Gradually Reconfiguring Virtual Network Topologies based on Estimated Traffic Matrices

Yuichi Ohsita[†], Takashi Miyamura[§], Shin'ichi Arakawa[‡], Shingo Ata[¶]
Eiji Oki[§], Kohei Shiomoto[§], Masayuki Murata[‡]

[†] Graduate School of Economics, Osaka University

[‡] Graduate School of Information Science and Technology, Osaka University
[§] NTT Network Service Systems Laboratories, NTT Corporation
[¶] Graduate School of Engineering, Osaka City University

Abstract— In this paper, we present a practical VNT (virtual network topology) reconfiguration method for large-scale IP and optical networks with traffic matrix estimation considerations. We newly introduce a partial VNT reconfiguration algorithm with multiple transition stages. By dividing the whole VNT transition sequence into multiple transitions, estimation errors are calibrated at each stage by using network state information of prior stages. Because estimation errors are mainly due to the fewer information in the estimated traffic matrix calculation, our approach tries to increase the constraint conditions for traffic matrix estimation by introducing partial reconfiguration, and to relax the impact of estimation errors by limiting the number of optical-paths reconfigured at each stage. We also investigate the effectiveness of our proposal through simulations and clarify the robustness against estimation errors by using partial reconfiguration.

I. INTRODUCTION

In a backbone network, optical layer traffic engineering (TE) is one efficient way for accommodating traffic that fluctuates unpredictably, which optimizes resource usage by dynamically reconfiguring a VNT (virtual network topology). Here, the VNT is defined as a set of optical paths that carry packet traffic between edge routers. Packet traffic between two IP routers is routed over the VNT. VNT reconfiguration methods are to construct the optimal VNT for a current traffic demand, which improve the efficiency of network resource utilization [1–8]. These approaches dynamically reconfigure the optical-layer topology, to accommodate traffic that fluctuates widely.

The VNT reconfiguration methods requires traffic matrix information in computing the optimal VNT, but it is infeasible to collect traffic matrix information of a large-scale network due to the N-square problem. Therefore, we introduce a traffic matrix estimation method, which presume the whole traffic matrix information by using the limited (i.e., not a whole) information collected in the network. Several papers have investigated the performance of existing TE methods in conjunction with estimated traffic matrices, and revealed that existing TE methods are less robust and do not work properly due to estimation errors [9], [10].

We thus develop a practical VNT reconfiguration method for optical networks with taking traffic matrix estimation into consideration. According to [10], the full reconfiguration approach, which computes the new optimal VNT without limitations on the number of reconfigured optical paths, is sensitive to estimation errors, because estimation errors in the traffic matrix cause addition of many unnecessary optical paths and deletion of many necessary optical paths. Therefore, we newly introduce a partial VNT reconfiguration algorithm with multiple transition stages, and an estimation method suitable for the VNT reconfiguration with multiple transition stages. By dividing the whole VNT transition sequence into multiple transitions, estimation errors are calibrated at each stage by using network state information of prior stages. Therefore, at each stage our estimation method improves the accuracy of traffic matrix estimation by using network state information of prior stages. Then, at the next stage, our partial reconfiguration method uses the traffic matrix whose accuracy is improved by our estimation method. In addition, our partial reconfiguration method limits the number of optical paths added or deleted mistakenly and relax the impact of estimation errors by limiting the number of optical paths reconfigured at each stage.

The rest of this paper is organized as follows. Section 2 proposes a VNT reconfiguration method with traffic matrix estimation. Next, we introduce simulations that demonstrate the limitations of the conventional method and evaluate the performance of our algorithm in Section 3. Finally, a brief conclusion is provided in Section 4.

II. PARTIAL RECONFIGURATION METHOD WITH TRAFFIC MATRIX ESTIMATION

A. Design Principle and Method Overview

We assume that the routes and VNT are calculated by PCE (Path Computation Element) [11]. A PCE first gathers the network information and estimate the traffic matrix by our estimation method. Then, PCE calculates the VNT and routes for the next stage by using the estimated traffic matrix.

