International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:3, No:3, 2009

Genetic Algorithm Based Wavelength Division Multiplexing Networks Planning

S.Baskar, P.S.Ramkumar, R.Kesavan

Abstract**—**This paper presents a new heuristic algorithm useful for long-term planning of survivable WDM networks. A multi-period model is formulated that combines network topology design and capacity expansion. The ability to determine network expansion schedules of this type becomes increasingly important to the telecommunications industry and to its customers. The solution technique consists of a Genetic Algorithm that allows generating several network alternatives for each time period simultaneously and shortest-path techniques to deduce from these alternatives a least-cost network expansion plan over all time periods. The multi-period planning approach is illustrated on a realistic network example. Extensive simulations on a wide range of problem instances are carried out to assess the cost savings that can be expected by choosing a multi-period planning approach instead of an iterative network expansion design method.

Keywords**—**Wavelength Division Multiplexing, Genetic Algorithm, Network topology, Multi-period reliable network planning

I. INTRODUCTION

CURRENT European transport networks are mainly based on the Plesiochronous Digital Hierarchy (PDH) and the Synchronous Digital Hierarchy (SDH). Until now, the role of optics in SDH has usually been restricted to transmission. However, Wavelength Division Multiplexing (WDM) is emerging from a research topic to a real alternative for network operators to upgrade their transport network infrastructure [1]. The first step is upgrading point to point links by using multiple channels (wavelengths) in one fiber in order to overcome fiber exhaust or to share the amplifier cost between more channels which lowers the cost per information unit. The next step is introducing flexibility in the optical layer by using optical crossconnects and add-drop multiplexers. This allows to avoid the cost for high-speed electronic processing equipment for transit traffic in the nodes. Moreover, it creates opportunities to increase the network capacity and to simplify the network management [2]. A variety of network architectures are proposed in the literature (see for instance [3], [4]) which use optical multiplexing and routing techniques to reduce the electronic processing bottleneck and to allow a more efficient use of the bandwidth potential of the installed fiber infrastructure.

A number of studies are addressing the network design issues of all-optical networks. They include [1], [5], [6]. These articles concentrate on the topology design, (wavelength) routing and capacity assignment of multi-wavelength networks on one single moment in time. To apply these design methodologies for long-term network planning, consecutive network expansion design steps can be carried out to obtain an expansion strategy over a large time scale (e.g., a planning horizon of 2 to 5 years). This results in a static approximation of the network evolution scheme.

However, multi-wavelength all-optical networks can be expected to exhibit a quite dynamic long-term behavior, due to rapid changes on both the demand and technology side. On the demand side, the customers require higher bandwidths and improved accessibility to new communication services. On the technology side, rapid innovations with respect to WDM equipment will reduce the cost of providing and maintaining services. A multi-period network planning approach attempts to take the dynamic long-term behavior of telecommunication networks into account [7].

Despite the practical importance of multi-period network topology design and capacity expansion, only a handful of investigations have been reported so far. From a more theoretical point of view, the problem was originally stated in pioneering research by Zadeh [8], Christofides and Brooker [9] and Doulliez and Rao [10]. The dynamic nature and the intrinsic complexity of the multi-period model were investigated more specifically by Minoux [11]. Chang and Gavish [7] present a tight formulation for the multi-period network topology and capacity expansion problem and propose new lower bounding schemes based on it. Garcia, Mahey and Leblanc [12] investigate different heuristic schemes to expand the capacity of a given network over a fixed horizon with budget constraints. From a more practical point of view, representative papers are Balakrishnan et al. [13], Wu et al. [14] and Parrish et al. [15]. Balakrishnan et al. concentrate on access telecommunication networks and present a variety of models for planning capacity expansion. Wu et al. focus on

*S.Baskar, Professor, Electrical &Electronics Engg Dept, Thiagarajar College of Engineering, Madurai-625015. Tamilnadu, India (Phone: 0091-452-2482240; e-mail: sbeee@tce.edu).
P.S.Ramkumar, R.Kesavan Lecturer, Electrical &Electronics Engg Dept, M.N.S.K. College of Engineering, Pudukkottai – 622305..Tamilnadu, India (e-mail: psreee@tce.edu, rkeee@tce.edu).

survivable network architectures in SONET networks. Parrish et al. present an algorithm for planning an optimal expansion of a private network of facilities to be leased from a local telephone company.

This paper presents a new heuristic approach to plan the topology and capacity expansion on a multi-period basis in the case of a WDM-based network. Our model differs substantially from the planning problems found in the literature enumerated above. Some particular characteristics of the problem definition are the integer routing of the commodities and the incorporation of reliability issues, as will be clarified in the next section.

The paper is structured as follows. Section 2 introduces the mathematical model of the multi-period reliable network planning (MPRNP) problem under study. The heuristic algorithm to solve this problem is described in section 3 and illustrated by a realistic case study in section 4. Based on extensive simulations, a comparison between multi-period planning versus iterative network expansion design is reported in section 5. Section 6 concludes the paper.

II. Multi-period reliable network planning

The origin of the multi-period planning problem is explained and some important properties are highlighted. Section 2.2 introduces the necessary notations and describes the essential assumptions that are made. The mathematical model of the MPRNP problem is presented in section 2.3.

