MINIMUM COST TOPOLOGY OPTIMISATION OF THE COST 239 EUROPEAN OPTICAL NETWORK

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A genetic algorithm is presented for the minimum-cost topology optimisation of the COST 239 European Optical Network (EON). The algorithm makes use of real traffic data where possible, and produces a network amongst twenty given nodes with two-shortest-node-disjoint routing between node pairs. Both routes are fully resourced, guaranteeing the network will survive a single component failure. The results are compared with the earlier 'hand-crafted' EON topology.

The Background

The work described in this paper was undertaken as part of COST Action 239. The COST framework (European Cooperation in the field of Scientific and Technical Research) is run by the European Commission, aiming to promote pre-competitive R&D cooperation between industry, universities and national research centres. COST 239, "Ultra-high Capacity Optical Transmission Networks", is studying the feasibility of a transparent optical overlay network capable of carrying all the international traffic between the main centres of Europe.

At the start of the project, twenty such centres were identified, each acting as the gateway for all (or half) of the European international traffic for their country.

The initial network design and analysis of a proposed European Optical Network based on those nodes was presented in [1,2]. The initial topology design was carried out by making what were presumed to be reasonable assumptions about the possible traffic distribution, given the node populations, and incorporating suitable structures to enhance reliability. The topological design was then analysed, using existing software [3,4], and incorporating the PD (population-distance) model for node-to-node traffic, two-shortest-link-disjoint-path routing and a simple model for link availabilities. This resulted in comparative link capacities, which were scaled to realistic levels for the immediate, medium and long term.

Subsequently, an improved model for European international telephony traffic, the PFD (population-factor-distance) model, has been developed [5].

The Problem

The problem this paper seeks to address is that of producing a minimum-cost topology for the COST 239 European Optical Network (EON), given the existing choice of twenty nodes. The traffic applied is the real traffic data (scaled to the long-term level estimated by COST 239, and completed, where not available, using the PFD model [5]); two-shortest-node-disjoint-path routing is used between node pairs; and a reliability constraint is employed. The latter is to ensure that there are two fully-resourced node-disjoint routes between node pairs, thereby guaranteeing that the network will survive the failure of any single component (node or link).

The size of the problem space is simply the number of different topologies. If only the nine central nodes are considered, then the space is 6.9×10^{10}, but for the full EON, this rises to 1.6×10^{57}.

Cost Models

To determine the cost of a given topology, separate models for both links and nodes are required.

Link First, the two-shortest-node-disjoint routes are determined for all node pairs. The 'length' of each path is taken to be the sum of the contributing link weights, with the weight of the bi-directional link between nodes i and j given by:

$$W_{ij} = 0.5N_i + L_{ij} + 0.5N_j \qquad (1)$$

where N_i and N_j are the Node Effective Distances of nodes i and j respectively (see below) and L_{ij} is the length of link (i,j) in km.

Then, the link carried traffic is determined for each link by summing the contributions from all the primary and alternative routes that make use of it. The alternative routes are fully-resourced, and thus are assumed to carry the same traffic as the corresponding primary routes i.e. the traffic they would be required to carry if their primary route failed.

The capacity of link (i,j) is taken to be:

$$V_{ij} = \text{ceil}_{2.5}[1.4T_{ij}] \quad (2)$$

where T_{ij} is the carried traffic in Gbit/s on the link, and $\text{ceil}_{2.5}$ rounds its argument up to the nearest 2.5 - the assumed granularity of the transmission links. The factor of 1.4 is to allow for stochastic effects in the traffic.

The cost of link (i,j) is then taken to be:

$$C_{ij} = L_{ij}V_{ij} \quad (3)$$

Node Node Effective Distance was used as a way of representing the cost of nodes in an optical network in equivalent distance terms. It can be regarded as the effective distance added to a path as a result of traversing a node. By including it in link weights (Equation 1) for the calculation of shortest paths, path weights reflect the cost of the nodes traversed (and half the costs of the end nodes). As a result, a longer geographical path may have a lower weight if it traverses fewer nodes, thereby reflecting the relatively high costs of optical switching. The Node Effective Distance of node i was taken to be:

$$N_i = E + n_i F \quad (4)$$

where n is the degree of node i, i.e. the number of bi-directional links attached to it. The constants E and F were taken to be 200km and 100km respectively. Node Effective Distance thus increases as the switch grows more complex.

