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Channel-Based RSA Approaches for QoS Protection of Slices Over Elastic Optical Networks

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ABSTRACT Resource efficiency and survivability are critical concerns in elastic optical networks (EONs) with virtualization. In this paper, we investigate some important aspects in network survivability design against single-link failure under dedicated protection and bandwidth squeezing schemes when multiple virtual topologies are employed. We propose a link-path integer linear programming (ILP) formulation to solve the joint virtualization and survivability problem in elastic optical networks for large network instances, and derive some different types of protection for each virtual topology considering a channel-based spectrum approach to solve the spectrum allocation. Besides, we propose a heuristic to find a pair of predefined paths to ILP formulation aiming to minimize the link load. The proposed ILP and heuristic provide effective survivability solutions and spectrum resource savings for a cooperative design of modern survivable virtualized EONs taking advantages of a link-path model.

INDEX TERMS Virtualized elastic optical networks, optimization, routing and spectrum allocation, survivability.

I. INTRODUCTION

Survivability is one of the most widely studied topics on network design [1], [2]. This kind of study is certainly important for optical communications technology because of the massive amount of traffic transported by these networks, notably in the currently developed elastic optical networks (EONs) [42]. EONs are expected to form the backbone of the fifth-generation (5G) networks and beyond. In addition, 5G networks are expected to satisfy different requirements of several new services and be the basis for a range of verticals use cases [3]. For example, the international telecommunication union (ITU) and fifth generation public private partnership (5G-PPP) have identified three broad use case families: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable and low-latency communication (uRLLC). Such heterogeneous requirements cannot be satisfied by a traditional one-sizefits-all architecture, leading to an alternative architectural proposal to accommodate use cases with diverse requirements: network slicing.

Therefore, it is important to ask how the EON substrate will support, in terms of planning, the composition of multiple isolated virtual optical networks (VONs), referred to as slices, simultaneously coexisting over the same physical optical network infrastructure [4], [5]. Indeed, that is a big challenge when implementing network virtualization. The main concern is designing optical link virtualization by flexibly embedding virtual optical links (i.e. lightpaths) onto a common set of spectrum slots in a physical optical infrastructure so that bandwidth requirements are satisfied under an efficient use of spectrum. As the bandwidth requirement differs for the wide range of services (along with other

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requirements), a good idea is to develop models that each VON selects an appropriate survivability mechanism. A promising strategy is to use squeezing protection [6] for virtualization as an efficient solution for the survivability of several VONs.

Fig. 1 illustrates two possible protection mechanisms that could be applied to an EON using virtualization: dedicated protection (DP) and/or dedicated protection with squeezing (DP + S) [2], [7], [20]. By admitting traffic squeezing in the used protection mechanism, the capacity of the backup path may be set for a fraction of the requested working traffic. Fig. 1b depicts an example where, under a network failure occurrence, the fraction of the requested traffic is kept at 50% (QoS = 0.5 or 50%). These values are pre-accorded in the service level agreement (SLA). This protection strategy could also be applied for all lightpaths of VON 2 or even for other VONs as well. Additionally, Fig. 1c illustrates the load generated by VONs 1 and 2 on three of the network physical links. These two aforementioned schemes are both efficient against a single link failure and very little is known about architectures with several protection schemes against failures by the use of several slices over the same physical substrate. The term slice embodies a multitude of concepts (including Spectrum-sliced Elastic Optical Path). However, in this paper it refers to VON.

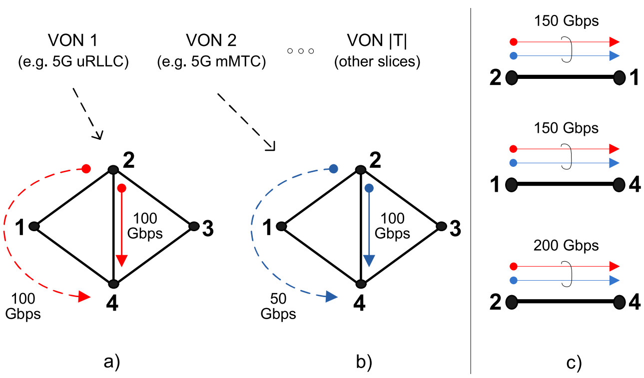


FIGURE 1. Different protection mechanism examples for two VONs (red and blue one): (a) DP, (b) DP + S, (c) load on physical links, [8].

An important aspect for VONs ILP designing models is the dilemma of long computational running time, such as the ILP formulation from [8] for VONs design with protection. It is an example of a multi-commodity network flow problem [9], a type of problem that deals with multiple demands (or commodities) that need to be routed in the network simultaneously and they compete for available resources (link capacities, in this paper). This is in fact a very common scenario in communication and computer networks. However, the formulation can not be practical for virtualization (in terms of running time), even for small instances as we have seen in [8].

In this paper we point out that a link-path formulation can be preferable for modeling large instance networks, since pre-processed paths may be used as input to link-path-based (also called the arc-path) models. Therefore, this paper reviews and extends the research conducted on [8] with a novel ILP formulation and a heuristic with pre-processed paths taking advantages of a link-path model.

The proposed model introduces pairs of candidate disjoint paths (work and protection) and the problem as an ILP formulation can be easily solved yielding solution with intermediate running time between the running time from the optimal solution (link node formulation) and the running time from a metaheuristic [8]. We carried out a series of experiments in order to validate the new proposed formulation and the heuristic with pre-processed paths, as well as demonstrate how bandwidth savings are achieved when different protection schemes are adopted for each VON.

It is worth mentioning that we consider transparent optical networks, i.e., there is neither spectrum conversion in the intermediate nodes nor bitrate conversion or grooming capability. In addition, the IP routers are attached to fixed locations whereas the placement of virtual nodes is an outcome of traditional virtual networks embedding (VNE) problem [2]. As a matter of fact, our formulation is merely a special case of VNE [7], [10].

The overall structure of the paper takes the form of eight sections, including this introductory section. Section II presents the related work. The channel-based with virtualization concept for solving the routing and spectrum allocation (RSA) problem is showed in Section III. Section IV presents the ILP formulation from [8]. Section V presents the novel ILP formulation proposed in this paper. In Section VI, we design the heuristics considering the survivable VON mechanisms. Section VII presents and analyzes the simulation results. Finally, Section VIII concludes this paper.

