We consider that each connection implies the use of one transponder at its source node and another one at its destination node. For the use of regenerators, different rules hold depending on the scenario. In the SC scenario, we consider that regeneration takes place only in nodes where this is needed, i.e., where the distances between nodes are greater than the transparent reach, even if the end-to-end path spans more than one domain. In the MC scenario, we consider that regeneration is only performed inside a domain if the intra-domain path distance is greater than the transparent reach; optical–electronic–optical (O–E–O) conversion is always assumed at the BNs. The regeneration at the BNs, in such a scenario, is performed even if the distance between the latest intra-domain node and the BN is less than the transparent reach. It has to be said that we consider that each node in the network is equipped with regeneration capabilities, so each node becomes a potential regeneration point for connections needing it. In this regard, we aim to evaluate the power savings that can be obtained through the use of the proposed mechanism without dealing with the regenerator placement problem, which is out of the scope of this paper. Table 1 displays the power consumption for each of the physical devices that we consider [25].

7.2 MILP Computation of the Intra-domain Virtual Topology

In this section, we discuss the general complexity of the proposed MILP model and its effectiveness upon execution on the tested intra-domain topologies. Looking

Table 1 Device power consumption

Device	Power (W)
Bidirectional amplifier	290
Transponder	350
Regenerator	420

Table 2 MILP evaluation in the multi-domain scenario

Domain	$\alpha = 0$				$\alpha = 0.5$				$\alpha = 1$			
	Time (s)	Z	M	T	Time (s)	Z	M	T	Time (s)	Z	M	T
1	0.556	1	1	0.33	0.218	1	1	0.33	0.22	1	1	0.33
2	0.319	3	2.33	1.17	6.912	3	2.33	1.5	7.839	3	2.33	1.17
3	0.676	10	5.76	0.67	1.33×10^4	7	4.81	0.86	1.33×10^4	7	4.81	0.86
4	1.389	12	6	0.64	7.2×10^3	7	5.36	0.75	7.2×10^3	8	5.28	0.64
5	0.354	4	3	1	6.489	2	2	1.67	5.462	2	2	1.67
6	0.283	3	2.6	0.3	1.644	3	2.4	0.5	2.02	3	2.4	0.4
7	1.519	8	4.9	0.71	7.2×10^3	6	4.8	0.95	7.2×10^3	6	4.5	0.81
8	1.581	9	5.53	0.87	3.4×10^3	4	3.13	0.87	6.3×10^3	4	3.13	0.8
9	0.169	6	4.33	0.67	0.35	2	1.67	0.5	0.334	2	1.67	0.5

back at its formal description in Sect. 5, it can be seen that the model is described using a link-path formulation, that is, the paths in the network are detailed explicitly by pre-calculated sets and the associated variables. The link-path formulation has the advantage that permits a fine tuning of the potential candidate paths by limiting the size of the path set. On the other hand, in highly meshed networks with several nodes and links, due to the high number of potential candidate paths between a source and a destination, its scalability can be somehow limited.

In terms of formulation complexity, the number of variables is in the order of $\mathcal{O}(2|E_v||\bar{P}_{sd}|)$ and the number of constraints is in the order of $\mathcal{O}(3|E_v||\bar{P}_{sd}|)$, with $|\bar{P}_{sd}|$ the average number of candidate paths from BN s to BN d. The main components that contribute to the MILP complexity, as hinted before, are the number of candidate paths in the intra-domain network and the number of BNs, since $|E_v|$ can be written as $|B|(|B|-1)/2$ considering a full-meshed domain abstraction and a bidirectional network scenario.

Table 2 reports the execution times for the model in the tested intra-domain network scenario for various values of α, in order to evaluate the complexity of the proposed MILP formulation. Moreover, we also depict the (non normalized) values of Z, M, and T, to observe how they evolve as functions of α. For all the depicted results, we have assumed $\beta = 0.5$. All the results have been obtained using standard Quad Core PCs at 2.66 GHz with 4 GB of RAM using Cplex v.12.2 [26] as the optimization software.

