Lightpath Optimization in Multi-Domain Optical Networks

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Abstract: A multi-objective optimization model is developed for lightpath provisioning in hierarchical multi-domain optical networks. The proposed formulation is then solved and its results compared against some existing distributed heuristic strategies.

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I. Introduction

Optical *wavelength division multiplexing* (WDM) networking technologies have delivered unprecedented terabit-level bandwidth scalability over fiber-optic substrates. Hence many carriers have extensively deployed related transport/switching infrastructures to deliver services to end-user clients. As these networks become more ubiquitous, there is a pressing need to automate interconnection across multiple *domains* to extend service reach [1]. In particular, network domains here can be delineated by geographic, technology, or administrative boundaries.

In light of the above, multi-domain *routing and wavelength* (RWA) algorithms has seen much focus in recent years, see [2]. Now most solutions here have treated dynamic "on-demand" scenarios and applied distributed routing/provisioning strategies as it is difficult (impossible) for a single entity to maintain "global" state information across all domains, i.e., due to clear scalability and privacy concerns. Moreover, these schemes have also leveraged from hierarchical inter-area/autonomous system routing protocols for packet-switching networks. For example, early multi-domain WDM solutions have tabled path-vector routing schemes for border *optical cross-connect* (OXC) nodes to exchange "next-hop" information to other domains [3],[4]. Meanwhile, later studies have also proposed more capable hierarchical link-state routing setups, i.e., where border nodes use topology aggregation to distribute "abstracted" domain-level wavelength/converter state for use in lightpath RWA, see [5],[6].

Nevertheless, these existing multi-domain RWA solutions are mostly heuristics-based and use graph-theoretic algorithms to compute intra-/inter-domain path sequences with dated/inaccurate routing state. Moreover, studies have also shown a notable increase in request blocking and resource inefficiency when operating with such information [2]. Hence it is difficult to determine the true achievable performance of these hierarchical multi-domain provisioning designs. Hence this paper presents a more formalized two-stage optimization model for multi-domain lightpath RWA pursuant to several objectives, i.e., throughput maximization, resource minimization, and load balancing. The overall aim here is to present an "idealized" solution against which to gauge existing heuristic solutions. Now carefully note that many studies have used optimization methods to bound single-domain (optical) network performance under idealized conditions with full a-priori demand knowledge. Nevertheless, the application of such strategies in multi-domain settings has not yet been considered, and this forms the key motivation here.

Overall, this paper is organized as follows. Section II first presents a detailed optimization model for hierarchical multi-domain lightpath provisioning along with its solution approach. Performance evaluation results are then presented in Section III to gauge this model against existing heuristic strategies, and future research directions identified. Carefully note that this solution is only presented for WDM lightpath routing networks but can be easily be extended to model regular bandwidth-provisioning networks and/or emerging *elastic optical networks* (EON).

II. Optimization Model

A novel *integer linear programming* (ILP) optimization model is now presented for multi-domain lightpath provisioning. The scheme assumes hierarchical routing with full-mesh topology abstraction and a-priori knowledge of requests. Furthermore, all WDM domains are assumed to be all-optical with full wavelength conversion at border OXC nodes, i.e., as most carriers use border regeneration to ensure *service level agreements* (SLA). Overall, the proposed scheme mimics the hierarchical multi-domain provisioning process by implementing a *two-stage* optimization, Fig. 1. Namely, skeleton path sequences are first computed for all requests over a global multi-domain abstract topology. These sequences are then used to identify individual "domain-traversing" route segments, which are then optimized over the local domain topologies. The requisite notation and ILP model are now presented.

