

High-Performance Routing for Hose-Based VPNs in Multi-Domain Backbone Networks

Xiuzhong Chen^{†*}, Marc De Leenheer^{†*}, Chaitanya S.K. Vadrevu^{*}, Lei Shi^{*}, Jie Zhang[‡], and Biswanath Mukherjee^{*} ^{*}University of California - Davis, USA [†]Ghent University - IBBT, Belgium

[‡]Key Laboratory of Information Photonics and Optical Communications (Beijing University of Posts & Telecom.), MOE, China {xzchen, mleenheer, svadrevu, leishi, bmukherjee}@ucdavis.edu; lgr24@bupt.edu.cn

Abstract—By utilizing Layer-1 Virtual Private Networks (L1VPN), a single physical network, e.g., optical backbone networks, can support multiple virtual networks, which is the basic infrastructure for cloud computing and other enterprise networks. The L1VPN hose model is an elegant and flexible way to specify the customers’ bandwidth requirements, by defining the total incoming and outgoing demand for each endpoint. Furthermore, multi-domain physical infrastructures are common in L1VPNs, since these are usually deployed on a global scale. Thus, high-performance Routing for Multi-domain VPN Provisioning (RMVP) for the hose model is an important problem to efficiently support a global virtual infrastructure. In this paper, we formulate the RMVP problem as a Mixed Integer Linear Program (MILP). Also, we propose a Top-Down Routing (TDR) strategy to compute the optimal routing for the hose-model L1VPN in multi-domain backbone networks. Results indicate that TDR approaches the minimum routing cost when compared to ideal case of single-domain routing.

Index Terms—High-performance routing, layer-1 virtual private networks, hose model, multi-domain, virtual infrastructure.

I. INTRODUCTION

Layer-1 Virtual Private Networks (L1VPN) are logical networks that are established on a shared physical infrastructure, e.g., global optical backbone networks, to obtain a private communication environment without investment in physical network resources [1]. For an Infrastructure Provider (InP), L1VPN can improve the utilization of the physical network and increase profit. In particular, both public and private cloud computing platforms can be based on virtual infrastructure provisioned over a global network [2].

Two popular models exist to describe the traffic demands in a L1VPN, based on what information is available on the bandwidth demands of the Customer Edge (CE) devices¹. One is the *pipe model*, in which the bandwidth demand for each pair of CEs is given, i.e., the traffic matrix of the pipe model is fixed as shown in Fig. 1(a). An alternative is the *hose model*, in which the total incoming and outgoing bandwidth demand for each individual CE is given, as shown in Fig. 1(b). Consequently, the key feature of the hose model is that the traffic demand for any CE pair can be variable during its lifetime. This allows more flexibility to the CEs [3], although it has been difficult to create a high-performance routing algorithm for the provisioning of L1VPNs under the hose

model. One solution that has recently been proposed [4] will be discussed and extended later in the paper.

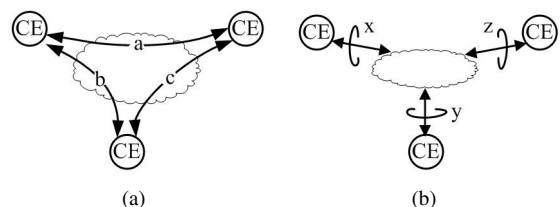


Fig. 1. Traffic demands in L1VPNs: (a) Pipe Model and (b) Hose Model.

As L1VPNs are generally deployed on a worldwide scale, they cannot be provisioned using only a single InP. Global L1VPNs are composed of multi-domain networks, where the details within each domain (intra-domain) usually remain hidden from the other domains [5]. Thus, solutions to high-performance Routing for Multi-domain VPN Provisioning (RMVP) for global L1VPN services are desirable but hard to obtain. In this paper, we formulate the RMVP problem under the hose model by MILP and propose an efficient Top-Down Routing (TDR) strategy for RMVP. One interesting global L1VPN scenario is designed to investigate our formulation and the TDR approach.

The rest of this paper is organized as follows. Related work is presented in Section II. The RMVP model and TDR strategy are described in Sections III and IV. Numerical results are given in Section V. Section VI concludes this paper.

II. RELATED WORK

Provisioning under the pipe model has been well studied [6]. The hose model, introduced recently [3], is starting to receive attention [4], [7], [8]. Specifically, tree routing was studied where the network links have infinite capacity [7]. The authors presented a polynomial algorithm to compute the optimal tree routing in case of symmetric incoming and outgoing bandwidth demands, and proved it NP-hard to compute the optimal tree routing for general traffic demands (which may be asymmetric). This work was extended in [8], improving the algorithm for computation of tree routings for general traffic demands and infinite link capacities. After that, the first polynomial-size LP formulation for maximum throughput routing of hose traffic demands along direct source-destination paths was developed by using the duality of LP in [4].

