INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Virtual Topology Reconfiguration Issues in Evolution of WDM Optical Networks

Gurvan Huiban — Pallab Datta

N° 5711

Octobre 2005

Thème COM

Rapport de recherche

ISSN 0249-6399 ISRN INRIA/RR--5711--FR+ENG

Virtual Topology Reconfiguration Issues in Evolution of WDM Optical Networks

Gurvan Huiban* , Pallab Datta†

Thème COM — Systèmes communicants
Projet Mascotte, commun I3S-CNRS/INRIA/UNSA

Rapport de recherche n° 5711 — Octobre 2005 — 17 pages

Abstract: We consider the reconfiguration problem in multi-fiber WDM optical networks. In a real-time network as the traffic evolves with time: the virtual topology may not remain optimal for the evolving traffic, leading to a degradation of network performance. However, adapting the virtual topology to the changing traffic may lead to service disruption. This optimization problem hence captures the trade-off between network performance and number of reconfigurations applied to the virtual topology.

The above problem is solved through a Mixed Integer Linear Programming formulation with a multivariate objective function, that captures both these parameters. However the problem is NP-hard and such an approach is unable to solve large problem instances in a reasonable time. In this paper, we also propose a simulated annealing based heuristic algorithm for solving problems of higher complexity.

We compare the performance and the computation time of the MILP model and the heuristic algorithm considering different tests instances. Our results indicate that simulated annealing obtains results within 5% of the optimal solution, thus making it a viable approach in large scale networks.

Key-words: WDM, dynamic routing, reconfiguration, heuristic.

* Gurvan Huiban is with the Mascotte project - I3S-CNRS/INRIA/UNSA - 2004, route des lucioles - BP 93 - 06902 Sophia Antipolis - France and also with the Computer Science Department (DCC) of the Federal University of Minas Gerais (UFMG) - Av. Antônio Carlos,6627 - 31270-010 Belo Horizonte - MG - Brazil. (ghuiban@dcc.ufmg.br)

† Pallab Datta is presently working as a Post-Doctoral Research Associate in Los Alamos National Labs, USA. (pallab@lanl.gov)

This work has been partially funded by a grant from CNPQ, by a grant from PACA province, by a Lavoisier grant from the French Ministry of Foreign Affairs, by ACI-SI PRESTO and by European project IST FET AEOLUS

Reconfiguration de topologie virtuelle dans les réseaux optiques WDM

Résumé : Nous nous intéressons au problème de la reconfiguration dans les réseaux optiques multifibres. Dans un réseau dont le trafic évolue en temps-réel, l'adéquation de la topologie virtuelle au trafic peut diminuer régulièrement. Ceci mène à une diminution des performances du réseau. Cependant, adapter la topologie virtuelle à un type de trafic peut nécessiter des interruptions dans le fonctionnement du réseau. Ce problème d'optimisation inclut un compromis entre les performances du réseau et le nombre de reconfigurations appliquées à la topologie virtuelle.

Le problème ci-dessus est résolu via une formulation mathématique en programmation linéaire entière et mixte, à l'aide d'une fonction objectif représentant les différents aspects du compromis. Le problème étant NP-difficile, une telle approche ne permet pas de résoudre des instances de grande taille en un temps raisonnable. Nous proposons également un algorithme basé sur la meta-heuristique dite du recuit simulé pour combler ce manque.

Nous comparons les performances et le temps de calcul de la résolution du problème par le modèle mathématique et par l'heuristique sur différentes instances de tests. Nos résultats indiquent que l'approche basée sur l'algorithme du recuit simulé obtient des résultats comparables aux résultats optimaux, à moins de 5% près, pour un temps de calcul cinq fois moindre. Ceci confirme que cette approche est viable pour des réseaux de grande échelle.

Mots-clés : WDM, routage dynamique, reconfiguration, heuristique.

1 Introduction

Even though the Wavelength Division Multiplexing (WDM) technology is more than 10 years old, it is still the key component of large-scale and long-distance data transmission. Used all over the world, this technology is now well known, still evolves and offers capacity to cope with the ever increasing traffic demand [16].

Most traditional optical networks defines an optical layer over a physical layer, called *virtual topology* or *logical topology*, and routes traffic on it. Such a topology is an intermediate layer, that represents the effective communication graph available to route the data. It is defined through the configuration of the switches installed in each network nodes and can be modified [13]. The virtual topology has a direct impact on the data traffic routing efficiency. Ideally, any change in the traffic would trigger a redefinition of the virtual topology. Unfortunately, this is not possible, since such an operation might lead to traffic disruption. The changes in the logical topology also needs to be propagated on to the physical layer [1]. This problem, is often referred in literature as the *reconfiguration problem*, and involves a trade-off between the adaptation of the virtual topology to the evolving traffic and the network disruption that may occur each time it is redefined. Different ILP approaches has been developed in literature which addresses short-term, mid-term and long-term network reconfiguration issues with respect to evolving traffic in WDM optical networks [14, 8, 5]. However these approaches are restrictive to limited traffic sets and static traffic defined over multiple generations of network evolution.

