Brown-field Gradual Migration Planning Toward Spectrally-Spatially Flexible Optical Networks

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***Abstract*—In this paper, we motivate a brown-field migration planning as a cost-efficient procedure to scale the capacity of short-term realizable elastic optical networks (EONs), gradually converting them into spectrally-spatially flexible optical networks (SS-FONs). After a formal statement of the brown-field EON to SS-FON migration planning problem, a Stochastic Iterated Local Search (SILS) metaheuristic is presented to solve it in realistic time-scales. Using the proposed metaheuristic, we study the migration of two different reference backbone EONs to SS-FONs based in realistic traffic forecasts up to year 2031, accounting for both unicast and anycast traffic types. The obtained results also serve to highlight the good performance of the proposed SILS metaheuristic versus alternative heuristic approaches used as benchmark.**

***Index Terms*—spectrally-spatiall flexible optical networks, gradual migration planning, brown field migration**

I. Introduction

Over the years, there has been observed a continuous traffic increase in backbone networks. Most of them utilize infrastructure built over a dozen years ago, based on *wavelength division multiplexing* (WDM). WDM is realized over *single-core single-mode fibers* (SMFs), which offer limited bandwidth due to the non-linear Shannon limit [1]. In the presence of growing traffic, it is a matter of time to exhaust available bandwidth. As a short-term solution, *elastic optical networks* (EONs) are proposed which more effectively adjust optical resources to the heterogeneous traffic, when compared to WDM. In more detail, EONs divide the available spectrum into narrow slots, and demands are realized using the just enough amount of slots to match their requested bandwidth [2]. However, as EONs are built on SMFs, increased flexibility only postpones the problem of future "capacity crunch". Recently, the *space division multiplexing* (SDM) technology gained much attention in the context of backbone networks. The key idea of SDM is to increase capacity significantly by parallel transmission in apropriately designed optical fibers. In its simplest form, several SMFs are aggregated in one *single-mode fiber bundle* (SMFB) [3]. In this paper, we consider *spectrally-spatially flexible optical networks* (SS-FONs) which are the combination of both mentioned orthogonal technologies — EONs and SDM, providing a significant increase in available capacity and better management of spectral resources when compared to legacy WDM networks [4].

As a short-term solution, network operators will tend to upgrade WDM to EON which can be realized on the same SMFs (i.e., only transponders and optical cross-connects need to be upgraded). However, at some point, an upgrade to SS-FON technology is unavoidable. Nevertheless, as one-time whole network upgrade is a significant expenditure, network operators would aim to postpone the cost in years by applying partial, i.e., gradual, migration where only required network components are upgraded [5]. As the deployment of optical fibers is an expensive and time-consuming process, most operators equipped networks with additional not used SMFs (i.e., so called "dark fibers") and the transmission in realized in only one SMF in a bundle. In an ideal scenario, a brown-field migration may be applied, where part of the currently deployed network infrastructure is used in the new technology. Indeed, if dark fibers are already predeployed in the network, only network nodes are required to be upgraded with *reconfigurable optical add-drop multiplexers* (ROADMs) that allow to switch spatially multiplexed traffic.

Meanwhile, according to CISCO prediction [6], *content delivery networks* (CDNs) will carry 71% of traffic in backbone network. CDNs are distributed using anycast transmission, i.e., one-to-one-of-many transmission, where client node is connecting with one of the available *data centers* (DCs) (or in opposite direction). Each DC provides the same content and service, thus, for the client it is irrelevant to which DC it is connected. According to the characteristic of anycast traffic, it allows for decreasing the overall network load, due to the shorter transmission distances, when compared to the conventional one-to-one unicast transmission.

