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IP・光マルチレイヤTEにおけるトラヒックマトリクス推定の影響

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abstract　トラヒックを効率的に収容する方法として、パケットレイヤ網とオプティカルレイヤ網で協調してトラヒック制御をおこなうマルチレイヤトラヒックエンジニアリングの研究が進められている。トラヒック収容効率を高めるためには、対地間トラヒック量を測定することでネットワーク全体のトラヒック発生状況を把握し、その上で最適なトラヒック制御を行うことが必須となる。しかし、ネットワークの規模が大きくなるとともに、すべての対地間トラヒック量を測定することは困難となる。そのため、リンク負荷などの一部の測定情報から対地間トラヒック量を推定するトラヒックマトリクス推定手法の適用が望まれるが、トラヒックマトリクス推定により対地間トラヒック量に推定誤差が生じ、その結果、効率的なトラヒック収容が達成できない可能性がある。本稿では、推定手法により得たトラヒックマトリクスを用いてトラヒックエンジニアリングを行った際に、推定誤差がネットワーク性能にあたえる影響の評価を行う。評価の結果、マルチレイヤトラヒックエンジニアリングを適用した場合、シングルレイヤによるトラヒックエンジニアリングよりも良い性能を示すものの、推定誤差による性能低下が大きくなることが明らかとなった。そこで、推定誤差を減少させることを目的として、トラヒックの経路の変更に基づいたトラヒックマトリクスの再推定手法を提案した。そして提案手法を用いて各対地間トラヒックの40%の精度を向上することによりネットワークに収容可能なトラヒック量が増加することがわかった。

keyword　トラヒックエンジニアリング、GMPLS、トラヒックマトリクス推定

Impact of traffic estimation on IP and optical multilayer TE

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Abstract　We consider multilayer traffic engineering (TE) strategies in IP and Optical networks. TE approach require a traffic matrix to compute the optimal topology, but it is infeasible to collect traffic matrix information for large-scale networks due the N-square problem. Hence we evaluate the impact of the traffic matrix estimation on multilayer TE. The results shows that even in the case of using the estimated traffic matrix, multilayer TE can improve the amount of traffic the network can accomodate, though the impact of estimation errors is not small. We also propose a new method to reduce the error of estimation errors by reestimating a part of traffic matrix. We evaluate the proposed method by simulation. The results shows that to reduce the impact of estimation errors on TE, we need to select the entries of traffic matrix to reestimate by considering the balance between total of underestimate and overestimate errors.

Key words　Traffic engineering, GMPLS, Traffic matrix estimation

1 Introduction

One of the key technologies in IP and Optical multilayer networks lies in multilayer traffic engineering (TE) which optimizes resource usage by dynamically reconfiguring the VNT (virtual network topology) in addition to route changes for packet-layer traffic to meet variations in traffic demand. Here, a VNT is defined as a set of optical paths that carry packet traffic between edge routers.

For a multilayer IP and Optical network, we can apply either packet-layer TE, optical-layer TE, or multilayer TE (the combination of packet-layer TE and optical-layer TE). In packet-layer TE, the routing of IP packets is controlled from the top of the lower-layer fixed topology, based on traffic demand variation and quality requirements of the traffic. The lower-layer fixed topology may be a physical topology itself, or may be a fixed logical topology, which is a fixed VNT. To perform packet-layer TE, there are two main approaches, One approach uses MPLS technologies, which establish label switched paths (LSPs) that accommodates classified packets. Each LSP route is explicitly controlled in a sophisticated manner [1]. The other approach is to control the packet route according to the minimum-cost routing policy, where metrics with Interior Gateway Protocol (IGP) like Open Shortest Path First (OSPF) are used as cost [2, 3]. Metrics are adaptively adjusted according to network conditions. The packet-layer TE approach is widely deployed in operational IP backbone networks, but it has a scalability concern because of the N-square number of edge-to-edge flows.

Optical-layer TE schemes assume that the network consists of electrical IP routers and optical cross-connects (OXC). Each port of an electrical IP router or an OXC is connected to another OXC port via WDM (Wavelength-division multiplexing)-based physical links. An optical path is established on top of the physical topology between two IP routers by configuring OXCs along the route between the routers, and it is terminated at a transceiver in an IP router. In the packet-layer network, an optical path is identified as a logical link, and a set of optical paths forms a VNT. Packet traffic between two IP routers is routed on top of the VNT using the MPLS explicit routing technology or IP routing technology. Optical-layer TE approaches are to configure an optimal or near-optimal VNT for a given traffic demand, which improves the efficiency of network resource utilization [4–6]. This approach dynamically reconfigures optical-layer topology, so it can accommodate the case in which traffic widely fluctuates within one day.