Our goal is to provide robust and scalable VNT reconfiguration methods based on traffic matrix estimation; performance degradation due to estimation errors is minimized. The objective function of our VNT reconfiguration algorithm is to minimize resource consumption for a given traffic matrix while avoiding excessive network congestion. Here, network
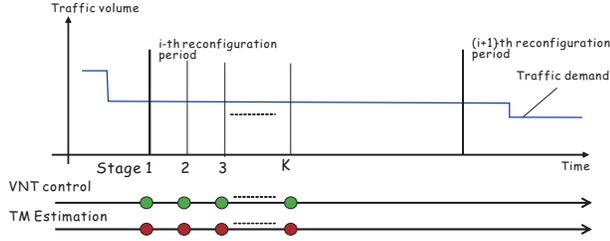
Fig. 1. Overview of gradual reconfiguration of VNT

congestion is measured by the maximum link utilization in the network, thus maximum link utilization should always be held below a given upper bound (e.g., 80% of link bandwidth).

The main challenges are as follows. 1) If we deploy the full reconfiguration approach, errors in a few elements can severely degrade the performance of the whole network according to [10]. 2) We need to estimate traffic matrices as accurate as possible to perform sophisticated VNT reconfiguration.

To solve these issues, we deploy the partial reconfiguration approach with multiple transition stages. This tactic provides robust and safe network control by reducing the negative impact of estimation errors. By introducing partial reconfiguration, network congestion caused by estimation errors will be limited to the small portion of the network, and even when estimation errors cause inadequate VNT reconfiguration, we can recover at the next stage. In addition, existing traffic matrix estimation methods use only instantaneous traffic information, which inevitably contains estimation errors because of the fewer constraint conditions imposed on the estimation. To avoid this issue, the proposed reconfiguration approach divides the whole VNT transition sequence into multiple transition stages and estimation errors are calibrated at each stage by using network state information of prior stages.

B. A Heuristic Algorithm for Partial Reconfiguration

We propose a heuristic algorithm for calculating the VNT, which is simple enough to adopt the large-scale ISP backbones. The heuristic algorithm consists of two phases: addition phase and deletion phase. The algorithm adds new optical paths to mitigate congestion and deletes existing underutilized optical paths if possible for reclamation.

We give preference to adding optical paths over deleting optical paths because network congestion degrades the performance of the communication using the network. Therefore, the heuristic algorithm adds new optical paths first until the congestion is resolved, and then removes underutilized optical paths.

In this algorithm, we limit the number of optical paths to be added or deleted in each stage. Nr denotes the maximum number of optical path to be added or deleted.

The heuristic algorithm uses two thresholds to define the congested or underutilized state of each optical path; T_H and T_L denote thresholds for path congestion and underutilization,

respectively. The general sequence of the heuristic algorithm is as follows:

Step 1 First we check the link utilizations of all optical paths. If at least one congested optical paths is found, go to the optical path addition phase (Step 2). Else if the link utilization of an optical path is less than T_L, then go to *Step 3*

Step 2 Perform the optical path addition phase of the algorithm, which is described below, then go to *Step 4*.

Step 3 Perform the optical path deletion phase of the algorithm, which is described below, then go to *Step 4*.

Step 4 The number of controlled paths is updated, $Nr = Nr - 1$. If $Nr > 1$, go to *Step 1*. Otherwise, go to *End*.

End

Then, at each stage, after the new VNT is determined, the routes of packets over the VNT is calculated by using CSPF (Constraint-based Shortest Path First) [12] so as to make maximum link utilizations under T_H.

The detail of the heuristic algorithm is described as follows.

1) *Optical path addition phase:*
   If the link utilization of an optical path exceeds T_H, a new optical path is set up to reroute traffic away from the congested optical path. The ingress and egress nodes of the newly added optical paths are selected from the ingress and egress nodes of packet paths on the congested optical path, and then the packet path is rerouted via the newly added optical path. If there are more than one packet path in the congested optical path, the packet path whose amount of traffic is the largest is selected.

2) *Optical path deletion phase:*
   If the link utilization of an optical path is less than T_L, the optical path is torn down for resource reclamation in order to improve resource efficiency after checking that the deletion of the optical path does not cause any congestions. If there is more than one candidate of deleted optical paths, each candidate optical path is tested in decreasing order of the link utilizations, so the most under-utilized optical path is selected among the candidates.

C. Traffic Models and TM Estimation Method

In this subsection, we propose a new estimation method which collaborates closely with partial VNT reconfiguration. As described in Subsection II-A, the objective of our TM estimation method is to increase the accuracy of estimation by effectively utilizing the feedback information from the results of the previous stage in partial VNT reconfiguration.

