

GENETIC ALGORITHMS - CASE STUDY: AVILABILITY–COST OPTIMIZATION OF ALL-OPTICAL NETWORK

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Abstract: Many of design problems in telecommunications could be treated as optimization problems that include some kind of searching among a set of potential solutions. The choice of the method depends mostly on the problem complexity. If the number of possible solutions is not too big, one could enumerate them all, evaluate their goal functions, and select the best solution(s). If the function to be optimized is done by a derivative continuous function, analytical methods could be applied. In all other cases, where the problem space is too big and analytical methods are not applicable, some sort of heuristic search for optimal solution could be applied. Genetic algorithms, could be classified as guided random search evolution algorithms that use probability to guide their search. Genetic algorithms are created by analogy with the processes in the reproduction of biological organisms. By natural selection or by forced selection in laboratories, new generations of organisms are produced. As a consequence of crossover and mutation processes on chromosomes and genes, the children could possess either better or worse features than their parents. The “better” organisms are those that have a greater chance than the “worse” ones to survive and to produce a new generation.

Keywords: Genetic Algorithm, telecommunication, optical network

1. INTRODUCTION

The problem to be described is an example of genetic algorithm application in telecommunication network optimization. Note that this type of optimization problem could be solved by other methods as well, for example, simulated annealing and taboo search. Many of the design problems in telecommunications could be treated as optimization problems that include some kind of searching among the set of potential solutions. The choice of the method for solving the problem depends mostly on the problem complexity. In all cases, where the problem space is too big and analytical methods are not applicable, some sort of heuristic search for pseudo-optimal solution could be applied. For example, if one should find some kind of optimal network topology, among the set of $n = 10$ nodes, the number of possible links connecting predefined nodes is $n(n-1)/2 = 45$. Assuming that every candidate link could be present or not in the solution to be evaluated, the total number of topologies is $2^{45} = 3.5 \cdot 10^{13}$. If an enumeration method is used, assuming evaluation for one solution takes 1 ms, the solution will be reached in 1115 years.

2. PROBLEM STATEMENT

This section deals with the issues involved in generating an optimum topology of a European core all-optical network — a case study within the framework of the European Commission project COST 239 “Ultra-high Capacity Optical Transmission Networks” [4]. The objective of the optimization is the minimization of network

unavailability and cost, while satisfying the traffic requirements among the major European cities, meeting current technological limitations in the optical domain, and the defined routing rules.

The problem could be defined in another way, too: how to minimize the network cost while keeping unavailability within the prescribed requirements, if possible. The goal is not only to have as minimum unavailability as possible, despite the high costs of the network, but to achieve a low-cost topology that fulfills the availability requirements, if any. In order to find an optimum topology for n nodes' network, one should consider $N_s = 2^k$, $k = n(n-1)/2$ different solutions (topologies). Even for a small number of nodes (in the case study the network comprises 11 nodes and has the set of $3.6 \cdot 10^{16}$ different topologies) only a quasi-optimal solution could be obtained.

The case study consists of 11 nodes representing the core part of European all-optical network with total number of 20 nodes (Fig. 1).

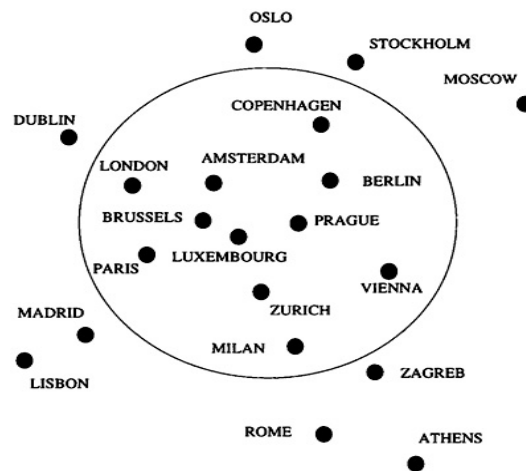


Fig.1 Case study: Core part of European all-optical network.

Every topology should fulfill symmetric traffic requirements (capacities) expressed by required bit rates, and take into account road distances between nodes (Table 1).

