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Collaboration over a Service-Oriented Fiber Optic Networking Platform

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Abstract—Collaborative tools are among the most resource intensive applications today. Broadband technologies such as fiber-optic communication provide a way to bring these tools, regardless of geography, in a collaborative platform. In this paper, we focus on the feasibility of the network architecture that supports the collaboration. We solve the RWA problem in this specific context while taking into account the availability of the shared non-network resources. Unlike the previous studies, a traffic demand is defined as a set of one-to-one simultaneous connections to model the traffic of collaboration over a non-multicast capable optical network.

The offline version of the problem is discussed, with and without the time as a parameter for scheduling purposes. The case where the network is meant to carry time-multiplexed traffic over the wavelengths is also discussed.

Several solutions based on Integer Linear Programs (ILP) and heuristics are proposed, implemented and their performance compared. Two types of ILPs are proposed: link and path formulations. While the link formulations give optimal solutions, they take a long time to solve and thus they can only be used for small problems. Path formulations and heuristics scale better but at the expense of optimality.

Index Terms—Collaboration, routing and wavelength assignment, linear programming, heuristic, advance reservation.

I. INTRODUCTION

The convergence of software and network technologies has paved the way to virtual organizations and distributed collaboration where scientists and engineers share access to world-class resources without regard to geography. Virtual Organizations (VO) like EarthScope, IPBIR (Integrated Primate Biomaterials and Information Resource), NESS (Network for Earthquake Engineering Simulation) [1] are a few examples that confirm this collaborative trend. The sophistication of the middleware tools, the emergence of the service oriented architecture paradigm and the huge bandwidth provided by optical networks are all key enablers to a state-of-the-art collaborative cyberinfrastructure. With the wide adoption of fiber-optic networking, supported by the Fibe-to-the-Home (FTTH) initiative [2], [3], social networks could also share network-intensive applications such as high definition videoconferencing and simultaneous access to large data feeds, such as graphics rendered in real time.

We are using these tools, in the smaller scale of a VO called HSWO (Health Services Virtual Organization). A VO can be thought of as a social network where we assume participants work intensely together with some previous knowledge of each other and some common infrastructure. However, allowing people to share resources and work simultaneously together over computer networks raises management difficulties, mainly because of the distance between

users and resources, as well as the concurrent use. This outlines the need for a management middleware capable of coordinating the collaboration and ensuring the availability of the resources including the bandwidth. In this paper we assume participants are interconnected by a tree or mesh network, with lightpath connectivity available via Argia [4].

The National Research Council developed SAVOIR (Service Oriented Architecture for a Virtual Organization's Infrastructure and Resources) for the purpose of managing collaboration. It is a platform that provides a single point of entry to the Web-service enabled shared resources. Even the underlying optical network infrastructure is a resource that can be configured. Optical networks, while they are the answer to bandwidth greedy applications, are an expensive technology. With a solution like Argia, provided by the CRC and Inocybe Inc, a wavelength routed network can be virtualized and leased to clients that can remotely configure its switches to create end-to-end connections (lightpaths). The physical topology is then transparent to the user, and with remote calls to Web-services one can set up or teardown a private network.

SAVOIR currently does not have a scheduler to reserve resources and bandwidth. In a wavelength routed optical network, reserving bandwidth means reserving a route and a wavelength. While this problem, commonly known as the Routing and Wavelength Assignment problem, has been the focus of many studies, less work has been done in the context of collaboration.

In this paper, the problem we address is the feasibility of the network architecture for moderate to large VO. We introduce the collaborative RWA (CRWA) problem, in the case of a non-multicast enabled network. A specific definition of the traffic demand is introduced and the availability of the non-network resources is taken into account so that bandwidth is not reserved and wasted between unavailable resources. The Offline version of the problem is considered in this paper. The presented solutions are based on Integer Linear Programming (ILP) and heuristics.

The paper is organized as follows. In section II, we define the problem and we compare it to the related previous work in section III. Section IV describes the proposed solutions and section V evaluates their performance. Conclusions are drawn in section VI along with some suggestions of future work.

II. COLLABORATIVE RWA PROBLEM

Scheduling bandwidth in a wavelength routed optical network means assigning a route and a wavelength for every lightpath. However it does not make sense to reserve

bandwidth to connect resources that are not available for use, especially in the context of collaboration and virtual organizations where resources are usually under different ownership domains and thus, their availability is uncertain. Taking into account the availability of the non-network resources is then important to avoid wasting bandwidth and eventually blocking other collaborations from being satisfied.