II. RELATED WORK

In order to provide a more efficient match between demanded traffic and allocated bandwidth, a flexible grid concept was proposed in 2009 [11], which is referred to Elastic Optical Networks, and is now standardized. In EONs, the capability of assigning a spectrum slice that matches adequately traffic bandwidth requirements (bit rate and required modulation format) is key for providing more efficient spectrum usage when compared to fixed-grid legacy WDM networks. In addition, emerging technologies enables EONs to extend its elasticity capability so that bandwidth can be squeezed whenever needed. Consequently, savings on spectral resources compared to the fixed-grid legacy WDM networks can be further achieved if just a fraction of the required traffic is protected, which mitigates the necessary spectrum over-provisioning in the protection mechanisms. Squeezing protection is then key to provide parsimony in the commitment of spectral resources to the spare capacity [20]. A large and growing body of literature has investigated squeezing protection [15], [18], [20].

In [12], the authors draw attention to a distinctive category of reductions in the extra bandwidth required for protection capability in EONs. The idea coordinate the distribution of the traffic and reserved bandwidth among the routes with some optimization aim, for instance spectrum saving. Surveys such as that conducted by [13] shows the state-of-the-art of survivable EON's and some technical solutions about squeezing are discussed.

Several studies investigating protection in EONs have been carried out on current literature. In [14], the authors introduce a channel-assignment (CA) approach which effectively reduces the spectrum assignment (SA) problem to a problem analogous to the old wavelength-assignment (WA) problem of legacy WDM networks, thus simplifying the ILP formulation and, most importantly, reducing its execution time. In [16], the authors propose a link-node MILP formulation that jointly solves the virtual topology design with grooming and physical topology design problems with different kind of squeezing for each lightpath.

A large and growing body of literature has investigated the virtual topology mapping problem in both optical "grid" and "gridless" networks [23], [24], [26]. Studies by [27]–[30] examined the virtual topology mapping problem in optical networks, including in their analysis some optical layer constraints, such as the optical transmission reach, spectral continuity/conflict constraints and/either, in case of EONS, the spectral contiguity (in EONs). [31] and [32] draw some experimental results. In an analysis of survivability, the authors in [33] provide solutions for mapping VON on a flexible grid optical network infraestructure when sliceable regenerators capable of providing spectrum and signal modulation format conversion are used. Additionally, an interesting work in [34] focused on investigating how to provision topology mapping with survivability criteria against physical node or link failures. The authors of [35] proposed an efficient link protection scheme that relies on constructing an enhanced topology with survivability in the virtual layer. Some recent studies have attempted to explain other aspects of VONs with protection, please see [40], [41].

In [7], the authors address the problem of creating a multi-tenant environment by network virtualization over an EON infrastructure with different kinds of protection for each virtual topology, also with a link-node formulation. In [8], the virtualization problem is re-discussed under a channel-assignment ILP formulation. However, the main weakness of the study is the failure to find the optimal or good solutions with an acceptable computational time, even for a 6-node network, basically because the problem is NP and the ILP spans all possible routes for the demands. This paper seeks to remedy this problem by a new ILP formulation with pre-defined paths for each demand. Therefore, the paper spans the research conducted on [8]. The idea is to use groups of link-disjoint paths and of contiguous slots so that the traffic can be assigned to one of them in order to attend VONs with different requirements. In this way, the problem is largely simplified.

III. CHANNEL-BASED PLUS VIRTUALIZATION APPROACH

Several works in the literature address the fact that once spectrum contiguity constraint is contemplated in the ILP formulations of RSAs, processor requirements increase significantly due to the introduction of a set of complicated requirements, and with several VONs this issue becomes even more pronounced [11], [14]. In order to lightening such processing burden and still considering spectrum contiguity in the formulation, in this paper we employ pre-computed sets of contiguous frequency slots and their selection for traffic demands of each VON, which constitutes the so-called spectral channels. The channel-based approach has been utilized in some works in the literature [14], [18], [43]–[45].

A spectral channel has been defined as the set of contiguous frequency slots of both: a particular number of slots and a specific position in the spectrum. For instance, suppose a total of $S = 4$ slots in the network and demands for $n = 2$ slots. The set of possible spectral channels is given by $C = \{(1, 1, 0, 0), (0, 1, 1, 0) \text{ and } (0, 0, 1, 1)\}$, where each position is set with 1 if the given channel uses that slot, and 0 otherwise. Therefore, C includes all possibilities how a demand can be allocated in the spectrum of the substrate network.

To enable allocation of demands with different protection requirements, referred to as QoS-aware protection, we have selected the channel-based approach and proposed the use of working and protection spectral channel sets together with the network virtualization concept.

In such strategy, demand ij (either its working or protection paths) on virtual topology t can be embedded on the physical substrate by using a route r and a spectral channel that does not overlap with a spectral channel assigned to any other working or protection path that shares any link with r.

Therefore, in addition to the existence of source-destination node pairs with different slot demands for working and protection paths, the different protection requirements included through virtualization introduces an additional dimension, since each virtual topology is proposed to represent the assignment of different QoS-aware protection services in the common physical substrate.

Let us define $C(ij, t)$ as the set of all candidate spectral channels that can be used for demands from source-destination node pairs $i - j$ at virtual topology t. If S is the number of available slots per link and $n_{ij,t}$ is the number of required slots by source-destination node pair i, j at topology t, it may be easily computed that the number of possible spectral channels is given by $|C(ij, t)| = S - n_{ij,t} + 1$.

Since working and protection paths may use a different number of slots, for the sake of notation clarity, let us extend the notation above and define $C_q(ij, t)$ and $C_{qq}(ij, t)$ as the set of all candidate spectral channels that can be used for working and protection demands, respectively.

The use of demand-tailored channels $C_q(ij, t)$ and $C_{qq}(ij, t)$ allows removing a devoted spectrum contiguity constraint from the mathematical formulation. In our previous model [8], $C_q(ij, t)$ and $C_{qq}(ij, t)$ have been computed through a preprocessing phase. Note that slot computation is trivial and thus negligible complexity is added to the preprocessing phase.

Thus, the RSA problem with virtualization for QoS-aware protection provisioning is defined as the problem of finding a proper spectral channel for each working and protection demands in each VON so that the active slots in the assigned spectral channels satisfy the contiguity, continuity and no spectrum overlapping constraints [8]. Note that, by precomputing the set of spectral channels that can be assigned to each demand, the complexity added by the contiguity constraint is removed. Finally, without loss of generality, we can consider that guard bands could be included as part of the requested spectrum.

