Gradually Reconfiguring Virtual Network Topologies based on Estimated Traffic Matrices

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***Abstract*— Traffic matrix, which is required as an input of traffic engineering (TE) methods, is difficult to be obtained directly. One possible approach to obtaining the traffic matrix is to estimate it from the limited information such as link utilizations. However, estimated traffic matrix includes estimation errors which degrade the performance of TE significantly. In this paper, we propose VNT reconfiguration and traffic matrix estimation methods that reduce estimation errors while reconfiguring the VNT by cooperating with each other. Our method reconfigures the VNT gradually by dividing it into multiple stages and limiting the number of optical layer paths reconfigured in each stage. By dividing the VNT reconfiguration into multiple stages, our traffic matrix estimation method calibrates and reduces the estimation errors in each stage by using information monitored in prior stages. In addition, by limiting the number of optical layer paths reconfigured in each stage, our method avoids mistakenly adding or deleting many optical layer paths. That is, our reconfiguration method can mitigate the impact of estimation errors. We also investigate the effectiveness of our proposal using simulations. The results show that our method can improve the accuracy of the traffic matrix estimation and construct an adequate VNT.**

I. Introduction

Network operators design their backbone networks to accommodate all traffic efficiently (e.g., without congestion or large delays). However, even if a backbone network suitable for actual traffic is constructed, traffic could significantly differ from the initial traffic as time goes on. As a result, the previously constructed backbone network becomes no longer suitable to the current traffic; it may happen that utilizations of some links are extremely high while utilizations of other links are extremely low. Especially, because high link utilizations cause congestion or large delays, we need to avoid high link utilizations even when traffic fluctuates.

Optical layer traffic engineering (TE) [1–8] is one efficient way of accommodating traffic that fluctuates unpredictably. Optical layer TE assumes that a network consists of IP routers and optical cross-connects (OXCs), as illustrated in Fig. 1. Each outbound port of an edge IP router is connected to an OXC port. Traffic imposed on the network between edge IP routers is carried over WDM links. Lightpaths (hereafter called optical layer paths) are established between two IP routers by configuring OXCs along the route between the routers. Optical layer paths terminate at the transceiver of the last IP router. A set of optical layer paths forms a VNT (virtual network topology). Traffic between two routers is carried over the VNT using IP layer routing. In these conditions, optical layer TE accommodates traffic that fluctuates widely by dynamically reconfiguring VNTs.

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A part of this paper was presented at IEEE INFOCOM 2007 mini-symposium, Anchorage Alaska, May 2007.

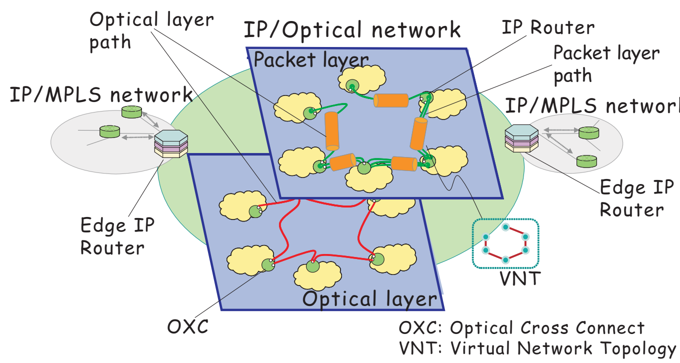


Fig. 1. IP/Optical network.

In optical layer TE, a traffic matrix, which indicates traffic volumes between all pairs of edge nodes, is required as an input. By using the traffic matrix, the VNT reconfiguration methods configure a new VNT in which constraints such as maximum utilization of optical layer paths are satisfied. One approach to obtaining the traffic matrix directly is to construct fully meshed label switched paths using MPLS. However, this approach does not scale because it requires N-square number of label switched paths. Another approach is to tally the number of packets of each end-to-end traffic flow at all the edge nodes. However, this is also difficult to apply in large-scale networks, because tallying the number requires a non-negligible amount of CPU resources of edge nodes, and gathering the tallied data of all end-to-end traffic consumes a non-negligible amount of network resources such as bandwidths.

Therefore, several methods to estimate traffic matrices have been proposed [9–12]. In such methods, a whole traffic matrix is estimated by using the information (e.g., utilizations of optical layer paths) that can be collected much more easily than traffic matrices. According to the paper on the performance of the above proposed TE methods in conjunction with estimated traffic matrices [13], estimation errors degrade the performance of current TE methods, and because of estimation errors, TE methods cannot reduce the maximum utilization of optical layer paths as expected.

One way of handling such estimation errors is to reconfigure the VNT redundantly, taking the estimation errors into consideration. Yang *et al.* [14] proposed a method of designing a VNT redundantly by modeling the uncertainty of elements of traffic matrices as probability functions. We can apply this method to reconfiguring a VNT by predicting estimation errors and setting probability functions based on the predicted estimation errors, and expect to avoid the impact of estimation errors. However, if the predicted estimation errors are large, the redundant reconfiguration may require an unacceptable amount of resources such as wavelengths. To avoid the impact of estimation errors, therefore, reduction of estimation errors is necessary.

Accordingly, we newly develop VNT reconfiguration and traffic matrix estimation methods that reduce estimation errors while reconfiguring the VNT by cooperating with each other. Our reconfiguration method divides the VNT reconfiguration into multiple stages and limits the number of optical layer paths reconfigured in each stage. By dividing the VNT reconfiguration into multiple stages, our traffic matrix estimation method calibrates and reduces estimation errors in each stage by using information (e.g., packet layer routing and utilizations of optical layer paths) monitored in prior stages. As stages are completed, a better VNT (e.g., VNT in which the maximum link utilization is reduced) is configured using the more reliable traffic matrix obtained by our estimation method. In addition, if the the new VNT is computed without any restrictions, the traffic matrix with estimation errors causes the VNT to make mistakes: underestimation of traffic may cause many necessary optical layer paths to be deleted, and overestimation may cause many unnecessary optical layer paths to be added. By limiting the number of optical layer paths reconfigured in each stage, our reconfiguration method avoids mistakenly adding or deleting many optical layer paths. That is, our reconfiguration method mitigates the impact of estimation errors.

The rest of this paper is organized as follows. Section II summarizes related works. Then, Section III presents an overview of the gradual reconfiguration method and the estimation method for the gradual reconfiguration. We explain the reconfiguration and estimation methods in detail in Sections IV and V, respectively. In Section VI, we discuss the simulations that we used to demonstrate the limitations of the conventional method and evaluate our methods. Finally, a brief conclusion is provided in Section VII.