Suppose that the estimated traffic matrix at the current stage has large estimation errors. As the result of VNT reconfiguration, some optical path additions/deletions are made. Under the assumption that the traffic demand of each source-destination is constant over the period from before to after the reconfiguration, we focus on two kinds of additional information in order to improve the accuracy of the estimation.

1) *Differences of link utilizations between before and after VNT reconfiguration:* Given a fixed traffic matrix, the change of routes of packet paths by the VNT reconfiguration directly impacts the link utilizations of optical paths that carry the packet paths whose routes are changed. That is, if the measured link utilizations of an optical path changes with VNT reconfiguration, the difference is caused by the change of routes of packets. The information of these differences can yield additional equations for solving the traffic matrix calculation.

2) *Difference between estimated link utilizations and actual link utilizations:* Since VNT reconfiguration is performed by using traffic matrices that essentially have estimation errors, the estimated link utilization of optical paths may be altered by the errors. After reconfiguration, there should be some difference between the estimated and actual link utilizations. The information of these differences is used as feedback to subsequent VNT reconfigurations.

In the proposed method, we consider both pieces of information above in order to improve estimation accuracy.

We assume that the durations of a stage and reconfiguration period are small enough and the traffic demand is constant throughout the reconfiguration period. We denote the actual traffic matrix by T. At stage i, we denote the routing matrix and the matrix of link utilizations by A_i and X_i, respectively.

Because link utilization is the sum of the traffic demands for the source-destination pairs using the links, we have

$$X_i = A_i T. \tag{1}$$

At stage n, by combining all relations from X_0 to X_n, we also have

$$
\begin{bmatrix} X_0 \\ \vdots \\ X_i \\ \vdots \\ X_{n-1} \\ X_n \end{bmatrix}
=
\begin{bmatrix} A_0 \\ \vdots \\ A_i \\ \vdots \\ A_{n-1} \\ A_n \end{bmatrix} T. \tag{2}
$$

The calculation of T from Eq. (2) requires huge computational overhead. However, partial reconfiguration changes only a small number of routes at each stage. That is, most entries of $\Delta A_i = A_i - A_{i-1}$ are expected to be 0. By applying this, we introduce following procedure to reduce the size of the matrix. First, we transform X_i and A_i into the matrices,

$$
\bar{X}_n =
\begin{bmatrix}
X_1 - X_0 \\ \vdots \\ X_i - X_{i-1} \\ \vdots \\ X_{n-1} - X_{n-2} \\ X_n - X_{n-1} \\ X_n
\end{bmatrix} \tag{3}
$$

and

$$
\Delta\bar{A}_n =
\begin{bmatrix}
\Delta A_1 \\ \vdots \\ \Delta A_i \\ \vdots \\ \Delta A_{n-1} \\ \Delta A_n \\ A_n
\end{bmatrix}. \tag{4}
$$

Second, we remove rows ΔA_i in $\Delta\bar{A}_n$ if $\Delta A_i = 0$. We also remove the same position of the row $X_i - X_{i-1}$ in $\bar{X}_n$. We denote $\bar{X}_n$ and $\Delta\bar{A}_n$ after row removal by $\bar{X}'_n$ and $\Delta\bar{A}'_n$, respectively. Finally, we use

$$\bar{X}'_n = \Delta\bar{A}'_n T, \tag{5}$$

instead of Eq. (2). To estimate the traffic matrix $\hat{T}$ from Eq. (5), we apply the pseudo-inverse calculation method described in [13]. The traffic matrix $\hat{T}$ is obtained from

$$\hat{T} = \mathrm{pinv}(\bar{A}_n)\bar{X}_n, \tag{6}$$

where $\mathrm{pinv}(\bar{A}_n)$ is the pseudo-inverse of matrix $\bar{A}_n$. If we simply apply [13] to calculate the pseudo-inverse of $\bar{A}_n$, some entries in $\hat{T}$ may have negative values, which are nonexistent as regards the traffic matrix. The following iteration eliminates such negative values. We define the estimated traffic matrix for the i-th iteration as $\hat{T}^{(i)}$.