¹Customer Edge (CE) devices are the points in the network where traffic originates or arrives, and can thus be considered the end users of the network.

Some other works studied the bandwidth efficiency of the hose model. A comparison of the hose and pipe models was done in [9], by defining the overprovisioning factor, which represents the additional capacity required for a VPN reservation in the hose model compared to the pipe model. In [10], the authors investigated the efficiency of the hose model by comparing tree routing, single-path routing, and multi-path routing, and demonstrated that multi-path routing offers significant advantages compared to the other two approaches.

A related problem is Virtual Network (VN) embedding, where the mapping of both virtual nodes and links is performed. In [11], the authors proposed VN embedding algorithms with coordination of nodes and links mapping. Then, the authors presented a policy-based VN embedding across multiple domains that embeds end-to-end VNs in a decentralized manner in [12]. However, these works focus solely on the problem under the pipe-model VPN, and are difficult to directly extend to the hose model.

To the best of our knowledge, Routing for Multi-domain VPN Provisioning (RMVP) under the hose model has not been solved in the literature before. In this work, we formulate RMVP with hose model as a MILP, and propose a Top-Down Routing (TDR) strategy to solve the RMVP problem.

III. PROBLEM FORMULATION

We outline the RMVP problem under the hose model in backbone networks which have mesh topology. We wish to minimize the cost of the bandwidth reserved for a L1VPN.

Let $V_p = \{1, 2, \dots, N_p\}$ denote the set of InP network nodes and $V_x = \{1, 2, \dots, N_x\}$ denote the set of nodes in domain x (thus, $V_x \subseteq V_p$) which belong to domain set $D = \{1, 2, \dots, X\}$. In other words, there are X network domains and $N_p = \sum_{x \in D} N_x$. Furthermore, let $V_c = \{1, 2, \dots, N_c\}$ denote the set of L1VPN Customer Edge (CE) devices, which connect with a single Provider's Edge (PE) device which are in turn elements of V_p . As such, the number of nodes in the complete topology is $N = N_c + N_p$. E is the set of links and contains inter-domain links, intra-domain links, and the links connecting CEs to their corresponding PEs. Inter-domain links are formed by a pair of nodes with each node in a different domain, and are denoted by L_{ij} . On the other hand, both nodes of an intra-domain are situated in the same domain, and are denoted as l_{ij} . Each link, both inter-domain and intra-domain, has an associated cost-per-unit-capacity value of $C_{o_{ij}}$ and a capacity C_{ij} . The hose-based traffic demand from CE m is defined by B_m^- (respectively B_m^+), indicating the incoming (respectively outgoing) bandwidth demand. The actual traffic matrix, composed of the bandwidth demands between any pair of CEs m and n is given by t_{mn} . Note that, in the hose model, the traffic matrix is not known in advance, so multiple matrices may be feasible, making it very flexible.

To solve the RMVP problem, first consider an ideal case where all intra-domain topologies are known, which reduces the problem to minimization of the total bandwidth cost in a single domain. Solutions for the single-domain L1VPN form a lower bound on the RMVP problem, since the intra-domain topologies are not known in a multi-domain routing scenario.

For a single domain, we define the node set as $V = V_p \cup V_c$, which contains both V_p and V_c . The objective is to minimize the total cost of bandwidth reserved for L1VPN demands. Since the feasible traffic matrix of hose model may be variable, the reserved bandwidth for each L1VPN should be sufficient for the worst case of all traffic matrices. For illustration, consider Fig. 2 where three CEs are attached to 7-nodes network. The traffic demand of the CEs is $B_m^- = B_m^+ = 8, \forall m \in \{A, B, C\}$. We assume that routing for this VPN is done over disjoint paths for each CE pair, e.g., t_{AB} passes through nodes 1, 2, 3, while t_{AC} passes through nodes 1, 6, 5. All other routing paths are shown as red arrows in Fig. 2. If the traffic matrix between any two nodes m and n equals $t_{mn} = 4, \forall m \neq n, \forall m, n \in \{A, B, C\}$, the hose demands can be routed by reserving a bandwidth of 4 on each link. However, in case the traffic matrix is changed to $t_{AB} = 8, t_{AC} = 0$ (which also corresponds to the given hose demand), the reserved bandwidths for links l_{12} and l_{23} are 8.

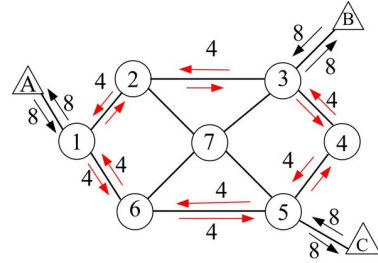


Fig. 2. Worst-case scenario of bandwidth reservations.

