Interference-and-Security-Aware Distance Spectrum Assignment in Elastic Optical Networks

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***Abstract*—In Elastic Optical Networks (EONs), two communications requests sharing common fiber links have to be separated in the spectrum domain by a guard band to prevent the interference or satisfy the security requirement, since there are types of physical impairments or attacks in the optical layer. For different interference or security levels, the size of guard band should be adapted, while it is supposed to be identical in most of the literature. To be more agile and realistic, we rise a new spectrum assignment model called Distance Spectrum Assignment (DSA): the size of guard band between two communications sharing a common fiber link varies according to the specific circumstance, and the goal is to minimize the maximum index of frequency slots assigned to satisfy all the guard band constraints. Since DSA is a strongly $\mathcal{NP}$-hard problem, we propose an Integer Linear Program (ILP) model for computing the optimal solution. For solving the DSA problem in large-scale EONs, we develop a heuristic algorithm with time complexity $\mathcal{O}(n^3\Delta)$, where n is the number of requests and Δ is the maximum degree of the conflict graph. We prove that the proposed algorithm achieves an approximate ratio of $\mathcal{O}(log(n))$ in complete conflict graphs. Numerical results demonstrate the proposed heuristic algorithm can find near-optimal spectrum assignments for solving the DSA problem in general topologies.**

***Index Terms*—Elastic Optical Networks (EONs), Guard band size, Distance Spectrum Assignment (DSA).**

I. Introduction

With the more and more rapid growth of traffic requests in recent years, how to improve the utilization efficiency of spectral resources is the key issue for all optical networks. Via Optical Orthogonal Frequency Division Multiplexing (O-OFDM) technology, Elastic Optical Networks (EONs) can be constructed [1] and reveals remarkable agility in optical layer [2]. The bandwidth-variable transponders in EONs operate on several narrow-band (12.5GHz or less) Frequency Slots (FS'), which are contiguous in the spectrum domain, and carry out the data transmission over them [3]. Thus, according to the needs of traffic requests, EONs can efficiently offer the just-enough bandwidth to them [4] with the aid of the finer bandwidth granularity. For example in Fig. 1, there are three communication requests R_1, R_2, R_3 in an EON, whose bandwidth corresponds to 2, 4 and 3 slots respectively. Then, EON assigns them with the corresponding amount of contiguous FS', as shown on blue, red and orange respectively. Two communication requests in an EON have to be separated in spectrum domain by a guard band as long as their lightpaths share one or more fiber links. These guard bands, as illustrated

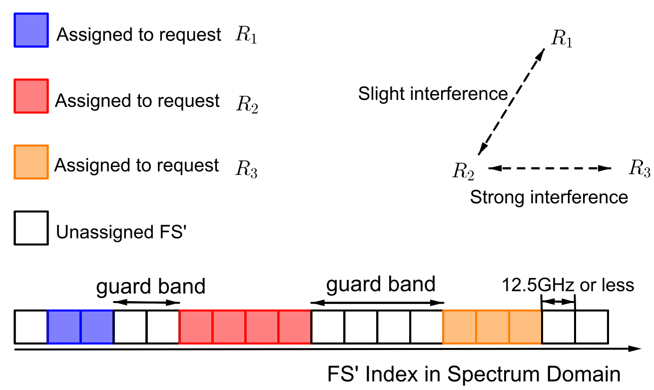


Fig. 1. FS' and Guard bands in EONs.

in Fig. 1 (assuming the lightpath of R_2 shares common fiber links with those of R_1 and R_3), are used to facilitate the physical frequency filtering to ensure the signal quality [5]. The size of the guard band, however, is not trivial and may be one or bigger. Basically, the stronger is the interference level, the larger is the guard band (*c.f.*, Fig. 1), while the interference level is affected by many factors such as the required bandwidth, the number of common fiber links, the transponder modulations, required security level and so on [6]. Therefore, in practice, mutative guard band requirements are laid between different traffic request pairs. Naturally, the size of the guard band significantly influences the overall utilization of spectrum resources.

