Design of Survivable Optical Networks with Minimum CAPEX

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***Abstract*—We present a genetic algorithm for the design of survivable networks with minimum capital expenditure. The survivability against any single link failure is ensured by path dedicated protection. An integer linear programming model to evaluate the quality of the genetic algorithm solutions is also presented. Using the integer linear programming model and the genetic algorithm near-optimal topologies are determined.**

I. INTRODUCTION

Optical networks that employ wavelength division multiplexing (WDM) are currently the first choice for transport networks. A link failure, such as a fiber cut, will result in service disruption for thousands of clients. Therefore, a network design that provides enough capacity to recover network connections is essential in nowadays network planning.

Survivable network design is defined as the problem of determining the network topology at minimum cost, such that all demands can be routed and some protection/restoration is provided [1]. In this contribution, we assume path dedicated protection to ensure survivability against any single link failure [2]. Within the dedicated protection scheme, capacity is reserved for two link disjoint paths, a working and a backup path, for each demand. When a working path link fails the affected demands are switched to the dedicated backup paths.

Given the node location and the traffic matrix, in this work we address the problem of obtaining the physical topology that minimizes the capital expenditure (CAPEX). This is an NP-hard [1], [3] optimization problem and heuristics are traditionally used to search for near-optimal solutions. In this work, we present a genetic algorithm to determine the minimum CAPEX topology. An integer linear programming (ILP) model is also presented and used to access the performance of the proposed heuristic.

This paper is organized as follows: the problem is formulated in Section II. In Section III we present an ILP model and the genetic algorithm in Section IV. Computational results obtained with the ILP model and the genetic algorithm are reported in Section V. Finally, in Section VI we drawn the main conclusions.

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II. PROBLEM DEFINITION

An optical network is a set of nodes connected by bidirectional links and can be represented as a graph, $G = (V, E, A)$, where $V = \{1, \dots, n\}$ is the set of nodes, $E = \{\{i, j\} : i, j \in V, i < j\}$ the set of edges and $A = \{(i, j) : i, j \in V, i \neq j\}$ the set of arcs. Bear in mind that each edge is associated with two directed arcs with opposite direction indicating the demand orientation traversing the physical link. Associated to each link there is a cost dependent on the distance between the nodes. The length in km between the node i and the node j will be denoted by C_{ij} and is the cost of the edge $\{i, j\}$.

The optical network has to support a given traffic, that is a set of demands between nodes. We assume bidirectional demands in this work. The demand between the origin, o, and the destination, d, will be denoted by $[o, d]$ and the set of all demands by $P = \{[o, d] : o, d \in V, o < d\}$. The bandwidth of the demand has to be reserved in each link of the working and of the backup paths. The traffic will be divided in rates of STM-16 channels ($\approx$ 2.5 Gb/s). The number of optical channels for the demand $[o, d]$ will be denoted by B_{od}.

The CAPEX can be divided in costs for bandwidth management (costs with nodes) and costs for signal transmission (costs with links). As the number of nodes and the traffic demand are known in advance, the nodes costs are fixed. To minimize the total cost it is necessary to minimize the transmission costs. Figure 1 represents the transmission system architecture considered in this work.

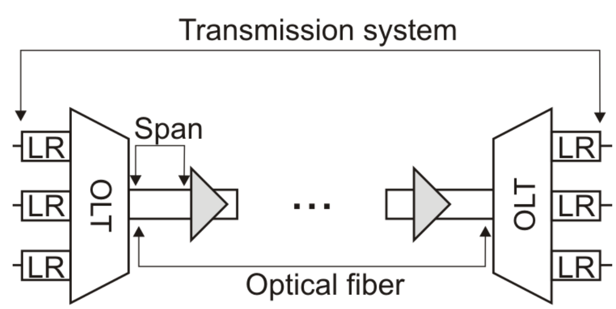

Fig. 1. Transmission system architecture composed by the optical fiber, the optical line terminal, the optical amplifier and the long reach transponders.

The architecture comprises the optical fiber, two optical line terminals (OLT) per link, one optical amplifier per span and two transponders per optical channel. The OLT has the function of multiplex/demultiplex wavelengths into the optical fiber. Two transponders per optical channel are needed for optical-electrical-optical conversion. The optical amplifier, amplifies the signals in the fiber.