Despite the importance of the migration planning problem, to the best of our knowledge, it still remains quite an open issue in the context of EONs and SS-FONs. Indeed, several papers cover migration planning from WDM networks toward EONs, i.e., from fixed- to flexible-grid. Ref. [7] considers a gradual migration planning, highlighting its advantages when compared to one-time whole network upgrade. In [8], a brown-field migration is presented where current network infrastrucutre is also utilized in migrated part of the network. As a previous work, we have already presented three papers covering the migration planning problem from EONs toward SS-FONs. In [9], we propose a simple greedy heuristic for

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brown-field migration planning from EONs to SS-FONs. In [10], we investigate the impact of *inter-core crosstalk* (IC-XT) on the same planning problem when *multi-core fibers* (MCFs) are used. In [5], we discuss the green-field migration planning from EONs toward SS-FONs. As the main novelty in the present paper, we propose *Stochastic Iterated Local Searchs* (SILSs) metaheuristic algorithm for brown-field migration planning problem and investigate the impact of anycast traffic on migration planning performance.

The rest of the paper is organized as follows. In Sec. 2, we discuss the brown-field migration planning problem. Section 3 presents our network model, while Sec. 4 describes our proposed migration planning algorithm. Finally, Sec. 5 depicts the obtained results in the conducted experiments, and Sec. 6 concludes this paper.

II. Brown-Field Migration Planning

The aim of migration planning problem is to provision all forecasted traffic while minimizing the cost of the replaced components. Initially, we consider a network operating solely in EON technology. In more detail, transmission in each link is realized using one SMF and network nodes are equipped with a conventional ROADMs, e.g. a *broadcast & select* (B&S) ROADM, that allow for traffic switching from nodes' input fibers to the desired output fibers. Moreover, as deploying new fibers becomes an expensive operation, we assume that the network operator equipped each network link with additional unused SMFs with the aim for future utilization. Thus, each network link is equipped with SMFB, where one SMF is used to realize transmission and the remaining ones are so called "dark fibers". According to CISCO predictions, the annual traffic in the backbone network increases. When the expected traffic exceeds the network capacity, the need for migration to SS-FON technology emerges. However, one-time whole network upgrade is expensive operation and could result in temporary service interruptions. Thus, to spare upgrade cost over time, the gradual network migration may be considered. In more detail, when the forecasted traffic in a given time period exceeds the available network capacity, part of the network can be migrated toward SS-FON to mitigate the increasing requirements. The SS-FON requires both fibers supporting parallel transmission, and SDM-capable ROADMs that allow to switch spatially multiplexed traffic. According to our previous assumptions, the network is already equipped with unused SMFs in the SMFBs (i.e., only one fiber is lit to realize transmission as in EON), thus, to enable parallel transmission migration of network nodes is only required. In more detail, to utilize remaining SMFs in the bundle in a given network link, nodes at both ends of the link have to be equipped with SDM-capable ROADMs. Therefore, during network operation, a sufficient number of network components should be upgraded/replaced in order to provision the whole forecasted traffic. As the optimization objective, the number of replaced components should be minimized, i.e., the number of network nodes equipped with SDM-capable ROADMs among all nodes in the network.

III. Network Model

SS-FON network is modeled as a directed graph $G = (V, E)$, where V is a set of network nodes, and E is a set of unidirectional links. Each link $e \in E$ is defined by the pair of source and destination nodes $e = (e_s, e_d)$. Each link comprises a set of SMFs in a SMFB $K(e)$. Each spatial mode (i.e., SMF in a SMFB) provides spectral resources denoted as set S. Set E_m denotes set of spatially-enabled fiber links (i.e., fibers where all SMFs are used for transmission). Contrarily, set E_m^c denotes links which are not SDM-enabled. Each link can be either SDM-enabled or not, thus

$$E = E_m \cup E_m^c, \tag{1}$$

$$E_m \cap E_m^c = \emptyset. \tag{2}$$

The number of utilized SMFs in the bundle depends on whether the fiber is migrated (SDM-enabled) and is defined as