Also, a distributed collaboration implies a hyperconnectivity between the set of users and the set of resources involved. However, when multicast is not available, this means that, at the network level, a collaboration request is actually a request to set up a set of end-to-end simultaneous connections. We define this set as a subsession, that has a start and end time, and define the collaboration session as a set of these subsessions. Indeed we can imagine a scenario of a collaboration session where resources are brought only when needed throughout the session.

The collaborative RWA problem (CRWA) can then be defined as the problem of assigning a route and a wavelength for every connection of every subsession of session, while taking into account the availability of the resources and users involved in this connection. Solving this problem is crucial to an efficient use of the network.

The problem can have two versions: an offline version (or static) and an online (or dynamic) one. The offline case is when traffic demands are queued and then processed all together while in the online case the problem is solved for one request at a time as soon as it is issued.

In this paper we study the problem with permanent and temporary traffic. Adding the time dimension allows non-overlapping sessions to use the same resources. The Time Division Multiplexing (TDM) capability, where a lightpath uses a certain number of TDM channels on the wavelength, is also studied.

III. CRWA AND THE CLASSIC RWA PROBLEM

Several schemes have been proposed to solve the classic RWA problem differing according to the assumptions that can be made on the problem. The RWA problem is known to be hard to solve. The problem is shown in [5] to be NP-hard in the offline case without wavelength converters. Several approaches to solve it are reviewed in [6]. Some of them attempt to tackle the problem as a whole while some break it into two sub-problems (a routing problem and a wavelength assignment problem). Integer Linear Programming (ILP), meta-heuristics and heuristic algorithms have been used to solve the problem.

ILP formulations of the RWA problem are, however, NP-complete, and thus cannot be used in practical cases with big networks or a big number of traffic demands. The alternatives are, then, heuristics and meta-heuristics such as simulated annealing [7], genetic algorithms [8] or tabu-search [9]. These algorithms do not guarantee optimal solutions, but their performance can be evaluated with the ILP solution as a bound.

Other studies propose algorithms that handle traffic requests sequentially and assign a path and a wavelength at a time. These algorithms differ according to the scheme used to sort the requests and to define the assignment. Some of these possible schemes are reviewed in [6].

While the RWA problem has been a focus of many researchers, there are few papers studying it in a collaboration context. The few papers that does assume a multicast enabled network. The communication is then 1-N: one source broadcasts to N destinations using multicast-capable switches that split a signal to N identical signals; or N-N where several sources deliver streams to all the sites. Dynamic multicast is still at its early stage since it is facing several design problems due to fabrication complexity and optical power loss when splitting the signal [10].

Finally, RWA can be seen as a special case of the introduced CRWA where the traffic demand has one subsession with one connection.

IV. PROPOSED SOLUTIONS

The optical network of interest is a WDM network with no wavelength conversion capabilities: the wavelength continuity constraint applies, a lightpath uses then the same wavelength on every link. The network is represented by an undirected graph where nodes are linked by single bidirectional fibers.

A. Notations

$\mathcal{V}$	Set of network nodes: $V_1, V_2, \dots, V_{ \mathcal{V} }$;
$\mathcal{E}$	Set of links $E_1, E_2, \dots, E_{ \mathcal{E} }$;
C_e	Bandwidth capacity of link E_e measured in number of OC-1 channels;
$G = (\mathcal{V}, \mathcal{E})$	Undirected graph;
$\mathcal{W}$	Set of wavelengths $\lambda_1, \lambda_2, \dots, \lambda_{ \mathcal{W} }$;
P_{sd}^j	j^{th} path between V_s and V_d ;
$\mathcal{P}_{sd}$	Ordered set of paths between V_s and V_d ;
L_{sd}^{ep}	Equals 1 if link $E_e \in P_{sd}^p$;
$\mathcal{R}$	Set of resources $R_0, R_1, \dots, R_{ \mathcal{R} }$;
σ_q	The maximum number of simultaneous connections a resource R_q can be part of;
$\mathcal{U}$	Set of users $U_0, U_1, \dots, U_{ \mathcal{U} }$;
$\mathcal{D}$	Set of sessions $D_1, D_2, \dots, D_{ \mathcal{D} }$;
w_i	Priority of sessions D_i ;
D_{ij}	j^{th} subsession of session D_i ;
$\theta_{ij}^s, \theta_{ij}^e$	Start and end time of subsession D_{ij} ;
Θ	Set, of size τ , of relevant time points: $\{\theta_{ij}^s, \theta_{ij}^e i = 1.. \mathcal{D} , j = 1.. D_i \}$;
Θ^r	Set, of size τ_r , of relevant time points for the online problem;
D_{ijk}	k^{th} source-destination (s-d) connection of subsession D_{ij} ;
Σ_{ijk}	$\langle \text{node, resource, user} \rangle$ source triple for connection D_{ijk} : $\langle s_{ijk}, q, u \rangle$;
Δ_{ijk}	Destination triple for connection D_{ijk} : $\langle d_{ijk}, p, v \rangle$;
$\mathcal{R}(\Sigma_{ijk})$	Resource of Σ_{ijk} ;
$\mathcal{U}(\Sigma_{ijk})$	User of Σ_{ijk} ;
B_{ijk}	Bandwidth requirement for connection D_{ijk} in number of OC-1 channels.