Consider an optical WDM network with D domains where the i-th domain has n^i OXC nodes and b^i border OXC nodes. This network is represented by a set of domain sub-graphs, $\boldsymbol{G}^i(\boldsymbol{V}^i,\boldsymbol{L}^i)$, where $\boldsymbol{V}^i = \{v^i_1, v^i_2, \ldots\}$ is the set of OXCs in domain i and $\boldsymbol{L}^i=\{l^{ii}_{jk}\}$ is the set of physical intra-domain links between nodes v^i_j and v^i_k with maximum wavelength capacity C_1. Physical inter-domain links $\{l^{ij}_{km}\}$ $(1\leq i,j\leq D,\ 1\leq k\leq b^i,\ 1\leq m\leq b^j)$ are also defined between border nodes in separate domains, i.e., v^i_k and v^j_m, $i\neq j$. Now given a hierarchical routing setup, a "global" abstract topology is also defined using domain abstraction. This graph is denoted by $\boldsymbol{H}(\boldsymbol{U},\boldsymbol{E})$, where $\boldsymbol{U}$ is the set of all border nodes and $\boldsymbol{E}$ is the set of global links. Namely, $\boldsymbol{E}$ comprises all physical *inter domain* links as well as abstract *intra-*

domain links, i.e., topology abstraction reduces a domain to a mesh of "abstract links" between border OXC pairs. The capacity of all links in $\boldsymbol{H}(\boldsymbol{U},\boldsymbol{E})$ is also set to C_2. Furthermore, the *n-th* multi-domain request is given by the 3-tuple (s_n, d_n, r_n), where s_n is the source, d_n is the destination, and r_n is the number of requested wavelengths.

The first stage of the ILP model implements a multi-objective optimization strategy over the hierarchical (abstract) graph, $\boldsymbol{H}(\boldsymbol{U},\boldsymbol{E})$, along the lines of that in [7] for a single domain, see Fig. 2. Namely, the objective function F in Fig. 2 is defined to pursue three goals, 1) maximize aggregate throughput, 2) minimize wavelength resource consumption, and 3) achieve load balancing by minimizing the *maximum link utilization* (MLU), α. Now in this formulation, the variable f_n denotes the number of wavelengths allocated to the n-th request, x^{nij}_{km} denotes the number of wavelengths routed over link l^{ij}_{km} for request n, and α is used to prevent link saturation. Meanwhile, Eqs. 1-6 in Fig. 2 represent additional/necessary model constraints. Namely, Eq. 1 represents the flow conservation constraint between the incoming and outgoing flows at each (border) node in the abstract graph. Meanwhile, Eq. 2 restricts the total *relative* traffic load carried on an inter-domain link to under the MLU value, i.e., less than αC_2. Additionally, Eq. 3 ensures that the number of allocated wavelengths is less than the number of requested wavelengths for each request. Finally, Eqs. 5 and 6 represent integrality constraints, whereas Eq. 7 bounds the MLU value to a positive fraction.

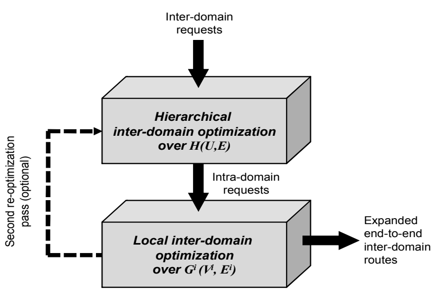

Figure 1: Two-stage ILP solution approach

$$\text{Max } F = w_1 \sum_{n\in N} f_n - w_2 \sum_{n\in N} \sum_{l^{ij}_{km}\in E} x^{nij}_{km} - w_3\alpha$$

$$\sum_{(j,m):l^{ij}_{km}\in E} x^{nij}_{km} - \sum_{(j,m):l^{ji}_{mk}\in E} x^{nji}_{mk} = \begin{cases} f_n; & if\ v^i_k = s_n \\ -f_n; & if\ v^i_k = d_n\ ; n\in N \\ 0; & otherwise \end{cases} \quad (1)$$