1) Let $\hat{T}^{(0)} \leftarrow \hat{T}$
2) Calculate $\hat{T}^{(i)}$ from $\hat{T}^{(i-1)}$ by using

$$\hat{T}^{(i)} = \hat{T}^{(i-1)} + \mathrm{pinv}(\bar{A}_n)(\bar{X}_n - \bar{A}_n\hat{T}'^{(i-1)}), \tag{7}$$

where $\hat{T}'^{(i)}$ is a matrix in which we replace all negative values of $\hat{T}^{(i)}$ with zero.
3) If all entries in $\hat{T}^{(i)}$ are non-negative values, go to Step 4, else back to Step 2.
4) Let $\hat{T}^{(i)}$ be the final result of traffic matrix $\hat{T}$

We discuss here why the above method offers better accuracy. As discussed before, we use two types of information to improve the estimation accuracy. In this model, both are included in Eq. (5). More specifically, we use the constant value of T for all stages to increase the number of relations in Eq. (2). Also, Eq. (6) offers an adjustment by keeping Eqs. (1) and (5). Though the errors are included in estimated traffic matrix $\hat{T}_i$, they do not appear if the routing is not changed, because the estimated traffic matrix and link utilizations even satisfy Eqs. (1) and (5). However, because routing changes are created by reconfiguration, the impact of estimation error on the new paths appears in Eq. (5).

III. PERFORMANCE EVALUATION

In this section, we first address to the aim of our simulation results followed by the description of simulation conditions. Second, we perform simulations to demonstrate the effectiveness of the partial reconfiguration method with traffic matrix estimation and some of these results are presented in this paper.
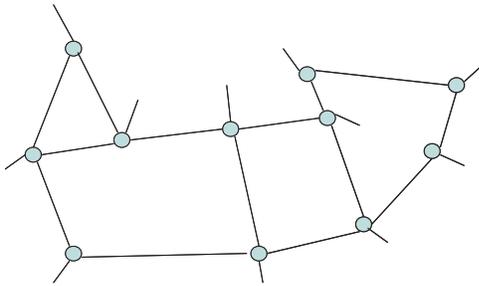
Fig. 2.   Abilene topology

A. Simulation Conditions

The simulation conditions used in our performance evaluation is as follows. We use the Abilene backnone as the network topology as shown in Fig. 2. The number of wavelengthes for each physical link is set to be eight. As a true traffic matrix, we adopt real data collected from the Abilene backbone network [14]. However, the actual traffic demand does not make a significant impact to VNT reconfiguration due to low variations of the actual traffic. In order to verify the effect of VNT reconfiguration, we scale the monitored traffic enough to make most of links to be congested. Furthermore, we add 1 Gbps of traffic to four randomly picked up source-destination pairs to cause significant route changes after VNT reconfiguration. On the simulation, we first create the initial VNT topology by using our VNT reconfiguration algorithm for a given traffic demand, we then change the traffic to above-mentioned one to evaluate how our proposed method works.

For performance measures, we evaluate followings: i) average of squared estimation error, and ii) maximum number of output ports additionally required for the VNT reconfiguration. The former is the metric which directly indicates the accuracy of the traffic matrix estimation method. The latter is a useful to consider the impact of estimation errors on the network cost, i.e., if the required number of ports is larger, we need more cost to construct the network.