IV. ILP FORMULATIONS TO MAXIMIZE THE SPECTRAL BENEFITS OF VONs WITH PROTECTION

In order to promote spectral usage benefits when QoS-aware protection is introduced in elastic optical networks with several virtual topologies, our previous work in [8] presents a mathematical channel formulation for optimal EON dimensioning with QoS-aware protection. The formulation takes the physical network topology, set of virtual topologies, set of traffic demands for each virtual topology as well as the premium and best-effort traffic fraction as input and produces the most efficient routing and spectrum assignment for spectrum occupancy minimization under protection services differentiation for each virtual topology.

Let us assume that both links and demands are directed, and consider a fixed demand between a pair of nodes and an arbitrary fixed node in the network. In addition, let us consider an ILP model as in [8], which computes for every demand its amount of traffic routed on each network link. (due to the large amount of links in the network and usually short routes, such traffic flow in many of the links in the network will be in general equal to 0.)

If one picks an arbitrary node in the network and analyses its incoming and outgoing link flows, two situations are risen: a) the node is neither source or destination node of the considered demand, so that all flow routed into this node on the incoming links are imperatively sent out on its outgoing links (which also applies for null flow). Such requirements are known as the flow conservation law [9]; and b) the node is either the source (destination) node of the considered demand, then the total outgoing (incoming) flow minus the total incoming (outgoing) flow must be equal to the demanded traffic volume. The flow equations for the link-node formulation presented in [8] is given by:

$$\sum_n x^{ij,t}_{mn,c} - \sum_n x^{ij,t}_{nm,c} = \begin{cases} a^{i,j}_{c,t} & i = m \\ -a^{i,j}_{c,t} & j = m \\ 0 & m \neq i,j \end{cases} \quad \forall m \in N, \quad (ij) \in D,\ c \in C_q(ij,t),\ t \in T, \tag{1}$$

$$\sum_n y^{ij,t}_{mn,c} - \sum_n y^{ij,t}_{nm,c} = \begin{cases} b^{i,j}_{c,t} & i = m \\ -b^{i,j}_{c,t} & j = m \\ 0 & m \neq i,j \end{cases} \quad \forall m \in N, \quad (ij) \in D,\ c \in C_{qq}(ij,t),\ t \in T. \tag{2}$$

where,

- $a^{i,j}_{c,t} \in \{1, 0\}$: 1 if channel c is used for the working path of demand *ij* on virtual topology t; 0 otherwise.
- $b^{i,j}_{c,t} \in \{1, 0\}$: 1 if channel c is used for the protection path of demand *ij* on virtual topology t; 0 otherwise.
- $x^{ij,t}_{mn,c} \in \{1, 0\}$: 1 if working path of demand *ij* on virtual topology t uses channel c in fiber *mn*; 0 otherwise.
- $y^{ij,t}_{mn,c} \in \{1, 0\}$: 1 if protection path of demand *ij* on virtual topology t uses channel c in fiber *mn*; 0 otherwise.

This link-node formulation searches among all possible solutions, which requires large amount of time to find the optimal solution. Please, see [8] for a complete link-node formulation aiming to minimize the spectrum.

On the other hand, the proposed mathematical formulation presented in this paper uses the notions of link and path to describe the network optimization problem (this is why the name, link-path formulation, makes sense), [9]. Since the topology is given, we can precompute a set of k distinct paths for each demand in the traffic matrix. Then, we can associate to each of these paths one of the possible forms of assigning it in the spectrum, which characterizes the formulation as a link-path, presented in next Section.

V. NOVEL ILP FORMULATION - WITH PREDEFINED PATHS

In the ILP node-link formulation presented before, the model spans all feasible regions and fields in a global optimal solution for the problem. Although a global optimum is guaranteed in this previous model, the solution time can be increased significantly, even for networks with few nodes, making its use impractical. Here, we propose a link-path that uses predefined paths to solve the problem.

Asymptotically a link-path formulation requires one order of magnitude (in terms of the number of nodes) less variables and constraints than the standard node-link formulation [9]. This observation suggests that link-path formulations are more efficient than the node-link formulations in terms of running time. If one compares these two types of formulations, it is observed that the link-path formulation requires a preprocessing stage for computing sets of candidate paths for the demands, which may be troublesome in some cases. On the other hand, the use of predefined sets of paths, by limiting the allowable set of paths, may, in an easy way, enable some kind of control in the chosen paths' properties; for instance, it may be imposed that paths with a limited number of hops are the only allowed, which might not be possible or demand intricate constraints in the node-link formulation. The process in the node-link formulations automatically scans all possible network paths and does not include a direct means for eliminating paths of certain undesirable features (e.g., too long, with minimum interfering links, etc).

In the link-path formulation, the form of representing a path for demands associated to a pair of nodes may not be limited to a regular single path in fact, but extended to consider a 'path' formed by both the working and protection paths of the demand. For example, in Fig. 2, (r, b) represents a pair and there are three candidate pairs $\{(r_1, b_1), (r_2, b_2), (r_3, b_3)\}$. Let $r \cap b$ be the set of physical links simultaneously present in routes r and b. In this paper, in order to ensure protection, for any pair of routes (r, b) for a demand ij, it is required that $r \cap b = \emptyset$.

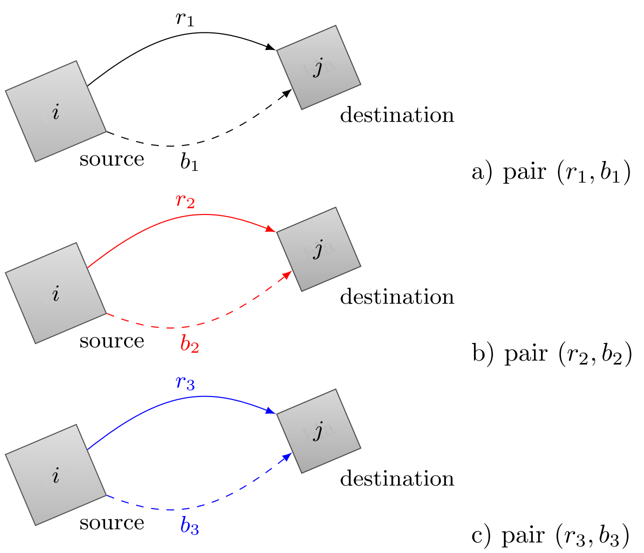


FIGURE 2. **Example of three candidates path pairs.**

A. ILP (PATH-LINK FORMULATION)

Given a graph G and a set D with the demands, we propose a ILP formulation with same objective as before, but it always uses at least a pair of disjoint routing paths provided to the formulation as parameters to the work and protection route to a demand ij. By this way, the path-link formulation calculates the best slot and assignments problem, decreasing the formulation's complexity substantially. In order to construct the new ILP formulation, new parameters and variables are defined below:

