

Non-Cooperative Design of Translucent Networks

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Abstract—This paper introduces a new game theoretic formulation for the design and routing of resilient and translucent networks. An integer linear programming (ILP) modeling is also presented and used as a reference to evaluate the game theoretic algorithm performances. Both formulations include primary and link-disjoint protection paths pre-calculation and take into account the system maximal optical reach distance. Numerical results show that the game theoretic formulation considerably decreases the optimization time and provides near optimal solutions, in term of required number of regenerator nodes.

I. INTRODUCTION

Although it is foreseen that future optical wide area networks (WAN) will rely on all-optical technology, current implementations are rather based on electronic switching. In today's WAN networks, most of the intermediate nodes are opaque. For now, optical-electrical-optical (OEO) conversion is the only viable alternative for 3R regeneration (re-amplification, reshaping and retiming).

Translucent networks are a combination of all-optical and opaque technologies. As long as the distance traveled by the optical signal is within the optical reach limit, all-optical switching is used. Otherwise, when the signal transmit distance exceeds the optical reach limit, it has to be regenerated by an OEO node. With the increasing availability of optical switching technology, improved savings can be achieved by replacing some of the opaque nodes by all-optical switching nodes. Translucent networks are a bridge between the all-optical and all-opaque approaches and are strong candidates for the next generation of optical networks.

Game theory has been largely applied in the study of economics. It now finds applications in politics, psychology, biology, sociology and engineering. In network design, control and optimization, game theory has many appealing properties. It is simple to implement and computationally "friendly"; it is well adapted to dynamics and real-time modeling; it can be easily adapted for distributed control and it represents well the interaction between users or service providers in a network, each having their own need and selfish objectives.

In this paper, an integer linear programming (ILP) and a game theoretic model are proposed for the design of translucent optical networks. The maximal reach distance of the optical signal and the network resilience are taken into consideration. The paper shows how to tackle the problem of locating OEO nodes using the two approaches. More specifically, the paper is organized as follow. In section II, the literature on translucent networks and game theory applications

is reviewed. In section III, the design model is presented and in section IV, the ILP and game theoretic formulations of the design problem are introduced. Finally, in section V, a numerical analysis of the optimization procedures is provided.

II. LITERATURE REVIEW

Translucent networks are a relatively recent research topic. They were first proposed and studied in 1999 by Ramamurthy and al. [1]. In their definition of translucidity, they state that "a signal from the source travels through the network as far as possible before its quality degrades, thereby requiring it to be regenerated at an intermediate node. The same signal could be regenerated several times in the network before it reaches the destination." In this study, this definition is applied.

There are two main approaches for the design of WAN translucent networks. The first allows the signal regeneration to take place at any nodes in the network while the second implies the creation of transparency domains, interconnected by OEO nodes. As noted in [2] and [3], sparse placement of OEO nodes usually requires less regeneration nodes and is more cost effective than the domains or islands of transparency approach.

Resilience in translucent networks has been investigated in [4-7] for static traffic and in [8] for the dynamic case. In [4] a 1+1 protection scheme is proposed, while in [5, 7-8] variants of shared path protection, allowing OEO sharing, are studied. Protection in [6] is envisaged in the context of generalized multiprotocol label switching (GMPLS) operation. Non-cooperative path protection have been studied in [9] with the primary paths already defined and fixed. The only actions or strategies left for the players to decide in this case are the backup paths. Although this approach reduces the search space, it is too restrictive when seeking an optimal solution.

Network design can be achieved by using exact algorithms such as ILP or by the use of heuristics. The problem associated with ILP models is that for even medium network sizes (8 to 14 nodes), they either become untractable or very time consuming. These are the main reasons why heuristics are developed. For WAN translucent networks, both ILP formulation [5-7, 10-12] and heuristic optimization [4-8, 10, 13-14] were proposed. These formulations take into consideration a large diversity of physical impairments such as chromatic dispersion, polarization mode dispersion, attenuation, amplified spontaneous emission and crosstalk.

Although there exists a rich literature on game theoretic applications in network design [15], to the best of the authors'

knowledge no game theory model has been developed for translucent networks optimization and design. In this study, a non-cooperative game theoretic model based on the so-called congestion games [16] is presented. An exact potential function [16] is also derived and used to describe the evolution of the game as an optimization procedure.