For each routing, there may be many feasible traffic matrices. Ref. [4] develops a dual LP as follows.

$$\text{minimize} \quad \sum_{i,j} C_{o_{ij}} R_{ij} \quad (1)$$

s.t.

$$\sum_i F_{ik}^{mn} - \sum_i F_{ki}^{mn} = \begin{cases} 1 & \text{if } k = n \\ -1 & \text{if } k = m \\ 0 & \text{if } k \neq m, n \end{cases} \quad (2)$$

$$\forall m, n \in V_c, \forall k \in V$$

$$0 \leq F_{ij}^{mn} \leq 1 \quad \forall l_{ij} \in E, \forall m, n \in V_c \quad (3)$$

$$\sum_{m \in V_c} B_m^- b_{ij}^{m-} + \sum_{n \in V_c} B_n^+ b_{ij}^{n+} \leq R_{ij} \quad \forall i, j \in V \quad (4)$$

$$0 \leq R_{ij} \leq C_{ij} \quad \forall i, j \in V \quad (5)$$

$$b_{ij}^{m-} + b_{ij}^{n+} \geq F_{ij}^{mn} \quad \forall m, n \in V_c, \forall i, j \in V \quad (6)$$

$$b_{ij}^{m-}, b_{ij}^{n+} \geq 0 \quad \forall m \in V_c, \forall i, j \in V \quad (7)$$

In this model, R_{ij} is the maximal reserved bandwidth for each link, while F_{ij}^{mn} is the proportion of t_{mn} passing through link l_{ij} . Eq. (2) represents the flow conservation constraints, which states that all the incoming/outgoing traffic of destination/source is equal to the traffic demand, while there is no net traffic at the intermediate nodes. Two non-negative variables, shadow prices b_{ij}^{m-} and b_{ij}^{n+} , represent the increase in flow on link l_{ij} when increasing B_m^- and B_n^+ . Eq. (4)

ensures that the worst-case traffic matrix can be carried by each link. Eq. (5) is the capacity constraint, which means that a link can not carry more flow than its capacity allows.

IV. TOP-DOWN ROUTING

In RMVP, the high-level topology is composed of the inter-domain links L_{ij} , the CEs, and their corresponding PEs. The intra-domain topology information is known only by the domain itself. Under the hose model, the traffic demand of each CE i is given (by the total incoming and outgoing bandwidths, B_i^+ and B_i^-). Based on the traffic demands and limited topology, the objective is to minimize the total cost of the reserved bandwidth for provisioning the LIVPN.

RMVP can be solved by using the LP from Eq. (1) to (7) when the inter-domain and intra-domain topology information is known. Unfortunately, most intra-domain nodes and links are unknown for global optimization. We propose Top-Down Routing (TDR) to solve the RMVP in two steps. The first step takes place on the virtual inter-domain topology, which can be generated by knowledge of the inter-domain links and CEs. The second step refines the solution, by considering the actual intra-domain topology and utilizing the bandwidth demands that result from the first step.

A. Inter-Domain Topology

The information we have for routing on the inter-domain topology are the inter-domain links L_{ij} , CEs, and corresponding PEs. As the intra-domain connectivity is unknown, we generate a full virtual mesh topology in each domain by connecting all known nodes, which are the inter-domain edge nodes and PEs. This is shown in Figs. 3 and 4, assuming at least one path between any two nodes in a domain.

B. Routing Strategy

To find the minimum cost for all CEs under the hose model, we first run the LP from Eq. (1) to (7) on the inter-domain topology as top-level routing. Instead of using the single domain set of nodes V , we replace this by the set of inter-domain nodes V_d . Based on our objective function, we obtain the minimal reserved bandwidth for each virtual link. The second step is to map the virtual links on physical paths in each domain V_x . To this end, we use the following LP model.

$$\text{minimize} \quad \sum_{\forall i,j \in V_x} C_{oij} r_{ij} \quad (8)$$

s.t.

$$\sum_{\forall i \in V_x} f_{ik}^{mn} - \sum_{\forall i \in V_x} f_{ki}^{mn} = \begin{cases} R_{mn} & \text{if } k = n \\ -R_{mn} & \text{if } k = m \\ 0 & \text{if } k \neq m, n \end{cases} \quad (9)$$

$$\forall m, n, k \in V_x$$

$$r_{ij} = \sum_{\forall m,n \in V_x} f_{ij}^{mn} \quad \forall i, j \in V_x \quad (10)$$

$$0 \leq r_{ij} \leq C_{ij} \quad \forall i, j \in V_x \quad (11)$$

$$f_{ij}^{mn} \geq 0 \quad \forall i, j \in V_x, \forall m, n \in V_x \quad (12)$$