1) PARAMETERS

- ρ is the number of candidate path pairs for any demand ij;
- $(r, b) \in P(ij)$ is a pair of disjoint routing paths for demand ij, $|P(ij)| = \rho$.
- $C_q(ij, t, p)$: set of candidate channels (precomputed slots) for working demand ij on virtual topology t and path $p = r$.
- $C_{qq}(ij, t, p)$: set of candidate channels (precomputed slots) for protection demand ij on virtual topology t and path $p = b$.
- $\delta_{mn}^{ij,t,p}$: 1, if link mn belongs to path $p = r$ realizing demand ij; 0, otherwise.
- $\beta_{mn}^{ij,t,p}$: 1, if link mn belongs to path $p = b$ realizing demand ij; 0, otherwise.
- $q_{c,s}^{ij,t,p}$ equal to 1 if slot s is used on the c-th channel and path $p = r$.
- $qq_{c,s}^{ij,t,p}$ equal to 1 if slot s is used on the c-th channel and path $p = b$.

2) VARIABLES

- $x_{p,c}^{ij,t} \in \{1, 0\}$: 1 if working path of demand ij on virtual topology t uses channel c in path $p = r$; 0 otherwise.
- $y_{p,c}^{ij,t} \in \{1, 0\}$: 1 if protection path of demand ij on virtual topology t uses channel c in path $p = b$; 0 otherwise.
- $w_{mn,s} \in \{1, 0\}$: 1 if slot s is used on link mn; 0 otherwise.
- $z_s \in \{1, 0\}$: 1 if slot s is used in any link of the network; 0 otherwise.
- F: number of used spectrum slots to support all traffic demands.

Again, the formulation proposed in this subsection is based on the concepts described in Section III. Now, the $C(ij, t, p)$ is the set of all candidate spectral channels that can be used for demands from source-destination node pairs $i-j$ at virtual topology t and path p.

Since S is the number of available slots per link and $n_{ij,t,p}$ is the number of required slots by source-destination node pair i, j at topology t and path $p = r$, it is easy to see that the number of possible spectral channels is given by $|C(ij, t, p)| = S - n_{ij,t,r} + 1$.

Since working and protection paths may use a different number of slots, for the sake of notation clarity, let us extend the notation above and define $C_q(ij, t, p)$ with $p = r$ and $C_{qq}(ij, t, p)$ with $p = b$ as the set of all candidate spectral channels that can be used for working and protection demands, respectively. $C_q(ij, t, p)$ and $C_{qq}(ij, t, p)$ have been computed through a preprocessing phase. The proposed ILP formulation is below.

$$Minimize : F \tag{3}$$

Constraints: Eqs. (4) and (5) guarantees that all demands are served by a single channel among the possible ones for respectively the working and protection paths of a demand. Eqs. (6) guarantees that the working and protection paths belong to the same set.

$$\sum_{p \in P(ij,t), \quad c \in C_q(ij,t,p)} x_{p,c}^{ij,t} = 1 \quad \forall (ij) \in D, \ t \in T, \tag{4}$$

$$\sum_{p \in P(ij,t), \quad c \in C_{qq}(ij,t,p)} y_{p,c}^{ij,t} = 1 \quad \forall (ij) \in D, \ t \in T, \tag{5}$$

$$\sum_{c \in C_q(ij,t,p)} x_{p,c}^{ij,t} - \sum_{c \in C_{qq}(ij,t,p)} y_{p,c}^{ij,t} = 0$$
$$\forall (ij) \in D, \quad t \in T, \ p \in P(ij, t) \tag{6}$$

The condition between the working and protection paths to find the variable u is formulated in Eq. (7).

$$\sum_{p\in P(ij,t)} \Big(\sum_{c\in C_q(ij,t,p)} x_{p,c}^{ij,t} \beta_{mn}^{ij,t,p} q_{ij,c,s}^{p,t} + \sum_{c\in C_{qq}(ij,t,p)} y_{p,c}^{ij,t} \delta_{mn}^{ij,t,p} qq_{ij,c,s}^{p,t} \Big) = u_{mn,s}^{ij,t} \quad \forall (mn) \in E, \quad (s) \in S, \; t \in T, \; (ij) \in D, \tag{7}$$

Eq. (8) and Eq. (9) work with Eq. (10) with the objective function of minimizing F.

$$\sum_{ij,t} u_{mn,s}^{ij,t} = w_{mn,s} \quad \forall s \in S, \; (mn) \in E \tag{8}$$

$$\sum_{mn\in E} w_{mn,s} \leq |E| z_s \quad \forall s \in S, \tag{9}$$

$$\sum_{s\in S} z_s \leq F. \tag{10}$$

VI. HEURISTIC ALGORITHMS

The problem of mapping a virtual network over EON is known as a nondeterministic polynomial (NP) problem [2]. Therefore, due to its complexity, the proposed ILP strategy may be very time-consuming when solving problems for large network scenarios, being not scalable.

Here, two alternatives for solving the RSA problem with virtualization and protection are presented; the first one is a meta-heuristic, also presented in [8] based on genetic algorithm. The second one is a strategy based on routing minimizing the load for a pair as input, $\rho = 1$.

A. GENETIC ALGORITHM (GA)

GA was run according to the procedure used by [8]. It usually presents robust results, however, as it is a meta-heuristic method, the solution can converge to a local minimum (presenting a false optimal response). This premature convergence can be circumvented by an appropriate adjustment in the number of generations, population size and genetic operators. In order to set a benchmark for our new ILP formulation with predefined paths, the same GA (and its parameters) adopted in [8] are used. The GA is represented by the flowchart illustrated in Figure 3 and detailed in the following steps:

1) INITIAL PARAMETER SETTINGS

At this stage, initial values are assigned to the input parameters. These parameters are:

-Population Size (P): defines the number of individuals present at the admission of each GA generation.