II. Related work

In this section, we summarize past research on VNT reconfiguration algorithms and traffic matrix estimation methods.

A. VNT reconfiguration method

VNT computation algorithms can be categorized as either full [1], [2] or partial reconfiguration algorithms [3–8]. In full reconfiguration, the new VNT is computed with no limitation on the number of reconfigured optical layer paths. Mukherjee *et al.* [1] formulated the full reconfiguration VNT design problems as optimization problems and proposed heuristic algorithms based on the simulated annealing approach that find nearly optimal solutions. Their main focus is on a method for designing VNT on a given physical topology and static traffic matrix. The full reconfiguration approach can yield a solution that is optimal in terms of network performance such as maximum utilization of optical layer paths.

However, if we reconfigure the VNT using a full reconfiguration approach, the traffic matrix with estimation errors causes the VNT to make mistakes. Because full reconfiguration approaches do not limit the number of optical layer paths to be reconfigured, many necessary optical layer paths are deleted due to underestimation and many unnecessary optical layer paths are added due to overestimation. Deleting necessary optical layer paths causes especially high utilization of other optical layer paths.

Therefore, in this study, we use a partial reconfiguration approach at each stage. In partial reconfiguration, the new VNT is computed with limitations on the number of reconfigured optical layer paths. There are several papers proposing partial reconfiguration approaches [3–8]. Banerjee and Mukherjee [3] present an integer linear programming (ILP) formulation for optimal VNT design. Their approach assumes that the future traffic matrix is given; the future VNT is determined by adapting the current one to accommodate the change in the traffic matrices. Thus, they did not consider how well the VNT reconfiguration interacts with the variability of unpredictable time-varying traffic matrices. Recently, Gieselman *et al.* [8] proposed a partial reconfiguration algorithm that efficiently adapts to fluctuations in traffic. However, their algorithm allows only one optical layer path to be added or deleted in each stage, so the VNT cannot adequately adapt to fluctuations when there are unpredictable changes in traffic or a large-scale network that requires a large number of controlled paths. Therefore, in this paper, we extend the partial reconfiguration method proposed in [8], enabling it to add or delete multiple optical layer paths for each stage. Our reconfiguration method is described in detail in Section IV.

B. Traffic Matrix Estimation

In the optical layer TE, information about network resources and traffic matrices is required as input.

A straightforward approach to collecting traffic matrices is to use fully meshed label switched paths that are configured between each pair of edge routers on top of a VNT in the network. However, this approach does not scale well because it requires N-square number of label switched paths. Another approach is to tally the number of packets of each end-to-end traffic flow at the all edge nodes. However, this is also difficult to apply to a large-scale network, because tallying the number requires a non-negligible amount of CPU resources of edge nodes and gathering the tallied data of all end-to-end traffic consumes a non-negligible amount of network resources such as bandwidths.

This means that a more scalable method of collecting traffic matrices is urgently needed for traffic engineering in large-scale IP/Optical networks. One possible method is to introduce a traffic matrix estimation approach. This estimates a traffic matrix based on indirect data (e.g., utilization of links). The estimated traffic matrix is used as an input of the TE algorithm. Several methods of estimating a traffic matrix have already been proposed. Zhang *et al.* [9] proposed a fast and accurate estimation method called the tomogravity method. Tomogravity extends a gravity model that assumes that the amount of traffic from a source to a destination node is proportional to the total of the incoming/outgoing traffic for each edge node. Results reported by [9] and [15] show that tomogravity can follow rapid changes in amounts of traffic, and can estimate the traffic matrix on a tier-1 ISP network within 5 seconds. However, in some cases, the assumption of gravity model is incorrect and the errors of tomogravity method are significant [16]. A method is needed that can estimate accurately even in these conditions.

One approach to increasing estimation accuracy is to use additional information. Recently, Soule *et al.* [10–12] proposed methods of obtaining and using additional measurements to estimate the traffic matrix by changing the routes of packet layer paths and observing the difference between utilization of links before and after routes are changed. However, these methods require changes in packet layer paths that are initially unnecessary. Also, they do not consider how to deal with the sudden changes in traffic that cause significant estimation errors. Our approach, in contrast, obtains additional information using the difference in utilizations of optical layer paths caused by the VNT reconfiguration with no unnecessary route changes. To avoid significant errors when traffic changes suddenly, our estimation method separates the information about sudden changes in traffic from the information (e.g., packet layer routing and utilization of optical layer paths) from prior stages.

III. Overview

A. Terminology

Before presenting overviews of our reconfiguration and estimation methods, we explain our terminology.

Traffic matrix
: A matrix indicating the amount of traffic between all pairs of IP routers.

Physical topology
: A topology physically constructed in the optical layer that consists of OXCs and WDM optical fibers. Two OXCs are connected by a single optical fiber.

Optical layer path
: A lightpath configured between two indirectly/directly connected OXCs. An optical layer path is a set of optical fibers between the two OXCs determined by the optical layer TE. An optical layer path occupies one wavelength of each optical fiber on the route of the optical layer path.

VNT
: A topology constructed with optical layer paths. From the packet layer, an optical layer path is regarded as a single directly connected link between IP routers.

Packet layer path
: An end-to-end packet-layer traffic traversing the VNT. Packet layer paths traversing the same optical layer path share the optical layer path bandwidth.

Route of a packet layer path
: A set of optical layer paths passed by the packet layer path.

Utilization of an optical layer path
: Amount of traffic traversing the optical layer path divided by the capacity of the optical layer path.

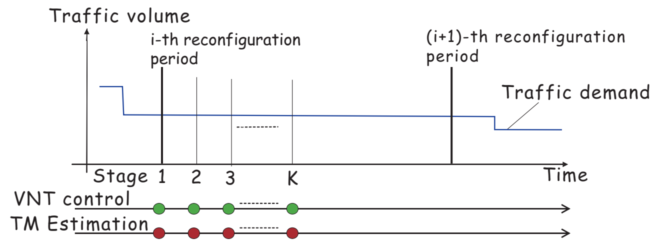


Fig. 2. Overview of gradual reconfiguration of VNT

B. Overview of gradual reconfiguration and traffic matrix estimation

We assume that routes of both packet and optical layer paths are calculated by a path computation element (PCE) [17]. A PCE first gathers network information, such as utilization of optical layer paths and packet layer routing, and estimates the traffic matrix. Then, the PCE solves the VNT and packet layer paths for the next stage.