A. Problem description

The ongoing deregulation and the increasing communication needs have opened up new markets for so-called long-distance carriers, who are building seamless fiber-optic networks to offer international broadband transmission services to their customers (such as established and emerging operators). For planning the future investments of such long-distance transport networks, it is of paramount importance to take into account the long-term consequences of accelerating or delaying investments. Hence a multi-period planning approach is expected to lead to significant cost savings when compared with a traditional single-period network design approach.

This paper studies for instance the situation of a network operator that wants to build a pan-European all-optical transport network with wavelength translation [1] in the optical nodes. This may become effective in the near future. To deploy extra connections between cities, optical fiber must be leased from other companies (e.g., telecom operators, railway companies, highway companies). Since these costs are roughly proportional to the number of optical fibers to be leased, the operator will try to keep this number as low as possible. Hence, to extend the capacity of an optical fiber, we will apply Wavelength Division Multiplexing, which is able to provide a large number of wavelength channels along one fiber. Hence it is realistic (if the demand is not extremely high) to assume that only one fiber pair per link will be sufficient to transport the traffic. The transport network is assumed to be all-optical, hence the granularity (i.e. the routing unity) of the network corresponds to one wavelength on a fiber, a so-called optical channel.

Because of the large distances covered by such networks and the high amounts of traffic carried along its links, it is very important to provide resilience against fiber cuts. In this paper, 1+1 optical path protection [16] is considered. This implies that, for each demand pair, the traffic is transported twice, along link-disjoint routes through the network.

In the remainder of the paper, we will concentrate on the problem situation described above. However, the mathematical problem formulation described below can also be useful to model other WDM planning problems with a similar cost model (e.g., an existing network operator considering a capacity upgrade of his network by introducing WDM on one optical fiber per link).

B. Notations and assumptions

G: $G = (N,L)$ is the undirected graph where N is the set of nodes and L is the set of links.

N: $\{1,2,\ldots,|N|\}$, set of nodes (cities) throughout the planning horizon. It is assumed that the number of nodes $|N|$ involved in the design is a given parameter and that their locations are known in advance. No costs are associated directly with the nodes. For instance the cost of all-optical crossconnects will be taken into account when considering link-associated costs.

L: The set of candidate bidirectional links (connections between cities), which is a subset of $\mathsf{L} \equiv \{ \{i,j\} \mid i<j,\ i,j \in N \}$, the set of all possible bidirectional links.

$\delta_G(M)$: $\{ \{i,j\} \mid i \in M, j \in N\backslash M, i,j \in N \}$, the cutset induced by a subset M $(\subset N)$ on graph G. Hence, the cutset $\delta_G(M)$ is the set of possible links separating the subset M from the other nodes of G.

K: $\{1,2,\ldots,|K|\}$, set of commodities. Commodities are defined so that each commodity k has a single origin node O_k and a single destination node D_k $(>O_k)$. In case of the all-optical network situation described above, we assume all traffic to be bidirectional. I.e. the routing is always symmetrical.

T: $\{1,2,\ldots,|T|\}$, set of time periods in the planning horizon. Period t refers to the unit period from time point t to t+1. Links and capacity can be installed during any point in time within a period. However, the costs incurred during the period are assumed to take place at the beginning of the time period in which the changes take place.

γ_k^t: Estimated (bidirectional) traffic demand for commodity k at period t. Since we are considering 1+1 protection, this traffic will be transported twice through the network. In general it is realistic to assume that the total traffic requirement which is the sum of those values over all commodities is increasing over time.

a_{ij}^t: The fixed (i.e. capacity independent) cost for installing a link $\{i,j\}$ at the beginning of period t. This cost type stands for the required investment in a link before any capacity on this link can be used. Since equipment buying costs will most probably decrease over time and taking into account the time value of money, it is realistic to assume that a_{ij}^t values are nonincreasing over time.

b^t: The cost per unit capacity augmentation for a link at the beginning of period t. In the remainder of this paper, the capacity is expressed as a number of optical channels. Again, it is realistic to assume that b^t values are nonincreasing over time.

c_{ij}^t : The fixed maintenance cost for link $\{i,j\}$ during the period t.

d^t : The maintenance cost per unit capacity for a link during the period t.

Note that all a_{ij}^t, b^t, c_{ij}^t, d^t are the present values of the associated costs discounted at an appropriate discount rate. If the links and link capacities of the last time period $|T|$ remain present after the planning horizon, these maintenance costs can be incorporated in the cost coefficients $c_{ij}^{|T|}$ and $d^{|T|}$. Considering the ever-growing demands and assuming that the fixed costs (a_{ij}^t and c_{ij}^t) will exhibit a more or less comparable cost evolution as the capacity dependent costs (b^t and d^t), it is a realistic assumption to exclude topology and capacity contractions. Hence only expansion and maintenance costs are mentioned, no contraction costs.

The capacity independent costs include for instance the leasing of fibers, cable and duct maintenance costs and equipment costs (e.g., multiplexers, demultiplexers, optical amplifiers, dispersion compensation management components and fixed crossconnect costs). The capacity dependent costs represent for instance the channel management and regeneration cost and equipment costs (e.g., transponders, wavelength converters and capacity dependent crossconnect costs) [6]. These costs are usually almost independent of the considered link (e.g., the length of the link has little or no influence on the capacity dependent costs). Therefore it is realistic to assume that the capacity dependent costs b^t and d^t are link independent.

