# An Efficient Algorithm for Designing Reliable IP Networks with an Access/Edge/Core Hierarchical Structure

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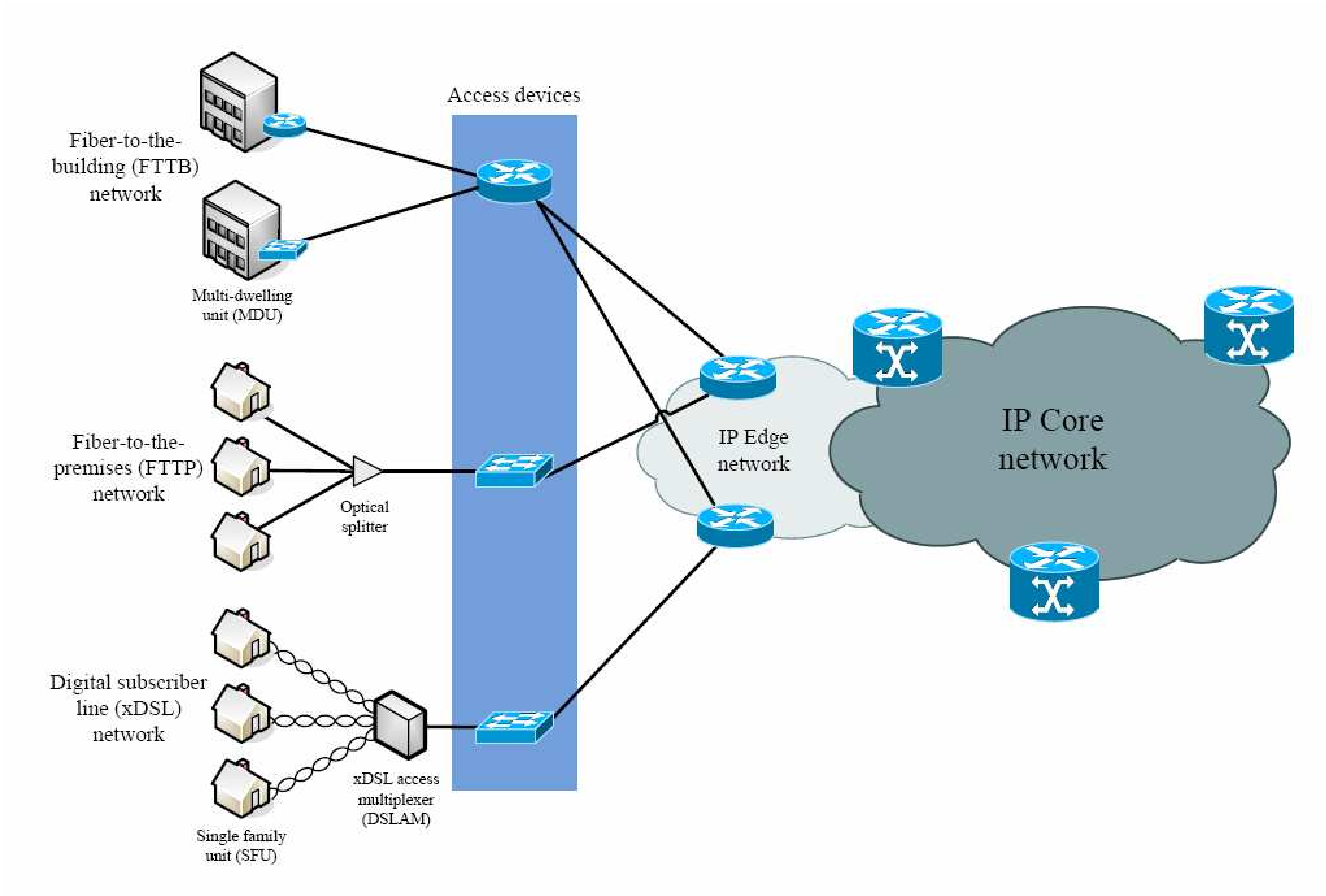
# Introduction

In this paper we propose:

- A mathematical model for the design problem of reliable IP networks with a three-level (access/edge/core) hierarchical structure. This problem consists in
  - selecting the location of the routers and their types to install at each hierarchical level;
  - selecting the port types to install in each router;
  - finding the access, edge and core networks;
  - selecting the link types;
  - routing the traffic within the network.
- A tabu search algorithm to find “good” feasible solutions.
- Finally, numerical results are presented and analyzed.

# Introduction (cont'd)

Illustration of a three-level IP network.



# Assumptions

We make the following assumptions about the network:

1. The network is composed of an access network, an edge network and a core network.
2. Each access device is connected to edge routers with one or more access links.
3. Each edge router is connected to two core routers. (Note that edge and core routers are relative terms. They are all just routers, but of different size and capacity.)
4. The core network is biconnected (between each pair of nodes, there are two or more paths without common intermediate nodes).
5. At most one edge (core) router can be installed at each potential edge (core) site.

