Optical Switching and Networking 13 (2014) 63–75

Contents lists available at ScienceDirect

Optical Switching and Networking

journal homepage: www.elsevier.com/locate/osn

Routing and spectrum allocation algorithms for elastic optical networks with dedicated path protection

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ARTICLE INFO

Article history:
Received 29 August 2013
Received in revised form
10 January 2014
Accepted 4 February 2014
Available online 13 February 2014

Keywords:
Elastic optical network
Routing and spectrum allocation
Dedicated path protection
Optimization algorithm

ABSTRACT

Elastic optical network (EON) architectures have been recently proposed as a candidate solution for provisioning of both huge bandwidth and flexible connections in next generation optical networks. In this paper, we focus on survivable EON scenarios and, in particular, we address an offline problem of routing and spectrum allocation (RSA) with dedicated path protection (DPP) in EON. We formulate RSA/DPP as an Integer Linear Programming (ILP) problem. Since RSA is a difficult problem itself, we propose to apply a metaheuristic approach to provide near-optimal solutions to RSA/DPP. Namely, we develop a Tabu Search-based algorithm (TS), and a hybrid Adaptive Frequency Assignment-TS (AFA/TS) algorithm. We investigate the efficiency of the algorithms for a set of network and DPP scenarios and we show that the proposed algorithms outperform other reference algorithms. Eventually, we present some comparative results for different path protection scenarios.

1. Introduction

The communication networking is undergoing fundamental changes which are governed by the development and integration of diverse network technologies and applications within a unified Internet Protocol (IP) packet-oriented network infrastructure. The observed trends result in an exponential growth of the traffic generated by network users and in the need for efficient and flexible optical transport networks able to support multi-rate and huge-bandwidth (100+Gb/s) connections. The currently deployed wavelength division multiplexing (WDM) optical networks operate within a rigid frequency grid and with single-line-rate transponders making use of single carrier modulation techniques. The evolution path of optical transport networks can be translated to the application of advanced single-carrier modulation formats (such as Phase-Shift Keying and Quadrature Amplitude Modulation), the introduction of multi-carrier transmission techniques (such as Optical Orthogonal Frequency Division Multiplexing), and the elastic access to spectral resources within flexible frequency grids (*flexgrid*) [1,2]. Thanks to these advances, future Elastic Optical Networks (EON) will utilize the spectrum resources more efficiently, adaptively, and according to the transmission path characteristics and bandwidth requirements.

In a flexgrid-based EON, the optical frequency spectrum is divided into narrow frequency *slices* (in the literature, also called as frequency *slots*) [3]. Any sequence of consecutive slices can be used as one channel, and such a channel can be switched in the network nodes to create an optical path (*lightpath*). Elastic spectrum allocation in EON differs with channel assignment in conventional fixed-grid wavelength division multiplexing (WDM) networks in that the channel width is not rigidly defined but it can be tailored to the actual width of the transmitted signal. Due to this difference, ordinary Routing and Wavelength Assignment (RWA) algorithms are not appropriate for EON.

In EON, the problem of finding unoccupied spectrum resources so that to establish a lightpath is called the Routing and Spectrum Allocation (RSA) problem. RSA concerns assigning a contiguous fraction of frequency

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http://dx.doi.org/10.1016/j.osn.2014.02.002
1573-4277

spectrum to a connection request – we refer to it as the *spectrum contiguity* constraint – subject to the constraint of no frequency overlapping in network links. The RSA optimization problem is $\mathcal{NP}$–hard [4] and it is more challenging than RWA in fixed grid WDM networks. Offline RSA has been addressed with both Integer Linear Programming (ILP) formulations [4–7], meta-heuristics (such as simulated annealing [5] and evolutionary algorithms [8,9]), and with heuristic algorithms, which are based either on ILP relaxations [5] and ILP decomposition methods [10] or on greedy, sequential processing of demands [5,11].

The problem of network survivability has been widely studied in conventional WDM networks (e.g., see [12,13]). Although the research on elastic optical networks is still in its infancy, the huge interest in the community concerning EON has resulted in several proposals for survivable EONs as well. Regarding offline network design, survivable RSA algorithms for dedicated path protection (DPP) and shared backup path protection (SBPP) in a ring network have been studied in [14]. DPP in a network with generalized connectivity has been addressed with both ILP formulations [15,16] metaheuristic [9], and heuristic algorithms [15,17,18]. Besides, the authors of [19] have proposed an ILP formulation and a heuristic algorithm for the survivable multipath RSA problem with DPP. A span restoration scenario was addressed with an ILP formulation in [20]. A power-aware routing and spectrum allocation algorithm with DPP and under varying traffic demands has been studied in [21]. Concurrently, ILP formulations [22–24], a metaheuristic algorithm [25], and heuristic algorithms [22–24,26,18] have been proposed for SBPP. In [27], a MILP formulation and a heuristic algorithm have been presented for the so-called squeezed protection scheme in which the protection of a lightpath may not cover its entire bandwidth but it is allowed to be partial. Eventually, dynamic survivable EON scenarios have been studied in [28,29]. All these solutions assure single-link failure survivability.

In this paper, we address an offline RSA problem with DPP consideration in an EON scenario with static traffic demands and subject to single-link failures. Recently, in [15], we have focused on RSA/DPP and we have shown that our novel Adaptive Frequency Assignment (AFA) heuristic algorithm provides better solutions than other algorithms from the literature. Here, we extend this study by considering an alternative algorithmic approach, in particular, we propose a Tabu Search-based (TS) algorithm to solve the RSA/DPP problem. TS is an effective metaheuristic for providing near-optimal solutions for large-scale optimization problems [30]. As shown in Section 5, both our TS algorithm and its hybrid extension which combines AFA with TS (referred to as AFA/TS) outperform other reference algorithms.

The main contribution of the paper is the proposal and evaluation of an efficient Tabu Search-based algorithm developed for solving the RSA/DPP optimization problem. To the best of our knowledge, there is no prior work on applying TS for solving RSA in EON. An additional contribution is the evaluation and comparison of SBPP, DPP, and no-protection scenarios with respect to their spectrum requirements.

The remainder of the paper is organized as follows. In Section 2, we describe an EON scenario. In Section 3, we formulate RSA/DPP as an ILP problem. In Section 4, we present our Tabu Search-based algorithm. In Section 5, we provide numerical results. Finally, in Section 6 we conclude the work.

2. Elastic optical network scenario

2.1. Flexible frequency grid

It is very likely that system vendors and network operators will opt for EON solutions that are compatible with existing standards. ITU-T has recently revised the G.694.1 recommendation and included the definition of a flexible DWDM grid [3]. Concurrently, IETF has been working on flexgrid extensions to signalling protocols [31–34]. Both ITU-T and IETF flexgrid definitions are very alike and they are backward compatible with the fixed DWDM grid (Fig. 1A).

According to [3], a flexgrid consists of a set of nominal *central frequencies* (CF) and a set of frequency slices, where each slice occupies the space between two CFs (see Fig. 1B). In [3], nominally, the CF granularity, i.e., the spacing between neighboring CFs, and the slice width is equal to $\Delta_f = 6.25$ GHz.

Moreover, an optical channel has flexibly (ad hoc) assigned spectrum, which covers both the frequency range occupied by the optical signal and the guard band required for the roll-off filters. The channel occupies the spectrum symmetrically around a CF, and the CF is the center of the channel (see Fig. 1B). Due to the symmetrical spectrum allocation, the channel consists of an even number of slices and, therefore, its width is a multiple of $2\Delta_f = 12.5$ GHz. In this paper, we focus on a network which implements such a flexible grid.

2.2. Network architecture

Two components are essential for EON architectures, namely, bandwidth-variable transponders (BV-T) and bandwidth variable wavelength cross-connects (BV-WXC). The role of BV-T is to adapt the client data signal to be sent to/received from the optical network using just enough frequency resources [35]. Concurrently, BV-WXC allow one to create an optical routing path through the network by

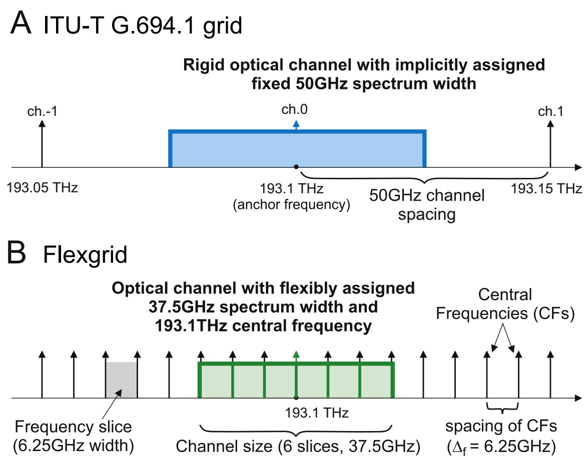

Fig. 1. (A) Fixed DWDM grid (with 50 GHz channel spacing) and (B) flexible grid (with 6.25 GHz spacing between central frequencies).

switching transmitted signals within their frequency bandwidth to appropriate switch output ports [36].