In our work, we focus on the computation of the virtual topologies with the evolution of the traffic. This problem is NP-hard by extension of the computation of the optimal virtual topology, which has already been proved to be a NP-hard problem [3].

In this paper we develop a *Mixed Integer Linear Programming* (MILP) formulation to solve this problem, similar to the approaches developed in [10]. However, the MILP approach is unable to solve large network instances within reasonable time limits. Meta-heuristics, such as the simulated annealing, are generally able to find good solutions to optimization problems for an affordable computational cost [4]. We compare the computation time required to solve the problem and the quality of the solution found by each approach. Our approach takes account of the trade-offs involved in the problem, which are generally absent in the articles found in the literature, focussing generally either only on network performance or on reconfiguration aspects.

The network reconfiguration problem is well known in literature. However, there are not too many satisfying methods to solve the problem: some works restrict themselves to very-specific cases. In [12], the authors develop reconfiguration algorithm for ring networks. The proposed algorithm is based on branch-exchange techniques. In [1] a Markovian process is used to study the trade-offs involved by the reconfiguration in single-hop broadcast WDM networks. We are more interested in the very general case of mesh networks, with all-to-all traffic,and multi-hop communication.

In order to maintain optimum network performance, a network should adapt to traffic changes across multiple generations of network evolution. Evolving traffic might trigger reconfiguration in the network. Such approaches have been discussed in [6, 7, 19]. As there is almost no prevision, there is no way to perform in-depth resource optimization with this kind of algorithms. An interesting discussion on the choice of an adaptation algorithm to be used can be found in [18].

The above problem has been also addressed in literature under the context of "dynamic traffic grooming" in [20, 11]. In both works, the authors modify the initial network graph. The modifications consist of splitting nodes to represent different part of the optical devices (electronic processing, purely optical router, and so on). That allows to use quite simple algorithms based on the shortest path [20] or to solve the problem with elegant mathematical models [11]. This mathematical model focuses on the grooming aspect and does not consider the adaptation of the virtual topology to meet the ever increasing traffic demands across multiple generations of network evolution. There has been significant other work done in the area of dynamic traffic grooming [15], but it doesnt address the issues of network reconfiguration and traffic evolution.

A very interesting survey about the dynamic traffic grooming problem can be found in [9]. However, it focuses on the "grooming" aspect of the problem and does not discuss any reconfiguration aspects. An MILP formulation is provided, which generates much more variables and constraints than ours and it also does not consider a network model with multi-fibers.

This paper is organized as follows: We describe the problem in section 2. In section 3, the MILP model is developed for solving the virtual topology reconfiguration problem. We describe the simulated annealing heuristic algorithm in section 4. Some experimental results are given and analyzed in section 5. We finally conclude the paper in section 6.

2 Problem description and notations

We consider a WDM network $\mathcal{P}$, constituted of a set of $\mathcal{N}$ nodes and a set of $\mathcal{L}$ links. The maximum number of fibers between nodes n_1 to node n_2 is given by $\mathcal{F}_{(n_1,n_2)}$. Each fiber carries a maximum number of $\mathcal{W}$ wavelengths. Each wavelength has a maximum capacity of $\mathcal{C}$ Mbps. We assume that $\mathcal{W}$ and $\mathcal{C}$ are the same all throughout the entire network. Many technological parameters (range of frequency used, type of optical fiber, and so on) are involved, and for simplicity we assume that the telecommunication providers build a homogeneous network.

The virtual topology is the logical communication graph used to route the traffic. It is constituted of lightpaths. A lightpath is a path on the physical topology, and corresponds to a link in the virtual topology. A lightpath is established using the same wavelength from the source to the destination, thus obeying the *wavelength continuity constraint*. The technology for full or partial optical wavelength conversion is not yet mature for most commercial applications. Another way to enable wavelength conversion, is using optical-electronic-optical converters, which are still very expensive and generates a high delay in the overall transmission time.

Each node routes the lightpaths without any restrictions. However, two distinct lightpaths cannot use the same wavelength in an optical fiber. Lightpaths are set up between the end points of the demands. In our network model, we allow multi-hop routing: i.e traffic from A to B can first use a lightpath from A to C, and then another lightpath from C to B.

The traffic flowing on the network evolves with time. As current optical technology deals with aggregated data streams, the data traffic shows a certain stability. Thus, we may consider the traffic evolution step by step. We call a *time period* the period of time between two traffic evolutions. In other words, the overall time period is divided into $\mathcal{T}$ periods $t_1, \ldots, t_{\mathcal{T}}$, and data changes occur each time a time period ends and another begins. The traffic remains constant during a whole time period. We note $\mathcal{D}_{s,d}(t)$, expressed in Mbps, as the demand for the source-demand pair $(s, d) \in \mathcal{N}^2$ during time period t.