Node capacity is simply the sum of the capacities of all the attached links, and node cost was taken to be:

$$C_i = 0.5N_iV_i \quad (5)$$

where V_i is the capacity of node i in Gbit/s. The cost is thus derived as if the node was a star of links, each of half the Node Effective Length, and each having the same capacity as the node itself.

Network The network cost is then taken to be the sum of the costs of all the individual links and nodes comprising the network.

Initial Topology Using the above cost models, the initial EON topology [1,2] has a cost of 7.22 million (in kmGbit/s), comprising 3.27M for the links and 3.95M for the nodes (see Fig. 1). It does not, however, meet the reliability constraint, as Luxembourg (LUX) has only one link, and cannot therefore support two node-disjoint routes.

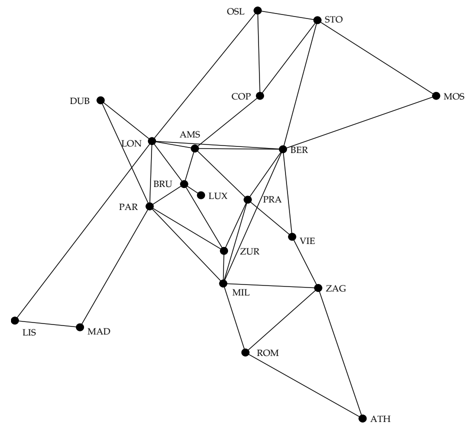


Fig. 1 Initial Topology (Cost: 7.22M)

Topology Optimisation

To search the vast problem space efficiently, a genetic algorithm (GA) was employed [6,7]. The objective was a topology of minimal network cost, although the fitness of a particular topology was not taken to be network cost alone, but network cost modified by a penalty function to ensure the reliability constraint was met. The penalty function adds P_A to the network cost for every node pair that has no alternative path, and P_N for every node pair with no routes at all between them. This avoids the false minimum of the topology with no links at all, whose cost, under the link and node cost models employed, would be zero.

GENESIS v5.0 was used [7], with topologies encoded as a simple binary string, each bit corresponding to a potential link in the topology.

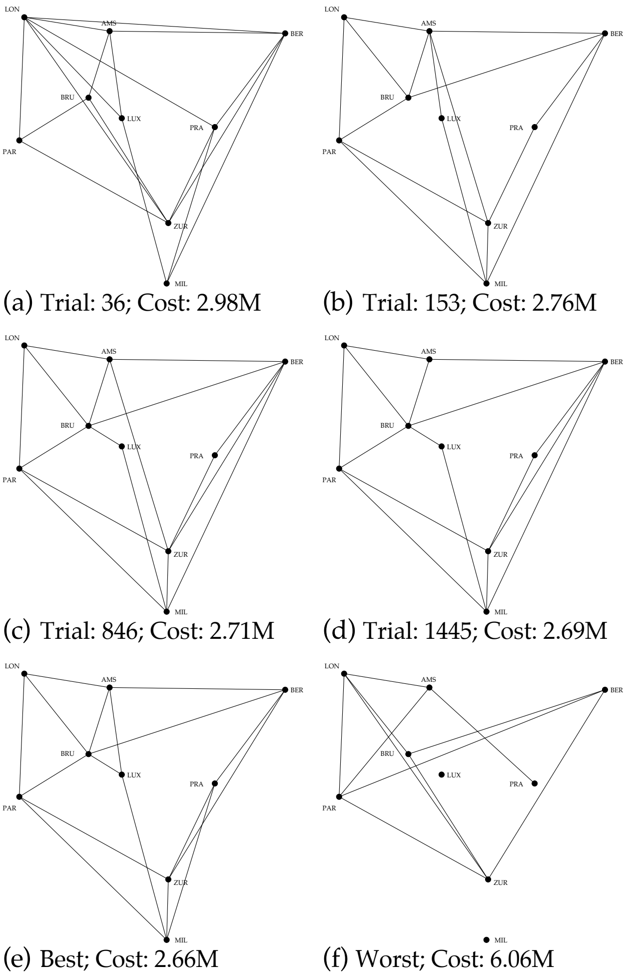
Results for Central Nodes

For illustrative purposes, the GA was run for the central nine nodes (London, Amsterdam, Berlin, Paris, Brussels, Luxembourg, Prague, Zurich and Milan). Structure length was $(9 \times 8)/2 = 36$, and the algorithm parameters are given in Table 1. The penalty constants P_A and P_N were 0.1M and 0.2M respectively. These values were selected using a few trial runs to obtain values sufficiently high to ensure that the reliability constraint was met in the best topologies found.