Our goal is to develop VNT reconfiguration and traffic matrix estimation methods that reduce the estimation errors while reconfiguring the VNT by cooperating with each other. Here, the objective of our VNT reconfiguration algorithm is to minimize the total amount of IP router ports (i.e., minimize the number of optical layer paths) used to accommodate the given traffic while avoiding excessive network congestion. This will preserve more IP router ports for future change of traffic. We measured network congestion based on maximum utilization of optical layer paths in the network, so maximum utilization should always be held below a given upper bound (e.g., 50% or 70% of bandwidth of an optical layer path).

There are two main challenges. First, we need to reconfigure a VNT that minimizes the impact of traffic matrix estimation errors. That is, even if there are some estimation errors in the traffic matrix, we need to add necessary optical layer paths, avoid adding unnecessary optical layer paths, and avoid deleting necessary optical layer paths. Second, we need to estimate traffic matrices as accurately as possible to increase the sophistication of the VNT reconfiguration.

To resolve these issues, we deploy the gradual reconfiguration approach shown in Fig. 2. To accommodate the current traffic, the VNT needs to be reconfigured once per reconfiguration period (e.g., on the order of hours). In the gradual reconfiguration, the VNT reconfiguration is divided into several stages. The period between two stages is configured on the order of minutes. For example, the period may be set to 5 min, which is a typical monitoring interval used in SNMP. A partial reconfiguration is carried out in each stage. Introduction of gradual reconfiguration will limit network congestion caused by estimation errors to a small portion of the network because limiting the number of reconfigured optical layer paths at each stage prevents deletion of a large number of necessary optical layer paths. We can quickly recover from whatever estimation errors cause inadequate VNT reconfiguration in the next stage.

Existing traffic matrix estimation methods use utilization of simultaneously monitored links, setting up equations that the traffic matrix should satisfy. Then, these methods find the traffic matrix that satisfies the equations. However, estimated traffic matrices contain estimation errors because the number of equations, which is equal to the number of utilizations used by existing estimation methods, is much smaller than the number of elements of the traffic matrix. To avoid this problem, our traffic matrix estimation method cooperates with the VNT reconfiguration method. In our estimation method, we increase the accuracy of traffic matrix estimation by using the utilization of optical layer paths monitored both before and after the VNT reconfiguration.

IV. Heuristic Algorithm for Gradual Reconfiguration

In each stage of the gradual reconfiguration, we use the heuristic algorithm proposed in this section to calculate the VNT for the next stage. The heuristic algorithm consists of two phases: *addition phase* and *deletion phase*. The algorithm adds new optical layer paths to mitigate congestion and, if possible, deletes currently underutilized optical layer paths for reclamation.

We prioritize adding optical layer paths over deleting optical layer paths because congestion, which can be caused by the optical layer path deletion, seriously damages the network. Therefore, the heuristic algorithm adds new optical layer paths until the congestion is resolved. Then, the algorithm removes underutilized optical layer paths. In this algorithm, we limit the number of optical layer paths to be added or deleted at each stage. N denotes the maximum number of paths to be added or deleted.

The heuristic algorithm uses two thresholds for the utilization of each optical layer path to define the *congested* and *underutilized* states. T_H and T_L denote thresholds for *congested* and *underutilized*, respectively. The general sequence of the heuristic algorithm is as follows:

Step 1 Check the utilization of all optical layer paths. If at least one congested optical layer path (i.e., a path whose utilization exceeds the threshold T_H) is found, go to the optical layer path addition phase (Step 2). If there is an optical layer path whose utilization is less than threshold T_L, go to *Step 3*

Step 2 Execute the *optical layer path addition phase* described below, then go to *Step 4*.

Step 3 Execute the *optical layer path deletion phase* described below, then go to *Step 4*.

Step 4 Decrement the number of optical layer paths to be added/deleted in this stage, i.e., $N = N - 1$. If $N = 0$, go to *End*. Otherwise, go back to *Step 1*.

End

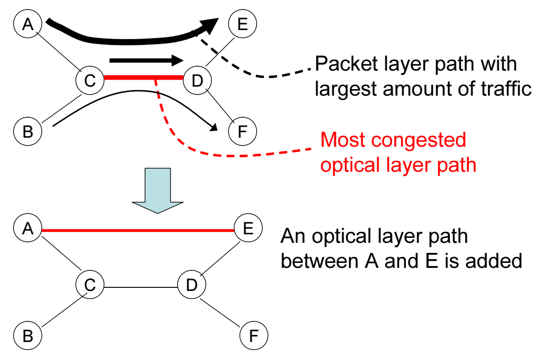


Fig. 3. Example of addition of optical layer path addition phase

After the new VNT is determined, the routes of packet layer paths over the VNT are calculated as follows. 1) When utilizations of all optical layer paths on the route of a packet layer path in the previous stage are lower than T_H, the route is kept in the current stage because there is no need to change it. 2) Otherwise, the route is calculated using constraint-based shortest path first (CSPF) [18] so as to limit maximum utilizations to less than T_H.

The details of optical layer path addition/deletion phases are as follows.

1) *Optical layer path addition phase:*
If the utilization of an optical layer path exceeds T_H, a new optical layer path is set up to reroute traffic away from the *congested* optical layer path. First, we collect a set of packet layer paths that pass the most congested optical layer path. Then, we select the busiest of the collected packet layer paths. Finally, we add the direct optical layer path between the ingress and egress nodes of the selected packet layer path. An example of optical layer path addition phase is shown in Fig. 3. In this example, the optical layer path from C to D is the most *congested*. Among packet layer paths traversing the optical layer path C-D, the packet layer path from A to E is busiest. In this case, an optical layer path from A to E is established.
2) *Optical layer path deletion phase:*
If the utilization of an optical layer path is less than T_L and the deletion of the optical layer path is shown not to cause congestion, the path is torn down so the IP router ports and wavelengths can be reclaimed for future use. The optical layer path is checked for potential for its deletion to cause congestion by calculating the utilization of optical layer paths after deletion using the traffic matrix estimated in the current stage. If there is more than one candidate for deletion, each candidate path is tested in ascending order of utilization. That is, the least utilized *underutilized* optical layer path is selected from the candidates.