# Assumptions (cont'd)

6. The number of ports installed in a router cannot exceed its number of slots.
7. The sum of the port rates for a router cannot exceed its switch fabric capacity.
8. The traffic is routed using the shortest paths using link metrics. (Shortest path routing is considered because several routing protocols in IP networks are based on it such as OSPF.)
9. A minimum information rate (MIR) traffic parameter (in bps) between each pair of access devices is guarantee for the normal state of the network (no failure) and also for all single edge and core link failure scenarios.

# Assumptions (cont’d)

We also assume that the following information is known:

1. The different types of bidirectional links and ports.
2. The different types of edge and core routers.
3. The location of the access devices.
4. The number and type of access links necessary to connect each access device to the edge routers.
5. The potential edge and core sites to install respectively the edge and core routers.
6. The cost of each router type and the cost of installing it at each site (including the cables, floor space, racks, labor, etc.).

# Assumptions (cont’d)

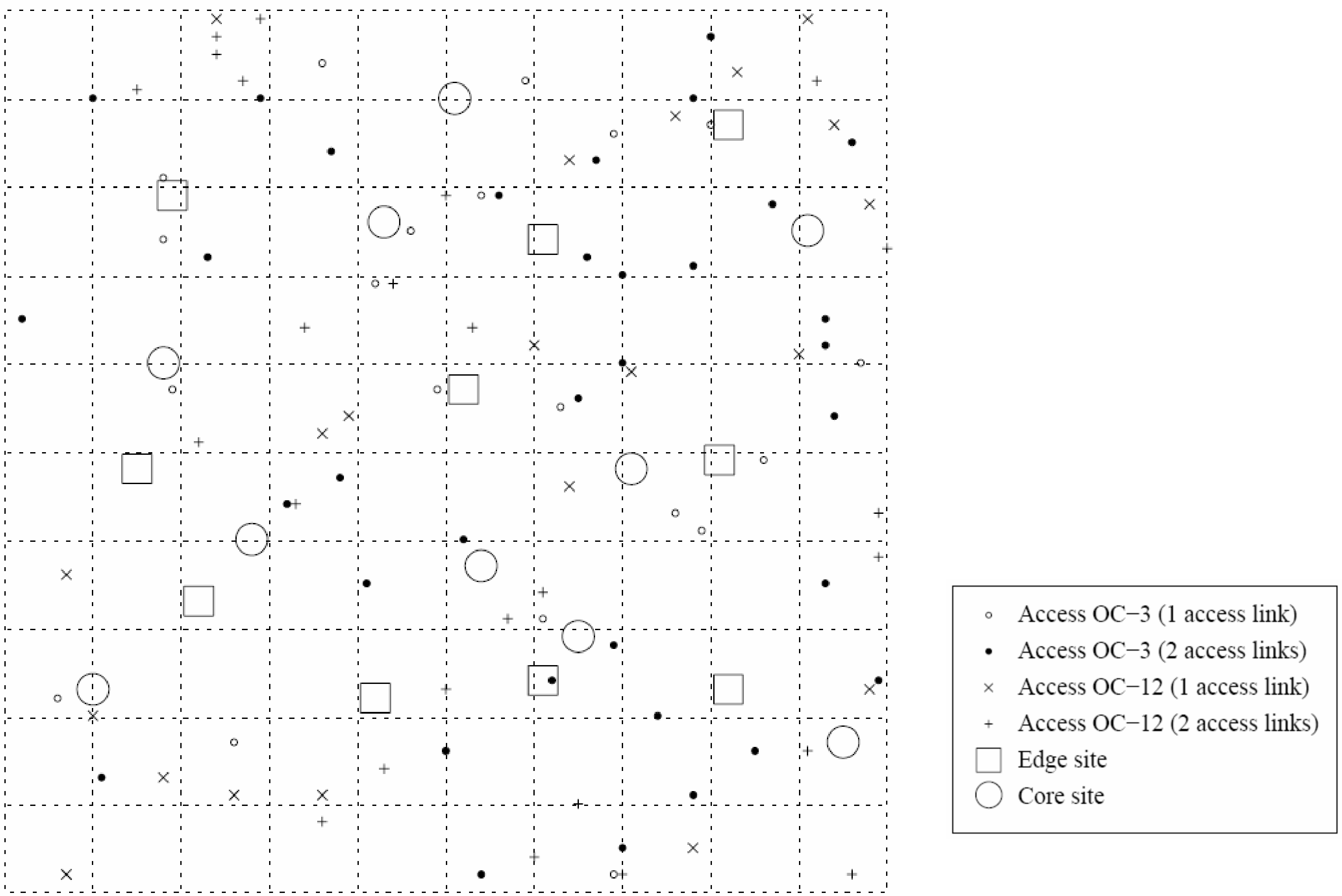
7. The cost of each port type and the cost of installing it at each site (including the cables, patch panel ports, labor, etc.).
8. The cost of connecting each pair of sites with a link of a given type and the cost of installing it (including the cables, layer one/two equipments and connectivity, labor, etc.).
9. The MIR traffic parameter between each pair of access devices.
10. The link metric (i.e., the “length”) of each link.