As we commented before, domains that are more meshed or have a higher number of BNs experience high execution times. Moreover, it can be seen that

$\alpha = 0.5$ and $\alpha = 1$, in general, lead to larger execution times, since in the corresponding working points the load-balancing term of the objective function plays an active role. Conversely, $\alpha = 0$ leads to lower execution times, as the objective function becomes trivial; it only has to minimize the average number of regenerators, which is tightly related to the length of the path.

As for the evolution of the values of variables Z, M, and T although the trends are highly dependent on the intra-domain topology, generally speaking it can be appreciated that $\alpha = 0$ leads to the lowest regenerator usage while having the worst sharing of physical resources between virtual links, while for the other values of α the use of regenerators slightly increases while the sharing is reduced.

7.3 Numerical Results

We have carried out multiple simulations to evaluate the performance of the proposed methods. For the tests done, we have assumed for the MILP $K = 1$, which means that we only map a virtual link to one physical path, and $\beta = 0.5$. The routing algorithms proposed and evaluated in this work have been compared in cases in which the intra-domain mapping is performed using values of $\alpha = 0, 0.5$, and 1. The simulations have been performed under a variable offered load. We considered the case where all the nodes provide the same amount of traffic to the network (uniform case) and the case in which a set of nodes provides four times more traffic than the other nodes (non-uniform case).[1] In particular, the overloaded nodes are the BNs of domain number 7. In our simulations all the connections are bidirectional.

Figures 4, 5 and 6 show the BP of the different solutions analyzed as a function of the total offered load. Figure 4 shows the comparison among the three solutions when the intra-domain mapping is computed using $\alpha = 0$. Figure 5 shows the case when $\alpha = 0.5$ is used to optimize the intra-domain mapping. Finally, in Fig. 6 $\alpha = 1$ is considered to perform the intra-domain virtual topology. We can notice that our proposed solutions, i.e., the LL and the RR algorithms, have BP values that are lower with respect to the case when the SP is used. The LL and RR algorithms produce BP figures of up to two orders of magnitude lower than the SP. The LL routing and the RR routing have a BP close to each other. For medium and high loads the LL provides a performance that is slightly better with respect to the RR algorithm. Anyway, the difference between the BP of the LL algorithm and the BP of the RR algorithm is $<2 \times 10^{-2}$. We can then observe that the RR routing, unlike the LL solution, provides the benefits of not requiring the exchange of any link state messages, paying only a minor BP increase, at least in the tested topology and with uniform traffic. Moreover, we observe that different values of α produce very similar BP figures, with $\alpha = 0.5$ and $\alpha = 1$ producing slightly better BP figures.

In Fig. 7, 8, and 9 we compare the solutions analyzed in this work in terms of power consumption in the SC case. The values of the α parameter used to perform the intra-domain mapping are $\alpha = 0$ in Fig. 7, $\alpha = 0.5$ in Fig. 8, and $\alpha = 1$ in

[1] Non-uniform traffic has been obtained by suitably adjusting the connection-request arrival rates of the BNs of the network.