$$K(e) = \begin{cases} 1, \text{ for } e \in E_m^c \\ k_m, \text{ for } e \in E_m, \end{cases} \tag{3}$$

where k_m is a number of spatial modes after migration. The set of migrated nodes, i.e., network nodes equipped with SDM-capable ROADMs is denoted as V_m. Contrarily, not migrated nodes equipped with conventional ROADM are represented as V_m^c. Thus,

$$V = V_m \cup V_m^c, \tag{4}$$

$$V_m \cap V_m^c = \emptyset. \tag{5}$$

The relation between migrated fibers, non-migrated fibers, and network nodes is defined with the following equations:

$$e \in E_m \Leftrightarrow e_s \in V_m \land e_d \in V_m \tag{6}$$

$$e \in E_m^c \Leftrightarrow e_s \in V_m^c \lor e_d \in V_m^c, \tag{7}$$

assuring that any link allows for parallel transmission only if its end nodes are both equipped with SDM-capable ROADMs. As the network is already equipped with SMFBs, the objective function F aims to minimize the cardinality of set V_m while supporting the whole forecasted traffic.

$$\min F = |V_m| \tag{8}$$

Moreover, the traffic is increasing during the defined time periods. Let us assume that set $V_m(t-1)$ denotes migrated nodes at a previous time period required to support forecasted traffic. In gradual migration, only new components are replaced towards SS-FON, and already upgraded components cannot be downgraded backward. Thus, once migrated, network nodes remain migrated in future time periods, which is defined as

$$V_m(t-1) \subset V_m \tag{9}$$

The transmission in the network is realized by the means of *super-channel* (SCh) which is a group of adjacent frequency slices. To allow for full compatibility between SS-FON and

EON in partially migrated network, in SS-FON only spectral SChs are considered, i.e., SChs realized only on one spatial mode. As it is required to allocate the traffic in the network at each migration step, the *routing, spectrum, and space allocation* (RSSA) problem is a subproblem of the migration planning problem. The RSSA is a problem of finding a routing path, and appropriate spectrum and spatial resources for each pending demand in the network, considering continuity, contiguity and spectrum non-overlapping constraints [4]. As a consequence, the effectiveness of migration planning strongly depends on the efficiency of finding RSSA solution.

IV. Optimization Algorithms

In this section, we focus on our SILS metaheuristic aiming to minimize the required number of migrated network nodes while the network can still provision the forecasted traffic. However, it is firstly required to define those subroutines applied in SILS algorithm, namely, *Greedy Allocation* (GAlloc), *Migrate Node* (MigNode) and *Greedy Migration* (GMig).

A. Greedy Allocation Algorithm

At each period it is required to find a feasible solution to the RSSA problem. To this end, we apply the Greedy Allocation (GAlloc) heuristic which is the modification of *PathAndSpectrumFF* algorithm presented in [11]. Greedy Allocation algorithm allocates set of pending demands D in the provided network containing $|S|$ slices in each fiber, finding for each demand an appropriate routing path and spectrum and spatial resources, so that the continuity, contiguity and spectrum non-overlapping constraints are not violated. The output of the procedure is a boolean $allocated$ determining whether it is possible to allocate all demands in the network. The procedure may be applied in EON, SS-FON or partially migrated network. In the preprocessing phase, GAlloc calculates for each demand a metric n_d equal to the required number of subcarriers on its shortest candidate path. Next, the demands are sorted in descending order according to that metric. Then, demands are consecutively processed, and for each demand $d \in D$, algorithm tries to find a SCh which has the lowest ending slice index considering a given set of candidate routing paths $P(d)$. If such SCh is found, the algorithm reserves appropriate resources to realize such demands and repeats this steps for the next pending demand. After processing all demands, GAlloc sets variable $allocated$ to $true$. Otherwise, when there is no feasible SCh for a given request, the algorithm stops the execution and returns information that it cannot find feasible solution (setting variable $allocated$ to $false$).