We consider that each time period is long enough to implement the configuration computed. We do not consider real-time changes in the data. The traffic is known *a priori*, and the optimizations are made once and for all. Our objective is to find a virtual topology that is adapted to the traffic for each time period. We solve the problem keeping in mind the trade-offs involved in the reconfiguration problem mentioned above. We intend to use the minimum amount of network resources but simultaneously also reduce the number of reconfigurations needed in the virtual topology.

A solution $\mathcal{S}$ corresponds to a set of virtual topologies; one for each time period. Let us call $O_{\mathcal{S}}$ the sum of the number of optical links used and $L_{\mathcal{S}}$ the sum of the number of lightpaths used for each time period. We also take into account the number of reconfigurations $C_{\mathcal{S}}$ incurred by a solution.

The objective function used to reflect this tradeoff between minimal network resource usage and minimal network reconfiguration is given by equation (1) if the network resources are measured as number of optical links, and by equation (2) if the resources are measured in terms of number of lightpaths.

$$F_{\mathcal{S}} = \alpha_O O_{\mathcal{S}} + \alpha_C C_{\mathcal{S}} \quad (1)$$

$$F_{\mathcal{S}} = \alpha_L L_{\mathcal{S}} + \alpha_C C_{\mathcal{S}} \quad (2)$$

where α_O, α_L and α_C are parameters that allows to create a multi-variate objective function. Depending on the value of each parameter, more weight is given to one or another aspect.

3 MILP model

In this paper we introduced a MILP model for the reconfiguration problem. With such a model, the reconfiguration problem is seen as a succession of flow problems - one flow problem for each time period - coupled by reconfiguration constraints.

We tried to achieve the most concise model possible. To do so, we aggregated all commodities from a given node. This led us to a source formulation of the reconfiguration problem. Such source formulation, already used in a virtual topology design problem in [17], significantly reduces the memory occupancy overhead while solving the problem.

We define the following variables:

- $p^i_{(m,n),w}(t)$ is the number of optical links w used by lightpaths having node i as source on physical link $(m,n) \in \mathcal{L}$ during time period t.
- $c^{(i,j)}_w(t)$ is the number of lightpaths from node i to node j using wavelength w during time period t.
- $c^{(i,j)}(t)$ is the number of lightpaths from node i to node j during time period t.
- $f^s_{(i,j)}(t)$ is the flow from source s using lightpath (i,j) during time period t.
- $\Delta p^i_{(m,n),w}(t)$ is the number of changes for the number of optical links w used by lightpaths having node i as a source on physical link $(m,n) \in \mathcal{L}$, between time period $t-1$ and t.

The overall number of variables is $O\left(|\mathcal{N}|^3 \mathcal{W}\mathcal{T}\right)$.

3.1 Virtual topology constraints

The constraints associated with the virtual topology design problem are the following:

$$\sum_{(i,n)\in\mathcal{L}} \sum_{w=1}^{\mathcal{W}} p^i_{(i,n),w}(t) = \sum_{j\in\mathcal{N}} c^{(i,j)}(t), \quad \begin{array}{l} \forall i \in \mathcal{N} \\ 1 \leqslant t \leqslant \mathcal{T} \end{array} \tag{3}$$

$$\sum_{(m,n)\in\mathcal{L}} p^i_{(m,n),w}(t) - \sum_{(n,p)\in\mathcal{L}} p^i_{(n,p),w}(t) = c^{(i,n)}_w(t), \quad \begin{array}{l} \forall i,n \in \mathcal{N}^2 \\ i \neq n \\ 1 \leqslant w \leqslant \mathcal{W} \\ 1 \leqslant t \leqslant \mathcal{T} \end{array} \tag{4}$$

$$\sum_{w=1}^{\mathcal{W}} c^{(i,j)}_w(t) = c^{(i,j)}(t), \quad \begin{array}{l} \forall i,j \in \mathcal{N}^2 \\ i \neq j \\ 1 \leqslant t \leqslant \mathcal{T} \end{array} \tag{5}$$

$$\sum_{i\in\mathcal{N}, i\neq n} p^i_{(m,n),w}(t) \leqslant \mathcal{F}_{(m,n)}, \quad \begin{array}{l} \forall\,(m,n) \in \mathcal{L} \\ 1 \leqslant w \leqslant \mathcal{W} \\ 1 \leqslant t \leqslant \mathcal{T} \end{array} \tag{6}$$

Constraint (3) corresponds to the flow conservation for each source node i. Constraint (4) corresponds to the flow conservation in demand nodes n, for each wavelength. Constraint (5) corresponds to the number of lightpath conservation. Constraint (6) corresponds to the capacity constraints.