**The network design problem**

The problem consists in finding the minimum cost network subject to all of the previous assumptions and facts.

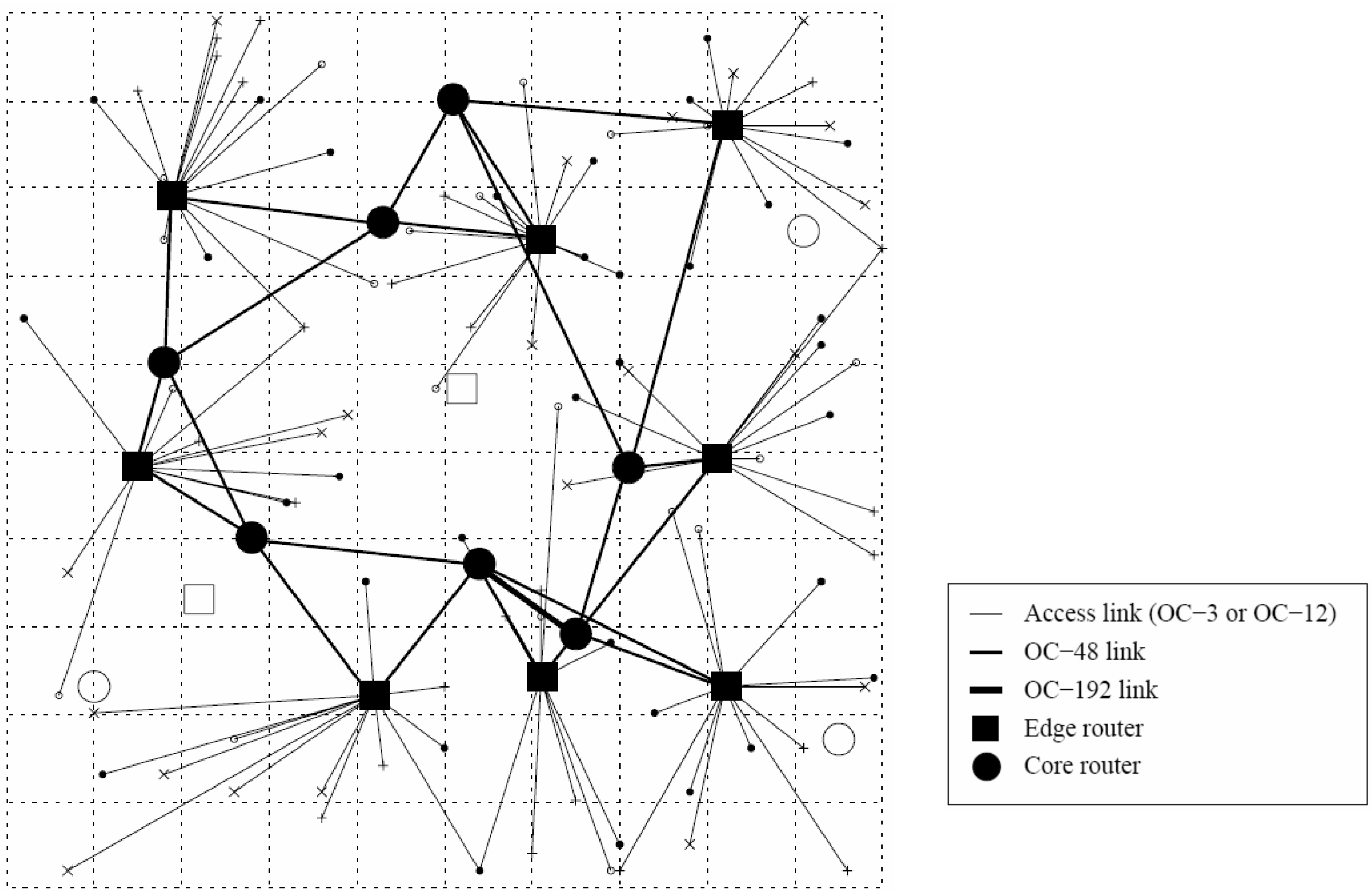
# An Illustrative Example

Access devices (100) and potential sites location to installed the edge (10) and core (10) routers.



# An Illustrative Example (cont’d)

A feasible solution.



# The model

P: Minimize

Cost of the network (i.e., the cost of the access, edge and core links, and the cost of the routers and ports)

Subject to :

Router type uniqueness constraints

Router capacity constraints
(slot and switch fabric levels)

Router capacity constraints (port level)

Access device assignment constraints
(access network topology constraints)

Edge and core network topology constraints

Access, edge and core link capacity constraints

Traffic flow conservation constraints

Routing constraints (shortest paths routing constraints)

Failure scenarios constraints
(single edge and core link scenarios constraints)

Intergrality constraints

# A tabu search algorithm

The following notation is used:

- $e(j)$, the state of the edge site $j$ such that $e(j) = 0$ if there is no router installed at this site and $e(j) = t$ if an edge router of type $t$ is installed at this site.
- $e(k)$, the state of the core site $k$ such that $e(k) = 0$ if there is no router installed at this site and $e(k) = t$ if a core router of type $t$ is installed at this site.