B. Network Nodes Migration Algorithm

According to the assumptions in Section III, key components which have to be replaced are the ROADMs. However, to enable SDM transmission through dark SMFBs, nodes at both ends of fiber have to be SDM-capable. Thus, when replacing nodes, it is required to track also which fibers are becoming SDM-capable. The Migrate Node (MigNode) algorithm takes as an input node v selected for migration and thos sets of already migrated nodes and links, i.e., V_m and E_m, respectively. As a first step, the algorithm adds node v to the set of migrated ones V_m (i.e., equips it with SDM-capable ROADM). Next, MigNode traverses each neighbor node of node v and checks whether this node is also migrated. If so, links (two unidirectional links) between node v and the neighbor node are appended to the set of migrated links E_m.

C. Greedy Migration Algorithm

The SILS meta-heuristic requires construction of a feasible initial solution, which is created using the greedy heuristic algorithm presented in our recent paper [9], i.e., Link with Highest Subcarriers First (LCS). In this paper, for the sake of simplicity, we refer to it as Greedy Migration (GMig). Greedy Migration iteratively upgrades nodes in the network until it is possible to accommodate the whole forecasted traffic. At each iteration, nodes are selected which are adjacent to links carrying the highest traffic measured in the number of subcarriers. In more detail, the algorithm simulates the allocation of the traffic assuming that there are unlimited spectrum resources in the current network using GAlloc heuristic,i.e., there is no restriction in the number of available frequency slices. Due to the unlimited resources, none of the forecasted demand is blocked and the objective of the Greedy Allocation heuristic is the minimization of the highest allocated slice index in the network. After that, GMig calculates the number of carried subcarriers by each not migrated link and selects the one with the highest value. Next, the algorithm selects two adjacent nodes to that link. Each of these two nodes, if not yet migrated, it is equipped with SDM-capable ROADM and appended to the set of migrated nodes V_m. Accordingly, the selected link is appended to the set of migrated links E_m. Note that one of these nodes may be already upgraded due to the selection of some other link. Next, it is required to check whether any other links become "automatically" upgraded due to the upgrade of these two nodes and add them to the list of migrated links E_m, i.e., the link is adjacent to two upgraded nodes but it was not selected during the execution of the algorithm. After migrating components, the Greedy Allocation algorithm is used to allocate forcasted traffic, this time assuming limited resources in each fiber. If it is possible to allocate whole traffic, the algorithm exits immediately, otherwise, the above-mentioned steps are repeated and algorithm selects next network components for upgrade. The output of the algorithm is the set of migrated nodes and links which allows for the allocation of whole forecasted traffic.

D. Stochastic Iterated Local Search Algorithm

Stochastic Iterated Local Search consecutively decreases the number of migrated nodes and checks whether it is still possible to allocate the forcasted traffic. Let us denote each aimed number of migrated nodes as a *stage*, and a tuple of sets (V_m, E_m) as a *solution*. For each stage, multiple solutions are created until it is possible to fit the traffic, i.e., a decision about which nodes should be selected is repeated multiple times and randomized. If the provided maximum number of iterations is reached at a given stage, the algorithm stops the execution, and a feasible solution from the previous stage is returned.