Table 1 Bit rate requirements and road distances

		Bit rates (Gbit/s)										
		0	1	2	3	4	5	6	7	8	9	10
		Par	Mil	Zur	Pra	Vie	Ber	Ams	Lux	Bru	Lon	Cop
Road distances $\times 10^3$ (km)	0 Par	-	12.5	15	2.5	5	27.5	12.5	2.5	15	25	2.5
	1 Mil	0.82	-	15	2.5	7.5	22.5	5	2.5	5	7.5	2.5
	2 Zur	0.60	0.29	-	2.5	7.5	27.5	7.5	2.5	7.5	7.5	2.5
	3 Pra	1.00	0.87	0.62	-	2.5	5	2.5	2.5	2.5	2.5	2.5
	4 Vie	1.20	0.82	0.80	0.32	-	22.5	2.5	2.5	2.5	5	2.5
	5 Ber	1.09	1.01	0.90	0.34	0.66	-	20	5	15	20	7.5
	6 Ams	0.51	1.14	0.85	0.91	1.16	0.66	-	2.5	10	12.5	2.5
	7 Lux	0.34	0.71	0.38	0.73	0.93	0.75	0.39	-	2.5	2.5	2.5
	8 Bru	0.30	0.93	0.60	0.91	1.12	0.78	0.21	0.22	-	10	2.5
	9 Lon	0.45	1.22	1.00	1.31	1.51	1.17	0.55	0.60	0.39	-	2.5
	10 Cop	1.24	1.52	1.20	0.74	1.04	0.39	0.76	0.95	0.92	1.31	-

2.1. Assumptions and Constraints

In order to obtain an acceptable network topology, let us call it a regular topology, different requirements, limitations, and routing rules have to be fulfilled. The network topology must fulfill the following requirements: all node-to-node connections should be established through the two shortest, mutually independent paths, primary and spare, the same for both directions of communication, ensuring network survivability in the case of single network element failure, the link or node.

A link failure is assumed to be caused by a failure in an optical amplifier, or in the fiber cable, causing an interruption of all services in the cable. The following definition is assumed: a node-to-node connection is available if both directions of the connection are available.

The traffic requirements between all pairs of nodes are given. All link capacities are multiples of 2.5 Gbit/s (standard capacity in digital transmission), achieved through a number of wavelengths in one or more different optical fibers on the same optical link. The node pair direct distances are derived from the road distances between major European cities. Because of the accumulated noise and distortions in optical fibers, amplifiers, and node elements, the optical path length limitation is fixed at 2000 km. The distances between optical amplifiers are assumed to be maximum 100 km. Component failure and repair rate data for calculating the unavailability of the future all-optical network are taken from the existing data set for mature optical components, whereas, for new photonic components, the calculation is based on estimated data. Steady-state unavailability (the asymptotic value of unavailability if time tends to infinity) is considered, assuming constant failure and repair rates. In the total path unavailability calculation, the impact of node unavailabilities is negligible compared to the unavailabilities of optical links.

3. COST EVALUATION

The cost model applied in the network availability optimization was taken from [5]. The total network cost for the set of nodes N is a sum of all link and node costs is

$$C = \sum_{i,j \in N} C_{L_{ij}} + \sum_{i \in N} C_{N_i} = C_L + C_N,$$

where $C_{L_{ij}}$ is the cost of the link between nodes i and j , and C_{N_i} is the cost of the node i . Link cost is a function of link length L_{ij} (km) and link capacity V_{ij} (Gbit/s),

$$C_{L_{ij}} = L_{ij} V_{ij}.$$

The link capacity is determined for each link by summing up the contributions from all primary and spare paths that make use of it. The node cost C_{N_i} is a function of node effective distance N_i (km) (N_i represents the cost of node in equivalent distance terms), and the total capacity of all links incident to the node — V_i (Gbit/s):

$$C_{N_i} = 0.5 N_i V_i, \quad N_i = E + d_i F,$$

where d_i is node degree (the number of links incident to node i), E and F constants assumed to be 200 km and 100 km, respectively.

4. SHORTEST PATH EVALUATION

For each topology, the solution proposed by GA between all pairs of nodes — the first shortest path as the primary path, and the second shortest path as a spare path — have to be evaluated using Dijkstra algorithm. The

weights W_{ij} of links to be used in shortest path evaluation reflect the influence of node parameters on the path “length”.

$$W_{ij} = 0.5 N_i + L_{ij} + 0.5 N_j.$$

5. CAPACITY EVALUATION

Superposing all traffic requirements between all pairs of nodes, using primary and spare paths, the capacities of links and nodes are obtained.

6. NETWORK UNAVAILABILITY CALCULATION

Network unavailability is defined as the worst case of all node-to-node connection unavailabilities (source-termination unavailability) [6]:

$$U = \max_{i,j} \{U_{ij}\}, \quad U_{ij} = \left(1 - \prod_{k \in pp} (1 - U_k)\right) \left(1 - \prod_{l \in sp} (1 - U_l)\right),$$

where U_k is the unavailability of a link from the primary path (pp), and U_l is the unavailability of a link from the independent spare path (sp). In other words, the unavailability model of a node-to-node connection could be described as a serial structure of two parallel.