-Number of generations (G): defines how many iterations the GA will run;

-Elitism Index (EI): defines the number of best individuals stored and reinserted in population in each generation;

-Mutation Probability (MP): defines gene's chance of mutation at each individual;

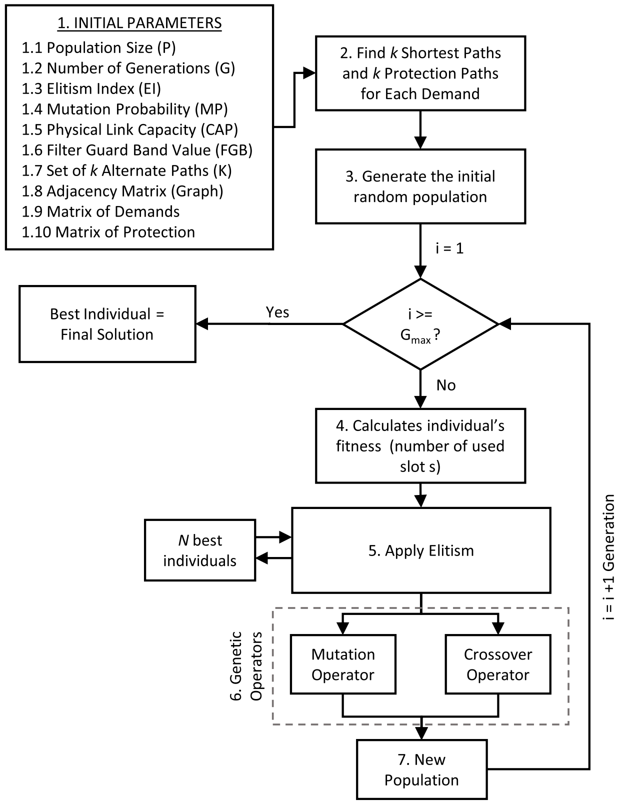


FIGURE 3. GA flowchart strategy, please see [8] for details.

-Physical Link Capacity (CAP): defines the number of slots in each physical link;

-Filter Guard Band Value (FGB): the minimum spectrum width between wavebands (in number of slots);

-Set of k Alternate Paths (K): Defines k paths provided for selection in the Routing step.

-Adjacency Matrix (Graph): defines the adjacency matrix of the physical network. The matrix size is $N \times N$, where N represents the network nodes and the value of each element is the distance (in km) among network nodes;

-Matrix of Demands: defines the demands for each VON. Each element represents the demanded traffic flow (in slots) from node i to node j in VON t.

-Matrix of Protection (QoS): defines the QoS value for each VON t (in %).

2) FIND k SHORTEST PATHS AND k PROTECTION PATHS FOR EACH DEMAND

Using the parameters provided in the previous step (step 1), the algorithm performs the calculation of the k shortest loopless paths for each demand, using the well-known Yen's algorithm [36]. The choice of this algorithm is due to the good performance and simplicity of its implementation. For each previously found path, the algorithm temporarily removes its links from the graph and calculates another shortest path, finding a disjoint route.

3) GENERATE THE INITIAL POPULATION

In this step, a set of P random individuals is generated, allowing a wide range of possible initial solutions. Each individual is represented by a line in the population matrix. This matrix is $P \times D_T$, in which P is the population size and D_T is the total number of demands in the network, i.e. for every source-destination pairs and in all VONs. In addition, the value (among 1 and k) of each gene of the individuals represents one of the possible working path (along with its protection path) for that specific demand. Thus, each individual represents a possible routing solution to be evaluated after the spectrum allocation problem in the next step.

4) CALCULATE THE INDIVIDUALS' FITNESS

At this point, the network physical links are filled with connections (demands) from the *Matrix of Demands* considering each individual of the population P. Then, each individual is evaluated in the fitness function in terms of used slots s. To calculate the fitness, the demands (considering working path and protection with QoS) are sorted according to the decreasing value of its spectrum necessity. After that, demands are allocated on the network using First-Fit spectrum allocation.

5) APPLY ELITISM

In this step, the P individuals are ordered according to their evaluated fitness and, in order to keep efficient solutions from the previous step, a percentage of the fittest individuals in P is stored in a set I.

6) APPLY THE GENETIC OPERATORS

All P individuals are passed to the crossover operation, which randomly combines them in pairs and applies a point-crossover operation through one, two or three intersection points in the set of genes of the individuals, with equal probability. Therefore, P individuals generate $P/2$ new individuals. Fig. 4 depicts the crossover operation with two intersection points. The second genetic operator, the mutation function, using roulette wheel selection, selects ($P/2$) individuals of the population and alters one or more characteristics (genes) to one of the possible k path identifier, based on the mutation probability, provided as an input parameter. Therefore, $P/2$ individuals generate $P/2$ new individuals. Fig. 5 depicts the mutation operator applied to a hypothetical individual.

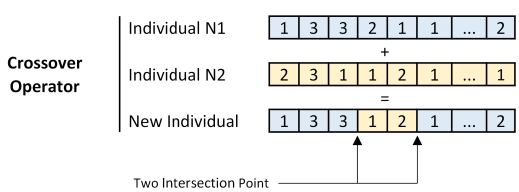


FIGURE 4. **Crossover genetic operator applied to a pair of hypothetical individuals. In the example it was considered two intersection points.**

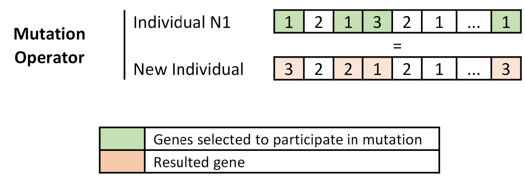


FIGURE 5. **Mutation genetic operator applied to a hypothetical individual. One or more genes are randomly altered from its initial state.**

7) NEW POPULATION

These P new individuals emerged from mutation and crossover operators are combined with the previously stored I best individuals of P and an elitism process is performed to generate P individuals (new population). Next, the algorithm performs G interactions (repeating the steps 4 to 7) until reaches the predefined value for generations. At the end of the process, the best individual is considered as the final solution to the proposed problem.

B. BEST AMONG THE SHORTEST ROUTES FOR A PAIR OF DISJOINT PATHS

The performance of the methods (ILP with pre-defined paths and GA) depend on the number of disjoints pairs paths for each demand. This choice leads to a trade-off between performance (in terms of used slots) and CPU time. For example, the use of one single disjoint pair could reduce the required CPU time but at the cost of reducing the performance (in terms of optimality). On the other hand, setting two or three pairs of disjoint paths could increase the chance of finding an optimal (or near optimum) solution but at the cost of a higher CPU time.

As aforementioned, for each demand, the well-known Yen's algorithm can be used to calculate the k shortest disjoint pairs. Recall that, for the case of unitary weighted graphs, finding the shortest path is equivalent to computing the k routes with a smaller number of hops. One drawback of this strategy is that the routes associated with a given demand may potentially share most of the links, thus yielding an undesirable number of unbalanced routes in terms of links load. As a result, this may prevent some demands to be allocated because of the congestion in such links.