In this paper, we put forward a new spectrum assignment model called Distance Spectrum Assignment (DSA) in EONs: Given a set of communication requests and diverse guard carrier requirements, the objective is to minimize the maximum FS' index used while satisfying all communication requests and guard band constraints. Different from those in the literature [5, 7], we suppose that the size of the guard bands depends on the interference level (as assumed in [6]) rather than identical for all requests, what thus makes our model more realistic but more difficult to resolve. In our model, we assume the spectral resource is sufficient to serve all requests (*i.e.*, no blocking) and their mutual interference levels are known beforehand, *i.e.*, we only consider the spectrum assignment phase. The DSA is a strongly $\mathcal{NP}$-hard problem.

We model it by a conflict graph and propose an Integer Linear Program (ILP) to solve it optimally. To efficiently resolve the DSA problem in a large-scale network, we develop a heuristic algorithm, which can guarantee an approximate ratio $\mathcal{O}(log(n))$ for complete conflict graphs. The obtained numerical results demonstrate the proposed algorithm can obtain a near-optimal spectrum assignment in general topologies.

The rest of the paper is organized as follows. Section II, presents our motivation and related work. In Section III, we formally define the DSA problem and model it by an Integer Linear Program. Then, we develop an approximate algorithm in Section IV, and present the numerical results in Section V. Finally, the paper is concluded in Section VI.

II. Motivation and Related Work

Recent advances in optical transmission techniques and devices, the concept of EONs has urged to come up and attracted researches ([4], [6], [8]). Authors of [4] systematically discussed some enabling technologies such as O-OFDM and Bandwidth-Variable (BV) Wavelength Cross-Connect (WXC) nodes, and proposed a novel, spectrum-efficient, and scalable optical transport network architecture, *i.e.*, EONs. With the aid of O-OFDM and BV-WXC nodes, EONs can allocate a flexible granularity optical bandwidth to a traffic request according to the customer demand. Thereby, EONs can achieve nearly double utilization efficiency of spectral resources than WDM (Wavelength Division Multiplexing) networks [6]. Optical signals in EONs, *i.e.*, FS' sets, transported in common links, should be isolated in spectrum domain by guard bands. Otherwise, various physical impairments will mix these signals resulting in signal noises, which will deteriorate the Quality of Transmission (QoT) acutely and the adjacent FS' interference can be readily utilized to realize snoop [9], which may lead to serious security problems.

A fundamental problem of all-optical networks, namely Routing and Spectrum Assignment (RSA) problem with guard band, has appealed to lots of researchers. In [5], the RSA has been formally defined along with the discussion of its complexity. ILP formulations and two efficient heuristic algorithms have been proposed for solving the static RSA problem. In [7], multicast requests over EONs with multicast-capable routing, modulation level, and spectrum assignment (RMSA) are investigated. ILP models and an adaptive genetic algorithm have been presented. Most of the previous works (*e.g.*, [5, 7]) supposed a constant and identical guard band for all request pairs. However, [6] reveals that the filtering characteristics and guard band are extremely sophisticated, depending on various factors such as the edge nodes, the bandwidths, the bit rates, the filter shape, etc. Consequently, after routing the given traffic requests, diverse interference-levels exist for different request pairs. Thus, the rigid size of guard band does not coincide with the practices and causes an inefficient utilization of spectrum resources. [10] demonstrated the advantage of spectrum efficiency under optimized guard size for two special sizes of supperchannel *i.e.*, 50GHz and 37.5GHz. Hence, the DSA, a new spectrum assignment problem under mutative guard band, requires urgent attentions.