B. Problem Variables

In order to define the problem we introduce the following variables:

- δ_i =1 if session D_i is accepted, 0 otherwise;
- δ_{ij} =1 if subsession D_{ij} is accepted, 0 otherwise;
- δ_{ijk} =1 if connection D_{ijk} is accepted, 0 otherwise;
- α_{ijk}^λ =1 if wavelength λ is assigned to the s-d connection D_{ijk} , 0 otherwise;
- $\gamma_{ijk}^{e\lambda}$ =1 if s-d connection D_{ijk} goes through the link E_e using λ , 0 otherwise;
- η_{ijk}^n =1 if s-d connection D_{ijk} goes through node V_n , 0 otherwise;
- $\beta_{ijk}^{p\lambda}$ =1 if s-d connection D_{ijk} uses path $P_{s_{ijk}d_{ijk}}^p$ and wavelength λ , 0 otherwise.

C. Problem Formulation

Two ILP formulations are proposed for the offline problem: a link and a path formulation.

1) *Link formulation*: In the link formulation the ILP defines the route by selecting each edge.

The objective is to maximize the number of sessions accepted while keeping the assigning routes short and use a minimum total number of wavelengths.

$$\max \left(10000 \sum_i w_i \delta_i - 100 \sum_{i,j,k,n} \eta_{ijk}^n - \sum_{i,j,k,\lambda} \lambda \alpha_{ijk}^\lambda \right) \quad (1)$$

In Eq. (1), the coefficients of the three terms are chosen to prioritize the different objectives.

The variables are subject to a set of constraints related to the network traffic and the availability of the resources:

- The wavelength continuity constraint implies that a lightpath enters an intermediate node using wavelength λ and leaves it using the same wavelength λ :

$$\sum_{\lambda \in \mathcal{W}} \sum_{e \in V(n)} \gamma_{ijk}^{e\lambda} = 2\eta_{ijk}^n \text{ where } n \in \mathcal{V} \setminus \{s_{ijk}, d_{ijk}\} \quad (2)$$

$$\sum_{\lambda \in \mathcal{W}} \sum_{e \in V(n)} \gamma_{ijk}^{e\lambda} = \eta_{ijk}^n \text{ where } n \in \{s_{ijk}, d_{ijk}\} \quad (3)$$

- An accepted connection is assigned a unique wavelength that is used on every assigned link:

$$\sum_{\lambda \in \mathcal{W}} \alpha_{ijk}^\lambda = \delta_{ijk} \quad (4)$$

- On each link a wavelength cannot be shared by two different connections:

$$\sum_{ijk} \gamma_{ijk}^{e\lambda} \leq 1 \quad (5)$$

- $\gamma_{ijk}^{e\lambda}$ has to be equal to zero except for the connections that use λ :

$$\gamma_{ijk}^{e\lambda} \leq \alpha_{ijk}^\lambda \quad (6)$$

- A subsession is accepted only if all its connections are accepted and a session is accepted only if all its subsessions are accepted. Later we explain why we do not use a unique variable instead of three.

$$\delta_{ijk} = \delta_{ij} = \delta_i \quad (7)$$

- D_{ijk} , if accepted, has to follow a path that goes from s_{ijk} to d_{ijk} :

$$2\delta_{ij} = \eta_{ijk}^{s_{ijk}} + \eta_{ijk}^{d_{ijk}} \quad (8)$$

$$2\gamma_{ijk}^{e\lambda} \leq \eta_{ijk}^n + \eta_{ijk}^m \text{ where } E_e = (n, m) \quad (9)$$