$$\sum_{n\in N} x^{nij}_{km} \le \alpha C_2;\ l^{ij}_{km}\in E \quad (2)$$

$$f_n \le r_n;\ n\in N \quad (3)$$

$$x^{nij}_{km} \in \{0,1,2,...\};\ n\in N, l^{ij}_{km}\in E \quad (4)$$

$$f_n \in \{0,1,2,...,r_n\};\ n\in N, l^{ij}_{km}\in E \quad (5)$$

$$0 \le \alpha \le 1 \quad (6)$$

Figure 2: Integer linear program (ILP) model formulation

Now solving the above ILP yields a set of "skeleton" inter-domain routes for the requested connections over the abstract topology, $\boldsymbol{H}(\boldsymbol{U},\boldsymbol{E})$. This information can then be used to determine the required number of "all-optical" sub-path segments that must be computed between all border node pairs in each domain, i.e., by simply counting the number of skeleton lightpaths traversing the respective *abstract* links. Hence the second stage of the optimization in Fig. 1 performs domain "expansion" by optimizing the domain-traversing sub-paths over the local domain graphs, $G^i(V^i,L^i)$. Furthermore, the same multi-objective function from Fig. 2 is re-applied here at the local domain level in order to ensure consistency. Once these local segments have been computed, intra-domain wavelength selection is done using the *most-used* (MU) strategy, i.e., as this generally gives lower blocking rates [8]. Finally, the complete end-to-end lightpath route sequences are then identified by concatenating all intra-domain segments (with the same flow index) with their respective inter-domain links in $\boldsymbol{H}(\boldsymbol{U},\boldsymbol{E})$. Note that special cases may arise if separate requests traversing two (or more) common domains fail second-stage ILP setup at different domains. These scenarios can result in multiple requests being denied even if there are available resources to support at least a subset of them. Hence in order to improve setup success, some of these overlapping requests can be pruned, i.e., deliberately failed, and the optimization re-run to allow others to be successfully provisioned (shown by the dashed line in Fig. 1). Nevertheless, this further iteration is not implemented here.

III. Performance Evaluation

The two-stage hierarchical ILP model is coded using the *PuLP* linear programming modeler (in the Python language) and then solved using the *GNU Linear Programming Kit* (GLPK). The performance of this ILP scheme is also compared with the multi-domain RWA heuristic in [5], which uses a distributed hierarchical routing/provisioning approach. Namely, this scheme is evaluated using discrete event simulation (in *OPNET Modeler*®) and all runs are averaged over 10 randomized combinations of the a-priori lightpath request set (infinite holding times, 10% significance change factors for distributed routing updates). All tests are

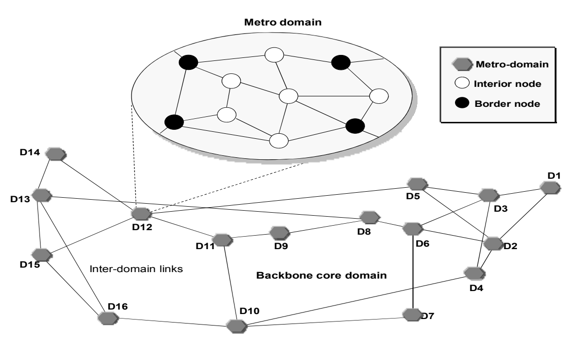

Figure 3: Modified NSFNET multi-domain network

done using a 16-domain WDM topology with 25 inter-domain links. Specifically, this network is shown in Fig. 3 and is modeled after the NSFNET topology by replacing the nodes with complete domains of size 7-10 nodes each.

Initial tests are done for equivalent intra-/inter-domain link wavelength capacities, i.e., C_1=C_2. Namely, Fig. 4 plots the number of successful setups for varying a-priori batch requests with C_1=16 and C_1=32 wavelengths (all requests generated between random nodes in random domains via uniform selection). These findings show that the proposed ILP scheme gives notably better performance, with almost three times lower blocking than the heuristic scheme at higher loads. The average hop count values are also plotted in Fig. 5 to gauge resource utilization, and the results show slightly higher usages with the ILP scheme (except at higher loads with fewer wavelengths, i.e., C_1=8). Finally these tests are repeated for larger inter-domain link sizes, i.e., since most carriers will typically deploy increased channel counts on such trunks. In particular, the resulting success rates for C_2=2C_1 are plotted in Fig. 6 and confirm sizeable improvements with the ILP approach as compared to the heuristic scheme, i.e., about two times more successful setups at medium-high loads. However the average hop counts are also slightly larger with the ILP scheme, i.e., albeit within 10-15% of the heuristic solution, see Fig. 7.