Generally, the spectrum assignment problem is studied by leveraging the graph coloring method in the conflict graph constructed after routing traffic requests. But, the studied DSA problem differs from the classical graph coloring problem [11] in two aspects: (1) each vertex in the conflict graph, representing one request, is assigned with a set of contiguous colors according to the bandwidth rather than only one color; (2) the distance of the color sets between two adjacent vertices is no longer one but a positive integer, representing the interference or security level, and it is not identical for all request pairs. The DSA problem is similar to fractional coloring problem [12], but they are also different: contiguous colors should be assigned to each vertex in DSA, while it is not the case for fractional coloring; mutative distances between adjacent color sets should be kept in DSA to mitigate the interference while color sets only need to be disjoint in the latter one. For clarity, Table I gives a detailed comparison of differences among classical coloring, fractional coloring, traditional models and DSA problem. Therefore, DSA is obviously a new combinatorial optimization problem, which has not yet been dealt with. In the next section, we will formally define the DSA problem.

TABLE I
Comparison among the four problems

	Classical coloring [11]	Fractional coloring [12]	Traditional models [5] [7]	DSA problem (this work)
Vertex color	single color	a set of colors	a set of colors	a set of colors
Color continuity	no	no	yes	yes
Adjacent color distance	just disjoint	just disjoint	identical distance	mutative distances

III. Interference-and-Security-Aware Distance Spectrum Assignment

Via O-OFDM technology, a set of FS' is available in each optical fiber of EONs. These FS' are critical resources in optical fibers. Therefore, efficient spectrum assignment algorithms are needed to optimize the spectrum usages in the case of accommodating multiple traffic requests, since spectrum overlap is forbidden in two lightpaths sharing a common link due to the optical layer constraint. Besides, the interference between communications is a big issue in optical networks, which will degrade the QoT greatly. As reported in [6], the interference level depends on many factors. Furthermore, some traffic requests may have a special security requirement for privacy reasons. The guard band permits to mitigate communication interference and satisfy security requirements. The bigger is the distance between the FS' of two requests, the more inter-communication interference can be mitigated. Besides, the FS' assigned to each communication should be contiguous, meanwhile the number of FS' should meet the bandwidth need of this communication. The following two problems are vital in EONs:

- How to assign spectrum for traffic requests to maintain a certain security level?
- How to mitigate the reciprocal interference to ensure the QoT for all communications?

Both of the two issues rely on the guard band deeply.

A. Problem Description

In this work, we mainly focus on distance spectrum assignment optimization with the considerations of inter-communication interference and traffic security requirement. We consider accommodating a set of traffic requests in EONs. Assuming that the route of each traffic request is given beforehand (*e.g.*, computed by some routing algorithms) and the specific interference or security levels have also been calculated out for each request pairs, our objective is to satisfy all requests by allocating enough spectrum to each route under different interference constraints while minimizing the maximum index of FS' in spectrum domain.

To this end, our method is to construct a conflict graph for spectrum assignment problem based on the set of traffic requests and the input parameters of interference and security in the following manner: (1) we use a vertex assigned a weight to represent a request and its bandwidth demand respectively; (2) a conflict edge assigned a weight is added to connect two vertices if there is an inter-communication interference between them or a set of guard FS' must be assigned between the two requests for customer-specified security reasons. The weight means the least distance the two requests should keep in the spectrum domain.

For example, there are four requests in Table II. Their bandwidth demands have been measured by the number of FS', and their routes have also been provided in a 4-cycle EON. Fig. 2 displays the explicit routes for them.