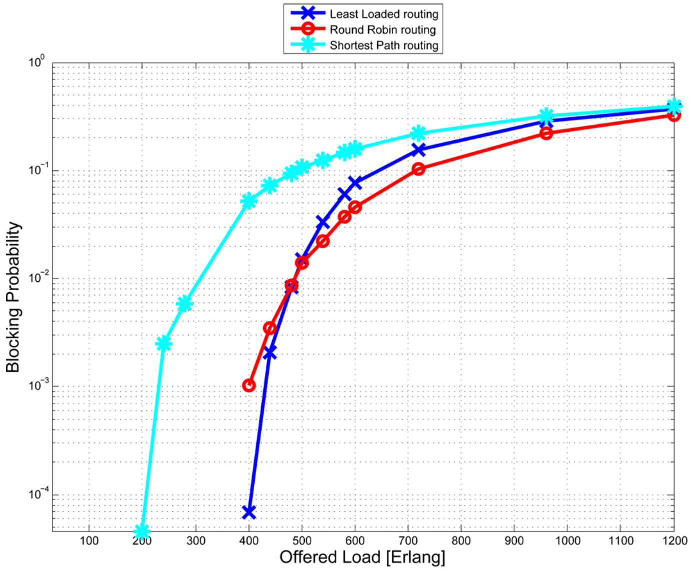

Fig. 4 BP achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 0$

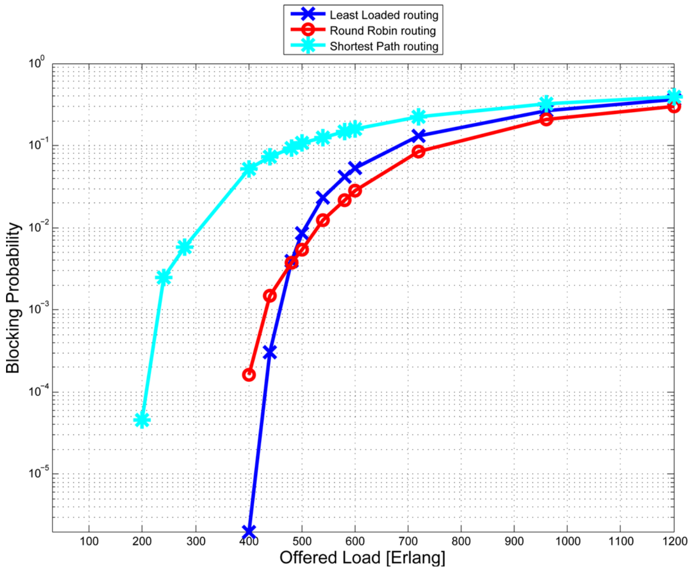

Fig. 5 BP achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 0.5$

Fig. 9, respectively. In particular, we show the average power consumption due to connections that use at least one extra fiber. In this way, the extra power consumption due to the utilization of the extra fibers is evaluated. In fact, the power

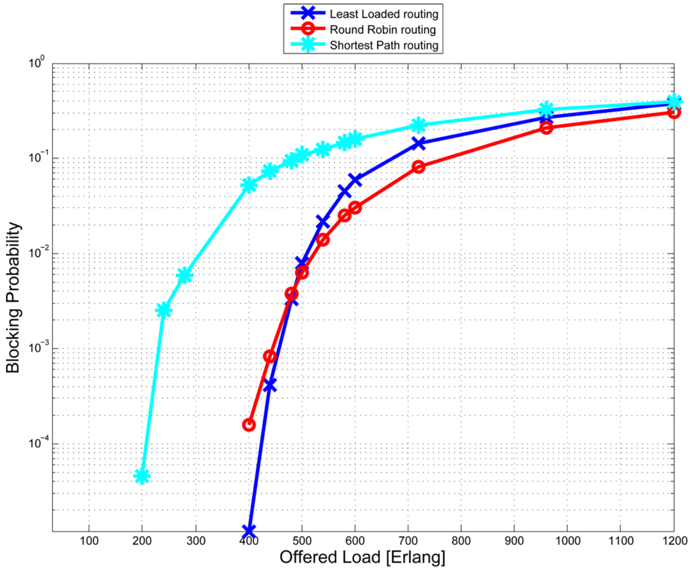

Fig. 6 BP achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 1$

consumption of the first fiber is the same in every case because we assume that such fibers are always switched on. We can observe that, in the range of loads where the network is overprovisioned, and the BP is very small, our proposed RR routing has the lowest values of power consumption. The LL routing also has values of power consumption that are lower than the SP case at least for loads lower than about 275 Erlang. Anyway, the power consumption provided by the LL routing solution is a little higher than in the RR case. At least for the tested scenario, we can then state that while the RR routing provides a BP slightly higher than the BP of LL, it shows lower power consumption values than the power consumption of LL. Conversely, the SP has a high power consumption due to the utilization of the extra fibers.

This is due to the fact that the SP policy tends to choose a limited set of paths (the shortest) so the first fibers are saturated rapidly. In such a way, the SP routing algorithm will switch on the extra fibers sooner than in the case where LL or RR policies are adopted. Again, we can appreciate that the impact of different values of alpha is minimal. After a certain load (about 300 Erlang), when the network is not overprovisioned, the power consumptions of the LL algorithm tend to become higher than with SP. This is due to the fact that for higher loads the paths allocated are always the shortest with the SP algorithm. On the contrary, the LL algorithm at high load will find a lot of overloaded links and therefore it tends to choose paths that are much longer leading to a higher power consumption. Instead, the RR algorithm chooses each path among a set of paths but without considering any link state information. For this reason, the power consumption of the RR algorithm still remains lower than the SP.