In a network, each optical connection has allocated a channel, which size is a function of the requested bandwidth, the modulation technique applied, the slice width, and the guard band introduced to separate two spectrum adjacent connections, among others. Once the requested frequency resources are allocated on each link belonging to the routing path, the optical connection can be used to convey single-carrier (m-PSK, m-QAM) or multi-carrier (O-OFDM) modulated signals [37]. We refer to some recent papers for more details on EON architectures [38,39] and for reports on proof-of-concept EON experiments [40–42].

Elastic optical networks and, especially, data-rate adaptive BV-Ts bring new capabilities in the context of network survivability when comparing with fixed (rate-specific) technologies. Firstly, BV-Ts can reduce the required spare resources since a single backup transponder can be shared between connections of different bit-rates [43,44]. Secondly, in restoration scenarios, the connection bandwidth (and bit-rate) can be "squeezed" whenever there is not enough spectrum resources for restoring the whole demand [45]. By these means, the number of surviving connections may be increased in the network [27]. Eventually, when using a reach-adaptable BV-T, i.e., such that it adjusts its capacity according to the transmission path characteristics (e.g., the transmission distance), its capacity can be still re-used on a backup path, however, it may be reduced due to the usually worse quality of the backup path.

3. Dedicated path protection problem in EON

In this section, we focus on ILP modelling of an offline problem of Routing and Spectrum Allocation with Dedicated Path Protection (RSA/DPP) in an EON with static traffic demands and subject to single-link failures. First, we discuss the considered path protection scenario and then we formulate the model. The model is used as a reference in the evaluation of the algorithm proposed in Section 4.

3.1. DPP scenarios

Among network survivability schemes, connection recovery through path protection, in which backup network resources (i.e., lightpaths) are provisioned in advance for each connection, is preferred due to its quick recovery time. In EON, network resources correspond to spectrum resources in optical fiber links and path protection is equivalent with provisioning backup lightpaths for working lightpath connections.

In DPP, each connection has its own backup resources, on the contrary to SBPP, in which backup resources can be shared between the demands whose primary paths are not likely to fail at the same time [46,47]. Thanks to this property, signalling complexity of DPP is lower than in SBPP.

In [15,17], there are distinguished two alternative scenarios for EON with path protection capability, namely:

- with Same Channel (*SC*) allocation;
- with Different Channel (*DC*) allocation.

Case SC is a cost-effective scenario in which the transponders are shared between primary (working) and backup connections and a traffic demand has allocated the same segment of optical frequency spectrum (i.e., channel) on its primary and backup path. Such a solution reduces the network cost and alleviates the connection switching time [17]. In the DC case, the SC constraint of having the same operating channel in both primary and backup connections is relaxed, by these means, reducing spectrum requirements in the network [15,17]. One way to implement this scenario is to install dedicated (for both working and backup lightpaths) transponders. However, this is an expensive approach since it doubles the cost of transponders installed in the network. An alternative solution is to use laser-tunable transponders which are able to modify the central frequency of the transmitted optical signal [48,49].

In the DC case, the SC constraint of having the same operating channel in both primary and backup connections is relaxed, at the cost of installing either tunable or dedicated (for both working and backup lightpaths) transponders.

In the following, we formulate the RSA/DPP problem in EON and we present ILP formulations of RSA/DPP under SC and DC constraints, which are denoted, respectively, as RSA/DPP/SC and RSA/DPP/DC.

3.2. Problem statement

The considered RSA/DPP problem can be formally stated as follows:

Given:

1. an EON represented by a directed graph $\mathcal{G}=(\mathcal{V},\mathcal{E})$, where $\mathcal{V}$ denotes the set of nodes, and $\mathcal{E}$ denotes the set of fiber links connecting two nodes in $\mathcal{V}$;
2. a frequency spectrum, the same for each link in $\mathcal{E}$ (without loss of generality), with the flexgrid represented by an ordered set of frequency slices $\mathcal{S}=\{s_1, s_2, \ldots, s_{|\mathcal{S}|}\}$;
3. a set $\mathcal{D}$ of static traffic demands to be transported with path protection guarantees; each demand d is represented by a tuple (o_d, t_d, n_d), where o_d and t_d are source and destination nodes, respectively, and n_d is the requested number of slices.

Find a primary lightpath and a backup lightpath over the EON for every transported demand subject to *constraints*:

1. *spectrum contiguity*: for each demand, the slices should be allocated each next to the other (i.e., adjacent) in $\mathcal{S}$;
2. *spectrum continuity*: for each demand, the subset of allocated slices should be the same for each link on the selected routing path;
3. *slice capacity*: a slice in a link can be allocated to one demand at most;
4. *same channel* (applies only for RSA/DPP/SC): for each demand, the primary and backup lightpaths should have allocated the same subset of slices;

and with the *objective* to minimize the width of spectrum resources (denoted as Φ) required in the network, similarly as in [22,15,17,14]. In particular, Φ corresponds to the largest slice index among all slices allocated in network links and it determines the width of spectrum that the network should support in a green-field network design [7].

The requested number of slices (n_d) is a function of the requested bandwidth, the modulation technique applied, the slice width in the flexgrid, and the guard band introduced to separate two spectrum adjacent connections, among others. For a given network scenario, where both the transmission parameters and flexgrid definitions are given, there is a relation between n_d and the requested bandwidth (e.g., see [5, Section II]). Therefore, without loss of generality, the demand volumes are expressed by means of the number of slices. Assuming the flexgrid definition presented in Section 2.1 and its requirement to have the spectrum allocated symmetrically around a central frequency, n_d is considered to be an even number, i.e., $n_d = 2i_d$, where $i_d \in \mathbb{Z}^+$. For more details, we refer to [3].

3.3. ILP formulation of RSA/DPP

We take a similar approach as in [6] for formulating the RSA/DPP problem as an ILP problem. In particular, a set of candidate optical channels is considered, where each channel consists of a subset of adjacent slices, and the RSA problem consists in finding a route and assigning a channel to a demand. By these means, the spectrum contiguity constraint is not involved explicitly into the problem constraints as in other ILP formulation presented in the literature [5,11,7]. Consequently, the proposed formulation is simple and more efficient (see [6]).

Channel c is defined as a contiguous (adjacent) subset of slices in ordered set $\mathcal{S}$, i.e., $c \subseteq \mathcal{S}$. Let $|c|$ denote the number of slices forming channel c. Assuming the flexgrid definition in [3], each channel covers an even number of slices (see Fig. 2). Let $\mathcal{C}_d$ denote the set of admissible candidate channels for demand d, i.e., $\mathcal{C}_d = \{c : |c| = n_d\}$. In this paper, we consider that each $\mathcal{C}_d$ consists of all candidate channels that can be defined in $\mathcal{S}$; since spectrum contiguity is ensured then, by counting, $|\mathcal{C}_d| = |\mathcal{S}| - n_d + 1$. Let $\mathcal{C}$ denote the set of all channels, i.e., $\mathcal{C} = \bigcup_{d \in \mathcal{D}} \mathcal{C}_d$.

We use the link-path modelling approach [50] and we consider that a set of candidate routing paths is given. Let $\mathcal{P}$ denote the set of all candidate paths. Each path $p \in \mathcal{P}$ is identified with a subset $p \subseteq \mathcal{E}$, and a subset $\mathcal{P}_e \subseteq \mathcal{P}$ identifies all paths that go through link e. Let $\delta_{pe} = 1$ whenever path p goes through link e and $\delta_{pe} = 0$ otherwise. Let $\mathcal{Q}$ denote the set of pairs of paths (p, q), where $p \in \mathcal{P}$ is a primary path and $q \in \mathcal{P}$ is a backup path; in this paper,

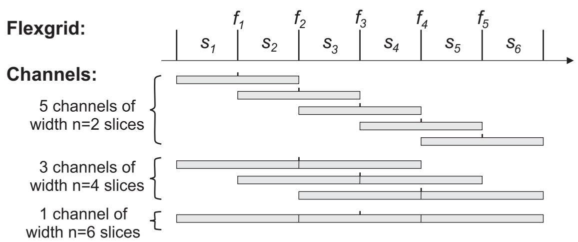

Fig. 2. A set of candidate channels in a flexgrid consisting of $|\mathcal{S}| = 6$ slices.

we consider that $\mathcal{Q}$ is a set of link disjoint path pairs. Let $\mathcal{Q}_d$ denote the set of path pairs for demand $d \in \mathcal{D}$; each set $\mathcal{Q}_d$ comprises only paths that have the origin in o_d and the termination in t_d.