Table 1 GA Parameters for Central Nodes

Elitist	
Population size	50
Crossover rate	0.6
Mutation rate	0.001
Generation gap	1.0
Scaling window	5

Five runs were carried out, all of which 'spun' within 3,000 trials. The best run was selected for detailed examination, and six of the topologies found are shown in Fig. 2.



(a) Trial: 36; Cost: 2.98M (b) Trial: 153; Cost: 2.76M

(c) Trial: 846; Cost: 2.71M (d) Trial: 1445; Cost: 2.69M

(e) Best; Cost: 2.66M (f) Worst; Cost: 6.06M

Fig. 2 Results for Central Nodes

The first five topologies in Fig. 2, (a) to (e), represent the best individuals of their respective generations - 0, 4, 30, 54, and 83. There is a clear progression from (a), with far too many links, and consequently, higher cost, to (e), which was the best of the run. Of particular interest is the development of the triangle of links between Amsterdam, Brussels and Luxembourg, combined with the need for only a single direct link between those three nodes and Milan/Zurich.

By way of contrast, topology (f) is the worst individual from generation 0. In addition to the underlying cost of 2.46M for the links and nodes, it incurred a total penalty 3.6M for the two disconnected nodes (Luxembourg and Milan) and the one single-parented node (Prague). Thus without the addition of the penalty, this topology would have had a lower cost than (e), despite its obvious deficiencies.

Results for EON

The full European Optical Network includes an additional eleven nodes (Oslo, Stockholm, Dublin, Copenhagen, Moscow, Vienna, Zagreb, Lisbon, Madrid, Rome and Athens). The structure length was $(20 \times 19) / 2 = 190$, the penalty constants P_A and P_N were 0.5M and 1.0M respectively, and the algorithm parameters were the same as those given in Table 1, except that several different population sizes were tried.

Five runs were made with a population size of 50. All of the runs spun in less than 8,000 trials, with the best result obtained as 7.00M.

Ten runs were carried out with a population size of 100. All of the runs spun in less than 48,000 trials, with the best result obtained as 6.85M.

Finally, five runs were carried out with a population size of 200. Three of the runs spun in less than 200,000 trials, with the best result obtained as 6.89M.

To further improve the results obtained by the GA alone, a simple hill-climbing algorithm was used on the best topology for each run. The hill climber removed that link which reduced the network cost most, and then iterated until no further reduction could be made.

The best topology overall is given in Fig. 3, and was found after 47,308 trials using a population size of 100. No links could be removed by the hill climber, and therefore the topology shown was that found by the GA alone.

The total cost of 6.85 million (in kmGbit/s) is made up of 3.09M for the links and 3.76M for the nodes.

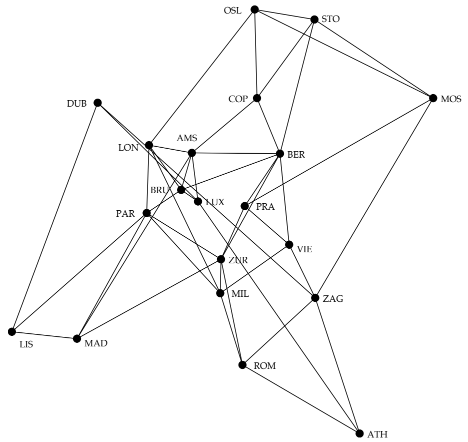


Fig. 3 Best Overall Topology (Cost: 6.85M)

Conclusions and Further Work

Although the initial EON topology [1,2], developed by hand, has a reasonably low cost (7.22M ignoring the penalty), it does not meet the reliability constraint. A single link failure could disconnect Luxembourg's international traffic.

In contrast, the topologies obtained so far using GA-based optimisation show both cost improvements (up to 5.1%) and superior reliability (in terms of the reliability constraint).

The work presented here could be extended by:

- Developing more rigorous cost models; for example [8] suggests link cost may only be proportional to the root of link capacity.
- Including maximising the network availability in the overall objective.
- Including wavelength allocation (assuming a multi-wavelength optical network), and the minimisation of the number of wavelengths used, in the overall objective.

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