Here, r_{ij} is the bandwidth reserved on intra-domain link l_{ij} . f_{ij}^{mn} is the flow passing through link l_{ij} from demand R_{mn} . Capacity constraints (10) and (11) guarantee that the flow on each link does not exceed the link's capacity. The cost of the virtual links can be calculated by mapping virtual links. In the main LP, the cost of virtual links will be replaced by the cost of physical links in Eq. (8). Finally, R_{mn} forms the input of the second LP, ultimately leading to a combination of both models in a single model, as shown below.

$$\text{minimize} \quad \sum_{\forall l_{ij} \in L_d} C_{oij} R_{ij} + \sum_{\forall x \in D} \sum_{\forall i,j \in V_x} C_{oij} r_{ij} \quad (13)$$

s.t.

$$\sum_{\forall i \in V_d} F_{ik}^{mn} - \sum_{\forall i \in V_d} F_{ki}^{mn} = \begin{cases} 1 & \text{if } k = n \\ -1 & \text{if } k = m \\ 0 & \text{if } k \neq m, n \end{cases} \quad (14)$$

$$\forall m, n \in V_c, \forall k \in V_d$$

$$0 \leq F_{ij}^{mn} \leq 1 \quad \forall i, j \in V_d, \forall m, n \in V_c \quad (15)$$

$$\sum_{\forall m \in V_c} B_m^- b_{ij}^{m-} + \sum_{\forall n \in V_c} B_n^+ b_{ij}^{n+} \leq R_{ij} \quad \forall i, j \in V_d \quad (16)$$

$$0 \leq R_{ij} \leq C_{ij} \quad \forall i, j \in V_d \quad (17)$$

$$b_{ij}^{m-} + b_{ij}^{n+} \geq F_{ij}^{mn} \quad \forall m, n \in V_c, \forall i, j \in V_d \quad (18)$$

$$b_{ij}^{m-}, b_{ij}^{n+} \geq 0 \quad \forall m \in V_c, \forall i, j \in V_d \quad (19)$$

$$\sum_{\forall i \in V_x} f_{ik}^{mn} - \sum_{\forall i \in V_x} f_{ki}^{mn} = \begin{cases} R_{mn} & \text{if } k = n \\ -R_{mn} & \text{if } k = m \\ 0 & \text{if } k \neq m, n \end{cases} \quad (20)$$

$$\forall m, n, k \in V_x$$

$$r_{ij} = \sum_{\forall m,n \in V_x} f_{ij}^{mn} \quad \forall i, j \in V_x \quad (21)$$

$$0 \leq r_{ij} \leq C_{ij} \quad \forall i, j \in V_x \quad (22)$$

$$f_{ij}^{mn} \geq 0 \quad \forall i, j \in V_x, \forall m, n \in V_x \quad (23)$$

The total cost for the VPN contains the cost of all reserved bandwidth on inter-domain links and intra-domain links. L_d denotes the set of inter-domain links.

The complexity of both models is shown in Table I. We consider the upper bound of complexity, such that the maximum number of links in the total topology is $N(N-1)$, and the maximum number of links in inter-domain topology is $N_d(N_d-1)$, where N_d is the number of nodes in the inter-domain topology. After comparison with the single-domain solution, it becomes apparent that TDR introduces additional variables and constraints in each intra-domain model, but reduces the complexity of routing in the inter-domain topology.

By running the LP from (13) to (23), we obtain the minimal bandwidth cost based on the limited inter-domain information. The TDR routing strategy will be analyzed by comparing results from the ideal single-domain topology in the next section. The LP used in the second step may be private and different in each domain, according to the policies or objectives enforced by each InP. As a result, in reality, the

TABLE I
COMPARISON OF COMPLEXITY OF TDR LP WITH SINGLE-DOMAIN LP.

Routing Strategy	Variables
Single Domain	$N(N-1)(N_c^2 + N_c + 1)$
TDR	$N_d(N_d-1)(N_c^2 + N_c + 1) + \sum_{\forall x \in D} N_x(N_x-1)(N_x^2 - N_x + 1)$
Routing Strategy	Constraints
Single Domain	$2N(N-1)(N_c+1) + N_c(N_c-1)(2N^2 - N)$
TDR	$2N_d(N_d-1)(N_c+1) + N_c(N_c-1)(2N_d^2 - N_d) + \sum_{\forall x \in D} N_x(N_x-1)(N_x^2 + 2)$

operator may run the second step individually by their own algorithm, and then reply the cost of virtual links. Based on this cost, we can calculate the total cost of the L1VPN.

V. ILLUSTRATIVE NUMERICAL EXAMPLES

In this section, we first study the performance of the TDR strategy through a special case, and then investigate the impact of different demand profiles on the total bandwidth cost.