III. DESIGN MODEL

Throughout this work, it is assumed that dense wavelength division multiplexing (DWDM) is used and that the number of available wavelengths is greater than the overall traffic demand in the network. No attempt will be made to reduce the number of wavelengths used in the network. The only design objective is to minimize the number of OEO nodes in a translucent network, which are usually the most limited and expensive resources in a DWDM optical network. It is also taken for granted that the chosen light transmission paths are properly power managed by periodically placed optical amplifiers.

In this study, only the optical reach distance will be considered which encompasses for most of the physical impairments. Real-world network planning is often accomplished without precise knowledge of the fiber plant and also relies on distance-based regeneration [17].

Given that chromatic dispersion can be compensated by the use of electronic signal processing algorithms [18], the main limitation in the transmission of optical signals is the attenuation caused by fiber loss. The optical reach (O_R) is defined as the maximal distance that the signal can traverse without amplification. The maximal number of spans (N_S) refers to the maximum number of amplified fiber spans above which signal regeneration is necessary. The reach limit (R_L) corresponds to the maximal distance that a signal can travel:

$$R_L = N_S \cdot O_R. \quad (1)$$

Transparent nodes use optical cross-connects (OXC) or wavelength selective switches (WSS) to commute the signal from one fiber to another. Opaque nodes, on the other hand, use regenerators and electronic switching. In translucent networks, opaque nodes can be “all-opaque” or “partly opaque”. In the all-opaque configuration, a transceiver pair is used for all incoming and outgoing wavelengths. In the partly opaque configuration, only the wavelengths that need to be regenerated are converted to an electronic signal, the others are processed in the optical domain. Since the optimization goal in the present work is to minimize the number of OEO sites, no distinction is made between all-opaque or partly-opaque nodes, the two being considered as OEO nodes.

IV. FORMULATION OF THE DESIGN PROBLEM

The design problem can be formulated as follow: given the network topology, a set of point-to-point demands (connections) along with candidate paths for the primary routes and candidate link disjoint paths for the protection routes, find the minimal number of OEO equipped nodes satisfying the working and protection paths constraints. The developed

algorithms are only for regenerator placement and routing, similarly to the work of [6] and [14]. While selecting the regenerator nodes, no traffic matrix or link capacity constraints are considered. The objective is to place a minimum number of regenerators to satisfy the requirement that there is at least two link-disjoint paths between any pair of nodes, satisfying the maximal reach distance constraint. This formulation is the equivalent of having a full demand matrix, such that a primary and secondary link disjoint path must exist between every possible connection. Wavelength assignment is not covered in our framework but, as shown in [17], separating the routing and wavelength assignment process is a common practice and yields in efficient network design.

Two different approaches are used to solve the problem. The first one involves ILP and the other, a game theoretic model. Both models rely on the pre-calculation of working and protection paths. For each path, the positions of OEO nodes are also pre-determined, based on the given reach limit.

The primary paths are calculated using Yen’s algorithm [19] that computes the k -shortest acyclic paths between a source and a destination. For each primary path, k -protection link-disjoint paths are computed by removing from the original network the links used in the primary path of interest. The OEO placement is done for each primary and protection path. Whenever the accumulated distance is greater than the reach limit, an OEO node is added.

A. ILP Formulation

ILP formulations for all-optical or translucent networks are usually intractable or very time consuming. By applying relaxation techniques, they can provide bounds on the performances of optimization heuristics.

In this work, an ILP formulation based on pre-calculated path is proposed. Not only is it easier to solve but, given that enough paths are considered, it is optimal or very close of being so. The results given by the ILP optimization will be used to compare the efficiency and accuracy of the game theoretic approach.

The following notation is used:

$G = (V, E)$: An undirected graph with the set of network nodes V and the set of optical links E .

i, j : Originating and terminating nodes of a lightpath.

Values given:

N : The number of nodes in the network.

P : The network physical topology matrix. If $P_{ij} = 1$, there exist a physical link between i and j .

T : The network traffic matrix, in terms of wavelengths required between i and j . In this work, the traffic matrix is full; indicating that a wavelength demand exists for all possible connections in the network.

c : The number of connections in the network, given by the number of nonzero elements in the matrix T .

x : The number of primary paths for each connection.

y : The number of protection paths for each primary path.