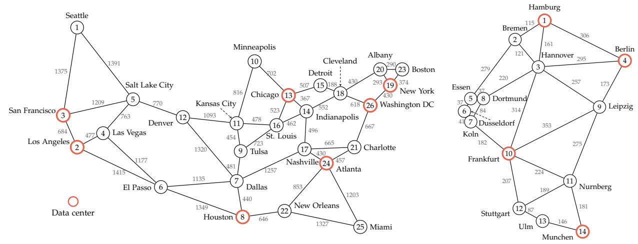
The pseudocode of SILS algorithm is presented in Alg. 1. As an input, the algorithm takes current network G, available spectral/spatial resources in each fiber in each link denoted as Ω, set of forecasted demands D, set of migrated nodes V_m, set of migrated links E_m, maximum number of iterations I and ratio of nodes to swap Γ. As a result it returns the information about whether it was possible to allocate whole traffic $allocate$ and best found set of migrated nodes and links $V_{m,best}$ and $E_{m,best}$, respectively. In line 2, the initially migrated nodes and edges are stored. Note that the algorithm may start the execution in a scenario where a network is already partially migrated. Next, the initial solution is provided with GMig algorithm (line 3) and stored as the best one — pair of sets $V_{m,best}$, $E_{m,best}$. If it is not possible to allocate the whole traffic with the greedy algorithm, i.e., migrating all nodes, SILS stops the execution. Further, set of newly migrated nodes Δ_{curr} and not migrated nodes $V^c_{m,curr}$ are obtained (lines 6 and 7, respectively). Note that set Δ_{curr} contains only nodes, which are appended to the set of initially migrated nodes and the cardinality of this set corresponds to the current stage of the algorithm. The lower is the cardinality, the better result is provided with the algorithm. In line 8, the main loop of the algorithm is performed with the following steps. First, it reduces the target number of migrated nodes $|\Delta_{curr}|$ (line 9) by moving the last element from set Δ_{curr} to set of currently not migrated nodes $V^c_{m,curr}$. Next, the candidate solution is created by copying the initial one and migrating nodes in set Δ_{curr} (lines 10–12). The feasibility of such a solution is evaluated with GAlloc heuristic (line 13). Further, if there is at least one newly migrated node at this stage and the created solution is not feasible, the current solution is altered until the feasibility is achieved or the maximum number of iterations I is reached (lines 14—16). In lines 17 and 18, the number of nodes to swap γ is evaluated. Firstly, it is equal to the lower from values of not migrated and newly migrated nodes multiplied by ratio Γ. Secondly, it is always greater or equal to 1. Next, γ randomly selected (distinct) nodes in set Δ_{curr} are replaced with γ randomly selected nodes in set $V^c_{m,curr}$. In lines 20–23 (similarly to lines 10–13), new solution is created based on the altered set of newly migrated nodes, and it is allocated using GAlloc to check its feasibility. Finally, the number of iterations is increased, and the execution of the loop is repeated until the solution is feasible or maximum number of iterations I is reached. At the end of each stage, if the current solution is feasible, it is stored as the best one (line 26). Next, if it is still possible to allocate the forecasted traffic and further decrease the number of newly migrated nodes, the algorithm repeats the execution of the loop in line 8 for the next stage. Otherwise, the execution of SILS algorithm is over.

Algorithm 1: SILS — Stochastic Iterated Local Search algorithm for migration planning problem.