3.2 Routing constraints

$$\sum_{j\in\mathcal{N}, j\neq s} f^s_{(s,j)}(t) = \sum_{d\in\mathcal{N}, d\neq s} \mathcal{D}_{s,d}(t), \ \forall s \in \mathcal{N}, 1 \leqslant t \leqslant \mathcal{T} \tag{7}$$

$$\sum_{i\in\mathcal{N}, i\neq s} f^s_{(i,k)}(t) - \sum_{j\in\mathcal{N}, j\neq s} f^s_{(k,j)}(t) = \mathcal{D}_{s,k}(t), \quad \begin{array}{l} \forall (s,k) \in \mathcal{N}^2 \\ k \neq s \\ 1 \leqslant t \leqslant \mathcal{T} \end{array} \tag{8}$$

$$\sum_{s \in \mathcal{N}, s \neq j} f^s_{(i,j)}(t) \leqslant \mathcal{C} \sum_{w=1}^{\mathcal{W}} c_w^{(i,j)}(t), \quad \begin{array}{l} \forall\,(i,j) \in \mathcal{N}^2 \\ 1 \leqslant t \leqslant \mathcal{T} \end{array} \tag{9}$$

Constraint (7) corresponds to the flow conservation constraints at source node s. Constraint (8) corresponds to flow conservation at demand nodes k. Finally, constraint (9) is the capacity constraint.

3.3 Reconfiguration constraints

$$p^i_{(m,n),w}(t) - p^i_{(m,n),w}(t-1) \quad \leqslant \quad \Delta p^i_{(m,n),w}(t), \quad \begin{array}{l} \forall i \in \mathcal{N} \\ (m,n) \in \mathcal{L} \\ i \neq n \\ 1 \leqslant w \leqslant \mathcal{W} \\ 2 \leqslant t \leqslant \mathcal{T} \end{array} \tag{10}$$

$$p^i_{(m,n),w}(t-1) - p^i_{(m,n),w}(t) \quad \leqslant \quad \Delta p^i_{(m,n),w}(t), \quad \begin{array}{l} \forall i \in \mathcal{N} \\ (m,n) \in \mathcal{L} \\ i \neq n \\ 1 \leqslant w \leqslant \mathcal{W} \\ 2 \leqslant t \leqslant \mathcal{T} \end{array} \tag{11}$$

We consider that each variation of the allocation variables (the $p^i_{(m,n),w}(t)$ variable) from one time period to another is a change of the virtual topology. Hence, it has to be taken into account. This is done by constraints (10) and (11).

3.4 Objective functions

$$O(t) = \sum_{i \in \mathcal{N}} \sum_{(m,n) \in \mathcal{L}} \sum_{w=1}^{\mathcal{W}} p^i_{(m,n),w}(t), \ 1 \leqslant t \leqslant \mathcal{T} \tag{12}$$

$$L(t) = \sum i \in \mathcal{N} \sum j \in \mathcal{N} c^{(i,j)}(t), \ 1 \leqslant t \leqslant \mathcal{T} \tag{13}$$

$$C(t) = \sum_{i \in \mathcal{N}} \sum_{(m,n) \in \mathcal{L}} \sum_{w=1}^{\mathcal{W}} \Delta p^i_{(m,n),w}(t), \ 2 \leqslant t \leqslant \mathcal{T} \tag{14}$$

Eq. (12) computes the overall number of optical links used. Eq. (13) computes the overall number of lightpaths defined.The overall number of changes is given by eq. (14).

Consequently, the objective function of our optimization model is the following to minimize:

- the number of optical links and the number of reconfigurations (15)
- the number of lightpaths and the number of reconfigurations (16)

$$F = \alpha_O \sum_{t=1}^{\mathcal{T}} O(t) + \alpha_C \sum_{t=2}^{\mathcal{T}} C(t) \tag{15}$$

$$F = \alpha_L \sum_{t=1}^{\mathcal{T}} L(t) + \alpha_C \sum_{t=2}^{\mathcal{T}} C(t) \tag{16}$$

3.5 Integrality constraints

The variables $p^i_{(m,n),w}(t)$ have to be integer, since it is not possible to allocate a fractional part of an optical link.

With such model, the number of integer variables is $O\left(|\mathcal{N}|^3\mathcal{W}\mathcal{T}\right)$, and the number of continuous variables is $O\left(\left(|\mathcal{N}^2|\mathcal{W} + |\mathcal{N}|^3\right)\mathcal{T}\right)$. Even for small networks and considering only a few time periods, the program generates thousands of integer variables and constraints, thus making it infeasable to solve large problem instances.

4 Simulated annealing algorithm

4.1 Algorithms

Simulated annealing is a Monte Carlo approach for minimizing multivariate functions. A temperature for the system is defined. The algorithm progresses by lowering gradually this temperature until the system freezes. At each temperature, a large number of different solutions for the problem is computed, allowing the system to reach a steady state. This process is called *thermalization*.