We introduce a set of *problem variables*:

$y_{pc} \in \{0, 1\}$ – equal to 1 if channel c on primary path p is assigned to a protected lightpath, and equal to 0 otherwise;

$w_{qc} \in \{0, 1\}$ – equal to 1 if channel c on backup path q is assigned to a protected lightpath, and equal to 0 otherwise;

$x_s \in \{0, 1\}$ – equal to 1 if slice $s \in \mathcal{S}$ is occupied in any of network links, and equal to 0 otherwise;

$x_{es} \in \{0, 1\}$ – equal to 1 if slice $s \in \mathcal{S}$ in link $e \in \mathcal{E}$ is occupied, and equal to 0 otherwise.

We formulate a set of common *problem constraints*:

3.3.1. Primary lightpath selection

For demand d, a primary lightpath (i.e., a path-channel pair) is selected

$$\sum_{(p,q) \in \mathcal{Q}_d} \sum_{c \in \mathcal{C}_d} y_{pc} = 1, \quad d \in \mathcal{D}. \tag{1}$$

3.3.2. Slice capacity

A slice can be allocated to one lightpath at most (here, the disjointness property is used)

$$\sum_{d \in \mathcal{D}} \sum_{(p,q) \in \mathcal{Q}_d} \sum_{c \in \mathcal{C}_d : c \ni s} (\delta_{pe} y_{pc} + \delta_{qe} w_{qc}) = x_{es} \quad e \in \mathcal{E}, s \in \mathcal{S}. \tag{2}$$

3.3.3. Slice occupancy

A slice is considered as occupied in the network whenever there is a link in which it is occupied

$$\sum_{e \in \mathcal{E}} x_{es} \le |\mathcal{E}| x_s, \quad s \in \mathcal{S}. \tag{3}$$

The *objective function* represents the width of spectrum, in terms of the number of slices, required in the network:

$$\Phi = \sum_{s \in \mathcal{S}} x_s. \tag{4}$$

Eventually, we have two ILP formulations for the offline RSA/DPP optimization problem which differ in the primary/backup channel selection constraint:

(1) *RSA/DPP/SC* (*Same Channel*)

$$\textbf{minimize} \quad \Phi \tag{ILP1}$$

$$\textbf{subject to} \quad y_{pc} = w_{qc}, \quad d \in \mathcal{D}, \ (p,q) \in \mathcal{Q}_d, \ c \in \mathcal{C}_d, \tag{5}$$

and constraints (1)–(3).

Constraints (5) guarantee that whenever a channel is assigned to a primary lightpath on path p it is also selected for its backup lightpath on path q.

(2) *RSA/DPP/DC* (*Different Channel*)

$$\textbf{minimize} \quad \Phi \tag{ILP2}$$

$$\textbf{subject to} \quad \sum_{c \in \mathcal{C}_d} y_{pc} = \sum_{c \in \mathcal{C}_d} w_{qc}, \quad d \in \mathcal{D}, \ (p,q) \in \mathcal{Q}_d, \tag{6}$$

and constraints (1)–(3).

Constraints (6) allow one to assign different channels to the primary and backup lightpaths.

4. Tabu Search algorithm

Tabu Search (TS) method was introduced by Fred Glover in 1989. Originally, it was applied for the Traveling Salesman problem, however it can be adapted to solve a variety of optimization problems [51–54]. The basic idea of TS is a search through a neighborhood of the current solution in order to improve the final result. The TS method uses two key elements: Tabu Move (TM) and Tabu List (TL). The former element denotes a move, which consists in a change of one solution into another (neighbor) solution. The latter element is a form of a memory structure used to store TMs. The algorithm starts with an initial solution (a reference solution). Next, the reference solution is slightly changed (by applying the TM). However, only TMs not included in the TL are feasible. If the obtained neighborhood solution is better than the reference solution, the neighborhood solution is selected as the reference one and the TM which led to the improvement is added into the TL. Then, the next iteration of the algorithm is run. In the TS method, there are two parameters, which may be tuned to improve the performance of the algorithm: Tabu List Size (TLS) and Depth of Search (DS). TLS parameter determines how long a TM should be remembered (locked) during the work of the algorithm. DS parameter indicates how deeply a neighborhood is evaluated before going back to referential solution. The higher the value of DS, the bigger the neighborhood that will be examined, however the number of iterations of TS has to be increased in order to maintain high accuracy of the search. Too small size of the TL may lead to a situation when neighborhood solutions are not examined with a satisfying accuracy. On the other hand, too large values of this parameter may result in finding only a local optimum.

Now we will describe the implementation of the Tabu Search method developed to solve the RSA/DPP problem. For ease of reference we call the algorithm TS. The first element of TS is a method to generate the initial solution. Since the initial solution may have a strong influence on the quality of the final result, three different methods are proposed: First Assign Allocation (FA), Random Allocation (RND), and Sorted Allocation (SRT). A pseudo-code of the methods is shown below.

- *First Assign Allocation* (demands are processed according to their initial order)
  1. For each demand $d \in \mathcal{D}$:
     (a) Choose first candidate path pair $(p,q) \in \mathcal{Q}_d$.
     (b) Search for candidate channel $c \in \mathcal{C}_d$ that has the lowest slice index and which has slices not occupied on path pair (p,q).
     (c) Allocate demand d using path pair (p,q) and slices $s \in c$.
- *Random Allocation* (demands are processed in random order)
  1. Sort set $\mathcal{D}$ randomly.
  2. For each demand $d \in \mathcal{D}$:
     (a) Choose randomly path pair $(p,q) \in \mathcal{Q}_d$.
     (b) Search for candidate channel $c \in \mathcal{C}_d$ that has the lowest slice index and which has slices not occupied on path pair (p,q).
     (c) Allocate demand d using path pair (p,q) and slices $s \in c$.
- *Sorted Allocation* (demands are processed in specific order – they are sorted according to decreasing value of demand size)
  1. Sort set $\mathcal{D}$ according to decreasing value of demand size n_d.
  2. For each demand $d \in \mathcal{D}$:
     (a) Search for candidate path pair $(p,q) \in \mathcal{Q}_d$ such that there is channel $c \in \mathcal{C}_d$ not occupied on (p,q) which has the lowest slice index.
     (b) Allocate demand d using path pair (p,q) and slices $s \in c$.

Besides, the elementary parameters used by the algorithm (i.e., TLS and DS), TS uses Worsening Criterion (WC) and Worsening Factor (WF). The former one is a mechanism, which is used to expand the neighborhood used in the search process. When WC is reached, the current neighborhood of the reference solution is expanded by the latter parameter which allows the algorithm to leave the potential local optimum. WC is defined as the number of iterations, which have passed since the last improvement of the solution occurred. In practice, when TS cannot find a better solution for some iterations (possible local optimum has been found), the WC is reached and the current reference solution is weakened by WF.

Moreover, TS applies an additional short-term memory structure – Used Tabu Moves List (UTML), which stores moves that have not improved the solution. UTML is used in the process of TM generation, i.e., it improves the efficiency by preventing the algorithm from evaluating an already examined candidate solution. When a new reference solution is found, the UTML is cleared allowing the whole new neighborhood to be examined. Evaluating a solution of RSA/DPP problem becomes computationally demanding adequately to the number of network nodes and number of demands. Thus, UTML eliminates the possibility of generating the same TM, if it was evaluated in one of previous iterations and solution improvement did not occur.

Now we focus on the RSA/DPP problem coding used in TS. Recall that in order to solve RSA/DPP problem for each demand, we must determine the pair of paths (among candidate pairs of paths) and the set of slices (channel). However, the order in which the demands are processed has a strong influence on the quality of the solution. Therefore, each unique solution considered in the algorithm contains two elements specifically determining the solution:

- The order in which all demands are processed by the algorithm. For ease of reference, we also call the order of demands as a demand processing queue.
- Index of candidate pair of paths and set of slices (channel) selected for each demand – allowing each demand to be allocated with respect to the model constraints.

According to the presented above coding of the algorithm, TS includes two types of Tabu Moves:

- Demand Swap – two demands placed in the processing queue are swapped, i.e., the processing order of demands is changed. The Demand Swap move operates on two randomly chosen demands from a set of demands. If those demands are not on the Tabu List, their order in the processing queue is swapped. Until chosen demands are on Tabu List new demands are randomly generated (Fig. 3).
- Path Change – a pair of paths is changed for a particular demand. In more detail, during the process of generation of the Path Change move also two random values are generated. The first value selects a demand which will be processed, the second one denotes a number of candidate pair of paths which will be used for this selected demand. The slice selection is made as in the First Fit algorithm [14], i.e., the allocation providing the smallest value of the selected slice index (Fig. 4).