1 **Function** *SILS*(G, Ω, D, V_m, E_m, I, Γ)**:**
  Require: graph $G = (V, E)$, spectral-spatial resources Ω, set of pending demands D, set of migrated nodes $V_m \subset V$, set of migrated links $E_m \subset E$, maximum number of iterations I, ratio of nodes to swap Γ,
  Ensure : $allocated$, V_m, E_m
2   $V_{m,init}$, $E_{m,init}$:= V_m, E_m
3   $allocated$, $V_{m,best}$, $E_{m,best}$:= `GMig`(G, D, V_m, E_m)
4   **if** $allocated = false$ **then**
5   **return** $allocated$
6   Δ_{curr} := $V_{m,best} \setminus V_{m,init}$
7   $V^c_{m,curr}$:= $V \setminus V_{m,best}$
8   **while** $|\Delta_{curr}| > 0$ **and** $allocated = true$ **do**
9   remove last element from Δ_{curr} and add it to the $V^c_{m,curr}$
10    $V_{m,curr}$, $E_{m,curr}$:= $V_{m,init}$, $E_{m,init}$
11   **for** $v \in \Delta_{curr}$ **do**
12   `MigNode`(G, v, $V_{m,curr}$, $E_{m,curr}$)
13    $allocated$:= `GAlloc`(Ω, D, G, $V_{m,curr}$, $E_{m,curr}$)
14   **if** $|\Delta_{curr}| > 0$ **then**
15      $iter$:= 1
16   **while** $iter \leq I$ **and** $allocated = false$ **do**
17   γ := $\lfloor \Gamma \cdot \texttt{min}(|\Delta_{curr}|, |V^c_{m,curr}|) \rfloor$
18   γ := $\texttt{max}(\gamma, 1)$
19   swap γ random elements from Δ_{curr} with γ random elements in $V^c_{m,curr}$
20        $V_{m,curr}$, $E_{m,curr}$:= $V_{m,init}$, $E_{m,init}$
21   **for** $v \in \Delta_{curr}$ **do**
22   `MigNode`(G, v, $V_{m,curr}$, $E_{m,curr}$)
23        $allocated$:= `GAlloc`(Ω, D, G, $V_{m,curr}$, $E_{m,curr}$)
24        $iter := iter + 1$
25   **if** *allocated = true* **then**
26      $V_{m,best}$, $E_{m,best}$:= $V_{m,curr}$, $E_{m,curr}$
27 **return** $allocated$, $V_{m,best}$, $E_{m,best}$

V. Numerical Experiments

In this section, we present results of numerical experiments which evaluate the effectiveness of proposed algorithms and the impact of different unicast to anycast traffic proportion on the migration planning. The experiments are run on two representative network topologies, namely, a USA National network topology US26 (26 nodes, 84 links and 754 km of average link length, Fig. 1a) and a National German network DT14 (14 nodes, 46 links and 182 km of average link length, Fig. 1b), where bold nodes represent network nodes connected to the DCs. Similar to [9], the considered SS-FON is composed of SMFBs, where each fiber provides 4 THz bandwidth divided into frequency slices of 12.5 GHz width. We assume that the network is equipped with coherent transceivers, each one operating at a fixed baud rate and transmitting/receiving an optical carrier that occupies 37.5 GHz. We consider 4 available *modulation formats* (MFs), namely, BPSK, QPSK, 8-QAM, 16-QAM that support bit-rates of 50, 100, 150 and 200 Gbps. Transmission reaches for each of the considered MFs are 6300, 3500, 1200 and 600 km, respectively [12]. We assume that the number of fibers per SMFB is 22. The transmission in the network is realized using only spectral SChs.



(a) US26 (b) DT14

Fig. 1: Network topologies.

TABLE I: Evolution of traffic over time

Year	US26 network Traffic volume (Tb/s)				DT14 network Traffic volume (Tb/s)			
	City to city	City to DC	DC to DC	Total	City to city	City to DC	DC to DC	Total
2019	2.1	13.6	9.3	25.0	4.2	27.2	18.5	50.0
2022	3.0	26.7	21.7	51.3	5.9	53.4	43.3	102.7
2025	4.2	52.3	50.6	107.2	8.4	104.7	101.3	214.3
2028	5.9	102.6	118.4	226.9	11.8	205.2	236.8	453.8
2031	8.3	201.1	276.8	486.2	16.6	402.2	553.6	972.3
CAGR [%]	12.1	25.2	32.7	28.1	12.1	25.2	32.7	28.1