V. Traffic Matrix Estimation Method Suitable for Gradual Reconfiguration

Our estimation method collaborates closely with the gradual VNT reconfiguration. As described in Section III, the objective of our traffic matrix estimation method is to increase the accuracy of estimation by effectively using the utilization of optical layer paths monitored both before and after the VNT reconfiguration carried out in the previous stage.

When the VNT is reconfigured, up to N optical layer paths are added or deleted. The change in routes of packet layer paths caused by the VNT reconfiguration directly impacts the utilization of optical layer paths that are passed by the packet layer paths whose routes are changed. Assuming that the network is stable (i.e., the variation in traffic is small) between two continuous stages, if the measured utilization of an optical layer path is changed by VNT reconfiguration, it is safe to conclude that the difference is caused by the change in routes of packet layer paths. These differences can yield additional equations for solving the traffic matrix calculation. In our proposed method, we use the utilizations monitored in the last M stages.

Hereafter, we call our estimation method the *additional equation method*. In Subsection V-A, we describe its basic idea. In a real network, the traffic may change during the M stages used in the additional equation method. A significant variation in traffic causes estimation error because it violates the fundamental assumption that the network is stable. To deal with obvious variations in traffic, we propose a method of eliminating the impact of the non-negligible change in traffic described in Subsection V-B.

A. Basic Idea

In our method, we use the utilization of optical layer paths monitored in the last M stages. That is, to estimate the traffic matrix at stage n, we use the utilization monitored from stage $n-M+1$ to stage n. We assume the duration of a stage is small. In stage i, T_i, A_i, and X_i denote the actual traffic matrix, the routing matrix (i.e., the matrix in which an element corresponding to a packet layer path and an optical layer path is 1 if the packet layer path passes the optical layer path or is set to 0 if not) and the matrix indicating utilizations of optical layer paths, respectively.

Because utilization of an optical layer path is the sum of the traffic for the packet layer paths using the optical layer path, we have

$$\begin{aligned} X_i &= A_i T_i \\ &= A_i T_n + \epsilon_{i,n}, \end{aligned} \tag{1}$$

where $\epsilon_{i,n}$ denotes the change in traffic between stages i and n. At stage n, by combining all relations from X_{n-M+1} to X_n, we also have

$$\begin{bmatrix} X_{n-M+1} \\ \vdots \\ X_i \\ \vdots \\ X_{n-1} \\ X_n \end{bmatrix} = \begin{bmatrix} A_{n-M+1} \\ \vdots \\ A_i \\ \vdots \\ A_{n-1} \\ A_n \end{bmatrix} T_n + \begin{bmatrix} \epsilon_{n-M+1,n} \\ \vdots \\ \epsilon_{i,n} \\ \vdots \\ \epsilon_{n-1,n} \\ 0 \end{bmatrix}. \tag{2}$$

Note here, that because we assume that the duration of a stage is small, $\epsilon_{i,n}$ is also small. To estimate the traffic matrix $\hat{T}_n$ from Eq. (2), we apply the pseudo-inverse calculation method described in [19]. The traffic matrix $\hat{T}_n$ is obtained from

$$\hat{T}_n = \mathrm{pinv}(\bar{A}_n)\bar{X}_n, \tag{3}$$

where $\mathrm{pinv}(\bar{A}_n)$ is the pseudo-inverse of matrix, and $\bar{A}_n$ and $\bar{X}_n$ are the matrices defined as,

$$\bar{X}_n = \begin{bmatrix} X_0 \\ \vdots \\ X_i \\ \vdots \\ X_n \end{bmatrix} \tag{4}$$

and

$$\bar{A}_n = \begin{bmatrix} A_0 \\ \vdots \\ A_i \\ \vdots \\ A_n \end{bmatrix}. \tag{5}$$

A pseudo-inverse matrix is a generalized inverse matrix and by using pseudo-inverse matrix, Eq. (3) can estimate $\hat{T}_n$ so as to minimize the squared sum of $\epsilon_{i,n}(n-M+1 \leq i \leq n)$.

However, if we simply apply the pseudo-inverse of $\bar{A}_n$ to solve Eq. (3), some elements in $\hat{T}_n$ 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 $\hat{T}_n^{(i)}$.

Step 1 Let $\hat{T}_n^{(0)} \leftarrow \hat{T}_n$

Step 2 Calculate $\hat{T}_n^{(i)}$ from $\hat{T}_n^{(i-1)}$ by using

$$\hat{T}_n^{(i)} = \hat{T}_n^{(i-1)} + \mathrm{pinv}(\bar{A}_n)(\bar{X}_n - \bar{A}_n \hat{T}_n^{'(i-1)}), \tag{6}$$

where $\hat{T}_n^{'(i)}$ is a matrix in which we replace all negative values of $\hat{T}_n^{(i)}$ with zero.

Step 3 If all elements in $\hat{T}_n^{(i)}$ are non-negative values, go to *Step 4*, or else back to *Step 2*.

Step 4 Let $\hat{T}_n^{(i)}$ be the final result of traffic matrix $\hat{T}_n$

B. Dealing with non-negligible changes in traffic

The basic idea described above assumes that the network is stable (i.e., the variation in traffic is small). However, in real networks, the traffic may change during the M stages we used in the additional equation method. Significant variation in traffic causes estimation error because it violates the fundamental assumption of the additional equation method.

Therefore, we remove the information about non-negligible change in traffic from the information monitored in previous stages in order to avoid violating the assumption. Our proposed estimation method contains the following steps.

Step 1 Identify the packet layer paths, including non-negligible changes

Step 2 Remove the information about the traffic of the identified paths from the information monitored in previous stages

Step 3 Estimate the traffic matrix by using the information in which information about the traffic of the identified paths is removed

In the rest of this subsection, we describe these steps in detail.

1) Identify the packet layer paths, including non-negligible change: First, we identify the packet layer paths including non-negligible changes. To do this, we use the method proposed in [20], which identifies source nodes of DDoS attacks based on increase in utilization. We identify the packet layer paths including non-negligible changes in stage n as follows.

First, we calculate differences D_n between the utilization monitored at stage n and the utilization forecasted using the estimated traffic matrix from stage $n-1$.

$$D_n = X_n - A_n \hat{T}_{n-1} \tag{7}$$

Then, we estimate matrix G_n indicating the increases in traffic flows between all pairs of edge nodes using D_n. Finally, if there are elements in G_n that are larger than a threshold Γ, we identify the packet layer paths that correspond to the elements as the paths that include non-negligible changes.