Optical link is treated as a nonredundant structure comprising fiber in optical fiber cable and optical amplifiers. For small unavailability values of link elements, an approximate formula for the total link unavailability can be used.

$$U_{link} = \lambda_F L MTTR_F + N_{OA} \lambda_{OA} MTTR_{OA}$$

where λ_F is fiber cable failure rate per km, λ_{OA} is the failure rate of the optical amplifier (OA), N_{OA} is the number of optical amplifiers on the link, L is the link length, $MTTR_F$ and $MTTR_{OA}$ are mean times to repair of fiber (F) and OA, respectively ($\lambda_F = 114$ fit/km, $MTTR_F = 21$ hours, $\lambda_{OA} = 4500$ fit, $MTTR_{OA} = 21$ hours, fit = number of failures per 10^9 hours).

7. SOLUTION CODING

Possible solutions are coded as binary strings with $n(n-1)/2$ bits. The position of every bit represents one direct link between two nodes. The value of the bit corresponding to 1 represents the existence of the link in the solution, while the value 0 stands for a missing corresponding link.

For instance, the case study network of 11 nodes should be coded by the string containing 55 bits. In the Fig. 2 one random string is presented and corresponding network is shown in the Fig. 3.

		direct links between nodes (<i>i, j</i>)									
nodes											
<i>i</i>	0000000000	1111111112	2222222333	3333444444	5555566667	77889					
<i>j</i>	1234567891	2345678913	4567891456	7891567891	6789178918	91911					
	0	0	0	0	0	0	0	0	0	0	0
	0010101010	1000111000	1000010110	0101101011	1001001010	00110					
random string											

Fig.2 An example of coded topology in the case study.

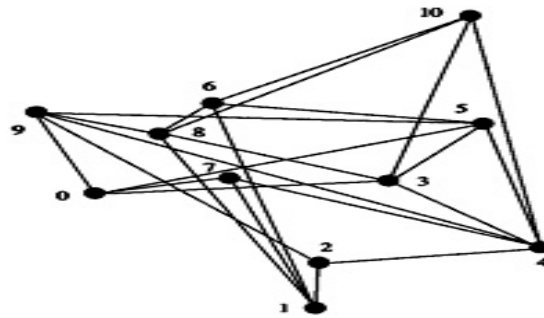


Fig.3 The topology representing a random string shown in Fig.2.

8. SELECTION PROCESS

Different approaches could be applied in creating the selection process. Any selection principle reflects the definition of the fitness function. Here, two extreme approaches will be analyzed.

8.1 Approach 1: Preselection rejection

In the preselection process, all solutions not satisfying some easy-to-test fundamental requirements are rejected. For example, if a generated graph has a node degree less than 2, or if the number of branches in a topology is less than $(N-1)$ (graph tree), it can surely be inferred that these solutions cannot satisfy the network requirement of two independent paths between all node pairs.

Fitness functions are very simple; in the case of cost minimization f_c and in unavailability minimization f_u , respectively,

$$f_c = \frac{1}{C}, \quad f_u = \frac{1}{U}.$$

The advantage of this approach lies in reducing the number of topologies to be evaluated in detail (shortest path, capacity, cost, and unavailability calculation). For example, for 11 nodes, as used in the case study, the number of acceptable topologies is reduced to $10^{-4}\%$ of all topologies, according to the “graph tree” preselection rule, as mentioned above.

On the other hand, the disadvantages of this approach are poor diversity of solutions in the population, and the very rough distinction between solutions — a solution is either regular, that is, acceptable, or irregular, that is, unacceptable. In the cases where solution limitations are very restrictive, the whole initial population could be rejected, disabling further search. Note that even a bad solution could produce a good offspring.

8.2 Approach 2: The use of fitness functions with penalizing

No topology is rejected but, is penalized, if assumptions or dynamic limitations are not satisfied. The advantage of this approach lies in the great diversity of solutions to be evaluated, increasing the probability of finding different areas of local minima to be tested, in order to select the global one. The disadvantage of this approach lies in an extensive evaluation time. Despite higher time consumption than in Approach 1, Approach 2 is selected for optimization application as the more efficient one.