The decision which Tabu Move is used is made at random with 0.4 probability for the Demand Swap and 0.6 probability for the Path Change. If applying the TM resulted in an improvement of the previous solution, then demands which were affected by this TM are added to the TL and for some time (defined by the TLS parameter) they cannot be changed. TS uses TMs to alter the Reference Solution (recall that Initial Solution is the Reference Solution at the first iteration of the algorithm) in order to obtain a solution providing a more satisfying objective function. In each iteration demands are processed with respect to the order taken from the reference solution.

The quality of a solution generated in each iteration of TS algorithm is calculated according to the following procedure. Having the solution, a particular processing queue (order of demands) is given. Therefore, demands are processed sequentially with respect to this processing queue. For each demand, all candidate pairs of paths are examined, i.e., the algorithm tries to allocate the demand to a particular pair of paths and for each pair of paths finds the best allocation of slices taking into account already made allocations, since some slices are already allocated to previously processed demands. The pair of paths yielding the smallest value of used slice index is selected. When the value of the new solution provides lower value of the objective function than all previously analyzed solutions, it is assigned as the new Reference Solution. Moreover, UTML is cleared and a new iteration is started. The overall scheme of the algorithm is shown in Fig. 5.

For more details on the algorithm refer to [55].

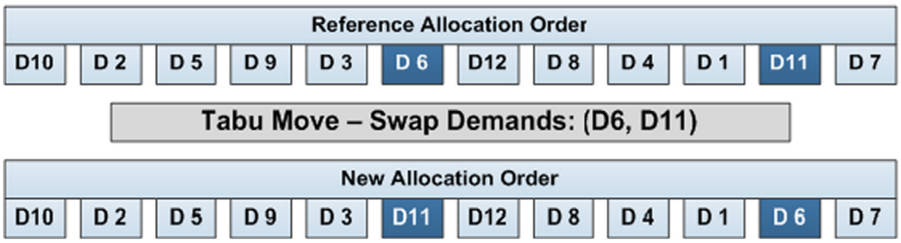

Fig. 3. Demand Swap operation of TS.

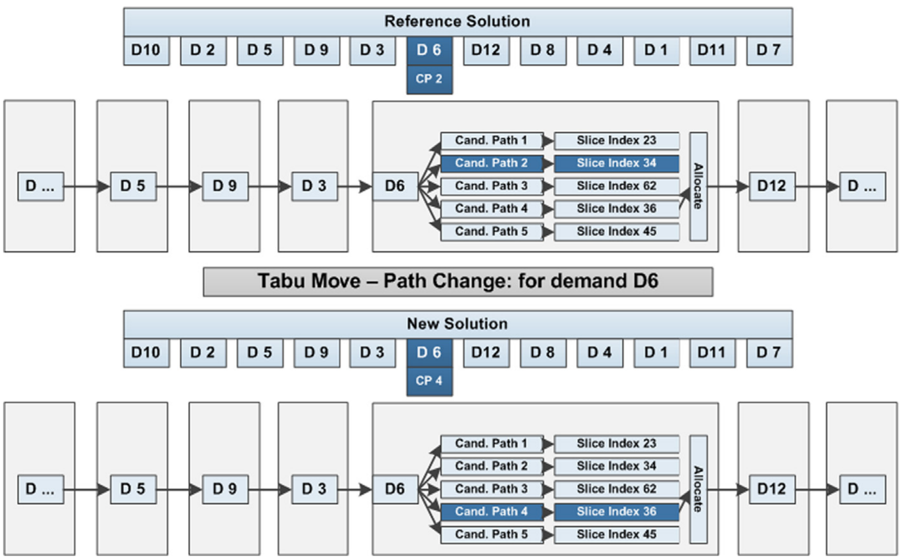

Fig. 4. Path change operation of TS.

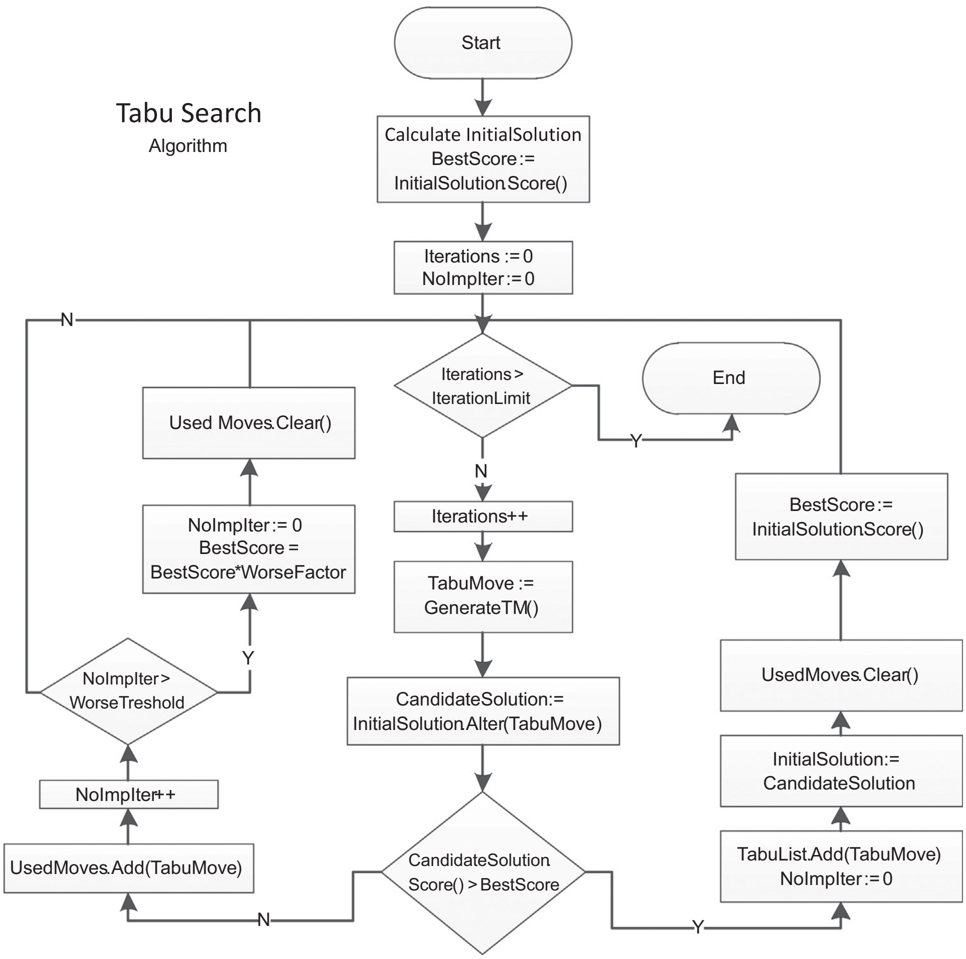

Fig. 5. Diagram of TS.

5. Numerical results

In this section, we evaluate the performance of our *TS* algorithm and its hybrid *AFA/TS* extension, and compare it with other reference algorithms. Our main focus is on the occupied spectrum width (Φ), in terms of the number of frequency slices, and computation time (T). As the reference algorithms we use:

- *FF*: a Fixed-alternate routing and First-fit frequency assignment algorithm [14].
- *LSF* and *MSF*: two RSA algorithms based on greedy processing of demands according to: (1) the length of routing path (LSF), and (2) the number of requested slices (MSF) [5].
- *AFA*: a heuristic RSA algorithm that adaptively chooses the sequence of processed demands; the adaptation of AFA to a DPP scenario has been presented in [15].

It should be noted that FF, LSF, and MSF were originally developed in the context of the RSA problem without additional survivability constraints in mesh networks. Therefore, we modified these methods in order to address new constraints following the application of the DPP approach. Additionally, for small network scenarios, we provide optimal results obtained with *ILP* formulations. We evaluate both channel allocation scenarios defined in Section 3.1, namely: (a) Different Channel (*DC*) and (b) Same Channel (*SC*). All heuristics are implemented in C. We use IBM ILOG CPLEX v.12.4 [56] (with default settings) to solve ILP. The evaluation is performed on an Intel *i*5 3.3 GHz 16 GB computer.