The decision variables used to formulate the model consist of:

y_{ij}^t : Topological variable; it is 1 if a fiber is leased on link $\{i,j\}$ by period t; it is 0 otherwise.

x_{ij}^t : Capacity variable; it is the capacity present on link $\{i,j\}$ at period t.

f_{ijk}^t : Flow variable; it is the directed flow of commodity k (from O_k towards D_k) flowing from node i to node j on link $\{i,j\}$ at period t, expressed as a number of optical channels. The granularity of an all-optical network is one optical channel, hence all flow variables must be integer-valued. Note that, since all traffic is assumed to be bidirectional, a positive value f_{ijk}^t implies in fact that the same amount of traffic will also be transported from node j to node i (coming from D_k and going to O_k).

Throughout this paper, $t = 0$ denotes the initial network infrastructure, present before the first time period. The values x_{ij}^0 and y_{ij}^0 are given for all $\{i,j\} \in L$.

C. Model formulation

The model can now be stated as:

MPRNP (Multi-Period Reliable Network Planning)

Minimize

$$z = \sum_{t\in T}\sum_{\{i,j\}\in L}\begin{bmatrix} a_{ij}^t \cdot (y_{ij}^t - y_{ij}^{t-1}) + b^t \cdot (x_{ij}^t - x_{ij}^{t-1}) \\ + c_{ij}^t \cdot y_{ij}^t + d^t \cdot x_{ij}^t \end{bmatrix} \quad (1)$$

subject to

$$\sum_{j\in N} f_{ijk}^t - \sum_{j\in N} f_{jik}^t = \begin{cases} 2\cdot\gamma_k^t & \text{if } i = O_k \\ 0 & \text{if } i \in N \setminus \{O_k, D_k\} \\ -2\cdot\gamma_k^t & \text{if } i = D_k \end{cases} \quad k \in K, t \in T \quad (2)$$

$$f_{ijk}^t + f_{jik}^t \le \gamma_k^t \cdot y_{ij}^t \quad k \in K, t \in T, \{i,j\} \in L \quad (3)$$

$$\sum_{k\in K}\left(f_{ijk}^t + f_{jik}^t\right) \le x_{ij}^t \quad t \in T, \{i,j\} \in L \quad (4)$$

$$x_{ij}^t - x_{ij}^{t-1} \ge 0 \quad t \in T, \{i,j\} \in L \quad (5)$$

$$x_{ij}^t \le K \cdot y_{ij}^t \quad t \in T, \{i,j\} \in L \quad (6)$$

$$y_{ij}^t - y_{ij}^{t-1} \ge 0 \quad t \in T, \{i,j\} \in L \quad (7)$$

$$\sum_{\{i,j\}\in\delta_G(M)} y_{ij}^t \ge 2 \quad M \subset N, \phi \ne M \ne N, t \in T \quad (8)$$

$$f_{ijk}^t, f_{jik}^t \ge 0 \text{ and integer} \quad k \in K, t \in T, \{i,j\} \in L \quad (9)$$

$$x_{ij}^t \ge 0 \text{ and integer} \quad t \in T, \{i,j\} \in L \quad (10)$$

$$y_{ij}^t \in \{0,1\} \quad t \in T, \{i,j\} \in L \quad (11)$$

where K is a large positive constant.

The total cost formula (1) contains four different types of cost terms, representing installation of links, installation of additional capacity, maintenance of links and maintenance of capacity, respectively. For each commodity k, the flow variables $\{f_{ijk}^t, f_{jik}^t\}$ support the routing of the traffic $2\cdot\gamma_k^t$ (1+1 protection) and satisfy the flow conservation constraints (2). The capacity limitations are expressed in constraints (4). Capacity and topology contractions are avoided by constraints (5) and (7), respectively. The constraints in (6) state that a positive capacity at period t implies the installation of a link by period t. The constraints (3) ensure that, for each commodity k and each period t, the traffic $2\cdot\gamma_k^t$ will be split up in two equal parts (or more parts) and routed along link-disjoint paths through the topology present by period t. The cut inequalities (8) enforce that removing a link preserves connectivity, hence ensuring a network topology with link-connectivity 2, at each period t.

III. Algorithm

The complexity of the MPRNP problem becomes clear when we examine the detailed problem structure. Firstly, the MPRNP problem contains a network design problem as a special case. Indeed, by considering only one time period ($|T|$ = 1), the MPRNP problem reduces to a joint topology design and capacity assignment problem. Moreover, the requirement of two-connectedness of the network (8) represents an additional complicating element. In the literature, several exact solution techniques are reported to solve related problems (see for instance [17]). These publications reveal how difficult it is to solve large problem instances (e.g., with a high number of nodes $|N|$ and a high number of candidate links $|L|$) to optimality. Especially the intrinsic complexity of topology design (based on a number of 0-1 decisions whether to place a link or not) can lead to considerable duality gaps. Secondly, the MPRNP problem represents a multi-period approach, consisting of $|T|$ network design problems, coupled by the constraints (5) and (7). This leads to an enormous dimensionality of the problem.