TABLE II
FOUR COMMUNICATIONS IN A 4-CYCLE EON

	Bandwidth Capacity	Route
Request R_1	3 FS'	B-A-D
Request R_2	2 FS'	C-B-A
Request R_3	3 FS'	A-D-C-B
Request R_4	1 FS'	C-B-A-D

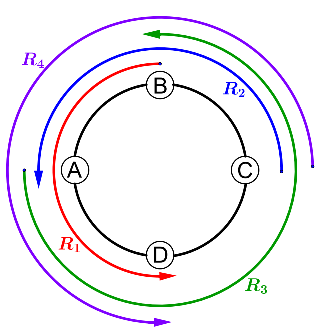
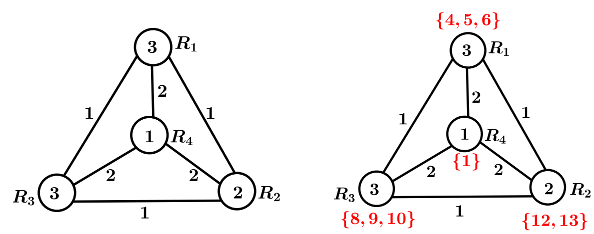


Fig. 2. The explicit routes for Table II.

Then, under this specific transmission conditions, the interference for each request pair can be given out. Many experimental results (*e.g.*, [6]) demonstrate that the interference levels are positive correlated with the number of common links. Here, for simplicity, we directly use the number of common links in their routes as the interference levels. Taking R_4 and R_1 as an instance, the route of R_1 B-A-D intersects with the R_4's C-B-A-D, and the number of common links is 2. Therefore, the size of the guard band between R_1 and R_4 is at least 2 FS'. Then, the conflict graph for this example is shown in Fig. 3(a), and its optimal solution is given in Fig. 3(b), where the FS' sets are indicated by the red sets.



(a) Conflict graph (b) Optimal solution

Fig. 3. The DSA conflict graph and optimal spectrum assignment.

B. DSA model and Integer Linear Program

In this paper, we suppose that all the communication requests have been routed and a conflict graph has been constructed based on the routing result in order to solve the distance spectrum assignment problem. Hence, from now on, our analyses only concentrate on the constructed conflict graph, and all the graph types talked below are only related to the conflict graph. For ease of expression, we first introduce the following notations.

Necessary Notations:

- $G(V, E)$: The DSA conflict graph, where V is the set of the requests, and E is the set of the conflict edges.
- $\mathbb{N}^+$: The set of natural numbers represents the FS' index set in spectrum domain, starting from 1.
- v_i: $v_i \in V$ represents the i-th communication request.
- v_i^w: The integer weight signifies the number of contiguous FS' (bandwidth requirement) required by request v_i.
- w_{v_i}: $w_{v_i} \subset \mathbb{N}^+$ and is the set of contiguous FS' assigned to v_i.
- v_i^b: $v_i^b \in \mathbb{N}^+$ and is the beginning index of w_{v_i}.
- v_i^a: $v_i^a \in \mathbb{N}^+$ and is the ending index of w_{v_i}.
- e or v_iv_j: The edge $e \in E$ linking vertex v_i and v_j represents there is an interference between the two requests. For convenience, we also directly use v_iv_j to indicate e.
- d_e or $d_{v_iv_j}$: The integer weight represents the least distance between w_{v_i} and w_{v_j} that should be kept. This distance weight can either correspond to the required FS' set distance to mitigate mutual interference or the customer-specified distance for security reasons.
- B: $B \in \mathbb{N}^+$ is a reasonable big index of FS' in each fiber link of EONs.

Our objective is to minimize the maximum FS' index used in G. Since G is a conflict graph, it is probably not connected.

If so, G can be partitioned into connected components, which are independent from each other. Then, we can assign FS' for each component independently, and the maximum FS' index is the final solution. Thus, without loss of generality, we assume the considered conflict graph G is connected.