The transmission costs can be divided into costs depending on the number of optical fibers, F_{ij}, and costs depending on the number of optical channels, O_{od}. The costs F_{ij}, are composed by the costs with optical amplifiers, OLTs and optical fibers. The number of optical amplifiers is dependent on the length of the fiber, C_{ij}, and the distance between amplifiers, *span*. Two OLT are needed, one in each extremity of the fiber. Therefore, F_{ij} is given by

$$F_{ij} = \left\lceil \frac{C_{ij}}{span} - 1 \right\rceil c_{oa} + c_{olt} + C_{ij} c_f, \tag{1}$$

in which c_{oa} is the cost of an optical amplifier, c_{olt} the cost of two optical line terminals and c_f the cost of the optical fiber per km.

The costs O_{od} correspond to costs with transponders. Two transponders per optical channel are needed. Given that c_t is the cost of two transponders, O_{od} can be calculated by

$$O_{od} = c_t B_{od}. \tag{2}$$

To obtain an ILP model we use two variables,

- integer non negative variables X_{ij} indicating the number of pair of fibers between the nodes i and j,
- binary variables Y_{ij}^{od} indicating whether the demand $[o,d]$ is routed in arc (i,j) or not.

The transmission costs are given by the sum of F_{ij} for all links plus the sum of O_{od} for all demands. The objective function is given by

$$\sum_{\{i,j\}\in E} F_{ij}X_{ij} + \sum_{(i,j)\in A} \sum_{[o,d]\in P} O_{od}Y_{ij}^{od}. \tag{3}$$

In the next sections we present two different approaches to obtain solutions that minimize expression (3) with survivability requirements.

III. Integer Linear Programming Model

In this section we present an ILP model to minimize the costs with links in an optical network. To guarantee survivability between all pair of nodes, at least, two edge disjoint paths must be obtained. Note that two disjoint paths are enough to protect the network against any single link failure. The model is based on the ILP model presented in [4] and is as follow,

$$min \quad \sum_{\{i,j\}\in E} F_{ij}X_{ij} + \sum_{(i,j)\in A} \sum_{[o,d]\in P} O_{od}Y_{ij}^{od}$$

$$subject\ to$$

$$\sum_{j\in V\setminus\{o\}} Y_{ij}^{od} - \sum_{j\in V\setminus\{d\}} Y_{ji}^{od} = \begin{cases} 2, & i=o \\ 0, & i\neq o,d \\ -2, & i=d \end{cases} \quad \forall [o,d]\in P, \forall i\in V \tag{4}$$

$$\sum_{[o,d]\in P} B_{od}(Y_{ij}^{od} + Y_{ji}^{od}) \le K_{ij}X_{ij} \quad \forall \{i,j\}\in E \tag{5}$$

$$X_{ij} \in \mathbb{N}_0 \quad \forall \{i,j\}\in E \tag{6}$$

$$Y_{ij}^{od} \in \{0,1\} \quad \forall [o,d]\in P, \forall (i,j)\in A \tag{7}$$

Constraints set (4) are the usual flow conservation constraints. These constraints together with constraints (5) guarantee the connectivity between nodes. The origin, o, send two flows and the destination, d, will receive those two flows. In all the other nodes, the received flow have to leave, constraints (4). Constraints set (5) connects the variables X_{ij} and Y_{ij}^{od}, guaranteeing that the total number of optical channels do not exceeds the fiber capacity, K_{ij}. The disjointness of the two flows is enforced by constraints (7). As the variables Y_{ij}^{od} are binary, the two flows cannot traverse the same edges.

IV. Genetic Algorithm

Genetic algorithms are search algorithms based on the mechanics of natural selection [5]. In every generation (iteration), a new set of artificial individuals (solutions) is created, using pieces of the fittest.

The initial population set is builded by adding links to a ring topology thus, guaranteeing that all initial solutions are feasible. The ring topology is builded by connecting each node i $(i = 2, \ldots, n-1)$ to nodes $i-1$ and $i+1$ and node n to $n-1$ and 1. Figure 2 displays two solutions for a network with four nodes. The solution A is exactly the ring topology that is common to all the individuals. The number and location of additional links is random. One example is the solution B displayed in Figure 2.