These considerations leave us little or no hope to solve MPRNP problem instances of realistic size to optimality. Since we are aiming at finding good feasible solutions without introducing extra simplifying assumptions (e.g., artificially restricting the number of candidate links $|L|$ to make the problem easier to deal with), we have opted for a heuristic approach. The teachers of state and central universities may get a uniform pay package with the pay revision commission set to make a recommendation to this effect in its report. The earlier committees, which were set up to study the pay pattern of university teachers, had left the issue of pay structure to the discretion of the state governments as a result there has been a lot of disparity in the salary and emoluments of the state universities and central universities.

After investigating several avenues for approaching the MPRNP problem heuristically, we settled on the following. In the first phase, a Genetic Algorithm enhanced with some deterministic optimization routines is used to generate several network (i.e. topology with capacities) alternatives for each time period. These alternatives are the building blocks in the second phase, where a shortest-path approach is used to generate a least-cost network expansion plan over the planning horizon. First a provisional plan is deduced, which is refined afterwards. A schematic overview of the solution method is shown in *Fig. 1*.

A. Generation of network alternatives for each time period

1)Network design alternatives

To stress the cost implications of topology and capacity expansions, (1) can be rearranged in function of the topology expansion variables $\psi_{ij}^t = y_{ij}^t - y_{ij}^{t-1}$ and the capacity expansion variables $\varphi_{ij}^t = x_{ij}^t - x_{ij}^{t-1}$.

Remark that both types of expansion variables will be nonnegative, due to (7) and (5), respectively.

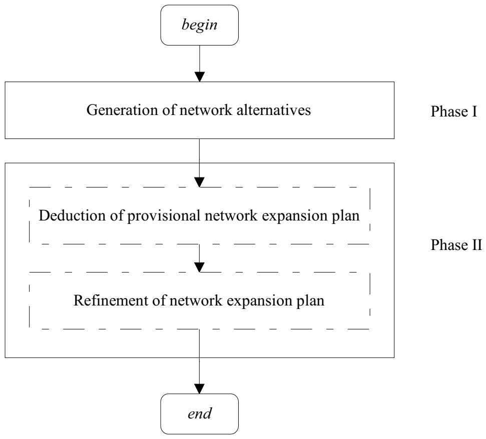

Fig. 1 Overview of MPRNP algorithm

The total cost then reduces to

$$z = \sum_{t \in T} \sum_{\{i,j\} \in L} \left[c_{ij}^t \cdot y_{ij}^0 + d^t \cdot x_{ij}^0 \right] + \sum_{t \in T} \sum_{\{i,j\} \in L} \left[\alpha_{ij}^t \cdot \psi_{ij}^t + \beta^t \cdot \varphi_{ij}^t \right] \quad (12)$$

where

$$\alpha_{ij}^t = a_{ij}^t + \sum_{u=t}^{|T|} c_{ij}^u \quad (13)$$

$$\beta^t = b^t + \sum_{u=t}^{|T|} d^u \quad (14)$$

represent the topology and capacity expansion cost coefficients, respectively.

The first part of the right-hand side of (12) represents the decision independent costs, i.e. the maintenance costs of the network infrastructure already present before time period 1. The second part clarifies the cost implications of topology and capacity expansions. From (13) and (14) it is seen that a topology (capacity) expansion at period t implies a installation cost at the beginning of period t and maintenance costs in all subsequent periods t, $t+1$, …, $|T|$.

The relevance of the expansion cost coefficients α_{ij}^t and β^t also appears in the following situation. Let us consider what happens if, from a certain period τ ($1 \le \tau \le |T|$) on, traffic demand remains constant (so-called steady-state assumption)

$$\gamma_k^\tau = \gamma_k^{\tau+1} = ... = \gamma_k^{|T|} \qquad k \in K \quad (15)$$

It is easy to see that in this case an optimal solution of the MPRNP problem can be obtained by simply copying the flow values of period τ to the subsequent periods

$$\begin{cases} f_{ijk}^\tau = f_{ijk}^{\tau+1} = ... = f_{ijk}^{|T|} \\ f_{jik}^\tau = f_{jik}^{\tau+1} = ... = f_{jik}^{|T|} \end{cases} \quad k \in K, \{i,j\} \in L \quad (16)$$

Hence, if the optimal values for the topological and capacity variables of the first τ-1 periods are known, we obtain an optimal solution for the overall MPRNP problem (1) - (11) with $|T|$ periods by considering a single-period network design problem at period τ with topology and capacity expansion cost coefficients α_{ij}^{τ} and β^{τ}, respectively. Stated otherwise, the variables α_{ij}^{t} and β^{t} are the relevant cost coefficients in case of a *steady-state approximation* of the MPRNP problem.

In phase I of the MPRNP algorithm, a number of network alternatives will be designed for each time period *t*. The values of the topology and capacity variables of the preceding periods 1, … , *t*-1 are hereby unknown, hence we assume a green-field situation at period *t*-1 (so-called *green-field approximation*). Based on the steady-state approximation and the green-field approximation, the objective becomes to minimize the network design cost

$$\zeta^{t} = \sum_{\{i,j\}\in L} \alpha_{ij}^{t} \cdot y_{ij}^{t} + \beta^{t} \cdot x_{ij}^{t} \qquad (17)$$

subject to the intra-period constraints (2), (3), (4), (6), (8), (9), (10) and (11) for period *t*.