Therefore, we put forward a new optimization problem called DSA problem. Let $s \in \mathbb{N}^+$ be the index of a FS' used, then the objective function can be written as

$$\min_{s \in \left(\bigcup_{v_i \in V} w_{v_i}\right)} \max s \qquad (\textbf{DSA}) \tag{1}$$

The DSA problem is subject to the following constraints:

- **Bandwidth Requirement constraint**. Each request should be assigned to enough FS' to satisfy the bandwidth requirement. In other words, the cardinality of FS' set assigned to a vertex $v_i \in V$ must be equal to its weight:
$$|w_{v_i}| = v_i^w, \forall v_i \in V \tag{2}$$
- **Spectrum Continuity constraint**. The FS' assigned to a vertex must be contiguous in $\mathbb{N}^+$. Then, the set of FS' w_{v_i} assigned to v_i can be expressed as $\{v_i^b, v_i^b+1, ..., v_i^a-1, v_i^a\}$, $v_i^b, v_i^a \in \mathbb{N}^+$. This is a physical layer constraint for all-optical communications in EONs.
- **Spectrum Set Distance constraint**. To mitigate mutual interference and satisfy the customer-defined security requirement, the distance between the FS' sets assigned to two adjacent requests should be big enough. For each edge $v_iv_j \in E$, the distance between w_{v_i} and w_{v_j} in $\mathbb{N}^+$ must be no smaller than the edge weight:
$$distance(w_{v_i}, w_{v_j}) \geq d_{v_iv_j}, \forall v_iv_j \in E \tag{3}$$
where,
$$distance(w_{v_i}, w_{v_j}) = \min_{s \in w_{v_i} t \in w_{v_j}} |s-t| - 1$$

It is easy to see that the classical graph coloring problem can be reduced to the DSA problem by setting vertex weight and edge weight as one. Therefore, DSA problem is a strongly $\mathcal{NP}$-hard problem. We propose an ILP model to compute the optimal spectrum assignment strategy.

Decision Variables:

- x_i^b: Integer variable to solve v_i^b.
- x_i^a: Integer variable to solve v_i^a.
- y: An artificial integer variable to represent the maximum of x_i^a.
- $o_{v_iv_j}$: A boolean variable of each edge v_iv_j to represent the order of x_i^b and x_j^b. If $x_i^b > x_j^b$, then $o_{v_iv_j} = 1$ and 0 otherwise.

Objective Function:

$$\text{Minimize } y \qquad \text{(ILP-DSA)} \tag{4}$$

s.t. **constraints:** (5)-(9)

$$x_i^a - x_i^b + 1 = v_i^w, \qquad \forall v_i \in V \tag{5}$$
$$o_{v_iv_j} + o_{v_jv_i} = 1, \qquad \forall v_iv_j \in E \tag{6}$$
$$x_i^a - x_j^b + d_{v_iv_j} + 1 \leq B \times o_{v_iv_j}, \qquad \forall v_iv_j \in E \tag{7}$$
$$y \geq x_i^a, \qquad \forall v_i \in V \tag{8}$$
$$x_i^a \in \mathbb{N}^+, x_i^b \in \mathbb{N}^+, \qquad \forall v_i \in V \tag{9}$$

IV. Time-Efficient Approximation Algorithms for DSA

A. The Greedy Algorithm

Given a DSA graph $G(V, E, \{v_i^w\}, \{d_{v_iv_j}\})$, the main idea to get the approximate solution is that: First we start from vertex $\underset{1 \leq i \leq n}{v_i} \in V$ where $n = |V|$, and arrange FS' set to v_i by a greedy strategy, *i.e.*, $v_i^b = 1$ and $v_i^a = v_i^w$. Meanwhile, we set a variable O_i to record the order in which these vertices have been assigned spectrum. Therefore, v_i first enters O_i. Then, we find the vertex v_j from the vertices not yet in O_i such that v_j^b be minimum to satisfy the three constrains of DSA with those vertices already in O_i. We add this v_j into O_i and assign the corresponding FS' set to it. The same procedure is repeated until all of vertices have been added into O_i. After n while-loops, n vertex orders $\{O_1, O_2, ..., O_n\}$ have been generated and we choose the one resulting in the minimum maximum FS' index used as our final solution. Algorithm 1 gives the pseudocode of the proposed Greedy Algorithm (GA). From step 1 to 3, starting from $j = 1$, we first initialize O_j as $\emptyset$ and use s_j to record the current maximum FS' index used in O_j, whose initial value is 0. From step 4 to 20, during the n while-loops, we generate n vertex orders. As mentioned above, from step 5 to 8, we first let v_j enter O_j and assign FS' set to it meanwhile changing $s_j = v_j^w$. In the for-loops from 2 to n, we organize the rest vertices for O_j one by one by the mentioned greedy strategy. Finally, at step 21, we set the vertex order resulting in the minimum maximum FS' index as the output. From the pseudocode, we can find that there are three cascading loops in FPGA, and calculating the minimum beginning index in the deepest loop. Therefore its time complex is $\mathcal{O}(n^3\Delta)$, where n is the number of vertex and Δ is the maximum degree of G.