- A resource has a limited number of simultaneous connections:

$$\sum_{i,j,k} \delta_{ij} \leq \sigma_q \text{ where } \mathcal{R}(\Sigma_{ijk}) = q \text{ or } \mathcal{R}(\Lambda_{ijk}) = q \quad (10)$$

- Integrity constraints:

$$\delta_i, \delta_{ij}, \delta_{ijk}, \alpha_{ijk}^\lambda, \gamma_{ijk}^{e\lambda}, \eta_{ijk}^n \in \{0, 1\} \quad (11)$$

The time awareness can be added to this formulation by changing only constraints (5) and (10) as follows:

$$\forall t \in [1..T-1] : \sum_{i,j,k | D_{ij} \text{ is active in } [\Theta_t.. \Theta_{t+1}]} \gamma_{ijk}^{e\lambda} \leq 1 \quad (12)$$

$$\forall t \in [1..T-1] : \sum_{i,j,k | D_{ij} \text{ is active in } [\Theta_t.. \Theta_{t+1}]} \delta_{ij} \leq \sigma_q \text{ where } \mathcal{R}(\Sigma_{ijk}) = q \text{ or } \mathcal{R}(\Lambda_{ijk}) = q \quad (13)$$

The TDM support can also be added easily by altering constraint (5) as follows:

$$\sum_{ijk} B_{ijk} \gamma_{ijk}^{e\lambda} \leq C_e \quad (14)$$

2) *Path formulation*: In the path formulation, the ILP chooses the path from an ordered set of possible paths. The paths are generated using a k-shortest dissimilar paths algorithm based on the Dijkstra's shortest path algorithm combined with an iterative penalty scheme inspired from [11]. The objective of accepting the maximum number of sessions and the minimum number of wavelengths still stands. In addition, the ILP favours paths with a lower index in the set of paths.

$$\max \left(10000 \sum_i w_i \delta_i - 100 \sum_{p,\lambda} \sum_{i,j,k} p \beta_{ijk}^{p\lambda} - \sum_{\lambda} \sum_{i,j,k} \lambda \beta_{ijk}^{p\lambda} \right) \quad (15)$$

- An accepted connection is assigned one wavelength and one route:

$$\sum_p \sum_{\lambda} \beta_{ijk}^{p\lambda} = \delta_{ij} \quad (16)$$

- On each link a wavelength cannot be shared by two different connections:

$$\sum_{i,j,k} \sum_p L_{s_{ijk}d_{ijk}}^{ep} \beta_{ijk}^{p\lambda} \leq 1 \quad (17)$$

$$\delta_{ijk} = \delta_{ij} = \delta_i \quad (18)$$

$$\sum_{i,j,k} \delta_{ij} \leq \sigma_q \text{ where } \mathcal{R}(\Sigma_{ijk}) = q \text{ or } \mathcal{R}(\Lambda_{ijk}) = q \quad (19)$$

$$\delta_i, \delta_{ij}, \delta_{ijk}, \beta_{ijk}^{p\lambda} \in \{0, 1\} \quad (20)$$

Again the time dimension can be added by modifying Eq. (17) as follows while Eq. (19) is replaced as in the link formulation:

$$\forall t \in [1..\tau - 1] : \sum_{i,j,k | D_{ij} \text{ is active in } [\Theta_t..\Theta_{t+1}]} \sum_p L_{s_{ijk}d_{ijk}}^{ep} \beta_{ijk}^{p\lambda} \leq 1 \quad (21)$$

The TDM support is defined by changing Eq. (17) with the following constraint:

$$\sum_{ijk} \sum_p B_{ijk} L_{s_{ijk}d_{ijk}}^{ep} \beta_{ijk}^{p\lambda} \leq C_e \quad (22)$$

Time awareness and TDM support can be combined by merging the corresponding constraints.

Table I sums up the different obtained ILPs.

V. EXPERIMENTAL RESULTS

In this section, we present experimental results of our proposed solutions. Simulation experiments were conducted with three networks: a tree network (HSVONET) with 9 nodes and two mesh networks, NSFNET (14 nodes, 19 edges) and EONNET (20 nodes, 38 edges). Links have 4 and 8 wavelengths. ILPs were solved with the solving framework SCIP and algorithms were implemented in Java. The tests were done on a 3.4 Ghz Intel Xeon Dual-Core hyperthreaded quad processor with 32 GB RAM.

The sessions and their requirements were generated randomly. The number of subsessions and the number of connections per subsession are drawn randomly in [1..3]. Instances of the Offline problem have a random number of sessions in [1..20] and their solving time limit is set to 4 hours.