A : The set of primary paths for each connection. A contains $c \cdot x$ paths.

- B*: The set of protection paths for each primary path. *B* contains $c \cdot x \cdot y$ paths.
- C*: The set of required regenerator nodes for every paths of *A*. *C* is the same size as *A*.
- D*: The set of required regenerator nodes for every paths of *B*. *D* is the same size as *B*.

Variables:

- X*: A binary vector of *N* elements representing the presence (1) or the absence (0) of regenerators at each node.
- a_{ij}^q : A binary variable indicating, when it equals to 1, that among the *x* possible primary paths between nodes *i* and *j*, the q^{th} path is selected.
- b_{ij}^{qr} : A binary variable indicating, when it equals to 1, that among the *y* possible protection paths of the primary path *q* between nodes *i* and *j*, the r^{th} path is selected.

The objective is to minimize the number of OEO nodes in the network. This can be written as:

$$\text{Minimize } \sum_{n=1}^N X_n. \quad (2)$$

The constraints on the primary paths are as follow:

$$\sum_{q=1}^x a_{ij}^q = 1 \quad \forall T_{ij} > 0, \quad (3)$$

$$\begin{aligned} & \forall T_{ij} > 0, \forall C_{kl} > 0 \\ C_{kl} & \geq a_{ij}^q \quad \forall c, q = 1, 2, \dots, x \\ & k = (d-1)x + q, d = 1, 2, \dots, c \end{aligned} \quad (4)$$

The constraint represented by (3) is necessary so that at least one path per connection is selected. The constraint represented by (4) is used to associate with a given path the OEO nodes that are needed. For example, if the 2nd possible path between nodes 1 and 3 is chosen, then $a_{13}^2 = 1$. If connection 1-3 (*i* = 1, *j* = 3) corresponds to connection number 2 (*d* = 2) and if 3 primary paths are pre-calculated (*x* = 3), then *k* = 5. Therefore, all the non-zero elements of matrix *C* fifth row, which indicate the required regeneration nodes for this path, must be superior or equal to a_{13}^2 . If in this case the fifth row of matrix *C* equals to [2 4 0 0 0], then nodes 2 and 4 must be OEO nodes.

To represent the resilience requirement, the following conditions are added:

$$\sum_{r=1}^y b_{ij}^{qr} = a_{ij}^q \quad \forall T_{ij} > 0, \quad (5)$$

$$\begin{aligned} & \forall T_{ij} > 0, \forall D_{gh} > 0 \\ D_{gh} & \geq b_{ij}^{qr} \quad \forall c, r = 1, 2, \dots, y \\ & g = (d-1)y + r, d = 1, 2, \dots, c \end{aligned} \quad (6)$$

The constraint expressed by (5) represents the dependence of the protection path in the primary path: a secondary path can only exist if the associated primary path is selected. The constraint denoted by (6) is to associate the OEO nodes

requirement with the pre-calculated protection paths, similarly to constraint (4).

B. Game Theoretic Formulation

A game is essentially described by the players that take part in it, by their possible actions or strategies and by their utility functions or “payoffs”. Non-cooperative players are selfish and care only about maximizing their own utility. They act independently. The non-cooperative approach was chosen primarily for its low implementation complexity and secondarily for its flexibility: in the non-cooperative framework, it is very easy to change the utility function while retaining the same convergence properties. In this work, the game theoretic formulation is used as an optimization procedure. The final goal is not to precisely model the players’ behavior, but to create a framework that facilitates simpler optimization setup.

The game is defined using the following notation:

G = (*V*, *E*): An undirected graph with the set of network nodes *V* and the set of optical links *E*.

n: The number of players. There are as many players as requested connections in the network. A connection is defined as a request for assignment of a wavelength from a source node to a destination node. For a given connection, a player must decide on 2 different actions. The first represents the primary the primary path selection while the second determines the choice of the secondary path. A path is formed of multiple links, between a source node and a destination node in the graph *G*.

s_{1i}: The chosen action of player *i*, representing the primary path of connection *i*.

s_{2i}: The chosen action of player *i*, representing the secondary path of connection *i*.

S: $S = s_1 \times s_2 \times \dots \times s_n$: the set of actions of the game.

u_i: $u_i : S \rightarrow \mathbb{R}$, the utility function of player *i*.