Figures 10, 11 and 12 show the comparison of the studied routing algorithms in terms of power consumption in the MC case. Particularly, the values of the α parameter used to perform the intra-domain mapping are $\alpha = 0$ in Fig. 10, $\alpha = 0.5$

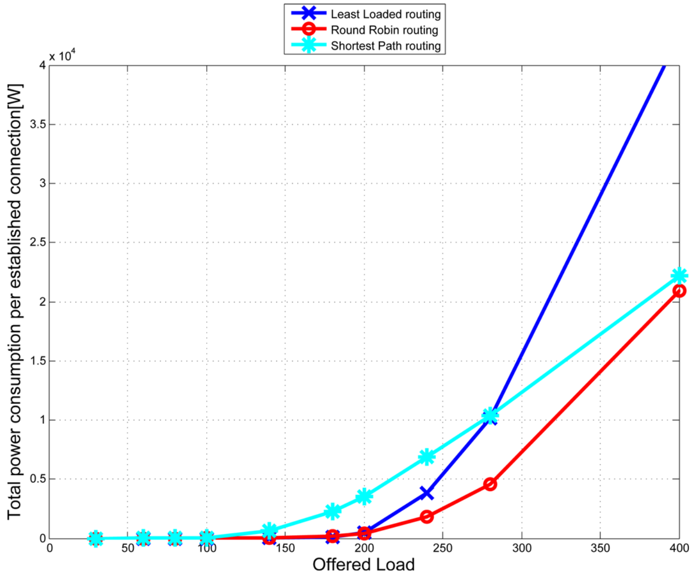

Fig. 7 Power consumption due to the utilization of the Extra-Fibers in the SC case achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 0$

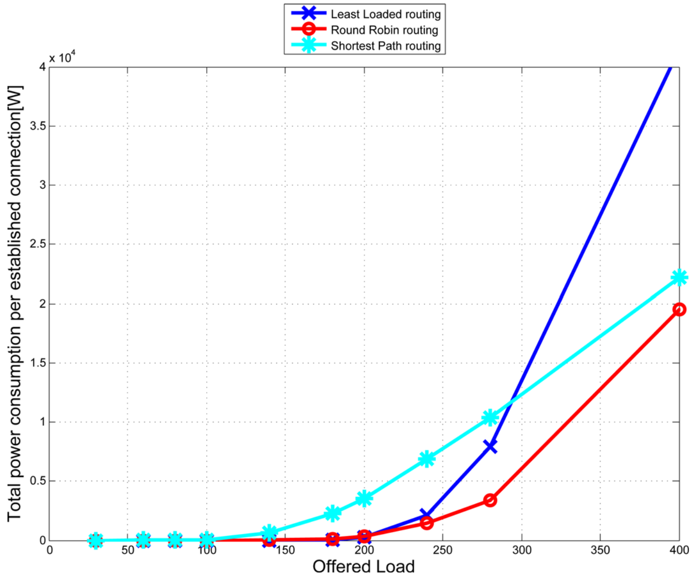

Fig. 8 Power consumption due to the utilization of the extra-fibers in the SC case achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 0.5$

in Fig. 11, and $\alpha = 1$ in Fig. 12, respectively. In the MC case, the same observations and conclusions that apply for the SC case are valid. The only difference is that, in the MC case, the values of the power consumption are scaled