We study SIMPLE6 (6 nodes, 16 links), INT9 (9 nodes, 26 links), NSF15 (15 nodes, 46 links) and UBN24 (24 nodes, 86 links) network topologies (see Fig. 6). Apart from ILP, for which we consider $|\mathcal{S}| = 48$, we set $|\mathcal{S}| = 1500$, which is large enough to accommodate all demands without blocking in the most demanding scenario; in other words, $\Phi \le |\mathcal{S}|$. Candidate pairs of primary-backup paths are link disjoint and they are calculated (and ordered) as shortest paths, taking into account the overall length of both paths. We consider $k \in \{2, 3, 5, 10, 30\}$. The requested spectrum n_d is an even number and it is generated with uniform distribution and for randomly selected demand pair (o_d, t_d), where $o_d, t_d \in \mathcal{V}$ and $o_d \neq t_d$. In particular, n_d is randomly selected from set $\{2, 4, \ldots, N\}$ where, depending on the scenario, N is equal to either 8 or 16. If not

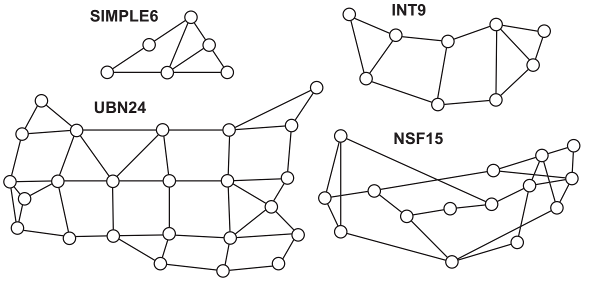

Fig. 6. Network topologies.

Table 1
Values of tuning parameters used in the experiments.

Parameter name	Analyzed values	Selected value
Iteration limit	500	500
Tabu list size	3,5,8,10,12,15,17,20	10 (5% of the number of demands)
Depth of search	1,2,3	1
Worsening criterion	20% of Iteration Limit	20% of Iteration Limit
Worsening factor	0.1	0.1
Initial solution method	FA, RND, SRT	SRT

mentioned otherwise, the results are averaged over 100 randomly generated demand sets.

5.1. *Tuning of TS algorithm*

The first goal of experiments is to tune the TS algorithm, i.e., to find most effective values of all tuning parameters that influence the performance of TS. The experiments related to tuning of TS are made for the following assumptions: NSF15 network, DC scenario, $k=10$, and 10 of 100 randomly selected demand sets.

Initially, we focus on the selection of an appropriative method for calculating the initial solution. In Table 1, we report values of tuning parameters selected to perform the experiments, the values were chosen according to some preliminary experiments and our experience in the field of Tabu Search algorithms. For each demand set, the experiment was executed 10 times in order to get statistically significant results. Figs. 7 and 8 show the obtained results for each tested demand set, in the context of average and minimal results, respectively. In both figures we can easily notice that the SRT (Sorted Allocation) yields the best results, comparing to other methods.

Next, we concentrate on tuning of TLS and DS parameters. According to the above results, as the initial selection method we apply SRT. Other tuning parameters (if not stated otherwise) have the values as in Table 1. Again, the experiment was repeated 10 times for each demand set. In Table 2, the performance of TS as a function of TLS and DS parameters is shown as an average result over three different demand sets. Note that the second column TS/Demands denotes the TLS divided by the number of demands. We can notice that in general the impact of two analyzed parameters is not high, all

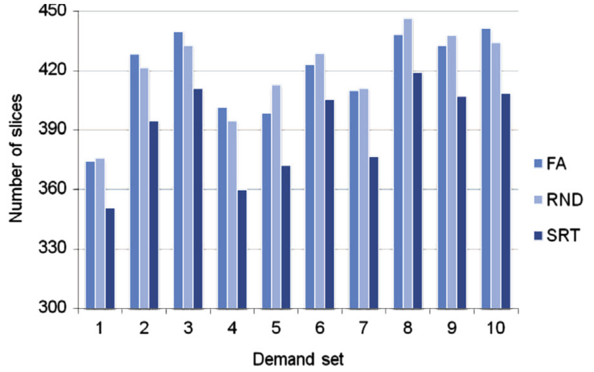

Fig. 7. The influence of the initial selection method on the TS performance—average results.

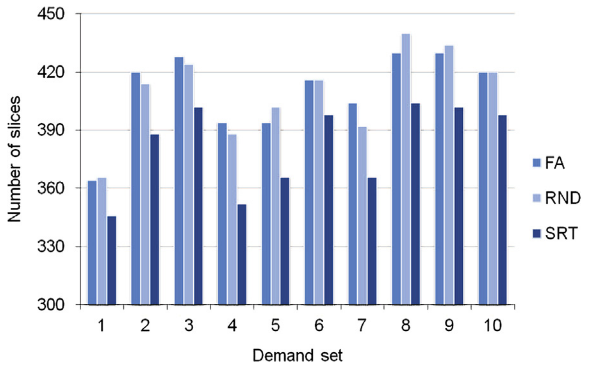

Fig. 8. The influence of the initial selection method on the TS performance—minimal results.

reported results are in the range from 410.53 to 415.33. Recall that the higher the value of DS, the larger the search space, but also more computational time is wasted to investigate potentially worse solutions. However, the solution space of the RSA/DPP problem is relatively big, consequently the increase of DS does not result in the improvement of the objective function. The experiment indicates that setting different values of TLS and DS parameters results only in minor changes in the objective function value. Higher values of TLS result in a slight decrease of the performance. In such a situation the memory structure is too big and it is blocking the algorithm from obtaining a better solution – TM which was once added into TL is never changed. Despite minor changes in the solution results, we decide to set DS to 1. In our opinion, the TLS is strictly connected to the set of demands size, since this parameter prevents a demand from being modified by the algorithm. Therefore, the TLS should depend on the number of demands. According to the results shown in Table 2, we set the value of this parameter for other tested network topologies as 5% of the number of demands. For instance, if there are 500 demands to allocate, TLS is equal to 25 (which is 5% of 500).

Finally, we focus on Iteration Limit parameter. In Figs. 9 and 10, we show the average results for three different demand sets and the average execution time, respectively.

Table 2
TS performance as a function of Tabu list size and depth of search parameters.

TLS	TLS/demands (%)	DS		
		1	2	3
3	1.43	411.67	413.33	411.27
5	2.38	412.40	410.80	412.13
8	3.81	412.73	413.40	411.93
10	4.76	410.53	413.60	413.40
12	5.71	411.60	412.53	412.93
15	7.14	414.87	414.00	412.93
17	8.10	413.53	413.60	415.33
20	9.52	413.87	413.73	414.67

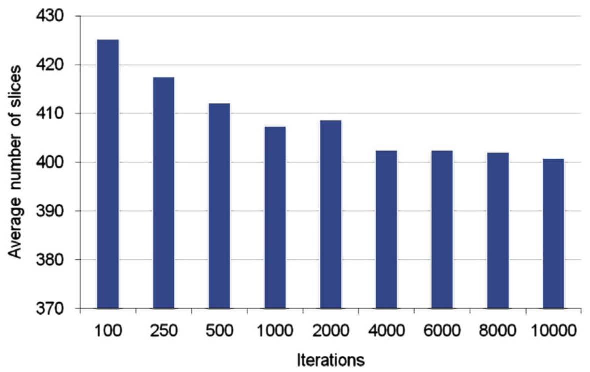

Fig. 9. The influence of the iteration number on the TS performance—average results; NSF15 network, $k=10$.

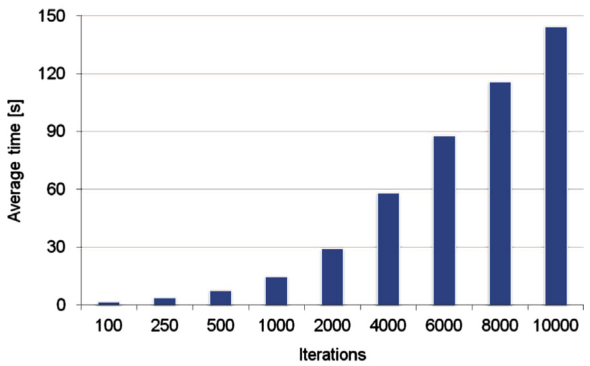

Fig. 10. The influence of the iteration number on the TS performance—execution time; NSF15 network, $k=10$.

Obviously, when the iteration number increases, the objective function decreases, however the execution time grows. In our opinion, the best trade-off between quality of results and execution time is obtained for the value of 500.

Above, we presented detailed analysis of four tuning parameters selection (i.e., Initial Solution Method, Tabu List Size, Depth of Search, and Iteration Limit). Other parameters were set according to our experience with Tabu Search methods. The tuning process is summarized in Table 1, where we show all parameters' values that will be used in further experiments.

Table 3
Optimality gap of heuristics.

Scenario		ILP		Optimality gap (%)				
Network	Channel	Φ	T (s)	FF	LSF	MSF	AFA	TS
SIMPLE6	SC	27.86	1004	11.47	2.81	6.13	1.66	0.03
	DC	25.28	1031	15.19	7.30	7.88	3.07	1.33
INT9	SC	34.79	22.6	11	3.98	7.67	2.83	0.32
	DC	33.61	9.4	10.1	4.90	7.94	3.69	1.08

Table 4
Width of 95% confidence intervals for results presented in Table 3.