The system is initialized with a particular configuration. Each new solution is constructed by imposing a displacement. If the energy of this new state is lower than the previous one, this new solution is kept. If not, this new solution is accepted with a given probability. This probability decreases with the temperature of the system, allowing to explore a large portion of the solution space at the beginning of the process. As the temperature decreases, the probability of accepting a bad solution decreases, leading to a local search converging towards the nearest local optima. The probability of acceptance is generally given by $\rho = exp^{-\delta/KT}$, where K is the Boltzman's constant, T the temperature and δ the temperature variation. With the execution of the algorithm, the temperature decreases, leading to a more stable system.

There are different possible annealing schemes to update the temperature T. We may use an annealing scheme where the temperature varies as $T_n = \alpha \times T_{n-1}$, where T is the temperature at the nth temperature update, and α is an arbitrary constant between 0 and 1. The parameter α decides how slowly T decreases. Typical values of α lie between 0.9 and 0.95. The parameters α and the initial value of T plays a critical role for the performance of the simulated annealing. We have an annealing scheme where the temperature update is made as $T_n = T_0/(1 + \alpha \times T_{n-1})$. The typical values of α can be of the order of 0.01 to 0.1 in-order to have a graceful degradation of the temperature.

We associate to each link $e = (n_1, n_2)$ of the network a weight w_e, creating the link weight vector $\mathcal{W}$. Depending on the weight, different routes will be found by a shortest path algorithm. The weights of the edges are mutated by a factor γ between each transition of the simulated annealing algorithm.

The detailed simulated annealing algorithm is given by algorithm 1. Our algorithm transforms the set of traffic matrices into an ordered list of requests, and then affect resources to each request.

Algorithm 1 Simulated annealing for the Reconfiguration problem

```
Initialize an empty ordered list of requests R
split request D_{i,j}(t), ∀i, j, t into a set of integer requests and a fractional request (if required) and add them to R
Initialize the link weight vector W to 1
Initialize temperature T_0
Compute the initial solution: S* = Solve(P,W,R)
for Y iterations / until T_n < ε do
  for X iterations do
    Evaluate the hop number h_r of each request r ∈ R
    Reorder the requests r ∈ R by decreasing h_r
    S = Solve(P,W,R)
    if Compute F_S < F_{S*} then
      S* = S (update the best solution found)
    else
      S* = S with a probability of e^{-δ/(K T_n)}
    end if
  end for
  Update the link weights with w_l = w_l (1 − γ), ∀l ∈ L
  Scale down temperature: T_{n+1} = T_0 / (1 + α T_n)
end for
```

The fast algorithm we use to generate solution is given by algorithm 2.

5 Experimental results

5.1 Experimental parameters

We present here some of the experiments we made in order to compare the two different approaches. We made our experiments on an hypothetical small network SN2, represented on figure 1, on the COST239 network [2], represented on figure 2, and on the NSFNET network 3. Note that the two latter networks are existing networks of medium size.

We chose the following parameters:

- For all existing links (n_1, n_2), $\mathcal{F}_{(n_1,n_2)} = 5$.
- $\mathcal{C} = 20$Mbps

Algorithm 2 `Solve(`$\mathcal{P}$`,`$\mathcal{W}$`,`R`)` algorithm

Require: A network $\mathcal{P}$, a link weight vector $\mathcal{W}$ and an ordered list of requests R
  for all request $r \in R$ **do**
    Let s_r, d_r, t_r and v_r be respectively the source node, the demand node, the time period and the size of r
    if v_r is integer **then**
      Find the shortest path from s_r to d_r considering the wavelengths available during time period t_r. The cost of a link corresponds to its weight.
      Make wavelengths allocation avoiding wavelength changes
      Update available wavelengths for the time period t_r
    else
      if Exists paths p_r from s_r to d_r at time period t_r using only available capacity within the lightpaths able to transport a request of size v_r **then**
        Use the shortest of the possible p_r
      else
        Find the shortest path from s to d, considering the wavelengths available during time period t. The cost of a link corresponds to its weight.
        Make wavelengths allocation avoiding wavelength changes
      end if
      Update the available capacity in used links
      Update the used link weights with remaining capacity: $w_l = w_l * v_i$
    end if
  end for
Ensure: A virtual topology for each time period

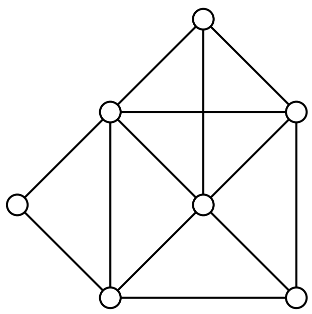

Figure 1: Small network 2 (SN2)

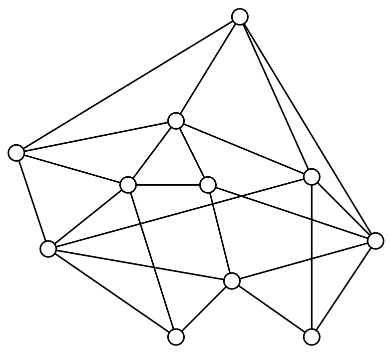

Figure 2: Cost239 network

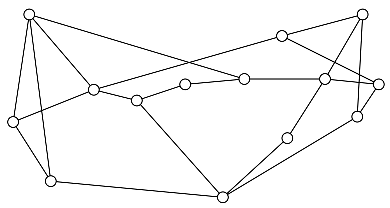

Figure 3: NSFNET network

The traffic is generated the following way: we first generate an initial traffic matrix. The initial demand from a node n_1 to a node n_2 is randomly chosen between 20 and 60Mbps. We then compute the evolution of the demand for each time period, based on the value of the demand at previous time period. This evolution is between -10 (that is, the traffic can decrease) and 10 Mbps. For instance, it is possible to have the following evolution of traffic from node A to node B, over five time period: 57Mbps, 67Mbps, 75Mbps, 68Mbps 77Mbps.