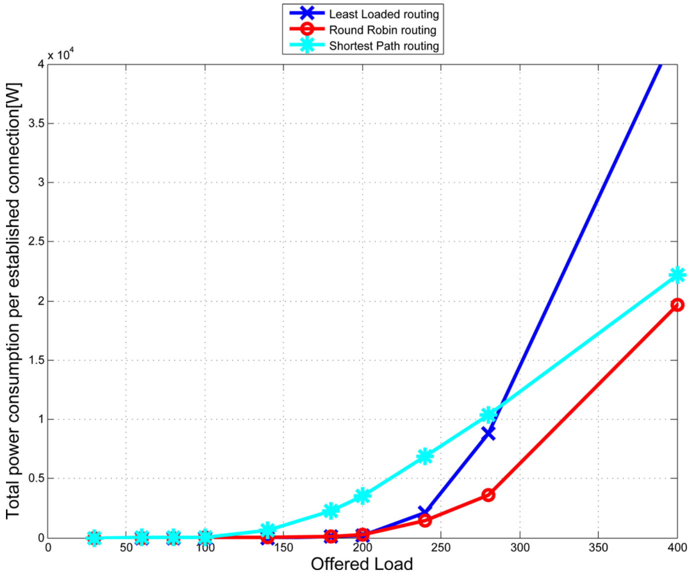

Fig. 9 Power consumption due to the utilization of the extra-fibers in the SC case achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 1$

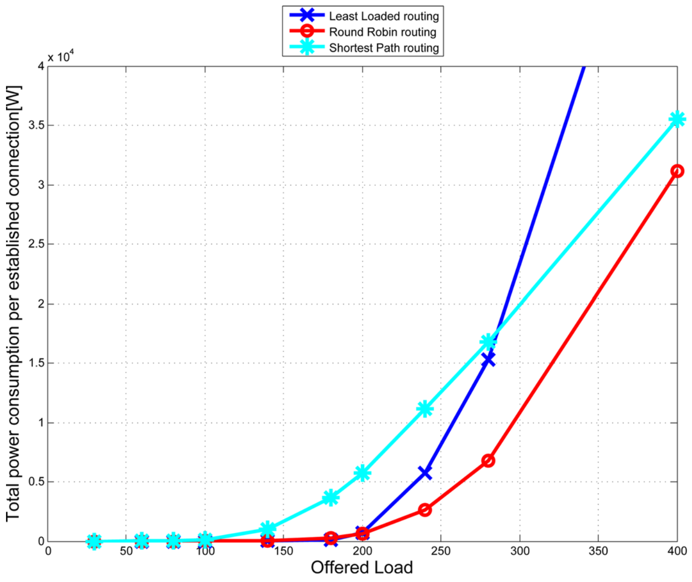

Fig. 10 Power consumption due to the utilization of the extra-fibers in the MC case achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 0$

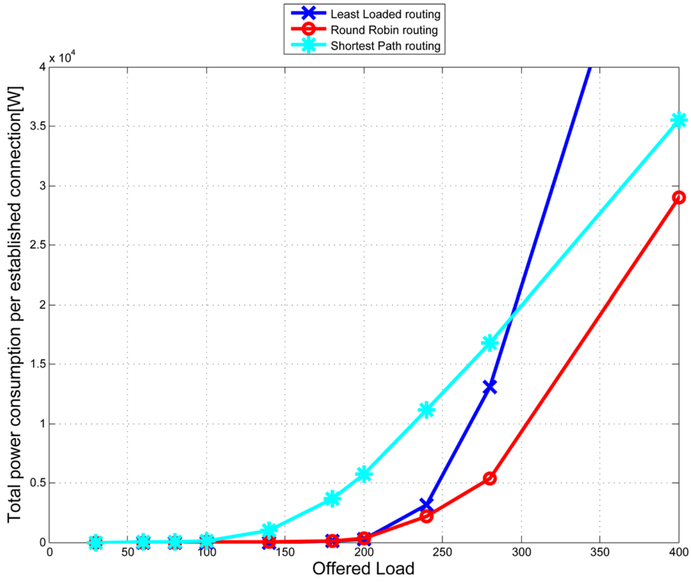

Fig. 11 Power consumption due to the utilization of the extra-fibers in the MC case achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 0.5$