A. Case Study

Consider 3 domains in a US-wide network (Fig. 3), where link length are used to calculate the links' cost, $Co_{ij} = dist(i, j) / max\{dist(i, j)\}$. There are 3 CEs connected with PEs 3, 6, and 14. For simplicity, let the demands of the 3 CEs be identical, $B_{25}^- = B_{25}^+ = B_{26}^- = B_{26}^+ = B_{27}^- = B_{27}^+ = 4$.

In the single-domain scenario, the complete topology is known. The optimal solution for the L1VPN request is shown in Fig. 3 as virtual network *b*, and the reserved bandwidth for each link is 4 in each direction. This leads to a total cost of 14.308. Given the symmetric demand profile between CEs, the solution is based on tree routing as in [7].

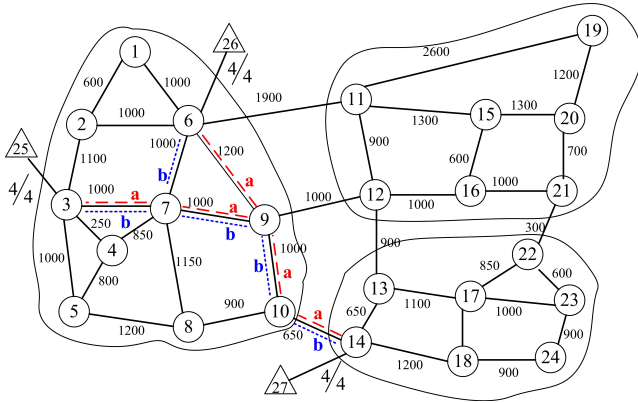


Fig. 3. Single-domain and TDR routing.

Using TDR, the optimal solution is shown in Fig. 3 as virtual network *a*. TDR returns the optimal tree as shown in Fig. 4 as the top-level routing solution, in which the reserved bandwidth of all links is 4. Virtual links l_{69} and l_{96} , as shown in Fig. 4, are mapped on physical links between nodes 6 and 9, which are the optimal mapping for virtual links. However, TDR is unaware of the existence of node 7 in the top-level topology, thus rendering it impossible to find the optimal tree *b* in Fig. 3. In contrast, single-domain routing can reduce the

total bandwidth cost by multiplexing most links; e.g., links $l_{7,9}$ and $l_{9,7}$ are shared by CEs 25 and 26. Nonetheless, the total L1VPN cost by employing TDR is 14.932, which is only slightly larger than the optimal value.

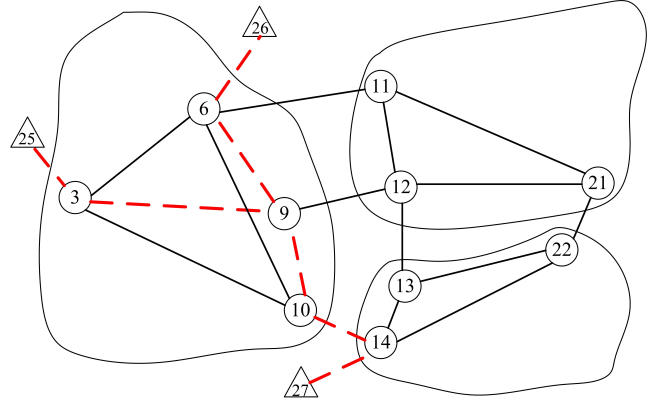


Fig. 4. Top-level routing in TDR strategy.

B. Global Backbone Network

In the previous section, we found that, in a simple test case, TDR obtains a cost which is close to the optimal value found in the ideal case of single-domain routing. To further demonstrate the features of TDR, we perform more extensive tests on a larger and more realistic scenario. According to [13], we assume that eight locations of a global enterprise request a L1VPN infrastructure for their inter-location networking support. These locations are in Asia (Beijing and Bengaluru), US (Silicon Valley, Portland, Redmond, and New England), and Europe (Cambridge and Aachen), as shown in Fig. 5. We assume there are 4 domains in this global backbone network which can provide the required bandwidth for the enterprise's L1VPN request, specifically domains US, Europe, India, and China. The respective topologies of these 4 domains are shown in Fig. 6, and the inter-domain links are selected from international connections [14].

In reality, the cost of inter-domain links are generally higher than intra-domain links. To investigate the features of TDR, we initially set the cost of each intra-domain link as 1, and the cost of each inter-domain link as 3. The cost of links between CEs and responding PEs are 0, since the reserved bandwidth on these links is identical, irrespective of the deployed routing strategy. Here, we set the capacity of each intra-domain link as 32, and the capacity of each inter-domain link as 96. Below, three scenarios are studied to see how the total bandwidth cost is impacted.