To compute an optimal VNT, information about network resources and information about traffic demand of edge-to-edge flows (hereinafter, called the traffic matrix) is required. To obtain a traffic matrix, fully meshed packet paths are configured between each pair of edge routers on top of the VNT. Traffic measurement information from the network should be periodically collected. However, this approach does not scale well because of the N-square number of packet paths. Thus, to realize traffic engineering in a large-scale IP and Optical network, a more scalable method for obtaining traffic matrix is necessary. One possible solution is the traffic matrix estimation approach. It presumes a traffic demand matrix based on indirect data (such as link utilization). Once estimated traffic demand matrix is obtained, we can pass it through the TE algorithm selected.

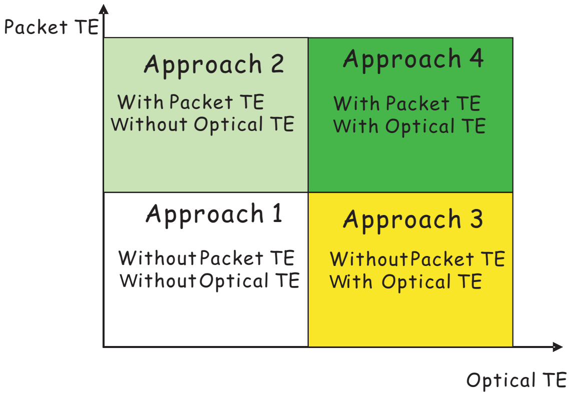

Figure 1 Approach overview

One of concerns is that the estimated traffic demand matrix inevitably contains some estimation errors. Roughan *et al.* [7] addressed the issue of such estimation errors with regard to IP and MPLS traffic engineering (i.e., packet-layer TE). However, few papers have studied the impact of estimation errors on multilayer TE. Thus, in this paper, we investigate the impact of such errors on multilayer TE and point out the limitations of the conventional estimation schemes. We then propose a traffic matrix estimation method suitable for both multilayer TE and packet-layer TE.

The rest of this paper is organized as follows; Section 2 summarizes strategies for packet-layer and optical-layer TE approaches and presents mathematical formulation for these approaches. Next, we show simulations that demonstrate the limitations of conventional traffic matrix estimation algorithms and propose our algorithm in Section 3. Finally, a brief conclusion is provided in Section 4.

2 Models of Multilayer Traffic Engineering

2.1 Approach overview

We first summarize TE approaches in multilayer IP and Optical network. Figure 1 illustrates our overview. In Approach 1, packet traffic is routed based on minimum hop routing on top of a fixed VNT, while Approach 2 introduces reoptimization of packet layer routing on top of a fixed VNT. In Approach 2, each packet path can be rerouted to accommodate changes in the traffic matrix. Thus, under dynamically fluctuating traffic demand, it can reduce the wastage of network resources more efficiently than Approach 1. Approaches 3 and 4 dynamically reconfigure the VNT itself unlike Approaches 1 and 2. The difference between Approach 3 and Approach 4 lies in packet layer routing. Approach 4 introduces reoptimization of the packet traffic routes, while Approach 3 uses minimum hop routing to determine packet layer routing. Accordingly, Approach 4 is expected to yield the maximum network resource utilization efficiency. In this paper, packet-layer TE, optical-layer TE, and multilayer TE correspond to Approaches 2, 3, and 4, respectively.

2.2 Details of TE approaches

Table 1 lists TE approaches for traffic engineering used in our

Table 1 Strategies for multi-layer traffic engineering

	minimum hop	single-path
Fiber-link	Approach 1	Approach 2
optical-layer TE	Approach 3	Approach 4

evaluations. For packet-layer TE, we consider minimum hop routing, single-path routing, and multi-path routing. Minimum hop routing simply selects the minimum hop-count routes on top of the VNT. Single-path routing poses a constraint that traffic is not split between a node-pair as is true for minimum hop routing, but unlike minimum hop routing, the route is optimized for a given performance objective. In our evaluation, we use the amount of traffic that the network can accommodate. Multi-path routing relaxes the constraint such that arbitrary amounts of traffic can be pushed onto two or more routes.