Though this step requires estimation of G_n, we do not have to estimate it accurately. The aim of this step is to identify packet layer paths that include traffic flows that increase significantly more than others. Therefore, when estimating G_n, we have only to estimate the elements corresponding to the packet layer paths with significantly increasing traffic as large values. If there is significantly increasing traffic, the elements in D_n corresponding to the optical layer paths passed by them are significantly larger than other elements. Moreover, elements in D_n corresponding to the incoming/outgoing traffic at the source and destination nodes of the packet layer paths with increasing traffic are also large. In this study, we used the tomogravity method to estimate G_n from D_n. In the tomogravity method, the elements of G_n are estimated as the value proportional to the incoming/outgoing traffic for each edge node. That is, the tomogravity method can estimate the elements in G_n that correspond to the packet layer paths with significantly increasing traffic as large values.

2) Removal of information about non-negligible changes: We remove the information about packet layer paths with non-negligible changes from the information monitored in the previous stages as follows.

We first remove the information of the identified packet layer paths from the routing matrices A_i by replacing the elements corresponding to the identified paths by 0. We denote the routing matrix after the replacement as A'_i, in which the element corresponding to the packet layer path from n to m and the optical layer path between k and l is given by

$$a_i'^{n,m,k,l} = \begin{cases} 0, & \begin{array}{l}\text{if traffic from } n \text{ to } m\\ \text{changes significantly}\end{array} \\ a_i^{n,m,k,l}, & \text{otherwise} \end{cases}, \tag{8}$$

where $a_i^{n,m,k,l}$ is the element of A_i indicating whether or not the packet layer path from n to m passes the optical layer path between k and l.

Then, we create the utilization matrix X'_i in which the information about the identified packet layer paths are removed, which is given by

$$X'_i = X_i - (A_i - A'_i)\hat{T}_{n-1}. \tag{9}$$

In this equation, $(A_i - A'_i)\hat{T}_{n-1}$ indicates the matrix of the identified traffic on each link caluclated by using the traffic matrix estimated at stage $n-1$.

3) Estimate the traffic matrix: To estimate the traffic matrix, we use the equation,

$$X'_i = A'_i T_n + \epsilon_{i,n} \tag{10}$$

instead of Eq. (1). Similar to Eq. (2), by combining all relations from X_{n-M+1} to X_n, we also have

$$\begin{bmatrix} X'_{n-M+1} \\ \vdots \\ X'_i \\ \vdots \\ X'_{n-1} \\ X_n \end{bmatrix} = \begin{bmatrix} A'_{n-M+1} \\ \vdots \\ A'_i \\ \vdots \\ A'_{n-1} \\ A_n \end{bmatrix} T_n + \begin{bmatrix} \epsilon_{n-M+1,n} \\ \vdots \\ \epsilon_{i,n} \\ \vdots \\ \epsilon_{n-1,n} \\ 0 \end{bmatrix}. \tag{11}$$

Note here, that because we remove the information about the traffic with non-negligible changes, X'_i does not include the information about the traffic with non-negligible changes. That is, $\epsilon_{i,n}$ is small.

Therefore, as in Eq. (3), we can estimate $\hat{T}_n$ as

$$\hat{T}_n = \mathrm{pinv}(\bar{A}'_n)\bar{X}'_n, \tag{12}$$

where $\mathrm{pinv}(\bar{A}'_n)$ is the pseudo-inverse of the matrix $\bar{A}'_n$, and $\bar{A}'_n$ and $\bar{X}'_n$ are the matrices defined as

$$\bar{X}'_n = \begin{bmatrix} X'_{n-M+1} \\ \vdots \\ X'_i \\ \vdots \\ X'_n \end{bmatrix} \tag{13}$$

and

$$\bar{A}'_n = \begin{bmatrix} A'_{n-M+1} \\ \vdots \\ A'_i \\ \vdots \\ A'_n \end{bmatrix}. \tag{14}$$

TABLE I
GRADUAL RECONFIGURATION VS FULL RECONFIGURATION USING TOMOGRAVITY METHOD

	Maximum utilization	Number of added optical layer paths	Number of deleted optical layer paths
Before the VNT reconfiguration	0.98	0	0
Gradual reconfiguration ($N = 1$, Stage 1)	0.95	1	0
Gradual reconfiguration ($N = 1$, Stage 15)	0.61	15	0
Full reconfiguration	0.73	15	0
Full reconfiguration using true traffic matrix	0.49	18	7

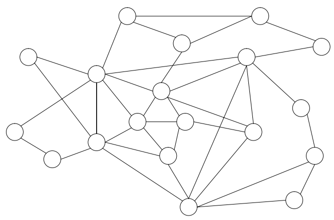


Fig. 4. EON topology

VI. Numerical Evaluation

In this section, we describe the simulation conditions, explain how the simulations demonstrate the effectiveness of the gradual reconfiguration method with the existing traffic matrix estimation, and evaluate the gradual reconfiguration method using the additional equation method.

A. Simulation Conditions

The simulation conditions used in our evaluation were as follows. We use the European Optical Network (EON) (19 nodes, 37 links) shown in Fig. 4 as the physical topology. In this figure, circles represent OXCs, and lines represent optical fibers. The number of wavelengths for each optical fiber is set to 16. The initial VNT is configured by the algorithm described in Section IV with $N = \infty$ using the initial traffic matrix.

In the gradual reconfiguration, we use two thresholds, T_H and T_L, to define the *congested* and *underutilized* states. Setting them to large values preserves more resources (e.g., IP router ports or wavelengths) for future use. However, setting them to large values makes the network sensitive to fluctuations in traffic. For example, packet loss rates or delays increase significantly when there is a spike in traffic. Therefore, to maintain a margin of safety, we set these thresholds to a slightly smaller value than the rate at which network performance degrades significantly (e.g., where delays increase significantly). In our simulations, we set the thresholds T_H and T_L to 0.5 and 0.3, respectively.

In the additional equation method, we use two parameters: Γ and M. Γ is the parameter indicating sensitivity for detection of change in traffic. The traffic whose increase is larger than Γ is identified as traffic including non-negligilbe changes, and the previously monitored information about the traffic is not used for estimating traffic matrix. If we set Γ to too large a value, there is still a non-negligible change in traffic in the information used by the additional equation method. This causes estimation errors. However, a too small Γ causes misdetection of traffic with no non-negligible changes (false positives). As a result, the additional equation method cannot use many of the utilizations monitored in the previous stages. Therefore, we should set the Γ to as small a value as possible such that it will not detect traffic with no non-negligible change by monitoring the traffic in advance. In our simulations, Γ is set to 500 Mbps.