Scenario		95% confidence interval				
Network	Channel	FF	LSF	MSF	AFA	TS
SIMPLE6	SC	2.20	1.18	1.89	0.83	0.04
	DC	2.29	1.71	1.88	1.14	0.63
INT9	SC	2.06	1.27	1.83	1.09	0.26
	DC	1.81	1.38	1.96	1.29	0.69

5.2. Tabu Search versus optimal results for small networks

In Table 3, we compare performance results of heuristic algorithms with the optimal results yielded by the ILP solver in small network scenarios. We consider $|\mathcal{D}|=10, k=3$ and $|\mathcal{D}|=15, k=2$, respectively, for SIMPLE6 and INT9, and $n_d \in \{2,4,6,8\}$ for both networks. In INT9, ILP has reached optimality in a 2 h period only for 88 out of 150 cases, therefore the results are averaged over these 88 demand sets. We can see that TS outperforms other heuristics and it achieves near-optimal solutions in the evaluated cases. The computation time of FF, LSF, MSF and AFA is below 2 ms on average. The TS method requires on average 0.6 s and 2.1 s for the SIMPLE6 and INT9 networks, respectively. In Table 4, we report the corresponding lengths of 95% confidence intervals.

5.3. Tabu Search versus other heuristics for larger networks

In Tables 5 and 6, we present performance results obtained with heuristic algorithms in larger networks (i.e., NSF15 and UBN24). To make the comparison of algorithms we apply the following procedure. For each unique test we run each heuristic. Next, we find the best results among all algorithms. Finally, for each algorithm we calculate the percentage difference to the best result. In the experiments we set, $|\mathcal{D}|=210$ and $|\mathcal{D}|=552$, respectively, for NSF15 and UBN24, and $n_d \in \{2,4,\ldots,16\}$ for both networks. We report results for all tested values of the number of candidate paths k. Recall that for each case (topology, path set, and channel scenario) 100 unique demand sets were tested. In Table 5, we show the average distance to minimum result and corresponding values of lengths of 95% confidence intervals regarding the average distance to minimum results. Table 6 includes the number of first places (of 100 cases) that particular algorithms achieved in a given test and the average execution time.

Table 5
Average distance to minimum results and lengths of 95 confidence intervals.

Scenario			Average distance to minimum result						Lengths of 95 confidence intervals					
Network	Channel	k	FF (%)	LSF (%)	MSF (%)	AFA (%)	TS (%)	AFA/TS (%)	FF (%)	LSF (%)	MSF (%)	AFA (%)	TS (%)	AFA/TS (%)
NSF15	SC	2	21.1	13.8	5.7	2.1	1.4	**0.0**	0.59	0.67	0.49	0.36	0.30	0.03
		3	22.1	11.9	4.8	0.8	1.5	**0.0**	0.61	0.65	0.48	0.23	0.32	0.01
		5	22.7	12.6	5.6	1.6	2.5	**0.0**	0.60	0.70	0.48	0.32	0.36	0.00
		10	27.6	11.0	4.0	**0.1**	6.2	**0.1**	0.52	0.65	0.51	0.10	0.44	0.09
		30	30.3	11.5	2.3	0.6	10.4	**0.5**	0.59	0.63	0.49	0.21	1.16	0.20
	DC	2	19.1	12.4	6.3	3.0	1.2	**0.0**	0.97	0.91	0.61	0.41	0.23	0.00
		3	21.9	11.8	6.2	2.7	1.3	**0.0**	0.85	0.82	0.59	0.45	0.24	0.00
		5	22.5	12.5	6.9	3.4	1.6	**0.0**	0.84	0.78	0.61	0.53	0.37	0.00
		10	28.8	8.6	4.1	0.6	2.6	**0.1**	0.82	0.50	0.48	0.24	0.51	0.07
		30	31.8	11.0	3.7	0.1	4.1	**0.0**	0.93	0.49	0.38	0.06	0.42	0.02
UBN24	SC	2	15.7	5.9	4.4	0.9	1.6	**0.0**	0.38	0.37	0.30	0.19	0.20	0.00
		3	19.0	4.8	3.7	0.5	2.8	**0.0**	0.44	0.44	0.33	0.15	0.28	0.01
		5	25.7	8.8	8.1	0.1	8.4	**0.0**	0.46	0.51	0.46	0.09	0.37	0.00
		10	31.4	8.9	8.5	**0.0**	14.1	**0.0**	0.53	0.55	0.57	0.01	0.45	0.00
		30	34.2	7.2	3.8	0.3	3.4	**0.0**	0.48	0.54	0.41	0.16	0.51	0.03
	DC	2	17.3	5.5	3.8	0.6	1.7	**0.0**	0.54	0.51	0.38	0.18	0.24	0.03
		3	24.7	5.8	5.2	0.4	5.4	**0.0**	0.52	0.50	0.37	0.16	0.38	0.06
		5	32.1	7.1	7.9	0.7	10.2	**0.0**	0.47	0.51	0.41	0.22	0.55	0.00
		10	38.2	8.2	9.2	1.0	10.2	**0.0**	0.55	0.48	0.56	0.29	0.61	0.00
		30	39.1	4.5	2.8	0.6	6.6	**0.0**	0.54	0.38	0.32	0.20	0.61	0.05

Table 6
Number of first places and average execution time; in each scenario, 100 demand sets were analyzed.

Scenario			Number of first places						Average execution time (s)					
Network	Channel	k	FF	LSF	MSF	AFA	TS	AFA/TS	FF	LSF	MSF	AFA	TS	AFA/TS
NSF15	SC	2	0	0	1	16	26	**99**	0.00	0.01	0.01	0.24	6.95	7.33
		3	0	0	1	57	31	**99**	0.00	0.01	0.01	0.32	7.65	8.88
		5	0	0	0	35	13	**100**	0.00	0.01	0.01	0.31	9.17	12.23
		10	0	1	10	91	1	**92**	0.00	0.03	0.03	0.82	13.13	22.60
		30	0	0	35	65	5	**70**	0.00	0.09	0.08	2.36	36.53	75.37
	DC	2	0	0	0	1	13	**100**	0.00	0.01	0.01	0.12	6.25	7.86
		3	0	0	0	9	18	**100**	0.00	0.01	0.01	0.15	6.72	10.28
		5	0	0	0	8	26	**100**	0.00	0.01	0.01	0.16	7.76	21.77
		10	0	0	8	69	18	**94**	0.00	0.02	0.02	0.46	11.00	40.96
		30	0	0	3	93	4	**97**	0.00	0.05	0.04	1.25	26.88	117.05
UBN24	SC	2	0	0	0	32	6	**100**	0.02	0.04	0.04	2.00	18.81	21.21
		3	0	1	1	56	1	**99**	0.02	0.06	0.05	2.81	21.68	28.67
		5	0	0	0	87	0	**100**	0.02	0.06	0.05	2.83	27.64	34.24
		10	0	0	0	99	0	**100**	0.02	0.15	0.14	8.94	46.27	71.45
		30	0	0	4	82	15	**97**	0.02	0.41	0.37	26.20	139.18	342.89
	DC	2	0	1	1	33	4	**98**	0.01	0.02	0.02	1.23	15.31	35.59
		3	0	2	0	64	0	**99**	0.01	0.03	0.03	1.72	17.66	52.22
		5	0	1	0	60	0	**100**	0.01	0.03	0.03	1.72	23.02	21.77
		10	0	0	0	51	0	**100**	0.01	0.08	0.08	5.20	37.11	149.60
		30	0	1	5	64	0	**95**	0.01	0.23	0.22	15.20	111.27	454.55

At the beginning of the experiments we applied the same TS algorithm as in Section 4. However, the results showed that the TS method outperforms AFA only for the NSF network and $k \in \{2, 3, 5\}$ in the case of the DC scenario and $k=2$ in the case of the SC scenario. For all other remaining cases, the AFA provided better results than TS. In general, when the problem size was growing (in terms of parameter k and network size) the gap between AFA and TS also increased. These results indicated that the TS method itself does not provide good scalability.

Therefore, we decided to make additional tests and construct a hybrid algorithm, denoted as AFA/TS, by combining algorithms AFA and TS. More precisely, the results found by AFA are used as the initial solution of TS. We can easily notice that the AFA/TS algorithm outperforms all other remaining methods. In more detail, AFA/TS can improve the solution provided by AFA for all tested cases, however the improvement in general decreases with the problem complexity expressed by the value of parameter k and the network size. However, the AFA/TS

Table 7
Performance of AFA/TS in a function of k; T in seconds.