For optical-layer TE, two approaches are considered: “fiber-link” and optical-layer TE. The fiber-link approach configures optical channels only between neighboring nodes. That is, optical channels are used only for increasing link bandwidth at that link, and are not used to relax packet processing at router nodes. The optical-layer TE approach designs the optimal VNT following our MILP formulation in Section 2. 3 and 2. 4. Here, optimal does not mean minimizing optical layer resource (i.e., wavelengths) utilization, but maximizing the amount of traffic by using all the network resources. Another possible approach designing VNTs is to minimize resource usage at optical-layer [8]. However, we do not consider this idea since our primary concern is whether multi-layer TE sufficiently resolves the network bottlenecks or not.

In Section 2. 3, we first describe the formulation for multi-layer TE (i.e., Approach 4 in Figure 1). A single-path case is then summarized in Section 2. 4. Since Approach 1 and Approach 2 that do not require VNT design, we obtain the results by fixing the variables related to VNT configuration. The first step in determining the results achieved by Approach 3 is to design the VNT assuming that packet routing is based on single path routing. Then, the minimum hop routing is applied on top of the VNT. Note that we will use the single-path routing as the packet-layer routing in multi-layer traffic engineering. We nonetheless present a formulation of multi-path routing for clarity.

2. 3 Formulation of IP-layer/Optical-layer TE approaches: Multi-path case

A graph is represented as $G(V, E)$ where V is a set of nodes and E is a set of fibers. Let N be the number of nodes in G, and W be the number of wavelengths carried in a fiber. The following notation is used for representing our networks.

s, d: source and destination nodes of IP traffic.

i, j: originating and terminating nodes of a logical link.

m, n: end nodes of a physical link. The physical link connecting nodes m and n is represented as e^{mn}.

l: The index number of logical links between nodes.

Note that we assume full wavelength conversion, and thus we do not have wavelength-level variables. We denote T_{sd} as the amount of traffic demand between nodes s and d. In our formulation, G, W and T_{sd} are given parameters. We then introduce following variables for our formulations.

$f^t_{ij,k}$: Amount of traffic toward node t which traverses the k-th logical link configured between node i and node j. This variable is continuous.

L_{ij}: An integer variable that represents the number of logical links between nodes i and j

l^k_{ij}: A Boolean variable. If the k-th logical link between nodes i and j is used by some traffic flow, it is 1, otherwise 0.

A^{ij}_{mn}: A Boolean variable. If logical links between nodes i and j use physical link $e^{mn} \in E$, it is 1, otherwise 0.

M: The maximum of link load on a logical link.

R: The maximum router load.

α: Scale factor.

Using the above notations and variables, we formulate packet-layer /optical-layer TE approaches as follows. We first introduce constraints for packet-layer and optical-layer TEs.

2. 3. 1 Constraints for Packet-layer TE

- For each destination node d, the amount of traffic that arrives at node d is given by $\sum_{l_{ij}} f^d_{l_{ij}}$. The amount of traffic is multiplied by the scale factor α. Note that our objective function in our formulation is to maximize the amount of traffic in the network. We achieve this by maximizing α.

$$\sum_{ij} \sum_{l:(ij)\in l} \sum_{k} f^d_{l,k} = \alpha \cdot \sum_{v} T_{vd} \quad \forall\, d \tag{1}$$

- At each node v and each destination node t, the amount of traffic bounds for t is equal to the sum of traffic that arrives at v and the traffic that originates from v.

$$\sum_{j} \sum_{l:(v,j)\in l} \sum_{k} f^t_{l,k} = \sum_{i} \sum_{l:(i,v)\in l)} \sum_{k} f^t_{l,k} + \alpha \cdot T_{vt} \quad \forall\, v, t \tag{2}$$

2. 3. 2 Constraints for Optical-layer TE

- For each physical link e^{mn}, the number of logical links that pass through the physical link e^{mn} must be less or equal than W,

$$\sum_{ij} A^{ij}_{mn} \leqq W \quad \forall\, e^{mn} \in E. \tag{3}$$

- The number of logical links between nodes i and j is defined as,

$$L_{ij} = \sum_{ij} \sum_{n} A^{ij}_{in} = \sum_{ij} \sum_{m} A^{ij}_{mj} \quad \forall\, ij. \tag{4}$$