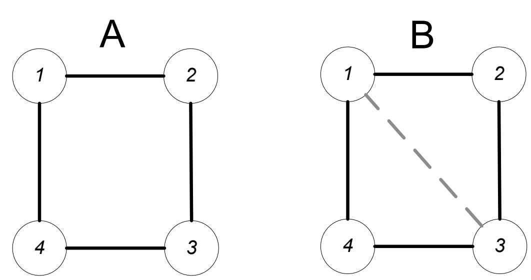

Fig. 2. Examples of solutions builded for the initial population. The ring topology displayed is common to all solutions. A random number of additional links are added in random locations, see the example B.

For the solutions encoding we used the concatenation of the upper triangular matrix of the graph adjacency matrix. An element of the adjacency matrix in position i,j is 1 if node i is connected to node j and 0 otherwise. As the network links are bidirectional the adjacency matrix is symmetric. The genetic code for the solutions A and B displayed in Figure 2 are,

$$ind_A : 1\ 0\ 1 \mid 1\ 0 \mid 1, \qquad ind_B : 1\ 1\ 1 \mid 1\ 0 \mid 1. \tag{8}$$

The solutions evaluation consists in determining the path of each demand (working and backup) and the number of optical channels in each link. We assume that the demands are routed through the shortest path in number of links, corresponding to Y_{ij}^{od}. The shortest path is determined using the Dijkstra algorithm. Afterwards, the links used in the working path are overweighted and the second shortest path determined using the Dijkstra algorithm a second time. After all the demands are routed, the number of optical channels in each link is easily obtained, and using (3) the transmission costs calculated. If the two disjoint paths cannot be obtained, the solution is retreated from the population.

For parents selection to crossover, we used the roulette wheel method [5]. In this method, solutions with smaller cost have greater probability to be chosen for crossover.

The crossover method is the uniform method [5]. In this method, a crossover mask is randomly generated. The parity of each bit in the mask, determines from which parent the descendent will inherit that bit. The following example illustrates the process:

$$\begin{array}{lcccccc}
Parent\ 1: & 1 & \mathbf{0} & 1 & 1 & \mathbf{1} & 1 \\
Parent\ 2: & 1 & \mathbf{1} & 1 & 1 & \mathbf{0} & 1 \\
\hline
\text{Mask}: & 0 & \mathbf{1} & 1 & 0 & \mathbf{0} & 1 \\
\hline
Descendent\ 1: & 1 & \mathbf{0} & 1 & 1 & \mathbf{0} & 1 \\
Descendent\ 2: & 1 & \mathbf{1} & 1 & 1 & \mathbf{1} & 1
\end{array}$$

If the crossover mask bit i is 1, the descendent 1 receive the bit i from the parent 1 and the descendent 2 the bit i from the parent 2. If the mask bit i is 0, the descendent 1 inherit the bit i from the parent 2 and the descendent 2 from the parent 1. In this way we produce novel offspring individuals which represent network topologies.

The final step is the mutation operation. For randomly selected individuals the mutation operation consists in a simple exchange of 0 to 1, or vice versa, at random locations of the genetic code.

After the individuals are evaluated, selected and reproduced, the next generation is created. Each generation is composed by 50 individuals in which 5 of them are the ones with greatest cost and the remaining 45 the ones with smallest cost. Moreover, a maximum of 20% of individuals are selected from the previous generation, the others 80% are generated offsprings.

V. Computational Results

In this section, the computational results obtained using the ILP model and the genetic algorithm are reported. The ILP model was solved using the optimization software Xpress. The exact method, used by the software, was the branch and bound method and allowed the reaching of an upper and lower bound for the optimal. The results were obtained on a PC Intel Core 2 at 1.83 GHz and 1 Gb RAM. The processing time limit established for the ILP model was of 7000 s.

The genetic algorithm was implemented in C++ and allowed us to obtain feasible solutions corresponding to upper bounds for the optimal value. The results were obtained on a PC Intel Pentium 4 at 2.00 GHz and 512 Mb RAM. The genetic algorithm performed 300 iterations.

In order to evaluate the performance of both methods, we use the following gap between the upper, b_u, and the lower bound, b_l,

$$gap = \frac{100(b_u - b_l)}{b_u}. \tag{9}$$

In order to access the quality of the solutions obtained with the genetic algorithm we used the node location of six real telecommunications networks. The network vBNS [6] with 12 nodes, the networks NSFNET [7] and ITALY [8] both with 14 nodes and the EON [9] network with 20 nodes. The two last networks are the PORTUGAL [10] network with 24 nodes and the NEWNET [11] network with 26 nodes.