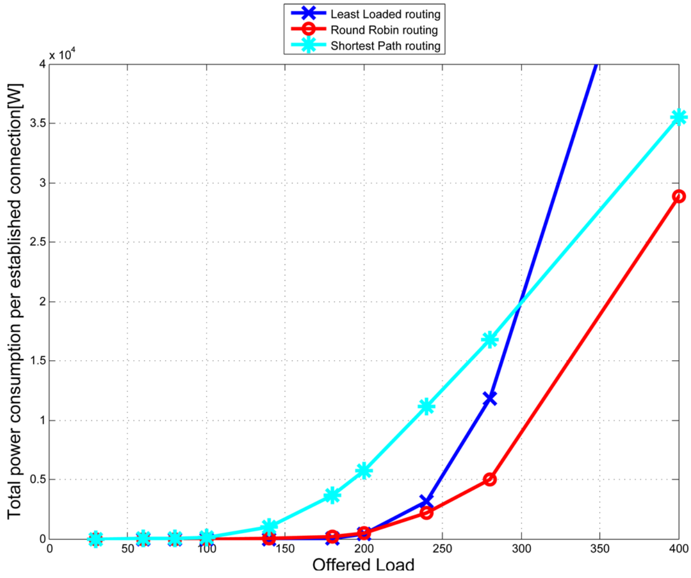

Fig. 12 Power consumption due to the utilization of the extra-fibers in the MC case achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 1$

up if compared to the SC scenario. This happens because, in the MC scenario, regeneration is performed in each BN that is included in the path. Therefore, the power consumed in the MC case is higher than in the SC case.

Finally, Fig. 13, 14 and 15 show the results of the simulations in a case where the nodes provide non-uniform traffic. Figure 13 shows the comparison in terms of BP among the three studied routing algorithms. LL routing provides the lowest BP; the

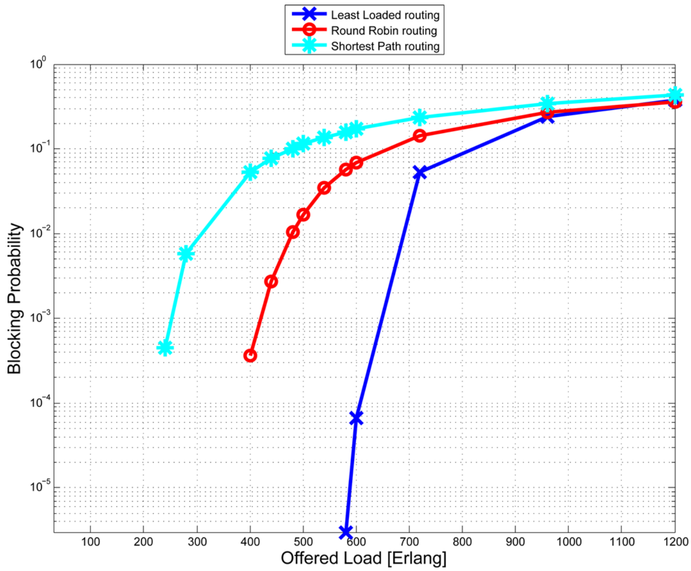

Fig. 13 BP achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 0.5$ in a scenario with non-uniform loads

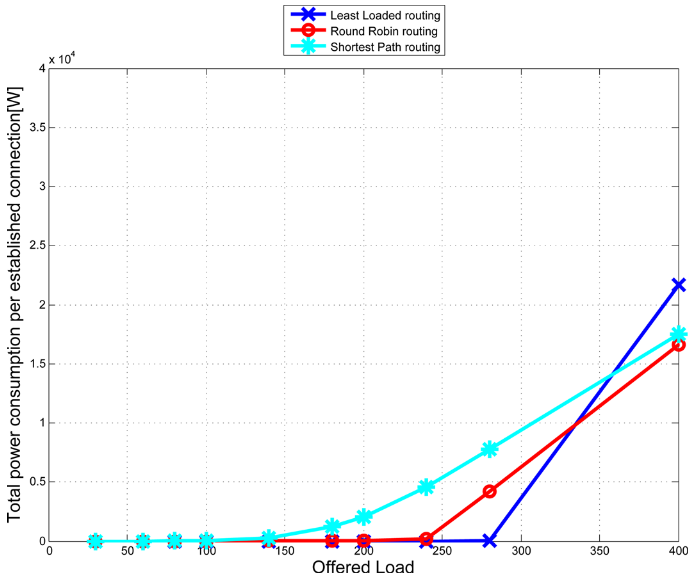

Fig. 14 Power consumption due to the utilization of the extra-fibers in the SC case achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 0.5$ in a scenario with non-uniform loads