The MILP model is solved using the commercial software Cplex[1] version 9, on a desktop PC with one gigabyte of RAM. We limited the computation time of our tests to one hour in the vast majority of our experiments. The simulated annealing algorithm has been run on a Powerbook[2] with 768 megabytes of RAM.

For the simulated annealing experiments, the total number of sub-transitions at a given temperature was chosen between 8-10 and the transitions across different temperatures was considered to be between 20-25 based on the size of the demand sets. This numbers were chosen because they were moderate enough for the simulated annealing to show different possible solution sets.

The Boltzman's Constant was chosen such that, $0 \leq \exp^{-\delta/(K \times t_i)} \leq 1$ where t_i is the temperature at the i^{th} iteration. The temperature mutation parameter α is taken to be 0.01 so that that the temperature does not drop abruptly. Higher values of α leads to a fast convergence for the simulated annealing procedure. The edge weight mutation parameter γ was chosen to be between 0.5 and 1.0.

5.2 Performance Analysis

The most representative results we obtained with the MILP approach and the simulated annealing are reported in tables 1 to 6. The $^+$symbol means that the solver hits the time-limit after having found at least a possible solution. In this case, it returns the best solution found. The ^{0}symbol means that the solver hit the time limit without finding any solution.

As we can see in the obtained results, we had difficulties to solve the problem with the mathematical model: even for the small network instances, within a bounded time limit. For some of the larger instances, the solver is unable to find even one feasible solution in one hour.

On the contrary, solving the problem with the simulated annealing always returns a solution, even for larger problem instances. One can also notice that the chosen parameters for the simulated annealing algorithms allowed it to explore a part of the solution space large enough to find a good solution: the simulated annealing algorithm returned solutions which was within 5% of the optimal solution found by the solver, with computation times at least 4-6 times lower.

We can also notice that the computation time to find solutions varies depending on the instance size - which was expected - but also on the metric used. Mixing the resource and reconfiguration objectives turns the problem much more difficult to solve than considering

[1] Copyright ©Ilog 1997-2004. Cplex is a registered trademark of Ilog.
[2] Copyright ©Apple computers

Table 1: SN2 network, $\mathcal{W} = 16$

SN2, $\mathcal{W} = 16$		
$(\alpha_O, \alpha_L, \alpha_C)$	(O, L, C)	Comp. time (s)
MILP		
$(1, 0, 0)$	$(555, 513, 844)$	3600^+
$(0, 1, 0)$	$(642, 428, 946)$	3600^+
$(0, 0, 1)$	$(1990, 1500, 0)$	46
$(1, 0, 1)$	$(580, 535, 0)$	3600^+
$(0, 1, 1)$	$(610, 450, 0)$	3600^+
Simulated annealing		
$(1, 0, 0)$	$(595, 534, 873)$	253
$(0, 1, 0)$	$(670, 462, 1005)$	261
$(0, 0, 1)$	$(2014, 1678, 5)$	53
$(1, 0, 1)$	$(624, 598, 7)$	302
$(0, 1, 1)$	$(696, 530, 7)$	352

Table 2: SN2 network, $\mathcal{W} = 32$

SN2, $\mathcal{W} = 32$		
$(\alpha_O, \alpha_L, \alpha_C)$	(O, L, C)	Comp. time (s)
MILP		
$(1, 0, 0)$	$(554, 509, 875)$	3600^+
$(0, 1, 0)$	$(622, 426, 946)$	3600^+
$(0, 0, 1)$	$(1960, 1525, 0)$	3600^+
$(1, 0, 1)$	$(580, 535, 0)$	3600^+
$(0, 1, 1)$	$(810, 455, 0)$	3600^+
Simulated annealing		
$(1, 0, 0)$	$(602, 531, 914)$	303
$(0, 1, 0)$	$(663, 458, 1003)$	352
$(0, 0, 1)$	$(1998, 1567, 3)$	121
$(1, 0, 1)$	$(602, 571, 5)$	459
$(0, 1, 1)$	$(864, 483, 5)$	483