Scenario		$k=2$		$k=5$		$k=10$		$k=30$		$k=2$ vs. $k=30$
Network	Channel	Φ	T	Φ	T	Φ	T	Φ	T	Improvement in Φ (%)
NSF15	SC	508.0	7.3	497.7	12.2	466.7	22.6	450.9	75.4	12.67
	DC	436.2	7.9	417.5	21.8	383.0	41.0	366.6	117.1	18.99
UBN24	SC	1034.2	21.2	910.2	34.2	840.4	71.5	806.6	342.9	28.22
	DC	964.5	35.6	791.0	80.2	719.4	149.6	709.7	454.6	35.90

method consumes much more execution time. For all evaluated algorithms, the value of confidence interval was below 1% – the largest value was observed for the FF algorithm, while the smallest was obtained in the case of the AFA/TS method. These results indicate that all examined algorithms provide relatively stable performance.

5.4. Influence of the candidate paths number

In Table 7 we present the AFA/TS performance results in a function of the number of candidate paths (k). The improvement between $k=2$ and $k=30$ is of about 13–36% in all scenarios, however, at the cost of extended computation time, which grows almost linearly with k. Accordingly, it is worth to have a large set of candidate paths since it has a great impact on Φ.

5.5. Shared backup path protection versus dedicated path protection

The last goal of experiments was to compare two protection scenarios, namely, Dedicated Path Protection (DPP) with Shared Backup Path Protection (SBPP). Moreover, as reference results we report the values of the objective function obtained for the not protection (NP) case, i.e., only working paths are established in the network and there are no backup paths. Note that the SBPP method was addressed in our previous work, where we presented ILP models, heuristic algorithms, and numerical results [24].

In Figs. 11 and 12, we report the results obtained for $k=30$, for NSF15 and UBN24 networks, respectively, and assuming the DC allocation. Each figure shows detailed data yielded for an individual demand set – on the whole, 100 demand sets were analyzed. We present both the number of required slices for each scenario (left axis) and the percentage of additional spectrum needed to provide SBPP and DPP protection in comparison to the NP scenario (right axis). On average, the additional spectrum (slices) needed in the network to provide the SBPP protection is 53.4% and 52.56%, respectively, for NSF15 and UBN24 networks. In the case of the DPP protection the corresponding numbers are 119.7% and 107.7%. Small differences observed between networks in the case of the DPP scenario follow mainly from the fact that the NSF15 topology is more sparse (average node degree is 3.07) comparing to the UBN24 topology (average node degree is 3.58). As a consequence, in NSF15 the backup paths are on average more longer comparing to working paths and

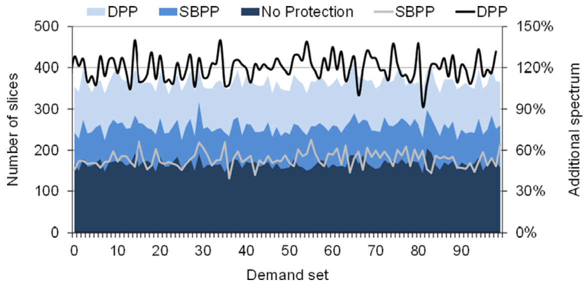

Fig. 11. DPP and SBPP versus no protection scenario for NSF15 network, $k=30$.

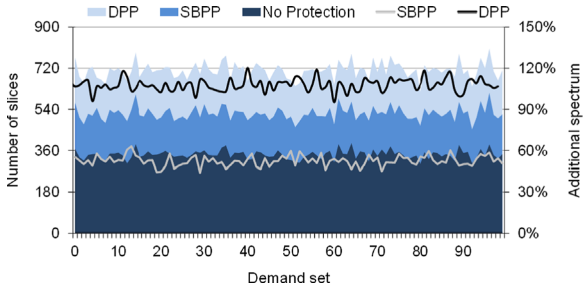

Fig. 12. DPP and SBPP versus no protection scenario for UBN24 network, $k=30$.

consume more spectrum resources in the network. In the case of the SBPP scenario, the gap between both networks is much smaller, since the possibility to share the backup capacity significantly reduces the influence of longer backup paths.

6. Conclusions

In this paper, we have concentrated on the problem of routing and spectrum allocation in survivable elastic optical networks. The network protection is provided by the use of the dedicated path protection method. We have formulated the problem as an ILP problem and in order to provide near optimal solutions for larger networks, based on the tabu-search metaheuristic, we have developed two optimization algorithms, namely, TS and AFA/TS. To examine the performance of the algorithms, we have compared them with state of the art RSA algorithms modified according to the DPP method. The performed numerical experiments show that both new algorithms outperform the reference heuristics and yield results close to the optimal ones. Our TS algorithm suffers from weak scalability and in terms of larger problem instances provides results worse than a reference AFA algorithm. However, a hybrid AFA/TS algorithm that uses the solution of AFA as a starting solution for the TS method can improve the result of AFA on average up to 3.37%, depending on the number of candidate paths, channel scenario (DC and SC) and network topology. Eventually, we assessed the performance of the DPP and SBPP scenarios and, in particular, we estimated spectrum requirements in implementing these scenarios in comparison to a network without path protection.

In future work, we plan to focus on the protection of EON with joint unicast and anycast flows – we are going to develop an ILP formulation as well as effective heuristic algorithms. Moreover, we consider to study the survivability of EON operating with various modulation formats.

Acknowledgments

This work was supported in part by the Polish National Science Centre (NCN) under Grant DEC-2012/07/B/ST7/01215. In addition, the work of Mirosław Klinkowski and Róża Goścień was supported in part by NCN under Grant DEC-2011/01/D/ST7/05884 and by the European Commission (EC) under the 7th Framework Programme (FP7) project IDEALIST, Grant Agreement Number 317999.