The first experiment compares the total bandwidth cost between the ideal single-domain method and our proposed TDR strategy, for varying symmetric traffic demands. A symmetric traffic demand implies that the incoming and outgoing bandwidth demands for each CE are equal, and, as demonstrated in [7], this will always lead to a solution based on tree routing when the network capacity is sufficiently high. As shown in Fig. 7, the cost of TDR increases along with increasing traffic demand in a linear way when the traffic

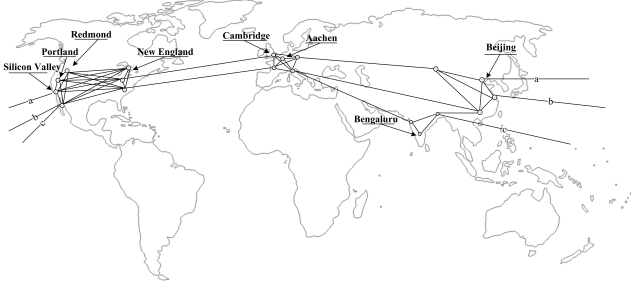


Fig. 5. A global enterprise's locations and top-level topology.

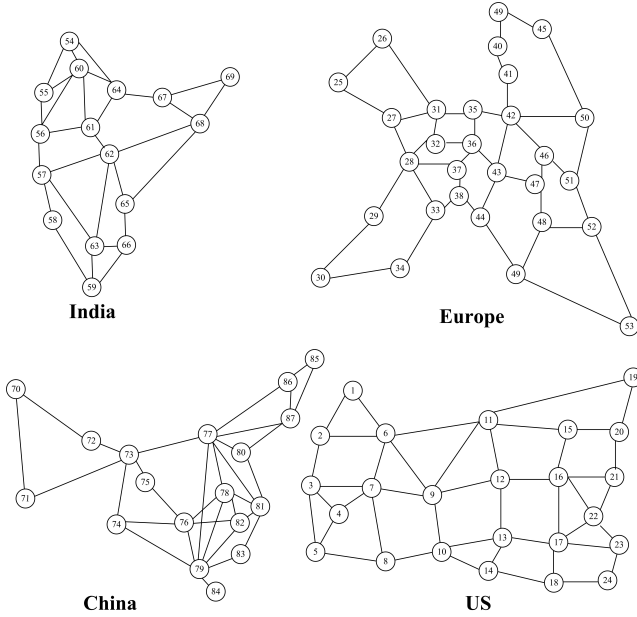


Fig. 6. Intra-domain topologies of the considered domains.

demand remains below 10. The reason is that identical tree-based routing is used when the demand is low compared to the capacity of links (in essence, the network may be considered uncapacitated). The reserved bandwidth on each link of the tree is thus increasing linearly with each increment of the traffic demand. However, when the demand becomes higher than 20, the routing will be based on a multi-path solution. In order to investigate the gap between two routing methods, we introduce a new variable, called extra-cost ratio, which is the ratio of extra cost between multi-domain routing and single-domain method. The extra-cost ratio can be calculated by $(Cost(TDR) - Cost(Sin))/Cost(Sin)$, where $Cost(TDR)$ is the cost of TDR solution for L1VPN, while $Cost(Sin)$ is the cost of single-domain solution. As shown in Table II, all the extra-cost ratios are 5% when the traffic is below 10, implying the cost is increasing linearly. However, the extra-cost ratios are around 10% when the traffic demand is increased from 20 to 40, since TDR leads to higher extra-cost ratios with multi-path routing.

The second experiment compares the cost for symmetric and asymmetric L1VPN demands, implying $B_m^- \neq B_m^+$, while the total incoming and outgoing bandwidth remains constant, i.e., $B_m^- + B_m^+ = B, \forall m \in V_c$. We fix the total bandwidth to $B =$

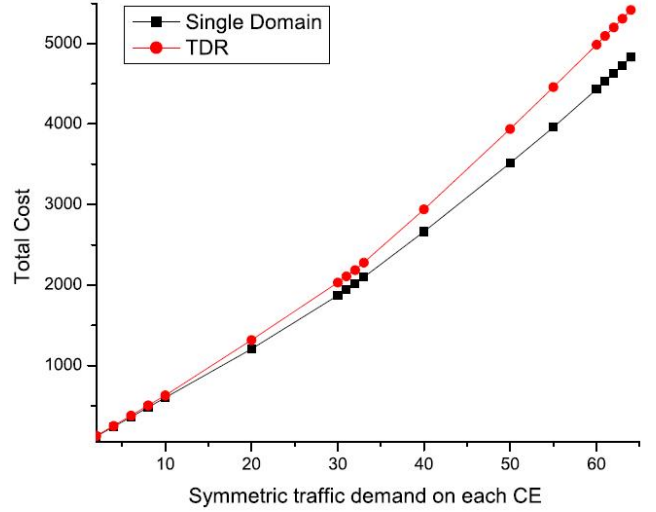


Fig. 7. Cost of symmetric traffic demands.