Table 3: Cost239 network, $\mathcal{W} = 16$

Cost239, $\mathcal{W} = 16$		
$(\alpha_O, \alpha_L, \alpha_C)$	(O, L, C)	Comp. time (s)
MILP		
$(1, 0, 0)$	$(955, 793, 1385)$	3600^+
$(0, 1, 0)$	$(1230, 609, 1798)$	3600^+
$(0, 0, 1)$	$(-, -, -)$	3600^0
$(1, 0, 1)$	$(-, -, -)$	3600^0
$(0, 1, 1)$	$(-, -, -)$	3600^0
Simulated annealing		
$(1, 0, 0)$	$(1002, 841, 1467)$	602
$(0, 1, 0)$	$(1297, 681, 1878)$	649
$(0, 0, 1)$	$(2367, 1179, 8)$	234
$(1, 0, 1)$	$(1023, 854, 11)$	675
$(0, 1, 1)$	$(1311, 703, 13)$	683

Table 4: Cost239 network, $\mathcal{W} = 20$

Cost239, $\mathcal{W} = 20$		
$(\alpha_O, \alpha_L, \alpha_C)$	(O, L, C)	Comp. time (s)
MILP		
$(1,0,0)$	$(1188, 946, 1810)$	3600^+
$(0,1,0)$	$(1425, 734, 2131)$	3600^+
$(0,0,1)$	$(-,-,-)$	3600^0
$(1,0,1)$	$(-,-,-)$	3600^0
$(0,1,1)$	$(-,-,-)$	3600^0
Simulated annealing		
$(1,0,0)$	$(1231, 1014, 1964)$	710
$(0,1,0)$	$(1489, 814, 2223)$	732
$(0,0,1)$	$(2154, 1210, 9)$	304
$(1,0,1)$	$(1246, 1109, 12)$	772
$(0,1,1)$	$(1309, 912, 15)$	798

Table 5: NSFNET network, $\mathcal{W} = 8$

NSFNET, $\mathcal{W} = 8$		
$(\alpha_O, \alpha_L, \alpha_C)$	(O, L, C)	Comp. time (s)
MILP		
$(1,0,0)$	$(705, 541, 858)$	3600^+
$(0,1,0)$	$(934, 386, 1189)$	3600^+
$(0,0,1)$	$(2724, 1368, 0)$	193
$(1,0,1)$	$(729, 564, 0)$	3600^+
$(0,1,1)$	$(-,-,-)$	3600^0
Simulated annealing		
$(1,0,0)$	$(767, 601, 913)$	735
$(0,1,0)$	$(997, 416, 1231)$	754
$(0,0,1)$	$(2768, 1489, 10)$	302
$(1,0,1)$	$(841, 676, 11)$	756
$(0,1,1)$	$(910, 684, 11)$	789

Table 6: NSFNET network, $\mathcal{W} = 16$

NSFNET, $\mathcal{W} = 16$		
$(\alpha_O, \alpha_L, \alpha_C)$	(O, L, C)	Comp. time (s)
MILP		
$(1,0,0)$	$(732, 515, 654)$	3600^+
$(0,1,0)$	$(894, 385, 866)$	3600^+
$(0,0,1)$	$(3086, 1530, 0)$	3600^+
$(1,0,1)$	$(-,-,-)$	3600^0
$(0,1,1)$	$(-,-,-)$	3600^0
Simulated annealing		
$(1,0,0)$	$(778, 568, 703)$	798
$(0,1,0)$	$(989, 402, 941)$	784
$(0,0,1)$	$(3187, 1670, 8)$	310
$(1,0,1)$	$(814, 612, 12)$	821
$(0,1,1)$	$(832, 646, 11)$	813

a single objective. This can be observed for the MILP and for the simulated annealing approaches.

6 Conclusion

In this paper we provided a framework for minimizing the virtual topology reconfiguration cost and also optimizing the network performance in a network with evolving traffic across multiple generations. We define a methodology for upgrade using the simulated annealing approach which always tries to minimize this dual objective function. The simulated annealing approach explores different alternative path sets during the search of an optimal solution. On the contrary the MILP presented in the paper is limited in its approach, since it turns out to be computationally far too expensive to solve the problem for medium to large instances. Hence the simulated annealing scheme can be used as a heuristic to arrive at near optimal solutions in cases of complex demand sets and moderately large networks, where the run-time of the ILP becomes practically infeasible. The proposed approaches are highly inexpensive, fast and can be ideally employed for all backbone networks.

Acknowledgements

The authors would like to thank Dr. David Coudert, INRIA, Sophia-Antipolis, for helping us in developing the heuristic approaches which tremendously improved the quality of the paper.

References

[1] I. Baldine and G.N. Rouskas. Traffic adaptive WDM networks: a study of reconfiguration issues. *Journal of Lightwave technology*, 19(4):433–455, April 2001.