A. Traffic Model

The study is made taking a realistic traffic model where the overall traffic volume increases over time. The model is applied for a period of 12 years from 2019 to 2031, based on the information provided in the "Cisco Visual Networking Index" [6] and "Cisco Global Cloud Index" [13]. Each traffic matrix contains three types of demands, namely, city-to-city, city-to-dc, and dc-to-dc. City-to-city is a unicast demand between two end nodes in the network. City-to-dc is an anycast demand between any of the available DCs and the client node; or in the opposite direction, from the client node to any of the available DCs. Dc-to-dc is a unicast request between two DCs in the network (the communication between DCs is realized in the backbone network). The initial ratio, i.e., the volume of traffic for the year 2019, of demand types mentioned earlier is evaluated based on the CISCO traffic predictions. The details of the applied traffic model are presented in Tab. I. The city-to-city demands correspond to 8.44% of the total traffic, while city-to-dc and dc-to-dc demands correspond to 54.49% and 37.07%, of it respectively. The compound annual growth rate (CAGR) for each traffic type is different, and it is equal to 12.06%, 54.49% and 32.72% for city-to-city, city-to-dc, and dc-to-dc demands, respectively. The initial total traffic is selected for each different network separately, allowing for the network saturation during experiments. Table I present the evolution of traffic over time for two types of network topologies, US26 (1a) and DT14 (1b), respectively, assuming that the initial traffic is equal to 25 and 50 Tbit/s for US26 and DT14 network topologies, respectively. For more details on the applied traffic model, please refer to [14].

B. Comparison with Reference Methods

The proposed SILS algorithm is compared to three reference algorithms: i) Greedy Migration (GMig) — SILS's initial solution construction procedure; ii) Random (RND) — random migration, where at each iteration node for migration is selected randomly; iii) Highest node degree (ND) — heuristic selecting nodes in the decreasing order of nodes degree until it is possible to accommodate whole traffic.

The tuning of the ILS metaheuristic has been initially performed and the best parameters setup has been selected. Figures 2 and 3 show the migrated nodes percentage and activated fiber number along the years for both network topologies.

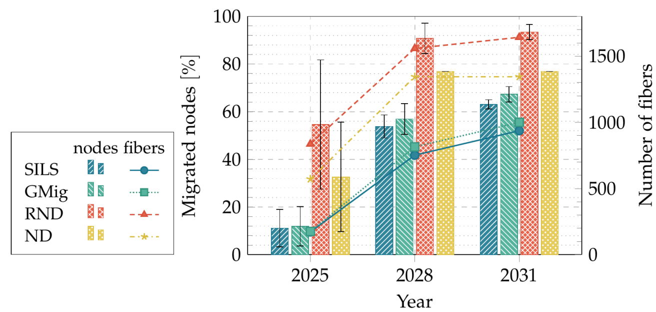


Fig. 2: Required percentage of migrated nodes during gradual migration for various algorithms along the years, US26 network topology.

The first observation is that for both network topologies, SILS algorithm outperforms reference ones. Secondly, the improvement is better for the DT14 network topology — e.g., for 2028 year, SILS is better than GAlloc algorithm by around 14.3% and 3.0% (in terms of the % of migrated nodes) for DT14 and US26 network topology, respectively. Further, ND migration immediately hits 100% migration ratio for the DT14 network topology, due to the lower number of nodes, while for US26 this strategy provides results between GAlloc and random migration. Moreover, the number of active fibers increases proportionally to the number of migrated nodes. Finally, taking into consideration the values from Table I, the DT14 network can accommodate a much higher amount of traffic for the same year with a lower ratio of migrated nodes. For example, for 2028 year in the US26 network, 226.9 Tbit/s of summary traffic can be allocated migrating 53.9% nodes, while in the DT14 network up to 453.8 Tbit/s when

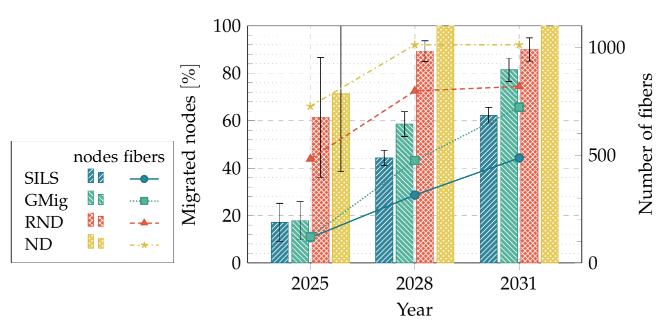


Fig. 3: Required percentage of migrated nodes during gradual migration for various algorithms along the years, DT14 network topology.