TABLE II
EXTRA-COST RATIO BETWEEN TDR AND IDEAL SINGLE DOMAIN.

Traffic Load	2	4	6	8
Extracost	5%	5%	5%	5%
Traffic Load	10	20	30	40
Extracost	5%	9.3%	8.7%	10.3%

16, such that, for example, the first bar in Fig. 8 is tested with $B_m^- = 2$ and $B_m^+ = 14$ for all CEs. We observe that, similar to the results for symmetric demands, the cost of TDR is greater than the cost of the single-domain approach. Furthermore, the symmetric demands incur a higher cost than all cases where an asymmetric demand is given. Taking the tree path b in Fig. 3 as example, the reserved bandwidth is 4 for both links l_{97} and l_{79} when all the incoming and outgoing demand of each CE is 4, while the reserved bandwidth is 4 for link l_{79} and 2 for link l_{97} when all the incoming is 6 and outgoing is 2 for each CE. So the total cost for an asymmetric demand is 6 on links between 7 and 9, and 8 in the symmetric scenario. This is similar for all links of a tree, so, asymmetric obtains less cost than the total cost of symmetric demands, although they have the same total incoming and outgoing traffic demands.

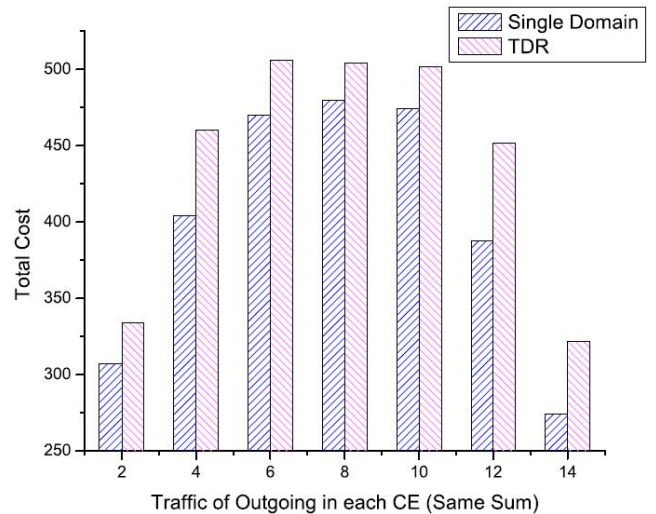


Fig. 8. Cost of asymmetric traffic demands.

The third experiment shows the contribution of inter-domain and intra-domain link cost on the total bandwidth cost. Fig. 9 shows the cost of inter-domain and intra-domain links when the cost of each inter-domain link is 3, while the cost of each intra-domain link is 1. Correspondingly, Fig. 10 is the result when the cost of each link equals 1. When the inter-domain links have a higher price than intra-domain links, the inter-domain links' cost in the TDR case is less than or equal to their cost in the single-domain solution. This is because TDR solves the problem in two steps, one of which is to minimize the total cost of inter-domain links, after which the mapping cost of each virtual intra-domain link is minimized. Instead, the single-domain approach minimizes the total cost without classification of inter-domain links and intra-domain links.

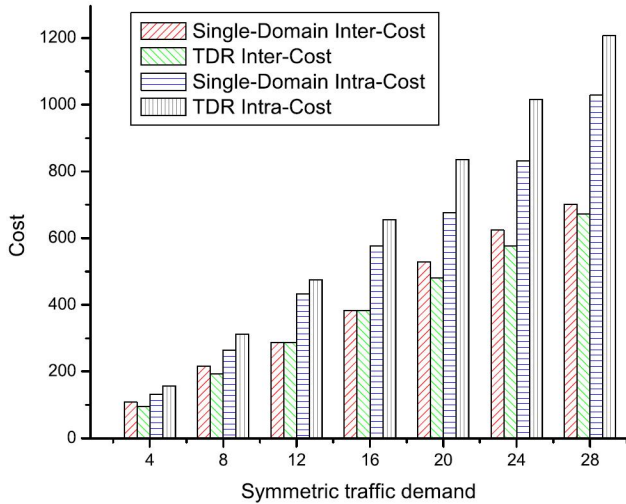


Fig. 9. Cost of inter-domain and intra-domain links when the cost of inter-domain link is 3.