The additional equation method uses the utilizations monitored at last M stages for estimating traffic matrix. That is, we uses more information for estimating the traffic matrix by setting M to large value. By using more information, we can reduce the number of estimation errors. However, using more information requires more memory because more monitored data must be stored. In our simulations, we set M to 50.

B. Effectiveness of gradual reconfiguration

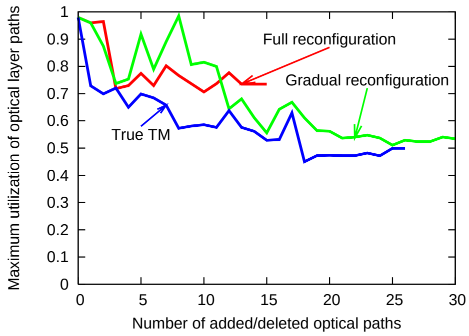
In this subsection, we evaluate the effectiveness of the gradual reconfiguration using the existing traffic matrix estimation method. Because we focus on the impact of estimation errors, we assume that the traffic is constant in all stages to avoid the impact of the change in traffic. We set the initial traffic matrix according to uniform random values. We added 2 Gbps to two randomly selected elements of the initial traffic matrix to form the true traffic matrix used for VNT reconfiguration and chose the tomogravity method [9] for the traffic matrix estimation.

First, we compare the gradual reconfiguration method with the full reconfiguration method. Here, we use the algorithm described in Section IV as our example of the full reconfiguration method by setting $N = \infty$.

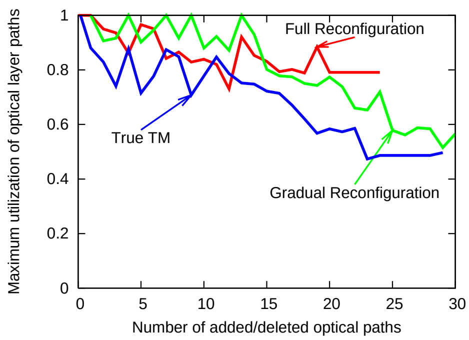
Table I compares the results of full and gradual reconfiguration. In the gradual reconfiguration, we set N to 1. As can be seen from this table, though full reconfiguration can reduce maximum utilization, it is still much higher than in the true traffic matrix and is even higher than in Stage 15 of the gradual reconfiguration where the same number of optical layer paths are added as in the full reconfiguration.

To investigate in more detail, we compared the maximum utilization when the full reconfiguration and the gradual reconfiguration both add the same number of optical layer paths. Figure. 5 shows the results for three different true traffic matrices that were randomly generated in the steps described above. Figuure. 5(a) corresponds to the case shown in Table I. In these graphs, the horizontal axis represents the number of added or deleted optical layer paths and the vertical axis represents maximum utilization. We also plotted the results for the full reconfiguration using the true traffic matrix as a comparison.

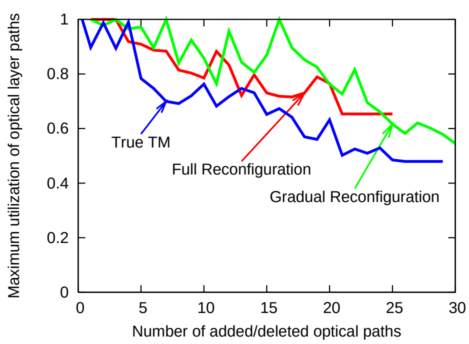
Figure. 5(a) shows the full reconfiguration using the estimated traffic matrix with 15 added optical layer paths. However, the optical layer paths added after the 12th path cannot reduce the maximum utilization. This is because the



(a) Case I



(b) Case II



(c) Case III

Fig. 5. Number of added/deleted paths vs maximum utilization (using tomogravity method)

full reconfiguration decides whether additional optical layer paths are needed based on utilization calculated using the traffic matrix estimated at the beginning of the VNT reconfiguration. In this case, after the 12th optical layer path is added, though the actual maximum utilization is 0.73, the estimated utilization of the optical layer path with the largest actual utilization is 0.50. As a result, the optical layer path is mistakenly identified as a path whose utilization is less than T_H. Therefore, no optical layer paths are added to circumvent traffic traversing the optical layer path. Finally, though the maximum utilization is still over the threshold, the VNT reconfiguration is completed.

The gradual reconfiguration, in contrast, is not completed until the maximum utilization drops to less than T_H, though the maximum utilization increases at some stages due to estimation errors. This is because the utilizations are monitored each time an optical layer path is added or deleted. By monitoring utilizations, the gradual reconfiguration algorithm decides whether additional optical layer paths are needed based on the monitored utilizations. Therefore, no optical layer paths are added that cannot circumvent traffic traversing the optical layer path with maximum utilization.

However, there are cases in which the addition of an optical layer path by the gradual reconfiguration also cannot reduce the maximum utilization. This is because the routes of packet layer paths over the VNT are inadequate due to estimation errors. For example, though the estimated maximum utilization after the addition of the 8th optical layer path is reduced to 0.80, the actual utilization is 0.98, which is much higher than before the 8th optical layer path is added. These increases in the maximum utilization caused by estimation errors also cause reconfiguration instability. In the case shown in Fig. 5(a), because of estimation errors, the maximum utilization never drops below the threshold, and optical layer paths continue to be added.

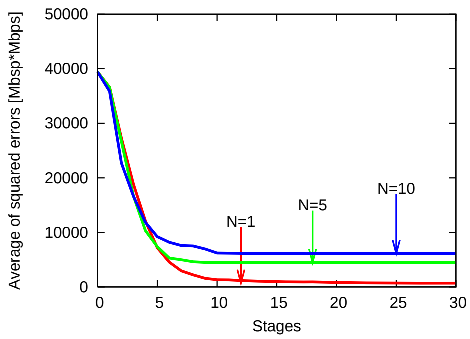
The results shown in Figs. 5(b) and 5(c) are similar to those shown in Fig. 5(a). In all cases, the full reconfiguration stops adding optical layer paths even though the maximum utilization is still high. The gradual reconfiguration, in contrast, continues to add optical layer paths until the maximum utilization drops below T_H. However, because of estimation errors, the maximum utilization never does drop below T_H. That is, estimation errors also have impact on the gradual reconfiguration. To avoid this impact, estimation errors must be reduced, which will be discussed in the next two subsections.