# A tabu search algorithm (cont'd)

The moves of the tabu search consist to change the vector **e**.

- For the edge site $j$ we can:

  1. Install a router of type $t$ (if $e(j) = 0$): $e(j) = t$.
  2. Remove a router of type $t$ (if $e(j) = t$): $e(j) = 0$.
  3. Change a router of type $t$ by another of type $s$ ($t \neq s$) (if $e(j) = t$): $e(j) = s$.

- For the core site $k$ we can:

  1. Install a router of type $t$ (if $e(k) = 0$): $e(k) = t$.
  2. Remove a router of type $t$ (if $e(k) = t$): $e(k) = 0$.
  3. Change a router of type $t$ by another of type $s$ ($t \neq s$) (if $e(k) = t$): $e(k) = s$.

# A tabu search algorithm (cont'd)

When **e** is fixed, P can be "decomposed" into two NP-hard subproblems.

1.Access network design subproblem

The purpose of this subproblem is to connect the access links to the edge routers and selecting the port types to connect them at minimum cost while considering the routers selected (given by vector **e**).

→ Heuristic for the first subproblem (HFS).

2.Edge and core network design subproblem

The purpose of this subproblem is to connect the edge and core routers to form a backbone network at minimum cost while respecting the edge and core networks topology constraints, the slots available in the edge and core routers, the routing protocol constraints and, finally, the failure scenarios constraints.

→ Heuristic for the second subproblem (HSS).

# Numerical results

- A Sun Java workstation under Linux with an AMD Opteron 150 CPU and 2GB of RAM was used for the tests.
- OC-3, OC-12 and GbE links are used in the access network, OC-48 links are used in the edge and core networks.
- For each access device, the number and the type of access links is randomly selected among 1×OC-3, 2×OC-3, 1×OC-12, 2×OC-12, 1×GbE and 2×GbE.
- The access devices' locations, the edge and core sites were randomly generated in the square of side length 100 km.
- The MIR between each pair of access devices is randomly generated in the interval [0,3] Mbps.
- Each edge router is connected to two core routers and a multiple-ring topology is used in the core network.

# Numerical results (cont'd)

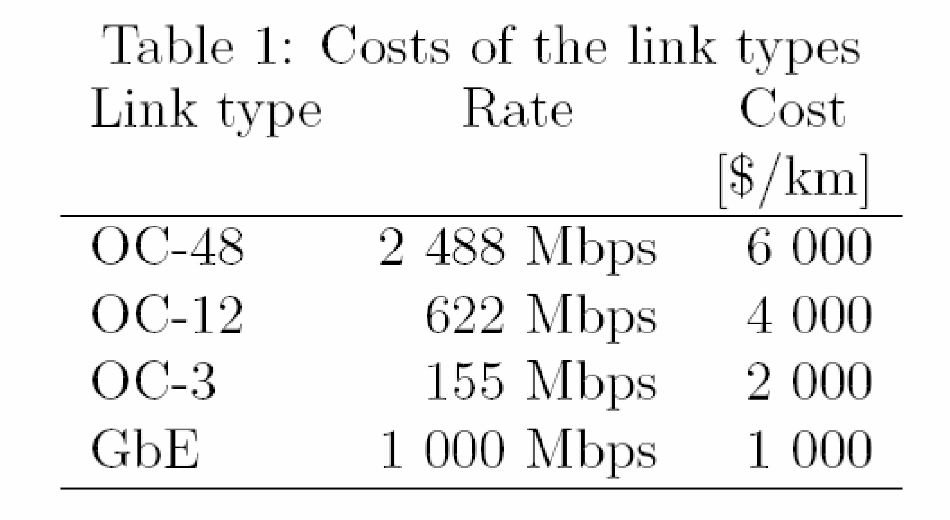


Table 1: Costs of the link types

| Link type | Rate | Cost [$/km] |
|---|---|---|
| OC-48 | 2 488 Mbps | 6 000 |
| OC-12 | 622 Mbps | 4 000 |
| OC-3 | 155 Mbps | 2 000 |
| GbE | 1 000 Mbps | 1 000 |