R: The set of resources. In this game, the resources are the OEO regenerators and the overall goal is to minimize the number of resources. The maximal number of resources equal to the number of nodes in the network, or graph *G*.

n_k: The number of players who select resource *e_k* on their primary and secondary path.

c_k: The cost associated with resource *e_k*, function of *n_k*.

The utility function is computed in the following way:

$$u_i = u_{1i} + u_{2i}, \quad (7)$$

where:

$$u_{1i} = \begin{cases} \sum_{k \in s_{1i}} c_k(n_k(s)) & \text{if } s_{1i} \text{ is not a direct path} \\ 0 & \text{if } s_{1i} \text{ is a direct path} \end{cases} \quad (8)$$

and

$$u_{2i} = \begin{cases} \sum_{k \in s_{2i}} c_k(n_k(s)) & \text{if } s_{2i} \text{ is not a direct path} \\ 0 & \text{if } s_{2i} \text{ is a direct path} \end{cases} \quad (9)$$

A direct path is an all optical path that does not require OEO, the total distance between the source and destination being inferior to the reach limit. In this game, players should share as much OEO as they possibly can, in order to reduce the overall number of OEO in the network. The goal of each player is to minimize his utility. The cost function associated with a resource k is therefore given by:

$$c_k(n_k(s)) = \frac{1}{n_k(s)}. \quad (10)$$

A Nash equilibrium (NE) is a particular set of actions s^* of the game where players have no incentive to deviate, that is, to choose another action. A NE is reached if:

$$u_i(s_i^*, s_{-i}^*) \leq u_i(s_i, s_{-i}^*) \quad \forall s_i \in S_i, \quad (11)$$

where s_{-i} can be interpreted as the actions of all other players, but i 's:

$$s_{-i} = [s_1, \dots, s_{i-1}, s_{i+1}, \dots, s_n]. \quad (12)$$

The game described by (7) falls in the category of congestion games. As such, it can be transformed in a potential game [16]. The potential function $\Phi(s): S \rightarrow \mathbb{R}$ describes the change in the objective function when one player modifies his action while the others keep their strategies. For this particular game, the potential function is given by:

$$\Phi(s) = \sum_k \sum_{j=1}^{n_k(s)} c_k(j). \quad (13)$$

The first summation represents the sum of costs of each player using the resource while the outer sum is over all resources used. Equation (13) is an exact potential function since:

$$u_i(x, s_{-i}) - u_i(z, s_{-i}) = \Phi(x, s_{-i}) - \Phi(z, s_{-i}) \quad \forall x, z \in S_i, \quad (14)$$

meaning that a change in the utility of a player is exactly reflected in the potential function value.

Since the number of strategy configurations is finite, one of them must lead to the minimization of the potential function. When this is so, no player can further decrease his utility and consequently, a NE is reached. The existence of a NE is therefore assured and a steady state, in which no player deviates, can be attained. In other words, the convergence of the optimization algorithm is guaranteed.

In this game setup, players update their action following a simple rule referred to in the game theory literature as the "best response dynamic". At every stage, or iteration of the game, a player chooses the action that minimizes his utility function, in light of the actions of other players that took place in the previous stage. With a_i^t the action of player i in stage t , the best response dynamic can be formulated as:

$$a_i^t = BR_i(a_{-i}^{t-1}). \quad (15)$$

The detailed game description is given below:

- Network initialization and k -shortest paths computation —
- 1. Specify the optimization parameters (number of primary and secondary paths, reach limit);
- 2. Load the network parameters (traffic, distance and adjacency matrices, nodes position);
- 3. For every connection, compute the x shortest primary paths using Yen's algorithm;
- 4. For every primary paths, compute the y shortest link disjoint protection paths using Yen's algorithm;
- 5. If for any primary path, the number of possible protection paths in the network is inferior to the number of specified protected paths, reduce the number of possible actions of the player representing the protection path of this connection;
- 6. For every primary path, determine the required OEO nodes;
- 7. For every secondary path, determine the required OEO nodes;

Strategies initialization

- 8. Assign a random action to every player representing the primary paths of all the connections in the network;
- 9. For every primary path, assign a random action to the player representing the protection path of the corresponding connection;

Start of the game

- 10. For every connection i :
 - a. Compute u_{1i} , the possible utilities of the player representing the primary path. The number of possible utilities depends on the specified number of primary paths;
 - b. Compute u_{2i} , the possible utilities of the player representing the secondary path. The number of possible utilities depends on the specified number of secondary paths;
 - c. Compute u_i , the global utilities, the sum of utilities calculated in (a) and (b);
 - d. Choose the actions of the player that minimize the player's utility (Best Response Dynamic);
 - e. Compute the potential function.