We assume that all possible links can be implemented and that the maximum number of optical channels supported by each fiber is 40. We also assume a uniform demand model and a *span* of 80km. The costs of equipments, considered in this work, are presented in Table I.

TABLE I
Costs with transmission system [12].

Equipment	Notation	Cost	Quantity
Optical Fiber	c_f	0.8	per km
Optical Amplifier	c_{oa}	3.8	per fiber and per span
OLT	c_{olt}	9	per fiber
Transponder	c_t	2	per fiber per channel

We observed that for small networks the genetic algorithm has a fast convergency rate to a solution. In Figure 3 the evolution of the best solution obtained using the genetic algorithm is depicted for the vBNS network with 12 nodes. Observe that there is a fast decrease in the earlier iterations however afterwards, there is no change.

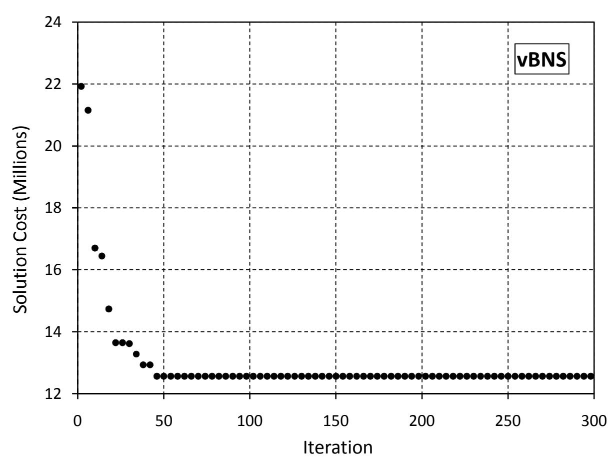

Fig. 3. Results obtained using the genetic algorithm for the vBNS network.

As the number of nodes increases such convergency is not visible within the 300 iterations. In Figure 4 the results obtained using the genetic algorithm for the NEWNET network, with 26 nodes, are depicted. A decrease on the cost of the best solution still exists near the last considered iteration. A better solution could be obtained if we increase the allowed number of iterations.

Table II shows the gaps and computational times used by both methods. For networks with less than 20 nodes good solutions can be obtained using the ILP models. The ILP model obtained the optimal solution for the network with 12

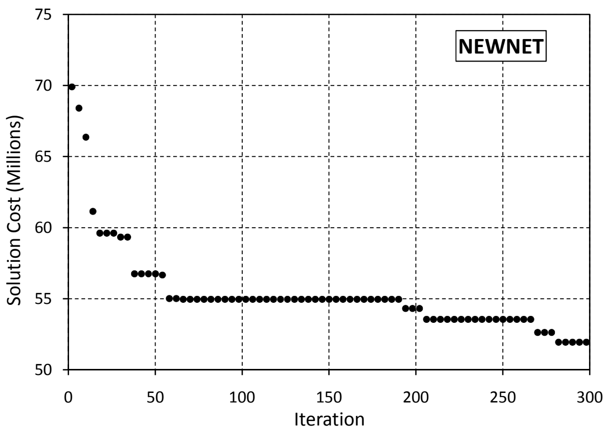

Fig. 4. Results obtained using the genetic algorithm for the NEWNET network.

nodes in 321 s. However, the genetic algorithm obtained a solution 5% above the optimal in 28 s and performed in a slower processor.

TABLE II
GAPS AND COMPUTATIONAL TIMES USED BY THE XPRESS TO OBTAIN THE ILP MODEL SOLUTION AND BY THE GENETIC ALGORITHM.

		ILP Model		**Genetic Algorithm**	
Network	**Dimension**	Time	*gap*	Time	*gap*
vBNS	12	321 s	**0.00%**	28 s	5.72%
NSFNET	14	7000 s	**2.76%**	48 s	13.82%
ITALY	14	7000 s	**7.83%**	51 s	11.53%
EON	20	7000 s	27.34%	136 s	**18.84%**
PORTUGAL	24	7000 s	36.07%	377 s	**35.83%**
NEWNET	26	7000 s	57.19%	435 s	**35.26%**

As the number of nodes increase, the genetic algorithm obtain better solutions than the ILP model in 7000 s. As an example, for the NEWNET network and using the ILP model, we obtained a solution with a gap of 57%. However, the genetic algorithm obtained a solution with a gap of 35% in 435 s. A better solution than the obtained can be achieved with the increase of the number of iterations. With such processing times, the increase of iterations do not penalize it.