# Numerical results (cont’d)

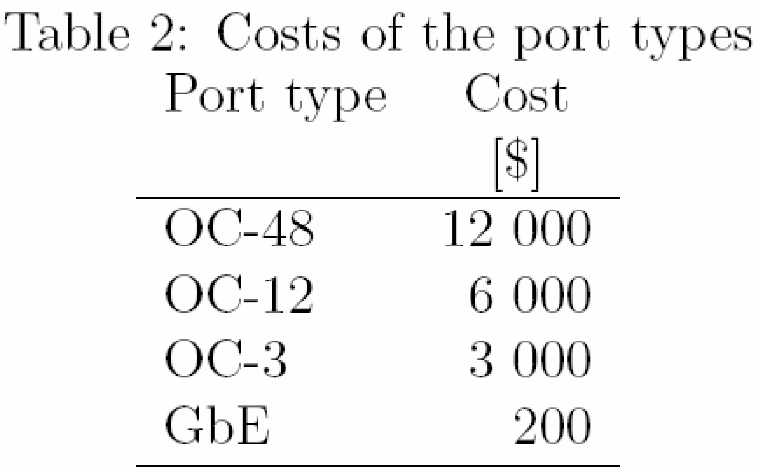


Table 2: Costs of the port types

| Port type | Cost<br>[$] |
|---|---|
| OC-48 | 12 000 |
| OC-12 | 6 000 |
| OC-3 | 3 000 |
| GbE | 200 |

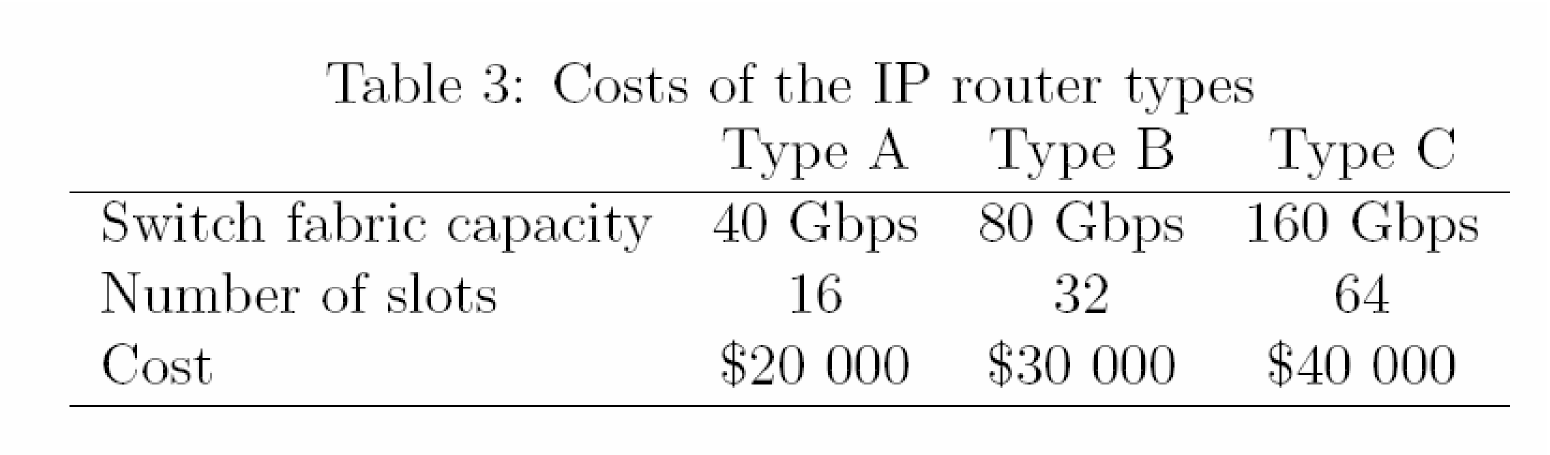


Table 3: Costs of the IP router types

| | Type A | Type B | Type C |
|---|---|---|---|
| Switch fabric capacity | 40 Gbps | 80 Gbps | 160 Gbps |
| Number of slots | 16 | 32 | 64 |
| Cost | $20 000 | $30 000 | $40 000 |

# Numerical results (cont'd)

- Solutions with CPLEX 9.0.