B. Algorithm Analysis

If the input DSA graph $G(V, E, \{v_i^w\}, \{d_{v_iv_j}\})$ is a complete graph satisfying the triangle inequality *i.e.*, $\forall v_i, v_j, v_k \in V$, $d_{v_iv_k} + d_{v_kv_j} \geq d_{v_iv_j}$, then each vertex pair is connected. Therefore, the sum of vertex weights $V^w = \sum_{i=1}^n v_i^w, n = |V|$ can not be optimized and the majority of optimization effort is to reduce the interval between any two adjacent FS' sets. It is easy to see that the sum of the intervals of all adjacent FS' sets produced by GA is equal to the length of the Hamilton path produced by *Nearest Neighbor* (NN) algorithm [13], which is an heuristic algorithm to find the minimum Hamilton path (MHP). Let $|NN(G)|$ denote the length of the Hamilton path produced by NN algorithm and $|MHP(G)|$ denote the length of a minimum Hamilton path, then, according to [13, 14], the

Algorithm 1: Procedure the GA

Input : $G(V, E, \{v_i^w\}, \{d_{v_i v_j}\})$

Output: A minimum vertex order and its maximum FS' index

$j \leftarrow 1$;
$O_j \leftarrow \emptyset$; % initialize vertex order O_1
$s_j \leftarrow 0$; % record the value of O_1
while $j \leq n$ **do**
  $O_j \leftarrow O_j \cup v_j$;
  $v_j^b \leftarrow 1$;
  $v_j^a \leftarrow v_j^w$;
  $s_j \leftarrow v_j^w$;
  for $i = 2 : n$ **do**
    $v_{next} \leftarrow \emptyset$;
    $v_{next}^b \leftarrow b$; % b is large enough
    for $k = 1 : n$ **do**
      if $v_k \notin O_j$ **then**
        $v_k^b \leftarrow \max\limits_{\forall v_l \in O_j, v_k v_l \in E} \{v_l^a + d_{v_k v_l} + 1\}$;
        if $v_k^b < v_{next}^b$ **then**
          $v_{next} \leftarrow v_k$; $v_{next}^b \leftarrow v_k^b$;
    $O_j \leftarrow O_j \cup v_{next}$;
    $v_{next}^a \leftarrow v_{next}^b + v_{next}^w - 1$;
    $s_j \leftarrow \max\{s_j, v_{next}^a\}$;
  $j \leftarrow j + 1$; $O_j \leftarrow \emptyset$; $s_j \leftarrow 0$;
$O^* = \underset{1 \leq j \leq n}{\underset{O_j}{argmin}}\ s_j$; $s^* = \underset{1 \leq j \leq n}{\underset{s_j}{argmin}}\ s_j$;

approximate ratio of the NN algorithm in a complete graph with triangle inequality is $\dfrac{|NN(G)|}{|MHP(G)|} \leq \dfrac{1}{2}(\lceil \log_2 n \rceil + 1)$, where $n = |V|$ is the number of vertices (requests).