These two network design approximations lead us to a straightforward optimal capacity assignment procedure for a fixed topology: using a minimum cost flow algorithm [18] each demand $2 \cdot \gamma_{k}^{t}$ is routed through the network with link costs β^{t} (these are the only cost components which depend on the capacity assignment and hence on the routing of the traffic) and link capacities γ_{k}^{t} (to ensure bi-routing along link-disjoint paths). Since all link costs are equal for the routing at a certain time period, the routing pattern will only depend on the network topology, not on the considered time period itself. Hence, if for a certain topology we have evaluated the network design cost ζ^{t} for some time period *t*, the network design cost $\zeta^{t'}$ for any other time period *t'* can be derived very quickly: we just copy the routing pattern from period *t* and based on the demands $\gamma_{k}^{t'}$ of period *t'* the link capacities $x_{ij}^{t'}$ are calculated. This property is fully exploited in the Genetic Algorithm below.

2) Genetic Algorithm with deterministic optimization routines

To generate a number of high quality network alternatives for each time period, a Genetic Algorithm enhanced with some deterministic optimization routines is used. We refer to [19] for a detailed description of the algorithm.

The Genetic Algorithm is in fact an intelligent process, generating and managing network topologies that are evaluated with respect to the network design costs ζ^{t}, for each time period *t*. During the Genetic Algorithm, a $|T|$ x $|A|$ matrix (θ_{a}^{t}), $1 \le t \le |T|$, $1 \le a \le |A|$ is saved. For each period *t* θ_{1}^{t}, θ_{2}^{t}, …, $\theta_{|A|}^{t}$ represent the best $|A|$ network design alternatives that are found so far, i.e. the topologies with at least link-connectivity 2 and the lowest network design cost ζ^{t} for the considered time period *t*.

The Genetic Algorithm enables us to explore the search space in a thorough and efficient way, but lacks some strong directives towards link-connectivity 2 of the created topologies. Therefore, in contrast with the standard Genetic Algorithm paradigm, some deterministic routines were introduced to optimize the chromosomes individually [19].

The performance of the Genetic Algorithm with deterministic optimization routines to create high quality network design solutions was tested extensively and compared with other solution methods (e.g., Integer Linear Programming techniques). The thrilling whodunit line and the court room drama that follows have never failed to woo audiences. Cast is immaterial here. It's the content and the handling of it that matter. Nevertheless with a battalion of experienced actors to bolster up the show, confidently dons the role of the protagonist in remake directed. With looks and demeanor quite uncharacteristic, who has made a couple of appearances on the big screen in character roles, takes off on a swash-buckling sojourn. Too many tight close-ups, an artificial curl that looks stuck on the forehead and the heavily made up visage notwithstanding, the actor strides through the role of a criminal lawyer who renders justice on his own terms, with ease, though his dialogue delivery could have been less studied.

We refer to [19] for a detailed analysis. From these experiments we can conclude that in general the algorithm provides near-optimal network designs within modest calculation times and with very modest memory requirements.

B. Calculation of network expansion plan

In phase II, the multi-period character of the MPRNP will be taken into account, i.e. we will now consider the coupling of the network design problems due to constraints (5) and (7).

1) Calculation of global network expansion plan

From phase I of the MPRNP algorithm, the matrix (θ_{a}^{t}) of best network design alternatives is obtained. These alternatives will now be embedded in a shortest-path graph. We therefore define a directed graph with the following nodes and arcs. Each network design alternative θ_{a}^{t} is represented by a node v_{a}^{t}. Two special nodes are added to this graph: the source node σ, representing the initial network before period 1, and a destination node δ, which is representing the end of the planning horizon (not a specific network design). Each transition from alternative $\theta_{a_1}^{t_1}$ at time period t_1 to alternative $\theta_{a_2}^{t_2}$ at time period t_2, $1 \le t_1 < t_2 \le |T|$, is represented by an arc ($v_{a_1}^{t_1}, v_{a_2}^{t_2}$). Moreover, the source node σ is connected to each alternative θ_{a}^{1} at the first time period by an arc (σ, v_{a}^{1}) and each alternative $\theta_{a}^{|T|}$ at the last time period is connected to the destination node δ with an arc ($v_a^{|T|}$,δ). An example of such a directed graph is shown in *Fig. 2* for $|A| = 2$ and $|T| = 3$.

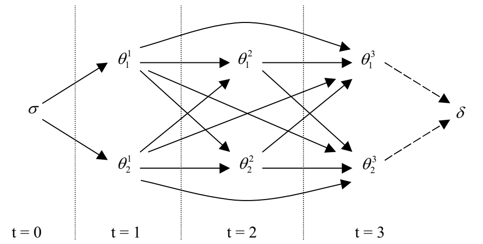

Fig. 2 Example of shortest-path graph for global expansion plan calculation

The full arrows represent real network transitions, the dashed arrows are needed to reduce the destination nodes $v_a^{|T|}$ to one destination node δ.

Each path from the source node σ to the destination node δ represents a possible network expansion plan over the planning horizon, which uses one of the network design alternatives θ_a^1, $1 \le a \le |A|$, at the first time period, some network design alternatives of periods 2, …, $|T|$-1 as intermediate steps (some periods are possibly skipped[1]) and one of the network design alternatives $\theta_a^{|T|}$, $1 \le a \le |A|$, at the last time period.