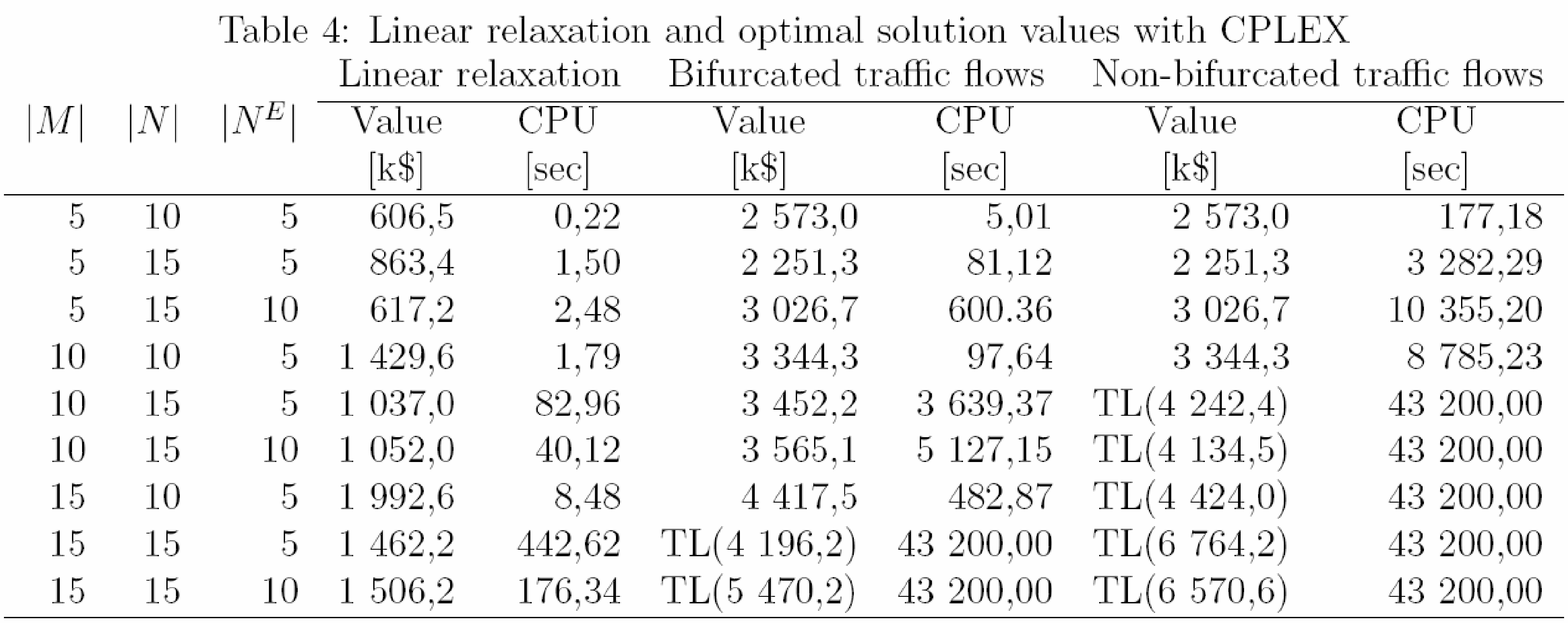
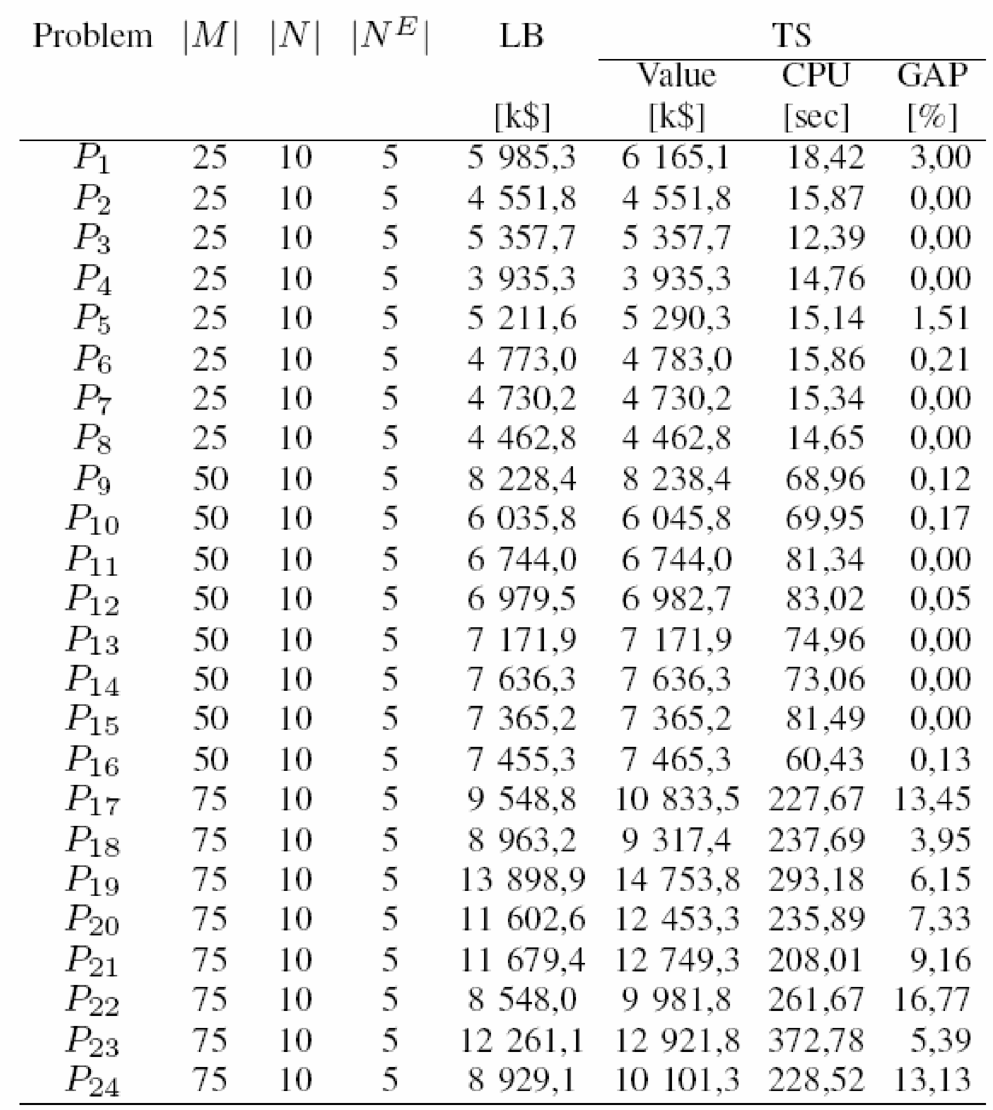