Figure 5 depicts the obtained topologies in ITALY using the ILP model and the genetic algorithm. The dashed links are the ones that differ in both solutions. The black dashed lines represent the links of the topology obtained using the genetic algorithm. The grey dashed lines represent the links of the topology obtained using the ILP model. The black solid lines represent the common links to both solutions. Neither the topologies are optimal, see Table II, however the majority of the links are already present in both solutions.

VI. CONCLUSIONS

We presented a genetic algorithm for the design of minimum CAPEX topologies. The survivability against any single link failure was ensured by dedicated protection. An ILP model

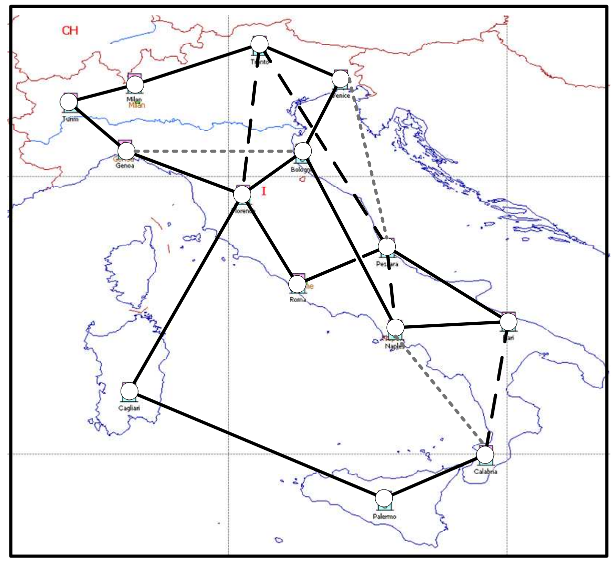

Fig. 5. Topologies in Italy obtained using the ILP model and the genetic algorithm. The dashed links differ in both solutions and the black links are common.

was also presented to evaluate the performance of the genetic algorithm. Results show that for large networks the genetic algorithm obtain good near-optimal solutions. The ratio between the gap and the processing time obtained using the genetic algorithm encourage the use of this kind of heuristic in the survivable optical network design problem.

REFERENCES

[1] H. Kerivin and A. R. Mahjoub, "Design of Survivable Networks: A Survey", *Networks*, vol. 46, issue 1, pp. 1-21, Wiley InterScience, 2005.

[2] S. Ramamurthy and B. Mukherjee, "Survivable WDM Mesh Networks, Part I - Protection", *Proc. IEEE Conference on Computer Communications (INFOCOM99)*, New York, USA, pp. 744-751, March 1999.

[3] M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness*, 1979.

[4] S. Soni and H. Pirkul, "Design of Survivable Networks with Connectivity Requirements", *Telecommunication Systems*, vol. 20, issue 1, pp. 133-149, Springer, 2002.

[5] D. E. Goldberg. *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Wesley, 1989.

[6] *The very-high-performance Backbone Network Service - vBNS* (2008, 17 November) [On-line] Available: http://www.cs.cmu.edu/ hzhang/HFSC/TALK/sld048.htm.

[7] R. Hülsermann, *et al.*, "A Set of Typical Transport Network Scenarios for Network Modelling", *Proc ITG Worshop on Photonic Networks (ITC'04)*, pp. 64-72, Leipzig, Germany, May 2004.

[8] D. Colle, "Data-Centric Optical Networks and Their Survivability", *IEEE Journal on Selected Areas in Communications*, vol. 2, issue 1, January 2002.

[9] *European Optical Network.* (2008, 17 November) [On-line] Available: http://www.optical-network.com/topology.php.

[10] J. Pedro, A. Teixeira, P. Monteiro, J. Pires, "On a Portuguese Backbone Network of Reference", *Proc. Symposium on Enabling Optical Networks*, Porto, Portugal, June 2005.

[11] *NewNet USA Topology.* (2008, 17 November) [Online] Available: https://wiki.internet2.edu/confluence/display/I2RevDoc/Architecture.

[12] M. Gunkel et al., "A Cost Model for the WDM Layer", *Proc International Conference on Photonics in Switching (PS06)*, pp. 1-6, October 2006.