To estimate the cost of a transition from network alternative $\theta_{a_1}^{t_1}$ at period t_1 to $\theta_{a_2}^{t_2}$ at period t_2, the following rough heuristic plan for network growth is assumed. From period t_1+1 on, all links present in $\theta_{a_2}^{t_2}$ but not in $\theta_{a_1}^{t_1}$ are added. The routing pattern of $\theta_{a_2}^{t_2}$ is adopted, i.e. all traffic is routed only along the links present in $\theta_{a_2}^{t_2}$, and hence the capacity on these links is gradually expanded as the demand grows from period t_1+1 to period t_2. Note that the capacity on links present in $\theta_{a_1}^{t_1}$ but not in $\theta_{a_2}^{t_2}$ will remain present during the time periods t_1+1, …, t_2, however it will not be used by the routing.

To measure the effective cost consequences of such a heuristic network growth step, it is important to take into account that all the links and all the capacity that is installed during the time periods t_1+1, …, t_2 must be maintained until the last time period. On the other hand, since maintenance costs (until the last time period) of links and capacity installed before time period t_1+1 are already accounted for in one of the previous network growth steps, these costs should not be taken into acount here. This leads to the following network expansion cost:

$$z_e = \sum_{t=t_1+1}^{t_2} \sum_{\{i,j\}\in L} \begin{bmatrix} a_{ij}^t \cdot (y_{ij}^t - y_{ij}^{t-1}) + b^t \cdot (x_{ij}^t - x_{ij}^{t-1}) \\ + c_{ij}^t \cdot (y_{ij}^t - y_{ij}^{t_1}) + d^t \cdot (x_{ij}^t - x_{ij}^{t_1}) \end{bmatrix} + \sum_{t=t_2+1}^{|T|} \sum_{\{i,j\}\in L} \left[c_{ij}^t \cdot (y_{ij}^{t_2} - y_{ij}^{t_1}) + d^t \cdot (x_{ij}^{t_2} - x_{ij}^{t_1}) \right] \quad (18)$$

This cost can be calculated very fast, since no new routing patterns must be determined, and is assigned to the arc ($v_{a_1}^{t_1}, v_{a_2}^{t_2}$). To calculate the cost of an arc (σ, v_a^1), the same formula (18) is used, where $t_1 = 0$ and $t_2 = 1$. To each arc ($v_a^{|T|}$,δ) a zero cost is assigned, since $\theta_a^{|T|}$ represents a final network.

The least-cost path between the source node σ and the destination node δ is then calculated, using Dijkstra's algorithm [18]. This path ($\sigma, v_{a_1}^{t_1}, v_{a_2}^{t_2}, \ldots, v_{a_P}^{t_P}, \delta$), with $1 = t_1 < t_2 < \ldots < t_P = |T|$, corresponds to a network growth plan which skips from one network design alternative to another, making interim adjustments according to the above procedure. With respect to the quality of this network growth plan, two remarks are in order here.

2) Refinement of network expansion plan

To overcome these two shortcomings, the global network expansion plan $\sigma \to \theta_{a_1}^{t_1} \to \theta_{a_2}^{t_2} \to \ldots \to \theta_{a_P}^{t_P}$ will be further refined in 2 steps. The first step serves at eliminating all topology contractions. The second step introduces a more refined network growth plan for the transitions and eliminates all capacity contractions.

Step 1 adapts the topologies of the network alternatives $\theta_{a_p}^{t_p}$, $2 \le p \le P$: first all links of $\theta_{a_1}^{t_1}$ not present in $\theta_{a_2}^{t_2}$ are added to $\theta_{a_2}^{t_2}$, then all links of $\theta_{a_2}^{t_2}$ not present in $\theta_{a_3}^{t_3}$ are added to $\theta_{a_3}^{t_3}$, and so on. For each of these adjusted topologies $\theta_{a_p}^{t_p}$, the routing pattern is determined and the link capacities are calculated for time period t_p. This refinement step leads to a new network expansion plan $\sigma \to \theta_{a_1}^{t_1} \to \theta_{a_2}^{t_2} \to \ldots \to \theta_{a_P}^{t_P}$ without any topology contractions. Note that transitions with topology contractions were already extra discouraged (see remark 1 above), so usually little or no changes will be introduced in step 1.

Step 2 refines the transitions $\theta_{a_1}^{t_1} \to \theta_{a_2}^{t_2}$, $\theta_{a_2}^{t_2} \to \theta_{a_3}^{t_3}$, …, $\theta_{a_{P-1}}^{t_{P-1}} \to \theta_{a_P}^{t_P}$ (in this order). First, a more refined network growth plan is created for the transition $\theta_{a_1}^{t_1} \to \theta_{a_2}^{t_2}$ by considering all possible intermediate network topologies between the topologies of $\theta_{a_1}^{t_1}$ and $\theta_{a_2}^{t_2}$ (including the topologies of $\theta_{a_1}^{t_1}$ and $\theta_{a_2}^{t_2}$ themselves). If $\theta_{a_2}^{t_2}$ contains E links more than $\theta_{a_1}^{t_1}$, then $|B| = 2^E$ intermediate topologies can be found[2]. For each of these topologies, the routing pattern is determined and the link capacities are calculated for the time periods t_1+1, …, t_2-1 (only needed if $t_2 > t_1$+1). This leads us to a (t_2-t_1-1) x |*B*| matrix (χ_b^t), $t_1+1 \le t \le t_2-1$, $1 \le b \le |B|$, of network design alternatives. In a similar way, these network alternatives are embedded as nodes in a shortest-path graph and a source node $\theta_{a_1}^{t_1}$ and a destination node $\theta_{a_2}^{t_2}$ are added. In this graph, all possible transitions from period *t* to period *t'*, $t_1 \le t < t' \le t_2$, without topology contractions are represented by an arc, with associated cost again given by (18). An example of such a directed graph is shown in *Fig. 3* for $t_2 = t_1 + 3$ and |*B*| = 2, where *b* = 1 corresponds to the topology of $\theta_{a_1}^{t_1}$ and *b* = 2 corresponds to the topology of $\theta_{a_2}^{t_2}$.