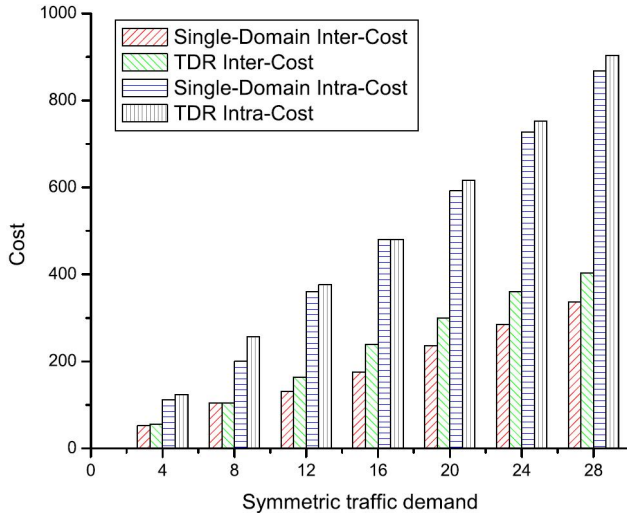


Fig. 10. Cost of inter-domain and intra-domain links when the cost of inter-domain link is 1.

VI. CONCLUSION

High-performance routing of L1VPNs in multi-domain backbone networks is a key element to support enterprises for

their communication needs. The high-performance Routing for Multi-domain VPN Provisioning (RMVP) plays a fundamental role for L1VPNs under the hose model. Its main challenges are formed by the limited topology information that is available, and the variability of the traffic matrix. We formulated a model for RMVP utilizing a MILP, and proposed a Top-Down Routing (TDR) strategy to solve the RMVP problem in two steps. Numerical results of an realistic global L1VPN were presented to verify the performance of TDR. By comparing TDR to the ideal single-domain method, we find that TDR is an efficient routing strategy to solve the RMVP problem.

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REFERENCES

- [1] T. Takeda, I. Inoue, R. Aubin, and M. Carugi, "Layer 1 virtual private networks: service concepts, architecture requirements, and related advances in standardization," *IEEE Communications Magazine*, vol. 42, no. 6, pp. 132–138, June 2004.
- [2] M. Chowdhury and R. Boutaba, "Network virtualization: state of the art and research challenges," *IEEE Communications Magazine*, vol. 8, no. 7, pp. 20–26, July 2009.
- [3] N. G. Duffield, P. Goyal, A. Greenberg, P. Mishra, K. K. Ramakrishnan, and J. E. van der Merive, "A flexible model for resource management in virtual private networks," *SIGCOMM Comput. Commun. Rev.*, vol. 29, no. 4, pp. 95–108, Aug. 1999.
- [4] M. Kodialam, T. V. Lakshman, and S. Sengupta, "Maximum throughput routing of traffic in the hose model," in *Proc. IEEE INFOCOM 2006*, pp. 1–11, 2006.
- [5] Q. Liu, M. A. Kok, N. Ghani, V. M. Muthalaly, and M. Wang, "Hierarchical inter-domain routing in optical DWDM networks," in *Proc. IEEE INFOCOM 2006, Joint Conference of the IEEE Computer and Communications Societies*, pp. 1–5, Apr. 2006.
- [6] D. Banerjee and B. Mukherjee, "Wavelength-routed optical networks: linear formulation, resource budgeting tradeoffs, and a reconfiguration study," *IEEE/ACM Trans. Netw.*, vol. 8, no. 5, pp. 598–607, Oct. 2000.
- [7] A. Kumar, R. Rastogi, A. Silberschatz, and B. Yener, "Algorithms for provisioning virtual private networks in the hose model," *IEEE/ACM Trans. Netw.*, vol. 10, pp. 565–578, Aug. 2002.
- [8] A. Gupta, J. Kleinberg, A. Kumar, R. Rastogi, and B. Yener, "Provisioning a virtual private network: a network design problem for multi-commodity flow," in *Proc. ACM Symposium on Theory of computing, STOC 2001*, New York, NY, pp. 389–398, 2001.
- [9] A. Jüttner, I. Szab, and R. Szentesi, "On bandwidth efficiency of the hose resource management model in virtual private networks," in *Proc. IEEE INFOCOM 2003*, 2003.
- [10] T. Erlebach and M. Rüegg, "Optimal bandwidth reservation in hose-model vpns with multi-path routing," in *Proc. IEEE INFOCOM*, 2004.
- [11] M. Chowdhury, M. R. Rahman, and R. Boutaba, "Virtual network embedding with coordinated node and link mapping," in *Proc. IEEE INFOCOM 2009*, pp. 783–791, 2009.
- [12] M. Chowdhury, F. Samuel, and R. Boutaba, "PolyViNE: policy-based virtual network embedding across multiple domains," in *Proc. ACM SIGCOMM Workshop on Virtualized Infrastructure Systems and Architectures*, (VISA 2010), New York, NY, pp. 49–56, 2010.
- [13] "Microsoft worldwide labs." <http://research.microsoft.com/en-us/labs/default.aspx>, 2010.
- [14] "Submarine Cable Map." http://www.telegeography.com/product-info/map_cable/index.php, 2010.