C. Effectiveness of reducing estimation errors: the case of no change in traffic

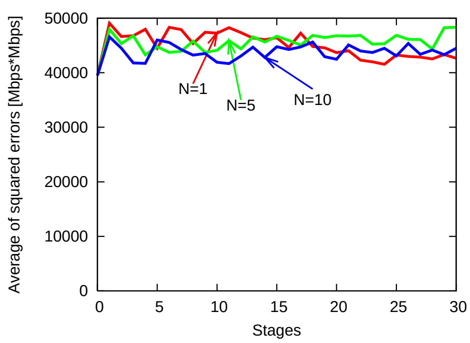
Here, we evaluate the gradual reconfiguration using the additional equation method to estimate the traffic matrix. First, to compare the result for this combined method with those discussed in the previous subsection, we evaluate our methods when traffic is constant in all stages. Then, we evaluate them when traffic changes in the nexe subsection.

First, we evaluate the combined method to estimate the traffic matrix when traffic is constant in all stages. In this simulation, we intend to compare the tomogravity method and the additional equation method setting N to 1, 5, and 10. We conducted the simulations using ten different traffic matrices generated by the same steps as discussed in the previous subsection. In this paragraph, we present the average of the results.

Figure. 6 shows the average of squared estimation errors for each stage. In this graph, the horizontal axis represents the number of stages after the beginning of the VNT reconfiguration, and the vertical axis represents the average of squared estimation errors. As can be seen in this figure, the additional equation method dramatically reduces estimation errors as the stages are completed, while estimation errors of



(a) Additional equation method



(b) Tomogravity

Fig. 6. Average squared errors of traffic matrix estimation

the tomogravity method are large in all stages. This is caused by the difference in the number of equations used in traffic matrix calculation. The tomogravity method uses only the utilizations monitored at each stage. That is, the tomogravity method uses only the same number of equations as the number of optical layer paths. On the other hand, when some routes of packet layer paths are changed, the additional equation method adds the equations about the packet layer paths whose routes are changed. As a result, the number of equations used by the additional equation method increases as it progresses through the stages.

Figure. 6 also shows that before Stage 5, the estimation errors are reduced to the same level regardless of N. This is because the number of packet layer paths whose routes are changed are almost the same regardless of N. In this simulation, a packet layer path is routed on the VNT according to the following policy; when a packet layer path can be accommodated to the same route as the previous stages without causing utilizations higher than T_H, the packet layer path is accommodated on the same route as the previous stage, otherwise the routes are re-calculated using CSPF so as to limit the maximum link utilization to less than T_H. When one or more optical layer paths are added, the packet layer path traversing the optical layer paths whose utilizations are higher than T_H moves to the optical layer paths whose utilizations are low. Because the number of packet layer paths traversing optical layer paths whose utilizations are higher than T_H before the VNT reconfiguration is the same regardless of N, the number of packet layer paths whose routes are changed is also almost the same regardless of N.

In contrast, in the final stage, by setting N to a smaller value, we can estimate the matrix more accurately. This is because, when we set N to a large value, the VNT reconfiguration is completed in a small number of stages. Therefore, the number of additional equations is smaller when setting N to a large value than when setting N to a small value. This way, by setting N to a small value, we can estimate more accurately and limit the number of optical layer paths to be added or deleted before reducing the estimation errors.

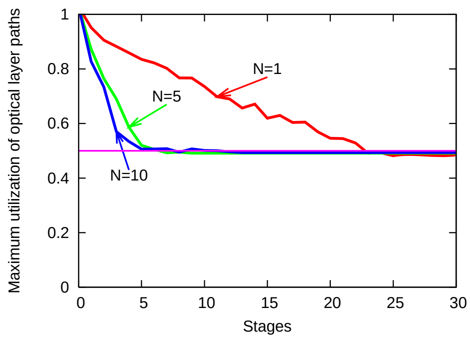
Figure. 7 shows the maximum utilization in each stage. In this figure, as described in the previous subsection, the gradual reconfiguration using the traffic matrix estimated by the tomogravity method is unstable and cannot reduce the maximum utilization to less than T_H. In contrast, the additional equation method can reduce the estimation errors as it progresses through the stages. Because of this, the gradual reconfiguration using the traffic matrix estimated by additional equation method can reconfigure an adequate VNT whose maximum utilization is under T_H. In the case of the gradual reconfiguration with the additional equation method, the larger N is, the faster the maximum utilization is reduced. This is because, if we set N to a small value, the number of optical layer paths added in each stage is limited, and more stages are required to reduce the maximum utilization.

Figure. 8 shows the number of optical layer paths added or deleted by the gradual reconfiguration using the additional equation method until the VNT becomes stable. In this figure, we compare the cases where $N = 1$, 5, and 10. In this figure, if we set N to a larger value, we need to add or delete more optical layer paths until the VNT becomes stable. This is because many optical layer paths are added or deleted before the estimation errors are reduced when there is a large N. As a result, due to estimation errors, many unnecessary optical layer paths are added.

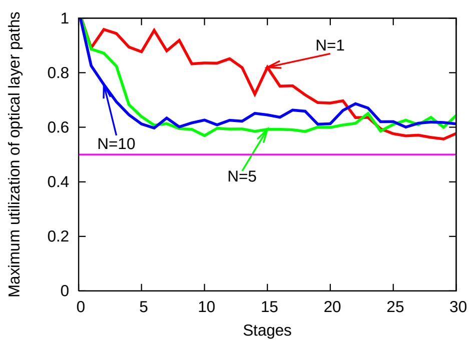
This means that there is a trade-off between the time needed to reduce the maximum utilization and the number of added or deleted optical layer paths. If we set N to a large value, the maximum utilization is reduced quickly. However, in this case, more optical layer paths are added or deleted, which requires more resources, such as IP router ports and wavelengths. By setting N to a small value, on the other hand, we can achieve the adequate VNT by adding or deleting a small number of optical layer paths even though it will take more stages to achieve the adequate VNT. Therefore, N should be set to as small a value as possible without leaving significantly high utilizations for multiple stages. One possible approach is to set N dynamically based on current utilization. However, this is beyond the scope of the current study and is left to future work.

D. Effectiveness of reducing estimation errors: the case that traffic changes

The evaluation described above assumes that the traffic is constant after the beginning of the VNT reconfiguration.