- For each node v and logical links between ij, the number of in-coming logical links at node v equals the number of outgoing logical links at node v,

$$\sum_{m} A^{ij}_{mv} = \sum_{n} A^{ij}_{vn} \quad \forall\, v, \forall\, ij. \tag{5}$$

2. 3. 3 Mapping traffic to logical links

- For each pair of nodes i and j, there must be a sufficient number of logical links between nodes i and j such that the traffic can be conveyed. That is,

$$L_{ij} \geqq \sum_{l:(ij)\in l} \sum_{t} \sum_{k} f_{l,k}^{t} \quad \forall\, ij, \tag{6}$$

and the minimum number of logical links is configured between nodes i and j,

$$L_{ij} \leqq \sum_{l:(ij)\in l} \sum_{t} \sum_{k} f_{l,k}^{t} + 1 \quad \forall\, ij. \tag{7}$$

We want to maximize the amount of traffic that the network can accommodate (Vo). However, since the current backbone network does not fully utilize the link capacity, we have a restriction on the maximum link-utilization (M), and a restriction on router processing capacity (R). The following equations codify such restrictions for VNT design.

- The total amount of traffic that pass through a logical link l is bounded by M,

$$M \geqq \sum_{l:(ij)\in l} \sum_{t} \sum_{k} f_{l,k}^{t} \quad \forall\, ij \in l. \tag{8}$$

- The total amount of traffic that pass through node v is bounded by variable R,

$$R \geqq \sum_{j} \sum_{l:(v,j)\in l} \sum_{t} \sum_{k} f_{l,k}^{t} + \sum_{i} \sum_{l:(i,v)\in l} \sum_{t} \sum_{k} f_{l,k}^{t} \quad \forall\, v.$$

The first term of the right equation represents the amount of incoming traffic to node v, and the second term represents the amount of out-going traffic from node v.

By using the above constraints, we maximize the amount of traffic that the network can accommodate, by maximizing scale factor α. That is,

$$\text{maximize} \quad \alpha. \tag{9}$$

2. 4 Formulation of IP-layer/Optical-layer TE approaches: single-path case

We introduce variables r_l^t that represent '0-1' indication of whether traffic bound for t passes through logical link l. By definition,

$$\sum_{k} f_{l,k}^{t} \leqq r_l^t \quad \forall\, t, l. \tag{10}$$

In the case of single-path routing, at most one logical link is selected as its single-path route. Thus, for each node v,

$$\sum_{j} \sum_{l:(v,j)\in l} r_l^t \leqq 1 \quad \forall\, v, t. \tag{11}$$

3 Applicability of traffic matrix estimation method

3. 1 Optimization of logical topologies using estimated traffic matrix

3. 1. 1 Applicability of existing methods

Prior to giving a brief summary of previous works, we first describe the basic requirements on traffic matrix estimation for multilayer TE.

（1） Basically, VNT reconfiguration is performed when the current traffic demand is significantly different from the previous demand. In other words, if VNT reconfiguration is invoked, the previous traffic demand is not a good indicator of current traffic demand.

（2） For large-scale IP/Optical networks, the estimation method should be scalable against the number of edge-to-edge paths.

（3） It is obvious that traffic matrix estimation should be as accurate as possible because the reconfiguration algorithm is optimum if estimation is completely accurate.

A fast estimation method was proposed by Zhang *et al* [9]. This method uses a gravity model, which assumes that traffic demands from a source to a destination node are proportional to the total of incoming/outgoing traffic for each edge node. Results in [9] show that the method can follow the rapid changes in traffic demands, and can estimate the traffic matrix on a tier-1 ISP network within 5 seconds.

Some other methods use traffic statistics measured on edge routers to improve the accuracy of estimation. Papagiannaki *et al* proposed [10] a data-driven method which uses 24 hour flow statistics to estimate the traffic matrix. Soule *et al* proposed [11] the Principal Component Analysis (PCA) approach, which classifies the most important flow patterns as identified by traffic monitoring. However, there are two problems in estimating traffic matrices for VNT reconfiguration. [11] showed that any estimation would have a significant error (but tomogravity [9] provides the best estimate) if the correlation between current and previous traffic demands is weak. Furthermore, these methods require the traffic between all pairs of edge nodes to be monitored for a certain period (e.g., 24 hours). This is a serious overhead for a large scale network.