In order to get better paths, a strategy similar to that used in [21] was performed. The strategy precomputes pair of disjoint paths for each demand in order to provide efficient network link load balance. The BSR (Best among the Shortest Routes) algorithm was done according to the procedure presented in [22], which aims at balancing the choice of routes determined by greedy algorithms. The balancing is performed by modifying the weights of the links according to their usage in terms of traffic load. Balanced routes are likely to decrease the chance of congestion, as well as of allocation conflicts.

The principal steps of the modified BSR algorithm are described in Figure 6. Initially, since the BSR focuses on finding routes with the minimum number of hops, all links receive unitary cost. In addition, since the traffic has not being

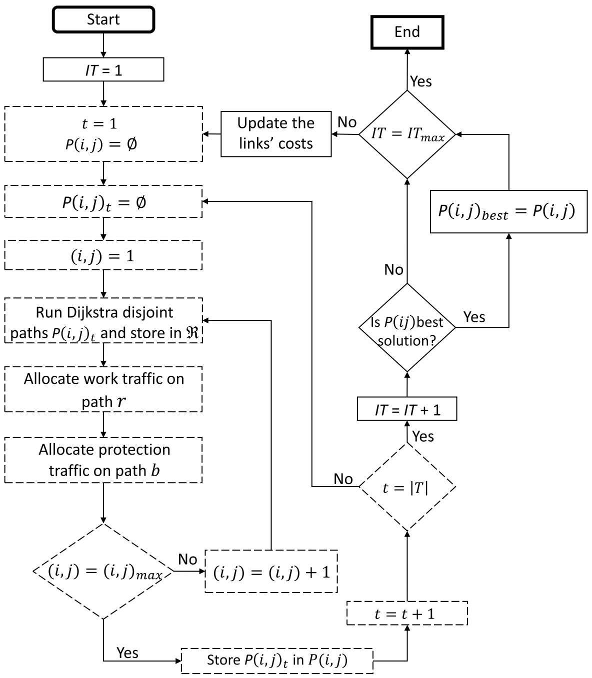


FIGURE 6. BSR flowchart modified (dashed line).

distributed yet, the link load has not been computed at this stage. During the main loop, the algorithm computes for each demand (i, j) the minimum-cost pair of disjoint paths from set $P(i, j)$ with $\rho = 1$ using Dijkstra's algorithm, and, for each link, the load is determined by summing the number of slots required by the corresponding incident demands. The difference between the original BSR algorithm and the version implemented in this work is that the maximum load value among the links was used as the criterion to evaluate the balancing quality for T virtual topologies. The main loop is executed for a predefined number of iterations IT_{max} and this number is the stopping criterion. The weighted graph that generates the least maximum load is chosen to build the final set of disjoint routes. Note that the main loop is executed until the maximum number of iterations is achieved.

At each iteration of the main loop, the weight of each link is updated based on the weight of the previous iteration and on the computed load. This computation takes into account some parameters, which define the level of impact that the previous weight and the current load has over the new weight of the link. Next, the graph is updated with the new set of weights for each link. Finally, a pair of disjoint routes is generated for each demand using Yen's algorithm over the best obtained weighted graph.

VII. NUMERICAL RESULTS

To quantify the effectiveness of the proposed ILPs formulations and heuristics, we conducted experiments on different network topologies (small and medium-large size networks). To solve the ILPs formulation, we used IBM ILOG CPLEX v.11.0 software [19] running on an Intel Xeon Silver 4216 2.10 GHz processor with 96GB RAM.

In our experiments we considered a flexible baud rate transponder for traffic provisioning and the baud-rate flexibility corresponding to 1, 2/3 or 1/3 of the working traffic, as shown in Table 1. We also assume that there is a pair of bidirectional fibers on each link and FGB is not required by the system. In each simulation, we considered a high enough network capacity in order to support all demands. In the following subsections we describe in details the conducted experiments.

TABLE 1. QoS-aware protection with PDM-QPSK transponder, adapted from [18].

Bit Rate	Prot. Level (QoS)	Baud Rate	Slots Occupancy (12.5 GHz/slot)
75 Gbit/s	1	24 GBd	3
50 Gbit/s	2/3	16 GBd	2
25 Gbit/s	1/3	8 GBd	1

A. SMALL NETWORK

For our first experiment, we used a 6-node and 7-link topology (as shown in Fig. 7) to quantify the performance of our proposed formulation. Initial parameters for GA are from [8] and they were set empirically as follows: P = 200; G = 100; EI = 0.1; MP = 0.2; CAP = 120; FGB = 0; K = 3. The presence of guard band does not imply in different solutions obtained by the ILP formulation. However, we preferred to keep it since the model becomes more complete/generic, which may be straightforwardly adapted to problems in which the consideration of guard bands makes difference.

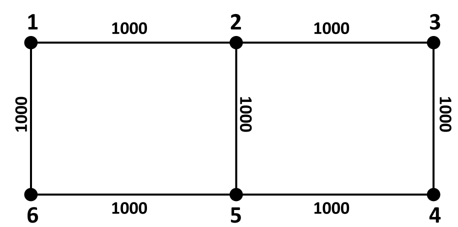


FIGURE 7. Network topology: 6-node network.

We simulated four different scenarios. For each case, we assumed three virtual topologies (VON1, VON2 and VON3) with 75 Gbit/s traffic requests between all node-pair. The protection traffic requirement was set according to the protection level (QoS) adopted by each VON (slot occupancy for each bit rate is shown in Table 1). The performance of the approaches, in terms of number of frequency slots, F, among all fiber links in the physical network, is summarized in Table 2. Our formulation with predefined paths is referred to ILP_p and ILP_{BSR}. We provide the number of used slots for each scenario using ILP_ρ (F_{ILP_p}) and ILP_{BSR} ($F_{ILP_{BSR}}$). The ILP (F_{ILP}) and lower bound LB (F_{LB}) from [8] are used in order to compare the results. LB stands for the ILP relaxation

TABLE 2. First experiment – mapping of three VONs with different protection values for the six nodes network. *CPLEX time limit = 48h.