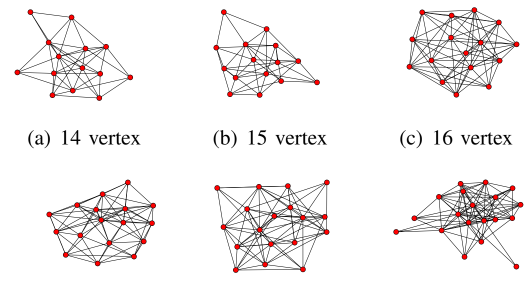
We note $|GA(G)|$ as the result obtained by the GA and $|opt(G)|$ is the optimal solution for a DSA graph G. Based on the above analysis, $|GA(G)| - V^w$ and $|opt(G)| - V^w$ are equal to $|NN(G)|$ and $|MHP(G)|$ respectively. Then, we get the following theorem.

Theorem 1: If $G(V, E, \{v_i^w\}, \{d_{v_i v_j}\})$ is a complete DSA graph satisfying triangle inequality, then the approximate ratio of GA is not bigger than $\frac{1}{2}(\lceil \log_2 n \rceil + 1)$, where $n = |V|$.

Proof. According to above analysis, we have $\dfrac{|GA(G)| - V^w}{|opt(G)| - V^w} \leq \dfrac{1}{2}(\lceil \log_2 n \rceil + 1)$. Because $|GA(G)| \geq |opt(G)|$, we have $\dfrac{|GA(G)|}{|opt(G)|} \leq \dfrac{|GA(G)| - V^w}{|opt(G)| - V^w} \leq \dfrac{1}{2}(\lceil \log_2 n \rceil + 1)$. ■

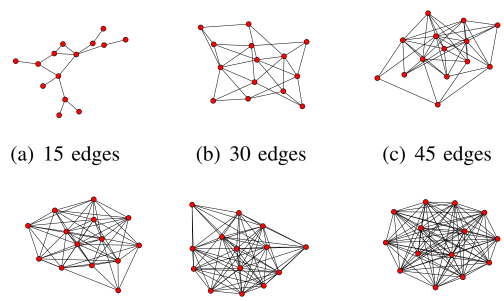
V. Numerical Results

In this section, we give some numerical results of GA and compare them with the optimal solutions obtained by ILP. As DSA is a new spectrum assignment model, there is no existing heuristic algorithm for comparison. Thus, we employed Pure Random Algorithm (PRA) as the benchmark algorithm, in which we randomly selected a vertex order at each iteration,



(a) 14 vertex (b) 15 vertex (c) 16 vertex (d) 17 vertex (e) 18 vertex (f) 19 vertex

Fig. 4. Six random graphs with vertex number from 14 to 19.



(a) 15 edges (b) 30 edges (c) 45 edges (d) 60 edges (e) 75 edges (f) 90 edges

Fig. 5. Random DSA graphs with 14 vertices and edges from 15 to 90.

computed the maximum FS' index under this vertex order, and PRA finally output the best solution after a certain number of iterations. We used the NetworkX package [15] to randomly generate DSA graphs (*c.f.*, Fig. 4 and 5), which were all Erdős-Rényi graphs with a possible probability 50% for each edge. The vertex and edge weights were generated with the integer uniform distribution $\mathcal{U}(1, n)$, where n was the number of vertices in a random graph. The ILP model for DSA was solved by MATLAB2015a with CPLEX toolbox and the approximate solutions by GA and PRA were both given by MATLAB2015a under the same iterations. All simulations were run on a computer with 3.2 GHz Intel(R) Core(TM) i5-4690S CPU and 8 Gbytes RAM.

We evaluate GA by comparing the maximum FS' index used, the average and worst gap to the optimal solution (ILP-DSA) with PRA. To show the efficiency of GA, we did our simulations in different scenarios:

(a) Table III presents the maximum FS' index used for the six random topologies in Fig. 4 with vertices from 14 to 19. We can see the maximum index used by GA is very close to the optimal one computed by ILP-DSA. The average and worst gaps of GA against ILP-DSA are 3.7% and 6.9% respectively while 18.9 % and 32% for PRA.