(a) Additional equation method



(b) Tomogravity

Fig. 7. Maximum utilization

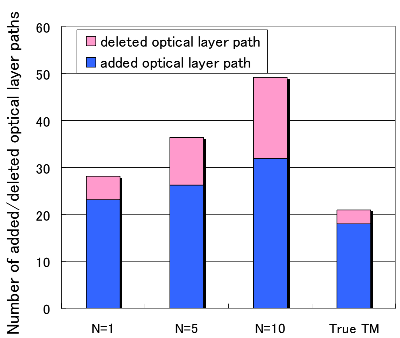


Fig. 8. Number of added/deleted optical layer paths of additional equation method

However, real traffic changes over time. Therefore, in this subsection, we evaluate our methods assuming that traffic changes.

1) Adaptability to the fluctuations in traffic: We evaluated the robustness of the additional equation method to changes in traffic, generating changes in traffic as follows.

$$t_{i,j,n} = \alpha_{i,j} + \gamma_{i,j,n} \tag{15}$$

where $t_{i,j,n}$ is the amount of traffic from node i to node j at stage n, $\alpha_{i,j}$ is the average of traffic from node i to node j, and $\gamma_{i,j,n}$ is the factor by which traffic fluctuates. In this simulation, we generated the value of $\gamma_{i,j,n}$ based on normal random values whose average is 0 and variance is $(\lambda\alpha_{i,j})^2$.

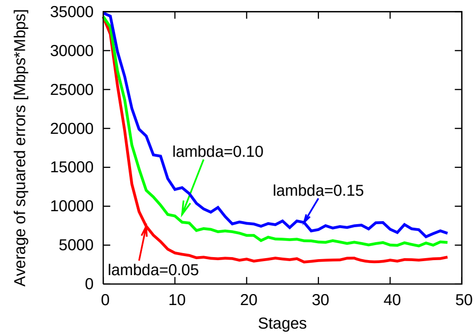


Fig. 9. Impact of fluctuations in traffic on estimation errors (additional equation method)

Then, by changing the value of λ, we changed the size of the fluctuation in traffic.

Figure. 9 shows the results for $\lambda = 0.05$, 0.10, and 0.15. In this simulation, we set N to 1. Like the simulation described in the previous paragraph, the initial traffic matrix was generated according to uniform random values. Then, we generated the traffic matrices after the beginning of the VNT reconfiguration using Eq.(15). We set $\alpha_{i,j}$ equal to the element of the matrix generated by adding 2 Gbps to two randomly selected elements of the initial traffic matrix. In this graph, the horizontal axis represents number of stages since the beginning of the VNT reconfiguration, and the vertical axis represents the average of squared estimation errors. From this figure, the smaller λ is, the faster we can reduce the estimation errors. However, even when $\lambda = 0.15$, the additional equation method can reduce estimation errors significantly because, in this method, the number of equations used to estimate the traffic matrix increases as it progresses through the stages. The additional equations constrain the solution of the traffic matrix estimation. Here, in this simulation, we generate the fluctuation component of traffic according to normal random values whose average is 0. Therefore, no utilization monitored in any stage is far from the traffic in the current stage. In addition, the utilizations monitored in stages with temporally high or low traffic are balanced out. As a result, since the constraints from the additional equations are appropriate to the current traffic, we can increase the accuracy of the traffic matrix estimation as we progress through the stages.

2) Adaptability to sudden change in traffic: There is another type of change of traffic. The real traffic may change suddenly. We evaluated the adaptability of our additional equation method to such sudden changes in traffic. In this simulation, we generated sudden changes in traffic by adding 2 Gbps to two randomly selected elements in the traffic matrix described in the previous paragraph. We set λ to 0.10 and N to 1 and added a sudden change in Stage 9.

Figure. 10 compares estimation errors for the following three methods.

- Additional equation method (with detection of non-negligible change)
- Additional equation method (without detection of non-negligible change)
- Tomogravity

In this figure, the horizontal axis represents stages since the

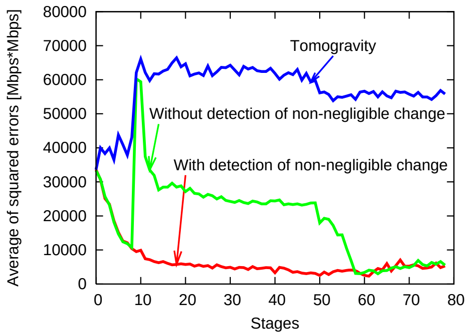


Fig. 10. Estimation errors when there is a sudden change in traffic

beginning of the VNT reconfiguration and the vertical axis represents the average of squared estimation errors. In this figure, as in the case shown in Fig. 6, the tomogravity method cannot reduce estimation errors because it uses only the utilization monitored at the current stage. On the other hand, the additional equation methods can reduce the estimation errors as they progress through the stages. However, after Stage 9, the estimation errors of the additional equation method without detection of non-negligible change increase significantly. This is because the utilization before the sudden change, which is far from the current traffic, is used to estimate the traffic matrix. These large estimation errors continue while the additional equation method uses the information before the sudden change (i.e., until Stage 59). On the other hand, the additional equation method with detection of non-negligible change can reduce the estimation errors even after Stage 9 because it can remove the information about the traffic with non-negligible change. That is, even when there is a sudden change in traffic, by identifying and deleting the information about the traffic with such changes, the additional equation method can estimate a traffic matrix accurately. As a result, an accurate traffic matrix is available for VNT reconfiguration.

VII. Concluding Remarks

We have proposed a VNT reconfiguration and traffic matrix estimation methods that reduce estimation errors during VNT reconfiguration by cooperating with each other. Our method reconfigures the VNT gradually by dividing it into multiple stages and limiting the number of optical layer paths reconfigured in each stage. By dividing the VNT reconfiguration into multiple stages, our traffic matrix estimation method calibrates and reduces the estimation errors in each stage by using information monitored in prior stages. As progresses through the stages, a more adequate VNT is configured with the more reliable traffic matrix obtained by our estimation methods. In addition, by limiting the number of optical layer paths reconfigured in each stage, our method avoids mistakenly adding or deleting many optical layer paths. That is, our reconfiguration method can mitigate the impact of estimation errors. We have also investigated the effectiveness of our proposal using simulations. The results show that our method can improve the accuracy of the traffic matrix estimation and construct an adequate VNT. In future work we plan to set parameters (e.g, N) automatically.

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