B. Effectiveness of partial reconfiguration with TM Estimation

We first compare the average squared errors of traffic matrix estimation between existing estimation method called tomogravity [15] and our method. Fig. 3 shows the results, where we set the threshold Nr to be 1, 3 and 5. From this figure, we can observe that our method can decrease the estimation error dramatically compared to the tomogravity. This is caused by the difference of number of equations used in the traffic matrix calculation. In the tomogravity model, the accuracy is improved only because the part of actual traffic matrix can be directly measured by setting up additional source-destination paths, while our method can improve the accuracy not only by the direct measurements but also by the increase of the number of equations. However, in some stages, even our method could not decrease the estimation error (e.g., Stages 14–18 for $Nr = 1$). This is because our method can improve the accuracy only if at least one route is changed from the previous stage. In cases such as when we set an
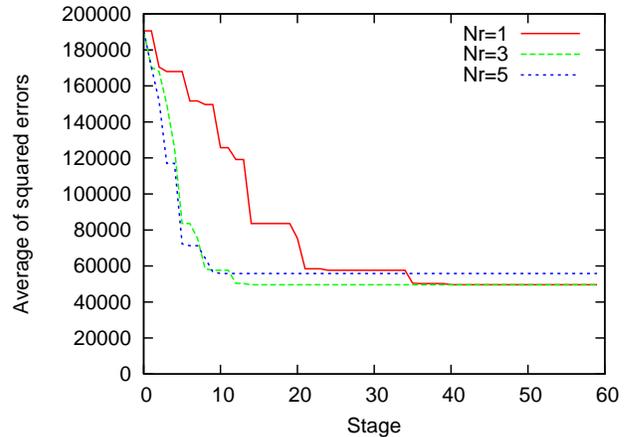
(a) Our method
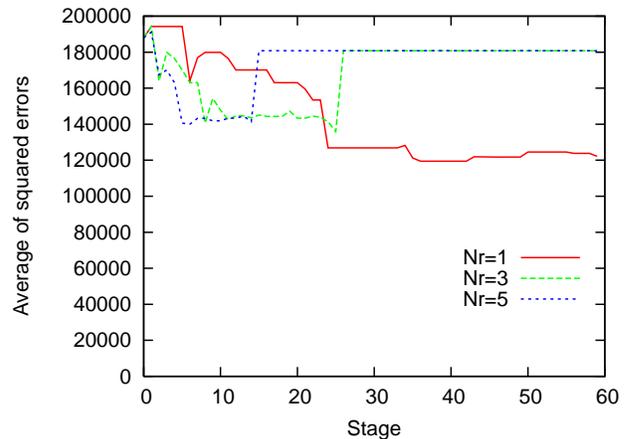
(b) Tomogravity

Fig. 3.   Average squared errors of traffic matrix estimation

additional path for the already connected source-destination pair, or when we delete one of multiple paths for the same source-destination pair.

Fig. 3 also shows the effect of the parameter Nr for the traffic matrix estimation. We found from this figure that there is a trade-off between the convergense time and the accuracy of estimation. That is, when $Nr = 5$ the VNT becomes stable faster (i.e., smaller number of stages) than the case when $Nr = 1$, while the accuracy becomes worse when $Nr = 5$. To improve the accuracy, the smaller Nr is better, however, small value of Nr requires a lot of stages to be converged, which lead a heavy measurement overhead or long time to make the VNT stable. One possible solution is to set Nr as small as possible for given acceptable maximum number of stages for partial reconfiguration which is determined by the traffic monitoring period and preferable duration for the reconfiguration.

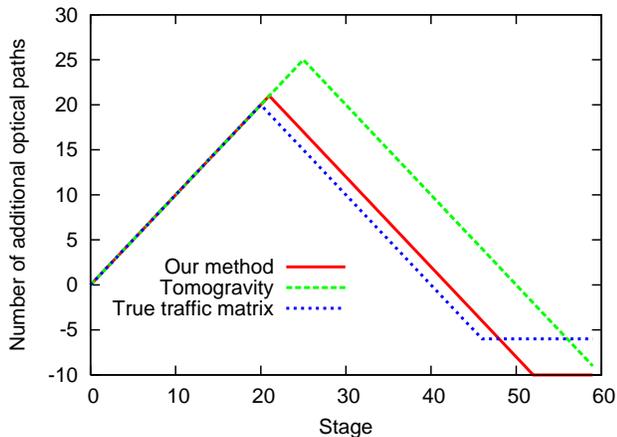We next evaluate the impact of reducing estimation errors.

Fig. 4. Variation of difference of the number of paths from the beginning of VNT reconfiguration

To reconfigure the VNT, we add the optical paths between nodes where estimated traffic is large. Thus, in the case of large estimation errors, the actual traffic on the added optical paths may be small. That is, estimation errors cause optical paths added unnecessarily. Therefore, we evaluate the impact of reducing estimation errors by investigating the number of added optical paths. Fig 4 shows the variation of difference of the number of paths from the beginning of VNT reconfiguration. The number of paths is increasing linearly by passing stages. When the VNT satisfies the condition that the maximum link utilization is less than T_H, the reconfiguration algorithm tries to delete as many unused paths as possible. The number of paths is therefore descreasing linearly. From this figure, more output ports are required when we use the tomogravity due to larger estimation errors. This is because the estimation errors cause the optical path added inadequately where the actual traffic is small. As a result, we cannot decrease the maximum link utilization as well as the case of small estimation errors and we add more optical paths to make the maximum link utilization under the threashold.