Table 4: Linear relaxation and optimal solution values with CPLEX

| | | | Linear relaxation | | Bifurcated traffic flows | | Non-bifurcated traffic flows | |
|---|---|---|---|---|---|---|---|---|
| $\lvert M\rvert$ | $\lvert N\rvert$ | $\lvert N^E\rvert$ | Value [k$] | CPU [sec] | Value [k$] | CPU [sec] | Value [k$] | CPU [sec] |
| 5 | 10 | 5 | 606,5 | 0,22 | 2 573,0 | 5,01 | 2 573,0 | 177,18 |
| 5 | 15 | 5 | 863,4 | 1,50 | 2 251,3 | 81,12 | 2 251,3 | 3 282,29 |
| 5 | 15 | 10 | 617,2 | 2,48 | 3 026,7 | 600.36 | 3 026,7 | 10 355,20 |
| 10 | 10 | 5 | 1 429,6 | 1,79 | 3 344,3 | 97,64 | 3 344,3 | 8 785,23 |
| 10 | 15 | 5 | 1 037,0 | 82,96 | 3 452,2 | 3 639,37 | TL(4 242,4) | 43 200,00 |
| 10 | 15 | 10 | 1 052,0 | 40,12 | 3 565,1 | 5 127,15 | TL(4 134,5) | 43 200,00 |
| 15 | 10 | 5 | 1 992,6 | 8,48 | 4 417,5 | 482,87 | TL(4 424,0) | 43 200,00 |
| 15 | 15 | 5 | 1 462,2 | 442,62 | TL(4 196,2) | 43 200,00 | TL(6 764,2) | 43 200,00 |
| 15 | 15 | 10 | 1 506,2 | 176,34 | TL(5 470,2) | 43 200,00 | TL(6 570,6) | 43 200,00 |

# Numerical results (cont'd)

- Solutions with the Algorithm TS.