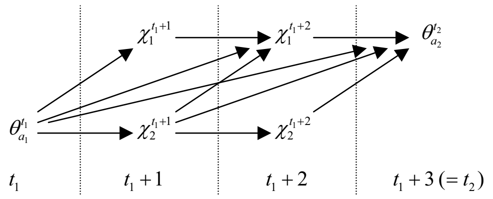

Fig. 3 Example of shortest-path graph for expansion plan refinement

The least-cost path from $\theta_{a_1}^{t_1}$ to $\theta_{a_2}^{t_2}$ is then calculated using Dijkstra's algorithm, resulting in a new sequence of network designs for the time periods t_1+1, …, t_2. Note that topology contractions are automatically avoided in this sequence, but capacity contractions can still occur. Therefore, while keeping all flow variables and topological variables fixed, the capacity variables $x_{ij}^{t_1+1}$, $x_{ij}^{t_1+2}$, …, $x_{ij}^{t_2}$ are possibly augmented to ensure that $x_{ij}^{t_1} \le x_{ij}^{t_1+1} \le x_{ij}^{t_1+2} \le \ldots \le x_{ij}^{t_2}$ for all $\{i,j\} \in L$. Note that this could lead to an adaptation of the capacities in network alternative $\theta_{a_2}^{t_2}$.

A more refined network growth plan can now be created for the transition $\theta_{a_2}^{t_2} \to \theta_{a_3}^{t_3}$ as well. This happens in a completely analogous way as described above for the transition $\theta_{a_1}^{t_1} \to \theta_{a_2}^{t_2}$. This procedure is repeated for all subsequent transitions, eventually leading to a final network expansion plan fulfilling all constraints (2) - (11).

IV. Case Study

To illustrate the MPRNP algorithm, a realistic case study on a pan-European network is presented. The network data (nodes, cost ratios and traffic ratios) were developed in the ACTS-project PHOTON [20]. A problem instance with 36 nodes over 10 time periods (covering 5 years) is considered. The initial network (see *Fig. 4*) contains only 9 links and no capacity is installed yet.

We considered 485 candidate links. The number of commodities |*K*| ranges from 66 in the first time period to 553 in the last time period. The evolution of the sum of the demands $\sum_{k \in K} \gamma_k^t$ is shown in *Fig. 5*.

To get an impression of the relative importance of capacity independent versus capacity dependent costs during the considered time periods, the average topology expansion cost coefficients

$$\alpha^t = \frac{1}{|L|} \cdot \sum_{\{i,j\} \in L} \alpha_{ij}^t \tag{19}$$

and the capacity expansion cost coefficients are shown in *Fig. 6* (normalized relative to the coefficient of the last time period).

Fig. 4 Topology of initial network

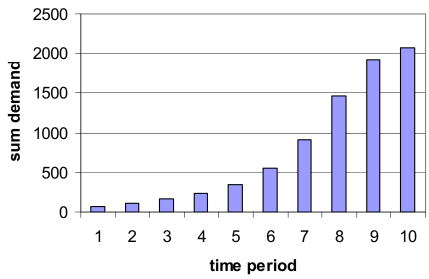

Fig. 5 Evolution of sum of demands

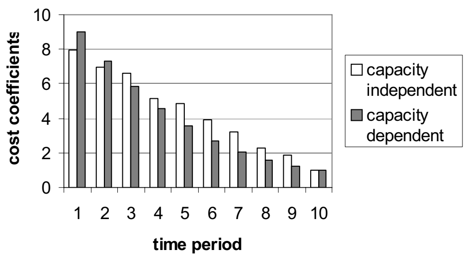

Fig. 6 Evolution of capacity (in) dependent cost coefficients

For the Genetic Algorithm, 10 generations were considered, containing 30 parent chromosomes, 30 children chromosomes and 5 mutant chromosomes. For each time period the |*A*| = 10 best alternatives were saved. A global network expansion plan was deduced from these alternatives, with an estimated total network expansion cost of 7495. This network expansion plan was further refined, leading to a final network growth plan with a cost of 7202. The total calculation time was about one hour[3].

Fig. 7 shows the obtained network topologies for each time period. To avoid overloading of the pictures, the link capacities are not mentioned. A large number of links are added at the beginning of time period 1. Also in the periods 2, 3, 4 and 8 some new links are introduced.