Scenario	VON #	Prot Level (QoS)	F_{LB}, [8]	F_{ILP}, [8]	$F_{ILP(\rho=3)}$	$F_{ILP(\rho=2)}$	$F_{ILP(\rho=1)}$	$F_{ILP(BSR)}$	F_{BSR}	F_{GA}, [8]
I	VON 1 VON 2 VON 3	1 1 1	87.43	90 (16.4h*) gap = 2.8%	90 (971.30s) gap = 2.8%	99 (10.40s) gap = 11.7%	117 (2.50s) gap = 25.3%	99 (2.9s) gap = 11.7%	99 (0.7s) gap = 11.7%	90 (22.99s) gap = 2.8%
II	VON 1 VON 2 VON 3	2/3 2/3 2/3	69	98 (48h*) gap = 30%	69 (8757.41s) gap = 0%	71 (5755.62s) gap = 2.8%	93 (1.69s) gap = 25.8%	75 (92.6s) gap = 8%	83 (3.7s) gap = 16.9%	70 (23.26s) gap = 1.4%
III	VON 1 VON 2 VON 3	1/3 1/3 1/3	51	53 (29.9h*) gap = 3.9%	53 (1959.53s) gap = 3.9%	53 (2815.43s) gap = 3.9%	69 (0.92s) gap = 26.1%	60 (56.9s) gap = 15%	62 (1.5s) gap = 17.7%	53 (22.56s) gap = 3.8%
IV	VON 1 VON 2 VON 3	1 2/3 1/3	69	69 (16.3h*) gap = 0%	69 (2123.00s) gap = 0%	71 (643.20s) gap = 2.8%	93 (1.80s) gap = 25.8%	75 (21.6s) gap = 8%	78 (0.9s) gap = 11.5%	69 (22.97s) gap = 0%

value. The gap is defined for each approach (F_*) as the ratio $(F_* - F_{LB})/F_*$.

In our experiments using a small network, our ILP_p formulation for QoS = 1 (Scenario I) was able to solve the problem in a short time (<971s for $p = 3$ and <2.6s for $p = 1$). Results with gap less than 12% to F_{LB} were found for all Scenarios with $p = 3$ and $p = 2$. Despite the values closer to LB for all scenarios when using the *ILP* and $ILP_{p=3}$, the running time was much lesser in $ILP_{p=3}$. For example, the *ILP* for the Scenario I takes 16.4h whereas $ILP_{p=3}$ takes only 971s. The ILP_{BSR} approach presented greater efficiency for all simulated scenarios (gap < 8.9%) and required less running time to solve the same problem. The GA was efficient for all Scenarios. However, the $ILP_{p=3}$ for Scenario II was a bit better, apart from the running time.

In addition, as expected, reducing the protection level from 100% (QoS = 1), as in the traditional protection case, to 2/3 and 1/3 (Scenario II and III) a reduction in spectral resource requirement was observed. For Scenario IV, when different QoS values were mixed, a reduction on spectrum usage were found too.

To assess the performance of the ILP_ρ with several VONs (1, 2, 3, 4, and 5), we simulate the $ILP_{\rho=1}$ approach with QoS = 1 for all T. The results, as shown in Figure 8, indicate the increase of used spectrum and running time in function of number of VONs. The running time was 2s to one VON and increased significantly to 12s with five VONs.

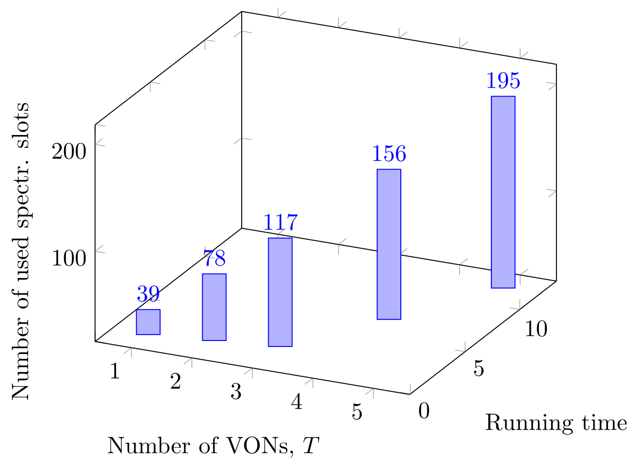


FIGURE 8. Running time and spectrum used in function of several VONs (approach: $F_{ILP(\rho=1)}$ with QoS = 1 for the 6-node network).

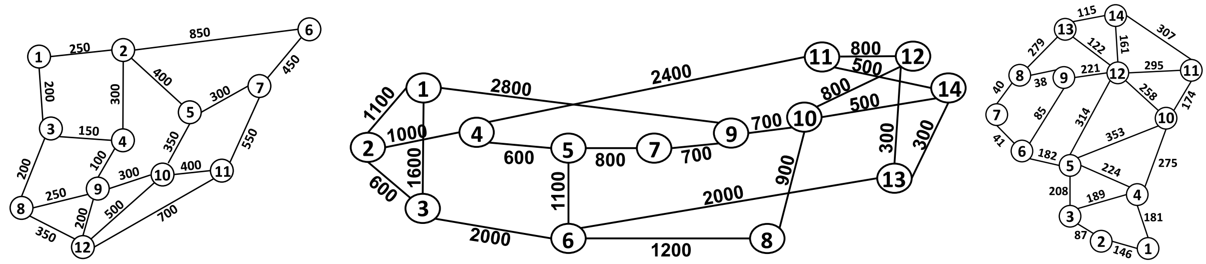
Therefore, a variety of methods are used to assess F. Each has its advantages and drawbacks. A case study approach with the original BSR heuristic (without ILP), F_{BSR}, was used to allow a comparasion with the other methods. F_{BSR} was prepared according to the procedure used by [22]. It can be seen from the data in Table 2 that F_{BSR} reported worse performance (in terms of slots) than $F_{ILP_{BSR}}$ and F_{GA} in most cases.

Over all simulations, see Table 2, the performance of squeezing was compared to that of dedicated protection (QoS = 1). The simulations show the advantages of the squeezing (QoS < 1) over dedicated protection. The charts demonstrate that the squeezing strategy, which provides different SLAs for each VON, can save a large amount of the total spectrum when compared to dedicated protection. This occurs because dedicated protection does not benefit from traffic squeezing, as occurs with QoS < 1. Comparing several schemes using squeezing against dedicated protection, we observe, for the same traffic profile, a clear gain in terms of saved bandwidth.

A number of researchers have reported the use of squeezing as a solution to meet customer and service providers needs. For example, see [37]–[39] for details and a theoretical demonstration in [20].