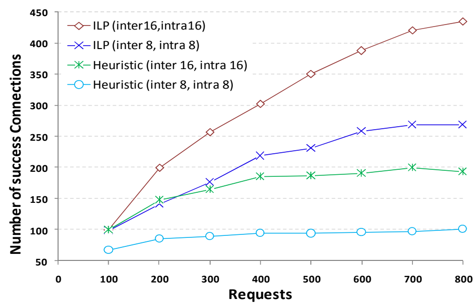

Fig.4: Successful requests (C_1,C_2=8 and C_1,C_2=16)

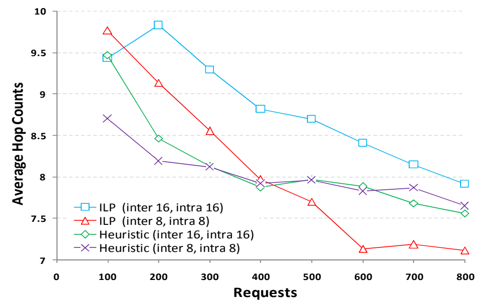

Fig.5: Average hop count (C_1,C_2=8 and C_1,C_2=16)

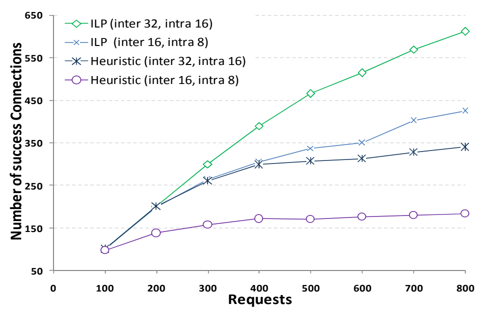

Fig.6: Successful requests (C_2=2C_1=16 and C_2=2C_1=32)

Fig.7: Average hop count (C_2=2C_1=16 and C_2=2C_1=32)

Overall, this paper presents one of the first optimization-based studies of hierarchical lightpath setup in multi-domain WDM networks. As such, this work provides an invaluable reference against which to gauge a range of distributed heuristic strategies. Building upon this, current efforts are looking at expanding the optimization formulation to model multi-domain lightpath protection for both single- and multiple link failures. The latter scenarios pertain to cases with highly-correlated (possibly cascading) failures, as triggered by catastrophic events.

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References

[1] M. Chamania, A. Jukan , "A Survey of Inter-Domain Peering and Provisioning Solutions for the Next Generation Optical Networks", *IEEE Communications Survey and Tutorials*, Vol. 11, No. 1, March 2009.

[2] N. Ghani, M. Peng, A. Rayes, "Service Provisioning and Survivability in Multi-Domain Optical Networks", *WDM Systems and Networks: Modeling, Simulations, Design and Engineering* (Editors N. Antoniades, G. Elinas, I. Roudas), Springer, 2011, pp. 481-519.

[3] B. St Arnaud, *et al*, "BGP Optical Switches and Lightpath Route Arbiter," *Optical Networks*, Vol. 2, No. 2, March/April 2001, pp. 73-81.

[4] X. Yang, B. Ramamurthy, "Inter-Domain Dynamic Routing in Multi-Layer Optical Transport Networks," *IEEE GLOBECOM 2003*, San Francisco, CA, December 2003.

[5] Q. Liu, M. A. Kok, N. Ghani, A. Gumaste, "Hierarchical Routing in Multi-Domain Optical Networks," *Computer Communications*, Vol. 30, No. 1, December 2006, pp. 122-131.

[6] Y. Zhu, *et al*, "Multi-Segment Wavelength Routing in Large-Scale Optical Networks", *IEEE ICC 2003*, Anchorage, AL, May 2003.

[7] J. Crichigno, *et al*, ``Dynamic Routing Optimization in WDM Networks," *IEEE GLOBECOM 2010*, Miami, FL, December 2010.

[8] H. Zang, J. P. Jue, B. Mukherjee, "A Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical Networks," *Optical Networks Magazine*, Vol. 1, No. 1, January 2000, pp. 47-60.