Also, tomogravity requires more stages to reach the stable VNT. It is because the VNT reconfiguration algorithm is required to delete more paths which are unnecessarily added caused by estimation errors.

On the other hand, our method needs almost the same number of paths as the true traffic matrix. That is, even though estimation errors at the first stage are as large as tomogravity method, improving the accuracy of traffic matrix by our method avoids adding the unnecessary optical paths.

IV. CONCLUDING REMARKS

In this paper, we proposed a practical VNT reconfiguration method with traffic matrix estimation considerations. We presented a partial VNT reconfiguration approach as optimization problems. We presented the heuristic algorithms for partial reconfiguration. The key technology lies in a partial VNT reconfiguration algorithm with multiple transition stages. By introducing the partial reconfiguration, network congestion caused by estimation errors can be limited to small portion of the network. We also investigated the effectiveness of our proposal through simulations and clarified the robustness of the proposed control method under estimated traffic.

One of our future works is to evaluate our method in the case of frequent change of traffic.

REFERENCES

[1] B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee, "Some principles for designing a wide-area WDM optical network," *IEEE/ACM Transactions on Networking*, vol. 4, pp. 684–696, Oct. 1996.

[2] D. Banerjee and B. Mukherjee, "Wavelength-routed optical networks: Linear formulation, resource budgeting tradeoffs, and a reconfiguration study," *IEEE/ACM Transactions on Networking*, vol. 8, pp. 598–607, Oct. 2000.

[3] J. Wei, C.-D. Liu, S.-Y. Park, K. Liu, R. Ramamurthy, H. Kim, and M. Maeda, "Network control and management for the next generation Internet," *IEICE Transactions on Communications*, vol. 83-B, pp. 2191–2209, Oct. 2000.

[4] L. Zhang, K. Lee, and C.-H. Youn, "Adaptive virtual topology reconfiguration policy employing multi-stage traffic prediction in optical Internet," in *Proceedings of Workshop on High Performance Switching and Routing*, pp. 26–29, May 2002.

[5] K. Shiomoto, E. Oki, W. Imajuku, S. Okamoto, and N. Yamanaka, "Distributed virtual network topology control mechanism in GMPLS-Based multiregion networks," *IEEE Journal on Selected Areas in Communications*, vol. 21, pp. 1254–1262, Oct. 2003.

[6] A. Gencata and B. Mukherjee, "Virtual-topology adaptation for WDM mesh networks under dynamic traffic," *IEEE/ACM Transactions on Networking*, vol. 11, pp. 236–247, Oct. 2003.

[7] S. Gieselman, N. Singhal, and B. Mukherjee, "Minimum-cost virtual-topology adaptation for optical WDM mesh networks," in *Proceedings of IEEE ICC*, vol. 3, pp. 1787–1791, June 2005.

[8] R. Hayashi, T. Miyamura, M. Aoki, and S. Urushidani, "Simulation of a dynamic multi-layer optimization algorithm with SRLG consideration," in *Proceedings of OECC/COIN 2004*, July 2004.

[9] M. Roughan, M. Thorup, and Y. Zhang, "Traffic engineering with estimated traffic matrices," in *Proceedings of ACM SIGCOMM Internet Measurement ConferenceIMC 2003*, pp. 248–258, Oct. 2003.

[10] Y. Ohsita, T. Miyamura, S. Arakawa, S. Ata, E. Oki, K. Shiomoto, S. Urushidani, and M. Murata, "Traffic engineering strategies in IP and optical multi-layer networks," *Technical Reports of IEICE (PN2006–11)*, pp. 7–12, Aug. 2006.

[11] A. Farrel, J. P. Vasseur, and J. Ash, "A path computation element (PCE)-based architecture." RFC 4655, Aug. 2006.

[12] B. S. Davie and Y. Rekhter, *MPLS: Technology and Applications*. Morgan Kaufmann Publishers, 2000.

[13] J. C. Nash, *Compact Numerical Methods for Computers: Linear Algebra and Function Minimisation*. Adam Hilger, 1990.

[14] "Abilene network status." available at http://abilene.internet2.edu/observatory/.

[15] Y. Zhang, M. Roughan, N. Duffield, and A. Greenberg, "Fast accurate computation of large-scale IP traffic matrices from link loads," in *Proceedings of ACM SIGMETRICS 2003*, pp. 206–217, June 2003.