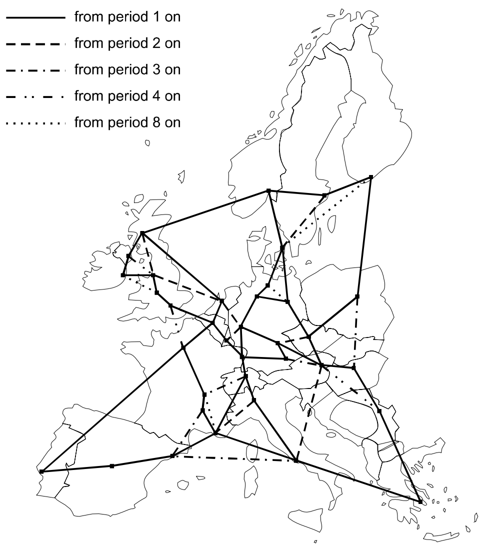

Fig. 7 Evolution of topology

Fig. 8 shows how the total network expansion cost is divided over the 10 transitions between consecutive periods.

$$z_t = \sum_{\{i,j\}\in L} \begin{bmatrix} a_{ij}^t \cdot (y_{ij}^t - y_{ij}^{t-1}) + b^t \cdot (x_{ij}^t - x_{ij}^{t-1}) \\ + c_{ij}^t \cdot y_{ij}^t + d^t \cdot x_{ij}^t \end{bmatrix} \quad (20)$$

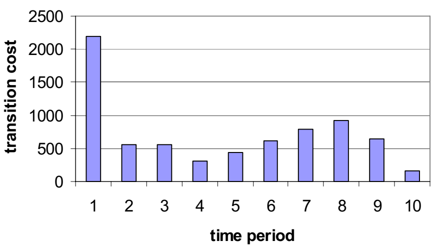

Fig. 8 Evolution of transition cost

As can be seen from *Fig. 8*, large investment costs are needed in period 1, mainly because a network topology with link-connectivity 2 must be built up, almost from scratch. Since demand increases by a factor 30 over the planning horizon (*Fig. 5*) while the ratio of capacity independent versus capacity dependent cost coefficients only shows some minor variations (*Fig. 6*), topology expansions can be expected in the next time periods as well. However, only in the periods 2, 3, 4 and 8 some new links are introduced, not in the periods 5, 6, 7, 9 and 10 (*Fig. 7*). As can be seen from *Fig. 6* this is because the multi-period algorithm usually prefers the periods with the lowest ratio of capacity independent versus capacity dependent cost coefficients to install new links. The exception for time period 10, where no additional links are introduced despite the low ratio, is mainly due to the small relative demand increase from period 9 to period 10.

V. Comparison with Single-period Network Design

The MPRNP algorithm was tested extensively on a wide range of randomly generated problem instances. We varied the size of the networks ($|N|$ = 10 to 50, $|L|$ = 23 to 236), the length of the planning horizon ($|T|$ = 5 to 15), the number of commodities ($|K|$ = 25 to 1217). We considered both situations with a small and a large demand growth over the planning horizon. Both problem instances with a smooth and an abrupt evolution of the cost coefficients α^t and β^t were examined. Also the initial network situation was varied: both situations where no initial network is installed yet and situations with a substantial initial network were considered.

For each of the problem instances, we compared the total cost of the network expansion plan created by the MPRNP algorithm with the result obtained by an iterative single-period network expansion design method. This single-period method is in fact a special case of the MPRNP algorithm: $|T|$=1. Starting from the initial network, a network expansion plan is created leading to a network design for time period 1. To obtain a realistic design, the topology and capacity expansion cost coefficients (13) and (14) should take all maintenance costs until the last time period into account. The period 1 network is now used as the initial network to design a new network at time period 2. This process is repeated until a full network expansion plan from the first till the last time period is obtained. Note that this design procedure is in fact based on the steady-state approximation. From these simulation results, it becomes clear that the network expansion plan obtained with the multi-period algorithm is on the average considerably cheaper (from 0.7 to 11.3%) than the expansion plan created by the iterative single-period design method. Moreover, the standard deviations on the results are usually small enough to conclude that the multi-period algorithm yields almost always better network expansion plans than the iterative single-period algorithm.

VI. Conclusion

An algorithm has been developed for the long-term planning of WDM networks, based on a multi-period model. The heuristic MPRNP algorithm consists of two phases. Phase I is a Genetic Algorithm, enhanced with some deterministic optimization routines, generating several network design alternatives for each time period. The second phase deduces from these alternatives a least-cost expansion plan covering the complete planning horizon.

The MPRNP algorithm is illustrated on a pan-European network case study. The result allows us to derive some important characteristics of a cost-efficient network expansion plan. We noticed a clear dependence of the topology investments on the evolution of traffic demand and capacity independent versus capacity dependent cost coefficients. Whenever possible, the multi-period planning approach exploits the low cost opportunities in the planning horizon.

Extensive simulation results on a wide range of randomly generated problem instances allow us to make a comparison between the multi-period approach and an iterative single-period network design method. The simulations reveal that opting for a multi-period approach leads to considerable cost savings on the investments, ranging from 1 to 11%. Remark that both network expansion plans (multi-period and iterative single-period) fulfill the same demand and reliability constraints, so these cost savings are solely due to the better scheduling of investments over time!

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