V. NUMERICAL EXAMPLES

The proposed ILP and game theoretic problem formulations were validated on two European WAN networks. The ILP solution for the German network presented in Fig. 1 (a) is 5 OEO nodes, represented by the bold circular markers. With a specified number of primary and protection paths of 12, and the reach distance set at 600 km, the problem formulation generates 21 233 variables and 31 327 constraints. Using ILOG's CPLEX 9.0 optimizer, the solution is obtained in 7 minutes on a Pentium D 3.4 GHz computer. The minimum number of primary and protection paths that can be specified to reach the optimal solution is 8, resulting in an optimization time of 4 minutes, for a total number of variables and constraints of 22 289 and 14 977, respectively.

For the same German network, the game theoretic optimization procedure results in a mean number of 5.05 OEO

nodes (average performance over 40 runs), very close to the social optimum of 5 nodes. This result is obtained by specifying 8 primary and protection paths. The game duration (the optimization time) is 27.4 seconds; 18.6 seconds are dedicated for the paths calculation and 8.8 seconds for the actual game consisting in the best response dynamic. The algorithm was implemented with Matlab, an interpreted language. The optimization time could be further reduced by using a compilable language such as C++.

When specifying 14 primary and protection paths and a reach limit of 600 km, the ILP problem formulation for the Italian WAN network presented in Fig. 1 (b) generates 44 121 variables and 66 737 constraints. This problem cannot be solved by the CPLEX version that was used. However, a solution is found by the game theoretic algorithm in 3.3 minutes, resulting in 6.00 OEO nodes (average performance over 40 runs).

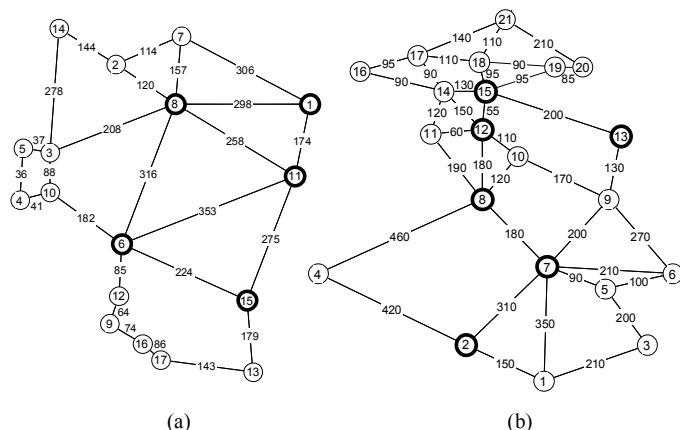


Figure 1. ILP and game theoretic results optimization on German (a) and Italian (b) WAN networks

VI. CONCLUSION

The main contributions of this work were to propose a scalable ILP formulation and a non-cooperative game theory framework for the design of resilient, WAN translucent networks. To the authors' knowledge, the present work is the first attempt at modeling translucent networks as games.

As with other heuristics such as genetic algorithms, tabu search and simulated annealing, a minimal knowledge of the algorithm behavior for different network sizes is required when choosing the parameters (number of primary and protection paths). This inconvenience is however mitigated by the fact that the convergence of the algorithm is fast. It can thus be run repeatedly with different parameters values, until a good solution is obtained. The advantages of the game theoretic approach for the design of resilient translucent network can be summarized as follow: it is fast and simple to implement, it is guaranteed to converge, and on average, it provides a solution very close to optimality.

Future work will include the evaluation of the proposed game model for the design of larger networks and the modification of the utility function to consider not only the signal attenuation but also other physical impairments. In this

work, only one possibility of regenerator nodes positioning is computed per path. To further reduce the overall number of OEO sites, more than one regenerator configuration for each path should be taken into account.

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