9. OPTIMIZATION PROCEDURE

In order to minimize unavailability–cost pairs, two types of optimization alternate. In odd optimization steps, the network cost is minimized. Fitness function for cost minimization is

$$f_c = \frac{1}{(C + PF) k (1 + UP)},$$

$$UP = \frac{U - U_{lim}}{U_{lim}} \text{ for } U > U_{lim}, \text{ and } UP = 0 \text{ for } U \leq U_{lim},$$

where k is the penalty slope and U_{lim} is the dynamic unavailability upper bound in an odd step, achieved as minimal in previous even step(s). PF is the penalty factor defined as follows:

$$PF = 2.5 \text{ PathOver CapOver},$$

where *PathOver* is the sum of all excesses of path length limitation and distances between the node pairs without primary and/or spare paths. *CapOver* is the sum of capacity demands between the node pairs contributing to the *PathOver*. In even optimization steps, the unavailability is minimized. Fitness function for unavailability minimization is equal to

$$f_u = \frac{1}{U k (1 + CP)},$$

$$CP = \frac{C + PF - C_{lim}}{C_{lim}} \text{ for } C + PF > C_{lim}, \text{ and } CP = 0 \text{ for } C + PF \leq C_{lim}.$$

The penalty is effective for the costs higher than the cost limit C_{lim} , — the dynamic cost upper bound reached in previous odd optimization step(s).

Note that the genetic material is transferred from one step to the next one, forming initial population.

10. OPTIMIZATION RESULTS

The optimization results refer to the case study of European all-optical network. The absolute minimum unavailability, as a reference value, was determined from the fully meshed network. The optimization target was to find the topology with the same or very close unavailability value and with cost as low as possible.

The genetic algorithm parameters are chosen as follows: population size = 100, string size = 55, crossover probability = 0.6, mutation probability = 0.05, two point crossover, roulette wheel selection scheme, generation gap = 1, the number of generations per step = 200, elitism. As a result of optimization running, several quasi-optimal unavailability-cost pairs were obtained. Table 2 shows the results of two GA generated topologies, the minimum cost topology (MinC) and the minimum unavailability topology (MinU) (Fig. 4), compared to the reference topology COST 239 (EON) and manually designed grid network (MG) (Fig. 5) and fully meshed topology (FM) [7].

Table 2 The comparison of topology performances

	FM	EON	MG	MinC	MinU
$U \times 10^{-5}$	2.502	3.789	4.235	3.130	2.502
$C \times 10^6$	4.537	3.765	3.903	3.706	3.793
$C_L \times 10^6$	1.441	1.685	1.711	1.576	1.615
$C_N \times 10^6$	3.096	2.080	2.192	2.130	2.178
$TFCL$ [km]*	44145	14775	11635	14610	19115
No. of links	55	25	22	25	29
d_{min}	10	4	2	3	4
d_{max}^{**}	10	5	6	7	8
<i>PathOver</i> [km]	0	50	675	0	0

*TFCL - total fiber cable length

** d_{min} , d_{max} - the minimum and maximum node degrees.

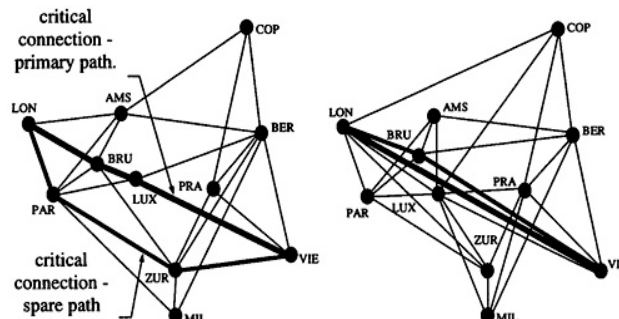


Fig. 4 Minimum Cost (MinC) and Minimum Unavailability (MinU) topologies.

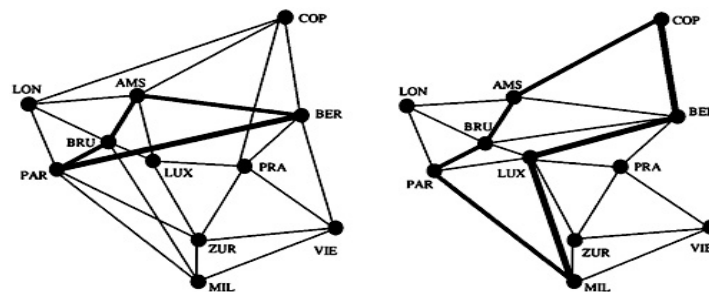


Fig.5 COST 239 case study (EON) and Manual--Grid (MG) topologies

11. CONCLUSION

In this application of genetic algorithms in telecommunications is described. Genetic algorithms are based by analogy with the processes in the reproduction of biological organisms. These algorithms could be classified as guided random search evolution algorithms that use probability to guide their search. A genetic algorithm application to a specific problem includes a number of steps and some of them are discussed in three different telecommunication system design problems. Two of them are related to a method for call and service process scheduling and call and service control in distributed environment, where a genetic algorithm is used to determine a response time. Genetic algorithm application in optimization is presented through the case study on availability–cost optimization of an all-optical network.

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