TABLE III
The number of spectrum slots used for Fig. 4

Fig.	4(a)	4(b)	4(c)	4(d)	4(e)	4(f)
PRA	72	76	103	124	142	170
GA	64	64	79	105	123	147
ILP-DSA	64	60	78	100	115	144

TABLE IV
THE NUMBER OF SPECTRUM SLOTS USED FOR COMPLETE GRAPHS

# vertex	14	15	16	17	18	19
PRA	159	187	215	250	253	263
GA	144	165	185	225	220	229
ILP-DSA	139	161	183	225	215	222

(b) Table IV gives test results in random complete graphs with vertex number from 14 to 19, whose vertex and edge weights follow the integer uniform distribution as above. The average and worst gaps of GA against ILP-DSA are 2.09% and 3.6% respectively while 15.8 % and 18.4% for PRA.

(c) Furthermore, in Tables V and VI, we evaluated GA in real EON testbeds 14-vertex NSFNET and the 28-vertex US Backbone. We only considered unicast communication requests and each request (source, destination and required bandwidth) was randomly generated with the uniform distribution. We employed the shortest path as the lightpath for each request. The edge distance between two requests was computed according to the number of the common fiber links in their lightpaths. In Tables V and VI, we can see that ILP-DSA is only able to get the optimal solution when the number of request is no bigger than 50. Meanwhile, GA can obtain almost the same solution as ILP-DSA.

TABLE V
SIMULATION RESULTS FOR NSFNET TOPOLOGY

# request	10	20	30	40	50	60	70	80
PRA	29	76	177	252	500	602	805	1155
GA	29	72	154	201	425	472	602	894
ILP-DSA	29	72	153	200	420	–	–	–

TABLE VI
SIMULATION RESULTS FOR US BACKBONE TOPOLOGY

# request	10	30	50	100	150	200	250
PRA	33	197	462	1898	4666	7743	13020
GA	33	190	366	1340	2843	3784	6349
ILP-DSA	33	186	351	–	–	–	–

Moreover, Fig. 6 plots the simulation results in six random graphs with 14 vertices and edge number ranging from {15,30,45,60,75,90} as shown in Fig. 5. It is shown that the approximate ratio of GA is very close to 1 and the spectrum usage rises rapidly with the number of edges in the conflict graph. These results coincide well with the intuitive observation that the more edges or the bigger edge distances a DSA graph has, the more spectrum resource may be consumed. The feature also inspires us that a good routing algorithm should be used to reduce the common links and link distances thus to globally optimize this new spectrum assignment in EONs.

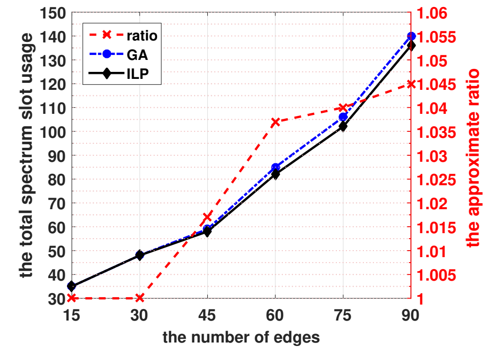


Fig. 6. Numerical results for the six DSA conflict graphs in Fig. 5.

VI. CONCLUSION

In this paper, we proposed a new spectrum assignment mechanism DSA, which is more consistent with reality. As DSA is a strong $\mathcal{NP}$-hard problem, we modeled it by an ILP and develop a heuristic algorithm named GA. We not only theoretically proved that GA can guarantee an approximate ratio of $\mathcal{O}(log(n))$ for complete graph with triangle inequality, but also demonstrated that GA can find near-optimal spectrum assignment in general topologies. The studied DSA may be extended and applied to solve spectrum assignments in other communication networks with similar characters.

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