References

[1] O. Gerstel, M. Jinno, A. Lord, S.J.B. Yoo, Elastic optical networking: a new dawn for the optical layer? IEEE Commun. Mag. 50 (2) (2012) 12–20.
[2] W. Wei, C. Wang, J. Yu, Cognitive optical networks: key drivers, enabling techniques, and adaptive bandwidth services, IEEE Commun. Mag. 50 (1) (2012) 106–113.
[3] ITU-T Recommendation G.694.1 (ed. 2.0), Spectral Grids for WDM Applications: DWDM Frequency Grid, February 2012.
[4] M. Klinkowski, K. Walkowiak, Routing and spectrum assignment in spectrum sliced elastic optical path network, IEEE Commun. Lett. 15 (8) (2011) 884–886.
[5] K. Christodoulopoulos, I. Tomkos, E. Varvarigos, Elastic bandwidth allocation in flexible OFDM based optical networks, IEEE J. Lightw. Technol. 29 (9) (2011) 1354–1366.
[6] L. Velasco, M. Klinkowski, M. Ruiz, J. Comellas, Modeling the routing and spectrum allocation problem for flexgrid optical networks, Phot. Netw. Commun. 24 (3) (2012) 177–186.
[7] Y. Wang, X. Cao, Q. Hu, Y. Pan, Towards elastic and fine-granular bandwidth allocation in spectrum-sliced optical networks, IEEE/OSA J. Opt. Commun. Netw. 4 (11) (2012) 906–917.
[8] L. Gong, X. Zhou, W. Lu, Z. Zhu, A two-population based evolutionary approach for optimizing routing, modulation and spectrum assignments (RMSA) in O-OFDM networks, IEEE Commun. Lett. 16 (9) (2012) 1520–1523.
[9] M. Klinkowski, An evolutionary algorithm approach for dedicated path protection problem in elastic optical networks, Cybern. Syst. 44 (6–7) (2013) 589–605.
[10] M. Ruiz, M. Pióro, M. Żotkiewicz, M. Klinkowski, L. Velasco, Column generation algorithm for RSA problems in flexgrid optical networks, Photonic Netw. Commun. 26 (2–3) (2013) 53–64, http://dx.doi.org/10.1007/s11107-013-0408-0.
[11] M. Klinkowski, K. Walkowiak, M. Jaworski, Off-line algorithms for routing, modulation level, and spectrum assignment in elastic optical networks, in: Proceedings of IEEE ICTON, Stockholm, Sweden, 2011.
[12] J. Zhang, K. Zhu, S. Yoo, L. Sahasrabuddhe, B. Mukherjee, On the study of routing and wavelength assignment approaches for survivable wavelength-routed WDM mesh networks, Opt. Netw. Mag. 4 (6) (2003) 16–28.
[13] Y. Liu, D. Tipper, P. Siripongwutikorn, Approximating optimal spare capacity allocation by successive survivable routing, IEEE/ACM Trans. Netw. 13 (1) (2005) 198–211.
[14] T. Takagi, H. Hasegawa, K. Sato, T. Tanaka, B. Kozicki, Y. Sone, M. Jinno, Algorithms for maximizing spectrum efficiency in elastic optical path networks that adopt distance adaptive modulation, in: Proceedings of ECOC, Torino, Italy, 2010.
[15] M. Klinkowski, K. Walkowiak, Offline RSA algorithms for elastic optical networks with dedicated path protection consideration, in: Proceedings of RNDM, St. Petersburg, Russia, 2012.
[16] G. Shen, Y. Wei, Q. Yang, Shared backup path protection (SBPP) in elastic optical transport networks, in: Proceedings of ACP, Guangzhou, China, 2012.
[17] A.N. Patel, P.N. Ji, J.P. Jue, T. Wang, Survivable transparent flexible optical WDM (FWDM) networks, in: Proceedings of OFC, Los Angeles, USA, 2011.
[18] J. Lopez, Y. Ye, V. Lopez, F. Jimenez, R. Duque, P. Krummrich, On the energy efficiency of survivable optical transport networks with flexible-grid, in: Proceedings of ECOC, Amsterdam, Netherlands, 2012.
[19] L. Ruan, N. Xiao, Survivable multipath routing and spectrum allocation in OFDM-based flexible optical networks, IEEE/OSA J. Opt. Commun. Netw. 5 (3) (2013) 172–182.
[20] Y. Wei, G. Shen, Span restoration for flexi-grid optical networks under different spectrum conversion capabilities, in: Proceedings of DRCN, Budapest, Hungary, 2013.
[21] J. Lopez, Y. Ye, V. Lopez, F. Jimenez, R. Duque, P. Krummrich, F. Musumeci, M. Tornatore, A. Pattavina, Traffic and power-aware protection scheme in elastic optical networks, in: Proceedings of NETWORKS, Rome, Italy, 2012.
[22] A. Eira, J. Pedro, J. Pires, Optimized design of shared restoration in flexible-grid transparent optical networks, in: Proceedings of OFC, Los Angeles, USA, 2012.
[23] C. Yang, N. Hua, X. Zheng, Shared path protection based on spectrum reserved matrix model in bandwidth-variable optical networks, in: Proceedings of IEEE CHINACOM, Kun Ming, China, 2012, pp. 256–261.
[24] K. Walkowiak, M. Klinkowski, Shared backup path protection in elastic optical networks: modeling and optimization, in: Proceedings of DRCN, Budapest, Hungary, 2013.
[25] A. Castro, M. Ruiz, L. Velasco, G. Junyent, J. Comellas, Path-based recovery in flexgrid optical networks, in: Proceedings of IEEE ICTON, Coventry, England, 2012.
[26] M. Liu, M. Tornatore, B. Mukherjee, Survivable traffic grooming in elastic optical networks—shared protection, IEEE J. Lightw. Technol. 31 (6) (2013) 903–909.
[27] K.D.R. Assis, R.C. Almeida, H. Waldman, MILP formulation for squeezed protection in spectrum-sliced elastic optical path networks, in: Proceedings of SPECTS, Genoa, Italy, 2012.
[28] X. Shao, Y.-K. Yeo, Z. Xu, X. Cheng, L. Zhou, Shared-path protection in OFDM-based optical networks with elastic bandwidth allocation, in: Proceedings of OFC, Los Angeles, USA, 2012.
[29] B. Chen, J. Zhang, Y. Zhao, J. Liu, S. Huang, W. Gu, J. Jue, Minimum spectrum block consumption for shared-path protection with joint failure probability in flexible bandwidth optical networks, in: Proceedings of OFC, Anaheim, USA, 2013.
[30] E.-G. Talbi, Metaheuristics: From Design to Implementation, Wiley, 2009.
[31] D. King, A. Farrel, Y. Li, F. Zhang, R. Casellas, Generalized Labels for the Flexi-Grid in Lambda-Switch-Capable (LSC) Label Switching Routers, IETF RFC Draft, March 2012.
[32] F. Zhang, O.G. de Dios, D. Ceccarelli, RSVP-TE Signaling Extensions in Support of Flexible Grid, IETF RFC Draft, March 2012.
[33] F. Zhang, X. Zi, R. Casellas, O.G. de Dios, D. Ceccarelli, GMPLS OSPF-TE Extensions in Support of Flexible-Grid in DWDM Networks, IETF RFC Draft, October 2011.
[34] F. Zhang, X. Zi, O.G. de Dios, R. Casellas, Requirements for GMPLS Control of Flexible Grids, IETF RFC Draft, October 2011.
[35] M.S. Moreolo, J.M. Fabrega, L. Nadal, F.J. Vilchez, Software-defined optical OFDM transmission systems: enabling elasticity in the data plane, in: Proceedings of IEEE ICTON, Coventry, England, 2012.
[36] S. Frisken, S.B. Poole, G.W. Baxter, Wavelength-selective reconfiguration in transparent agile optical networks, Proc. IEEE 100 (5) (2012) 1056–1064.
[37] M. Jinno, B. Kozicki, H. Takara, A. Watanabe, Y. Sone, T. Tanaka, A. Hirano, Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network, IEEE Commun. Mag. 48 (8) (2010) 138–145.
[38] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, S. Matsuoka, Spectrum-efficient and scalable elastic optical path network:

architecture, benefits, and enabling technologies, IEEE Commun. Mag. 47 (11) (2009) 66–73.

[39] G. Meloni, F. Paolucci, N. Sambo, F. Cugini, M. Secondini, L. Gerardi, L. Poti, P. Castoldi, PCE architecture for flexible WSON enabling dynamic rerouting with modulation format adaptation, in: Proceedings of ECOC, Geneva, Switzerland, 2011.

[40] R. Casellas, R. Munoz, J.M. Fabrega, M.S. Moreolo, R. Martinez, L. Liu, T. Tsuritani, I. Morita, GMPLS/PCE control of flexi-grid DWDM optical networks using CO-OFDM transmission, IEEE/OSA J. Opt. Commun. Netw. 4 (11) (2012) B1–B10.

[41] F. Cugini, G. Meloni, F. Paolucci, N. Sambo, M. Secondini, L. Gerardi, L. Poti, P. Castoldi, Demonstration of flexible optical network based on path computation element, IEEE J. Lightw. Technol. 30 (5) (2012) 727–733.

[42] D.J. Geisler, R. Proietti, Y. Yin, R.P. Scott, X. Cai, N.K. Fontaine, L. Paraschis, O. Gerstel, S.J.B. Yoo, The first testbed demonstration of a flexible bandwidth network with a real-time adaptive control plane, in: Proceedings of ECOC, Geneva, Switzerland, 2011.

[43] A. Klekamp, F. Buchali, R. Dischler, F. Ilchmann, Comparison of DWDM network topologies with bit-rate adaptive optical OFDM regarding restoration, in: Proceedings of ECOC, Torino, Italy, 2010.

[44] A. Morea, O. Rival, Advantages of elasticity versus fixed data-rate schemes for restorable optical networks, in: Proceedings of ECOC, Torino, Italy, 2010.

[45] Y. Sone, A. Watanabe, W. Imajuku, Y. Tsukishima, B. Kozicki, H. Takara, M. Jinno, Bandwidth squeezed restoration in spectrum-sliced elastic optical path networks (SLICE), IEEE/OSA J. Opt. Commun. Netw. 3 (3) (2011) 223–233.

[46] K. Walkowiak, J. Rak, Simultaneous optimization of unicast and anycast flows and replica location in survivable optical networks, Telecommun. Syst. 52 (2) (2013) 1043–1055.

[47] J. Rak, K. Walkowiak, Reliable anycast and unicast routing: protection against attacks, Telecommun. Syst. 52 (2) (2013) 889–906.

[48] J. Buus, E.J. Murphy, Tunable lasers in optical networks, IEEE J. Lightw. Technol. 24 (1) (2006) 5–11.

[49] R. Blum, Evolving tunable technologies in transponder and transceiver modules, ⟨http://www.jdsu.com/ProductLiterature/Robert-Blum-FOE-Presentation-Evolving-Tunable-Technologies-small.pdf⟩, 2010 (accessed in September 2013).

[50] M. Pióro, D. Medhi, Routing, Flow, and Capacity Design in Communication and Computer Networks, Morgan Kaufmann, 2004.

[51] M. Gendreau, J. Potvin, Handbook of Metaheuristics, Springer, New York, 2010.

[52] F. Glover, Tabu search—part I, ORSA J. Comput. 1 (3) (1989) 190–206.

[53] F. Glover, Tabu search fundamentals and uses, Technical Report, University of Colorado, 1995.

[54] W. Jaziri, Tabu Search, I-Tech, 2008.

[55] B. Rabiega, Optimization of routing and spectrum assignment in elastic optical networks with the use of tabu search algorithm (Master's thesis), Wroclaw University of Technology, 2008.

[56] IBM, ILOG CPLEX Optimizer, ⟨http://www.ibm.com⟩, 2012.