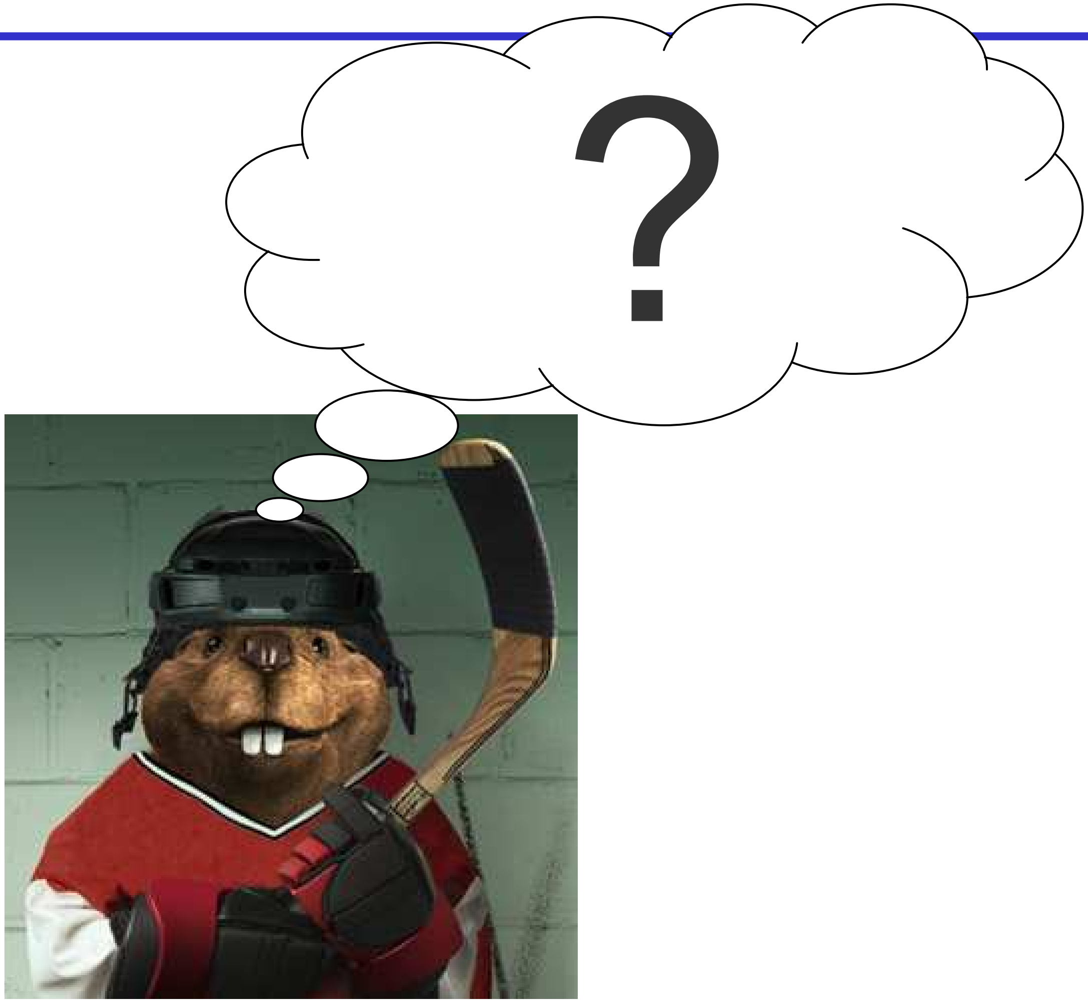


| Problem | $\|M\|$ | $\|N\|$ | $\|N^E\|$ | LB [k$] | TS Value [k$] | TS CPU [sec] | TS GAP [%] |
|---|---|---|---|---|---|---|---|
| $P_1$ | 25 | 10 | 5 | 5 985,3 | 6 165,1 | 18,42 | 3,00 |
| $P_2$ | 25 | 10 | 5 | 4 551,8 | 4 551,8 | 15,87 | 0,00 |
| $P_3$ | 25 | 10 | 5 | 5 357,7 | 5 357,7 | 12,39 | 0,00 |
| $P_4$ | 25 | 10 | 5 | 3 935,3 | 3 935,3 | 14,76 | 0,00 |
| $P_5$ | 25 | 10 | 5 | 5 211,6 | 5 290,3 | 15,14 | 1,51 |
| $P_6$ | 25 | 10 | 5 | 4 773,0 | 4 783,0 | 15,86 | 0,21 |
| $P_7$ | 25 | 10 | 5 | 4 730,2 | 4 730,2 | 15,34 | 0,00 |
| $P_8$ | 25 | 10 | 5 | 4 462,8 | 4 462,8 | 14,65 | 0,00 |
| $P_9$ | 50 | 10 | 5 | 8 228,4 | 8 238,4 | 68,96 | 0,12 |
| $P_{10}$ | 50 | 10 | 5 | 6 035,8 | 6 045,8 | 69,95 | 0,17 |
| $P_{11}$ | 50 | 10 | 5 | 6 744,0 | 6 744,0 | 81,34 | 0,00 |
| $P_{12}$ | 50 | 10 | 5 | 6 979,5 | 6 982,7 | 83,02 | 0,05 |
| $P_{13}$ | 50 | 10 | 5 | 7 171,9 | 7 171,9 | 74,96 | 0,00 |
| $P_{14}$ | 50 | 10 | 5 | 7 636,3 | 7 636,3 | 73,06 | 0,00 |
| $P_{15}$ | 50 | 10 | 5 | 7 365,2 | 7 365,2 | 81,49 | 0,00 |
| $P_{16}$ | 50 | 10 | 5 | 7 455,3 | 7 465,3 | 60,43 | 0,13 |
| $P_{17}$ | 75 | 10 | 5 | 9 548,8 | 10 833,5 | 227,67 | 13,45 |
| $P_{18}$ | 75 | 10 | 5 | 8 963,2 | 9 317,4 | 237,69 | 3,95 |
| $P_{19}$ | 75 | 10 | 5 | 13 898,9 | 14 753,8 | 293,18 | 6,15 |
| $P_{20}$ | 75 | 10 | 5 | 11 602,6 | 12 453,3 | 235,89 | 7,33 |
| $P_{21}$ | 75 | 10 | 5 | 11 679,4 | 12 749,3 | 208,01 | 9,16 |
| $P_{22}$ | 75 | 10 | 5 | 8 548,0 | 9 981,8 | 261,67 | 16,77 |
| $P_{23}$ | 75 | 10 | 5 | 12 261,1 | 12 921,8 | 372,78 | 5,39 |
| $P_{24}$ | 75 | 10 | 5 | 8 929,1 | 10 101,3 | 228,52 | 13,13 |

Conclusions

- In this paper, we have proposed:
  - A mathematical model for the design problem of reliable IP networks with a three-level (access/edge/core) hierarchical structure.
  - A heuristic algorithm based on the tabu search principle.
- It was found that it is difficult to find the optimal solution even for small-size instances of the problem (i.e., with 10 access devices and 15 potential sites for the routers).
- For the test problems considered, the heuristic algorithm found solutions, on average, within 3,26% of a lower bound. Considering the complexity of the problem, these first results are promising.
- Further works:
  - Explore exact algorithms.
  - Improve the heuristic algorithms.

# Questions



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