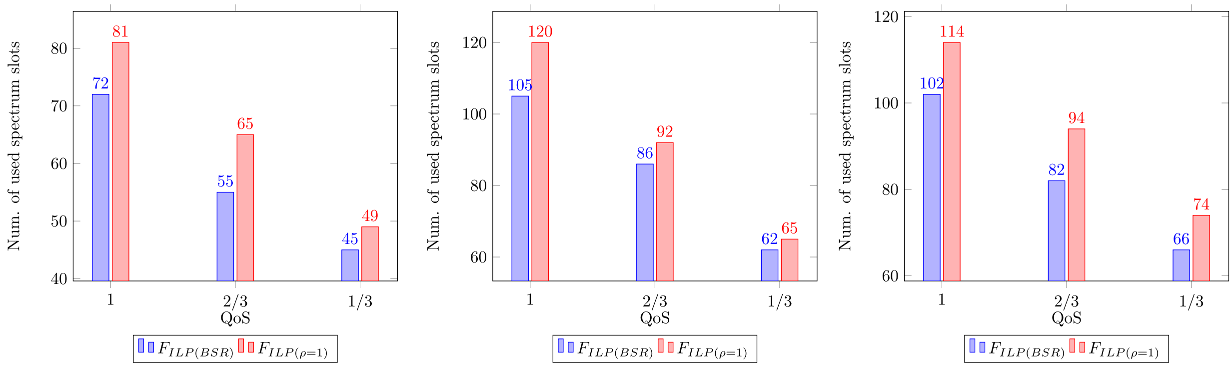
As a repercussion, cheaper transponders with less power consumption can be applied, and less spectrum resources (i.e., narrower channels) are necessary. Note that bandwidth squeezed protection, feasible in EONs due to the use of flexible frequency grids, is not available in fixed-grid wavelength switched optical networks (WSONs), [17].

Due to the intrinsic complexity of the complete strategy presented in Section V, the required time to find the optimum solution for large networks may be considerably high. For instance, the time required to run the complete ILP for the network shown in Fig. 7 on an Intel i3 2.27 GHz 2 GB machine was less than 5s. Once we added an additional node connected to nodes 1 and 6, the required simulation time increased to few minutes. Finally, when a new node was included between nodes 3 and 4, a simulation time of around 1 h was observed, showing that, even with the link



(a) FINLAND (b) NSFNET (c) DEUTSCHE

FIGURE 9. Three physical topologies over study.



(a) Different QoS, FINLAND. (b) Different QoS, NSFNET. (c) Different QoS, DEUTSCHE

FIGURE 10. Spectrum usage for $|T| = 1$ and different squeezing levels.

path formulation, we rapidly need a heuristic model to deal with moderate to large networks. If we add VONs as well, for example about 100 VONs, the simulation time becomes extremely long. Therefore, *BSR* and *GA* can be seen as useful alternatives to this problem as they present an interesting balance between CPU time and results. Another way would be to use relaxation techniques, as seen in Table 2. In this case, the results would be the lower bound, F_{LB}.

B. LARGE NETWORKS

To investigate the performance of the approaches for large instances, the proposed ILP_ρ, ILP_{BSR}, *BSR* and GA were used for three large networks (FINLAND, NSFNET and DEUTSCHE, see Figure 9).

1) ILP_p FORMULATION AND PERFORMANCE GAIN DUE TO SQUEEZING

The dilemma of long simulation time such as ILP formulation from [8] is an example of a multi-commodity network flow problem [9]. The term multi-commodity comes from the fact that there are multiple demands (or commodities) that need to be routed in the network simultaneously and they compete for available resources (link capacities, in this paper). This is in fact a very common scenario in communication and computer networks. However, the formulation may not be practical for virtualization, even for small instances, as we saw in Table 2.

We have emphasized previously that the link-path formulation can be preferable for communication and computer modeling, since the possibility of selecting pre-processed paths as input to the link-path-based (also called the arc-path) model may bring some advantages. Therefore, in this subsection, we show the efficiency of our $ILP_{\rho=1}$ formulation, ILP_{BSR} as well as the advantages of squeezing protection compared to dedicated protection.

The performance of ILP_{BSR} for moderated networks were compared for the $ILP_{\rho=1}$ for the following topologies: FINLAND, NSFNET and DEUSTCHE (see Fig. 9). This simulation is relevant because it clearly shows the advantages of the ILP_{BSR} strategy over shorthest path routing, as discussed in former section. For the simulations, it was assumed only one slice or one virtual topology ($|T| = 1$) with the three different kinds of protection from Table 1 and protection for all demands.

As can be seen in Fig. 10, the performance, in terms of number of utilized spectrum slots, is compared for three different networks. Again, the simulations demonstrate that the ILP_{BSR} technique, which provides a adequate pairs of paths, can save a large amount of the total spectrum when compared to shortest path pairs and both strategies can be useful for moderately large networks.

2) MIX PROTECTION SCENARIOS WITH $|T| = 3$

It was assumed a mix protection level or Secnario IV from Table 2 ($t = 1$, 2/3 for $t = 2$ and 1/3 for $t = 3$). Results are summarized in Table 3. It was a significant positive result that all networks with ILP_{BSR} and *BSR* heuristic take a less

TABLE 3. Mapping of three VONs with different protection values for three large networks.

Network id	Name	N (number of nodes)	L (links)	Nodal Degree (mean)	$F_{ILP(BSR)}$	F_{BSR}	F_{GA}	$F_{ILP(\rho=1)}$
(a)	FINLAND	12	2x19	3.16	173	173	190	195
(b)	NSFNET	14	2x21	3.00	236	237	255	277
(c)	DEUTSCHE	14	2x23	3.28	246	246	260	282

number of slots than $ILP_{\rho=1}$ and GA. For large networks, there was no decrease in the number of slots with $ILP_{\rho=1}$ when compared to GA. That is a strong evidence that paths found with ILP_{BSR} and *BSR* approaches, mainly for large networks, are useful. In terms of running time, the $ILP_{\rho=1}$ and ILP_{BSR} take the results with a long time (about 2h) for those networks. On the other hand, the GA and *BSR* take few seconds.

VIII. CONCLUSION

In this paper we considered and compared two basic types of formulations to design EONs with virtualization and protection: the link-path model and the node-link model. Both models have their pros and cons; It was shown in our studies that the link-path model is more powerful for some cases, mainly in terms of running time. The advantage of the link-path model in this aspect was shown to be even more profound in study of large networks. In fact, the only advantage of the node-link model over link-path is that, in the ILP formulation, the former model can make effective use of all available network paths to be used by the demanded traffic flows. This cannot be accomplished so easily by link-path formulations for which some path generation techniques must be used to extend the routing lists if they are not sufficient for achieving optimal solutions. In order to provide efficient groups of disjoint routes, we proposed a modified version of the BSR heuristic and showed that it provides good results in terms of spectrum saving.

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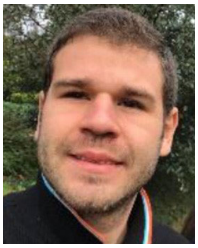

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