[2] P. Batchelor, B. Daino, P. Heinzmann, C. Weinert, J. Späth, B. Van Caenegem, D.R. Hjelme, R. Inkret, H.A. Jäger, M. Joindot, A. Kuchar, E. Le Coquil, P. Leuthold, G. de Marchis, F. Materaand, B. Mikac, H.-P. Nolting, F. Tillerot, and N. Wauters. Ultra high capacity optical transmission networks : Final report of action cost 239. Technical Report ISBN 953-184-013-X, Faculty of Electrical Engineering and Computing, HR, Zagreb, 1999.

[3] I. Chlamtac, A. Ganz, and Karmi G. Lightpath communications: An approach to high-bandwidth optical WAN's. *lEEE Transactions on Communications*, 40(7):1171–1182, July 1992.

[4] P. Datta, M. Sridharan, and A.K. Somani. A simulated annealing approach for topology planning and evolution of mesh-restorable optical networks. In *8th IFIP Working conference on optical networks design and modeling (ONDM)*, February 2003.

[5] R. Dutta and G. N. Rouskas. A survey of virtual topology design algorithms for wavelength routed optical networks. *Optical Networks Magazine*, 1:73–89, January 2000.

[6] N. Geary, N. Parnis, A. Antonopoulos, E. Drakopoulos, and J. O'Reilly. The benefits of reconfiguration in optical networks. In *10th International Telecommunication Network Strategy and Planning Symposium*, 2002.

[7] A. Gençata and B. Mukherjee. Virtual-topology adaptation for WDM mesh networks under dynamic traffic. In *IEEE Infocom*, June 2002.

[8] A. Gencata and B. Mukherjee. Virtual topology adaptation for wdm mesh networks under dynamic traffic. *IEEE/ACM Transactions of Networking*, 11:236–247, 2003.

[9] S. Huang and R. Dutta. Research problems in dynamic traffic grooming in optical networks. In *Broadnets*, 2004.

[10] G. Huiban and G. R. Mateus. A MILP model for the reconfiguration problem in multifiber WDM networks. In *SBRC Simpósio Brasileiro de Redes de Computadores*, May 2005.

[11] Z.K.G. Patrocínio Jr., P.P.R.Teixeira, and G.R. Mateus. Traffic grooming and reconfiguration for incremental traffic in WDM optical networks. In *International Network Optimization Conference (INOC)*. Informs, October 2003.

[12] A. Narula-Tam and E. Modiano. Dynamic load balancing in WDM packet networks with and without wavelength constraints. *IEEE Journal on selected areas in communications*, 18(10):1972–1979, 2000.

[13] R. Ramaswami and K.N. Sivarajan. *Optical networks. A practical perspective*. Morgan Kaufmann Publishers, 1998.

[14] M. Sridharan, M. Salapaka, and A. K. Somani. A practical approach to operating survivable wdm networks. *IEEE Journal of Selected Areas in Communication*, 20(1):34–47, January 2002.

[15] R. Srinivasan and A. K. Somani. Request specific routing in wdm grooming networks. *Proceedings of IEEE International Conference on Communication (ICC)*, 5:2876–2880, April-May 2002.

[16] France Télécom, editor. *Les communications optiques du futur*, June 2002. Mémento technique France Télécom 19. http://www.rd.francetelecom.fr/fr/conseil/mento19/index.html.

[17] M. Tornatore, G. Maier, and A. Pattavina. WDM network optimization by ILP based on source formulation. In *Infocom*. IEEE, June 2002.

[18] Yand X and B. Ramamurthy. An analytical model for virtual topology reconfiguration in optical networks and a case study. In *International Conference on Computer and Communications Networks*. IEEE, 2002.

[19] W. Yao and B. Ramamurthy. Dynamic traffic grooming using fixed alternate routing in WDM mesh optical networks. In *Broadnets*, 2004.

[20] H. Zhu, H. Zang, K. Zhu, and B. Mukherjee. Dynamic traffic grooming in WDM mesh networks using a novel graph model. In *Globecom 2002*, pages 2681–2685, 2002.

Unité de recherche INRIA Sophia Antipolis
2004, route des Lucioles - BP 93 - 06902 Sophia Antipolis Cedex (France)

Unité de recherche INRIA Futurs : Parc Club Orsay Université - ZAC des Vignes
4, rue Jacques Monod - 91893 ORSAY Cedex (France)
Unité de recherche INRIA Lorraine : LORIA, Technopôle de Nancy-Brabois - Campus scientifique
615, rue du Jardin Botanique - BP 101 - 54602 Villers-lès-Nancy Cedex (France)
Unité de recherche INRIA Rennes : IRISA, Campus universitaire de Beaulieu - 35042 Rennes Cedex (France)
Unité de recherche INRIA Rhône-Alpes : 655, avenue de l'Europe - 38334 Montbonnot Saint-Ismier (France)
Unité de recherche INRIA Rocquencourt : Domaine de Voluceau - Rocquencourt - BP 105 - 78153 Le Chesnay Cedex (France)

Éditeur
INRIA - Domaine de Voluceau - Rocquencourt, BP 105 - 78153 Le Chesnay Cedex (France)
http://www.inria.fr
ISSN 0249-6399