Fig. 1 plots, in a logarithmic scale, the average solving times for ILP_1 to ILP_4 according to the total number of connections in the problem. The number of connections represents the size of a problem better, since sessions can have a random number of connections.

When the size of the problem is small, the time values for the different ILPs are close to each other in the milliseconds range. However, when the problem's size increases, the solving time increases exponentially for the link formulations of the problem, ILP_1 and ILP_3 . For the same problem, ILP_3 takes less time than ILP_1 to solve. ILP_1 starts reaching the limit of 4 hours for some problems with a number of connections between 18 and 24. For problems with more than 24 connections, ILP_1 always failed, while

TABLE I: Offline ILPs

ILP	Link	Path	Time	TDM
ILP_1	✓			
ILP_2		✓		
ILP_3	✓		✓	
ILP_4		✓	✓	
ILP_5	✓			✓
ILP_6		✓		✓
ILP_7	✓		✓	✓
ILP_8		✓	✓	✓

Fig. 1: Comparison of the average solving times of ILP_1 , ILP_2 , ILP_3 and ILP_4 . (NSF, $\lambda = 4$)

ILP_3 succeeded in solving every single problem of the set in less than 4 hours.

Fig. 2 compares the average percentage of blocked connections for ILP_1 and ILP_2 , using the NSFNET and 4 wavelengths. When ILP_1 does not fail to solve the problem in less than 4 hours, its blocking percentage is never worse than ILP_2 . The maximum difference is around 28%.

Fig. 3 plots the number of accepted connections by ILP_2 according to the number of accepted connections by ILP_1 . Only the solved problems are plotted. A linear regression is also plotted. The trend line shows how far ILP_2 solutions are from the optimal solutions. All the problems under the line have a gap of more than 18.77% with the optimal solution.

The huge difference of scale in the solving times between the link and path ILPs is obvious in Fig. 1. The exponential behaviour of the solving time is more evident in the next figure. Fig. 4 is a scatter diagram of the solving time according to the number of connections in the case of HSVONET with 4 wavelengths. An exponential trend line is drawn to confirm that. We notice also that the dispersion of the values obtained for the same number of connections increases with that number.

Fig. 2: Comparison of ILP_1 and ILP_2 . (NSF, $\lambda = 4$)

Fig. 3: Comparison of ILP_1 and ILP_2 . (NSF, $\lambda = 4$)

The next scatter diagram shows the solving time for all the path formulations, ILP_2 , ILP_4 , ILP_6 , and ILP_8 . Adding the TDM support (ILP_8) to the time-aware ILP (ILP_4) does not change the solving time significantly, while adding it to the non-time aware ILP (ILP_2) unexpectedly increases the average solving time.

VI. CONCLUSION AND FUTURE WORK

We studied the routing and wavelength assignment problem in the context of collaboration. A new definition of a traffic demand is introduced and the availability of the non-network resources used in the collaboration is taken into account to allow efficient advance reservation of all the involved resources. Solving this problem is crucial for an efficient collaborative use of the network and the resources. The solution gives the network enough bandwidth for different kind of social interaction. While this work is currently limited to interactions open to participants with fiber connections, it can be relevant in the future to social networks, with the spread of the Fiber-to-the-Home.

In this paper the solution to the offline version was presented. It is based on Integer Linear Programming. Two types of formulations were developed: a link-based formulation and a path-based formulation. While path formulations

Fig. 4: Exponential solving time. ILP_1 . (HSVO, $\lambda = 8$)

Fig. 5: Comparison of ILP_2 , ILP_4 , ILP_6 , and ILP_8 . Average solving time. (EON, $\lambda = 4$)

lead to small size problems and thus take millisecond to second times to solve, they give mediocre blocking percentages comparing to the optimal link formulations. However, the link formulations have an exponential scaling behavior making them inefficient in practice even for tree networks.

It was expected that, for the same number of connections, time-aware link formulations would take more time to solve, but the opposite was obtained. For the same number of connections, the solver seemed to take more time to give a solution when more sessions are to be blocked.

The use of Integer Linear Programming limits the constraints on the resources to linear ones. While in this work we model the constraint on the number of simultaneous connections a resource can be part of, more and different constraints should be considered.

The path formulation could probably be improved by looking into other methods to generate the set of possible paths. It would also be interesting to compare suboptimal solutions of the link formulations with the solutions of the path formulations.

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