44.3% nodes are migrated. This is the consequence of shorter average link length in DT14 network, thus, higher percentage of requests can apply more spectrally efficient MFs when compared to the US26 network.

TABLE II: Average execution time [s] along the years.

Year	SILS	GMig	RND	ND
2025	52.40	0.07	0.10	0.14
2028	382.43	0.20	0.16	0.24
2031	402.03	0.25	0.23	0.09

Table II presents average execution time in seconds along the years, averaged for both network topologies. The proposed SILS metaheuristic requires higher computational time when compared to reference algorithms. Execution times for reference heuristics are quite similar and the differences between them are in order of tens of milliseconds which may be highly affected by the execution environment. Despite higher SILS computational time, it is worth noting that it requires at most less than 7 minutes (for 2031), which is fully acceptable taking into the account the characteristic of problem and available time to compute the solution.

C. Comparison of Different Unicast to Anycast Traffic Rations

In this section, we compare the efficiency of the migration algorithm in the presence of different ratios of anycast and unicast traffic along the years. In more detail, for each year, the overall traffic corresponds to the values presented in Tab. I; however, only city-to-city (unicast) and city-to-dc (anycast) traffic are considered. Six different scenarios, with different ratios of unicast/anycast traffic, have been investigated, namely, 1.0/0.0, 0.8/0.2, 0.6/0.4, 0.4/0.6, 0.2/0.8 and 0.0/1.0. For example, the 0.8/0.2 scenario indicates that 80% and 20% of the traffic is unicast and anycast, respectively.

As can be observed in Fig. 4 for the US26 network scenario, the growth of the percentage of migrated nodes along the years is quite steady. Moreover, an increasing amount of anycast traffic allows decreasing migrated nodes in each year significantly. For example, in 2028, the difference between 1.0/0.0 and 0.6/0.4 is equal to 15.7%, and between 0.6/0.4 to 0.2/0.8 equals 51.2%. The reason is that increase of anycast traffic ratio results in higher number of connections on shorter distances, i.e., the connections to the nearly located DCs. Thus, higher percent of demands is realized using more efficient MFs. In consequence, higher traffic load can be realized in the same stage of network migration, which postpones the migration. As the results obtained for the DT14 network topology have similar trends and support this conclusions, they are not included in the paper.

VI. Concluding Remarks

In this work, we present SILS algorithm for brown-field migration planning problem from EONs toward SS-FONs. According to the obtained results, our proposed SILS algorithm outperforms reference ones postponing network migration. As a consequence, potential expenditures related to migration may be realized over the years. Further, we compare the impact of anycast to unicast traffic ratio on migration planning performance, showing that the increase of anycast traffic result with lower migration ratio. As a future work, we plan to design machine learning based methods for EON to SS-FON migration planning.

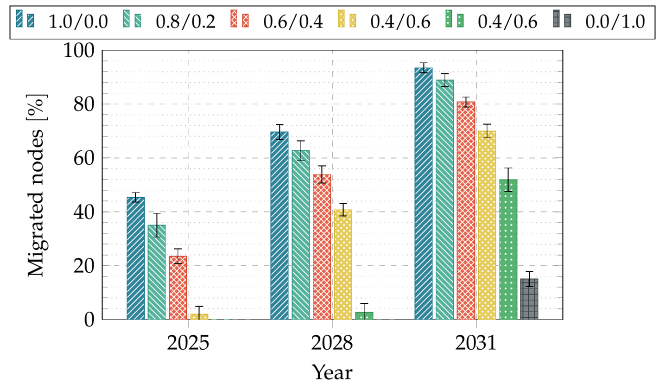


Fig. 4: Percentage of migrated nodes along the years for various unicast/anycast traffic ratios for the US26 network topology.

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