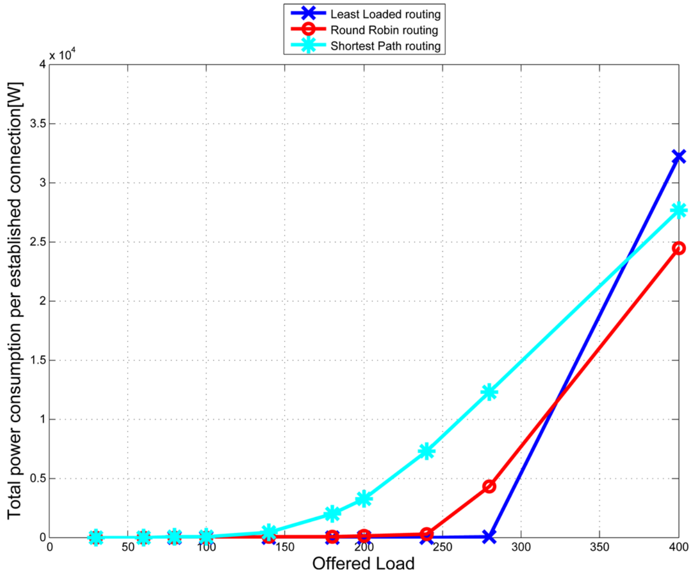

Fig. 15 Power consumption due to the utilization of the extra-fibers in the MC case achieved by the SP, LL, and RR algorithms. Intra-domain mapping computed with $\alpha = 0.5$ in a scenario with non-uniform loads

difference between the BP of RR and LL algorithms is higher than in the uniform case. Indeed, when a domain of the network is highly overloaded, the LL algorithm detects the overloaded links and can route the connections, if possible, over other paths. On the contrary, the RR tries to uniformly balance the connection over all the links of the network regardless of their occupancy state, and therefore, it has a poorer performance.

Figures 14 and 15 show the power consumption due to the utilization of the second fiber in both the SC and MC scenarios. We can notice that in the non-uniform case, the LL has the lowest power consumption while, again, the SP has the highest. Since the RR algorithm tries to uniformly spread the traffic over all the paths in the network, in the portion where the network is highly loaded the paths tends to use more second fibers. Conversely, the LL will choose the paths with most free resources, avoiding to switch on the second fibers as much as possible. For this reason, the RR provides a higher power consumption if compared with the LL case. Anyway, the RR continues to show a power consumption that is lower than the power consumption of the SP case. These observations apply for both the SC and MC cases, even if in the MC case the overall power consumption of the three solutions is higher than in the SC case.

8 Conclusions

In this work we have proposed a novel multi-domain connection routing mechanism that is composed of two parts: (a) the intra-domain topology abstraction design model; and (b) the inter-domain routing algorithms. The presented mechanism is successful in lowering the BP (up to two orders of magnitude) and power consumption compared to the SP routing mechanism. Moreover, we have demonstrated that our solution can effectively be applied both to SC and to MC scenarios, making it a valuable option as a unique routing mechanism for both scenarios.

As for the parts that compose the proposed mechanism, we analyzed their performance in detail. For the MILP formulation in the intra-domain part, we have tested its performance with regard to the value of the parameter α: $\alpha = 0$ means that the solution of the MILP is the one that uses the minimum average number of regenerators in each domain; $\alpha = 1$ means that the solution of the optimization is the one with the minimum path sharing among intra-domain paths in each domain; with $\alpha = 0.5$ the optimization finds the best trade-off between the two previous cases. We have shown that very small differences can be found between these values of α.

Concerning the inter-domain routing algorithms, we compared different solutions to choose the end-to-end paths: the SP algorithm, the LL algorithm, and the RR algorithm.

We demonstrated that the RR results are close to the results of the LL option (low BP and low energy consumption), at least for the simulated topology with uniform traffic and with the added benefit that it requires much less state information to be disseminated between the domains. Moreover, while LL needs an H-PCE architecture, RR can operate in a simpler NH-PCE architecture. In a non-uniform case, the performance of the RR algorithm becomes worse than with the LL routing solution, but always better than with the SP algorithm. For all these reasons, we can conclude that our proposed mechanism with the RR algorithm is a valuable solution to provision connections in multi-domain translucent WSONs, combining low BP and power consumption with a reduced state-information dissemination between domains.

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