Based on this background, we choose the approach that provides the most accurate estimation (requirement 3)), while satisfying requirements 1) and 2). Accordingly, we use the gravity/tomogravity model [9].

Although the tomogravity model is more accuracy than the gravity model, its errors are significant in some cases [12]. We discuss this in the next subsection, and clarify what kinds of error significantly impact VNT reconfiguration performance. We then propose a new traffic estimation method which makes multilayer TE more efficient.

3. 1. 2 Impact of estimation errors

In this subsection, we first show the impact of estimation errors in the tomogravity model and discuss what kinds of error are dominant factors with regard to multilayer TE.

We investigate the impact of errors, by the following steps.

（1） Assume a traffic matrix (referred *true traffic matrix*) as the input

（2） Estimate the traffic matrix (referred *estimated traffic matrix*) using the tomogravity method

（3） Reconfigure the virtual topology from the estimated traffic matrix

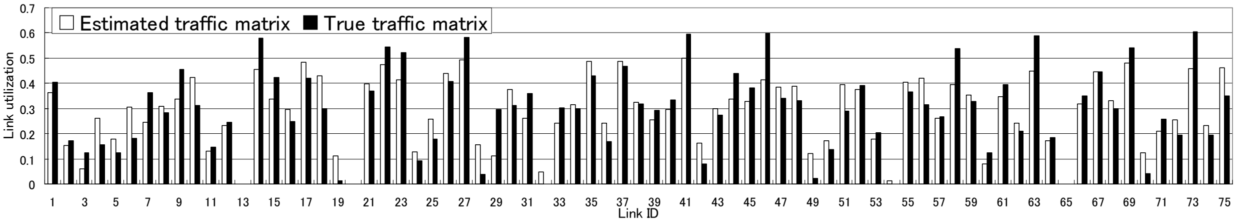

Figure 2 Utilization of logical links (random traffic model)

Table 2 Impact of estimation errors on TE approaches

	Pr	Vo
Approach 1	N/A	99 Gbps
Approach 2	1.05	100 Gbps
Approach 3	1.09	100 Gbps
Approach 4	1.21	119 Gbps

（4） Calculate the utilization of each logical link on the reconfigured topology

In this simulation, we use the backbone topology of NSFnet, and set the maximum number of wavelengths to be 4. We assume the single path case. For each TE approach, we set R and M to 40 Gbps and 0.5 respectively. Bandwidths of all optical paths are identical, i.e., 10 Gbps.

As the true traffic matrix, we use a randomly generated traffic, which sets the traffic demand for each edge pair according to a random value whose mean is 1.05 Gbps, in order to investigate how multilayer TE works when the traffic estimation is inaccurate. It is because the accuracy of the tomogravity method worsens when the traffic demands are random, where this condition exhibits no correlation between the total amount of ingress/egress traffic at source and destination nodes.

The link utilization of the topologies configured for the random traffic model is shown in Figure 2. From this figure, some link utilizations are higher than their estimated utilizations. The VNT reconfiguration is performed using the estimated traffic matrix. That is, each traffic demand entry in the traffic matrix may contain negative or positive error. When the traffic demand is underestimated (negative error), the actual utilization based on traffic passing the logical link exceeds the underestimated level and becomes higher than the utilization expected.

The link utilization higher than the expected utilization decrease the amount of traffic the network can accommodate. Therefore, we evaluate impact on the amount of traffic the network can accommodate with comparing other TE approaches. The maximum amount of traffic the network can accommodate (Vo) is compared among four TE approaches. According to the similar way of calculating Vo, we map the true traffic matrix scaled by maximized α in Eq. (1) with the constraint of R and M. For each TE approach, we also analyze the proportion Pr of the observed maximum link utilization to its estimated value after VNT reconfiguration.

Table 2 shows that Approach 4 has the largest value of Pr, which indicates that Approach 4 is the most sensitive to estimation errors. The difference between estimated and true link utilizations after reconfiguration is the sum of estimation errors of traffic passing the logical link. Because the tomogravity method uses link utilization monitored before TE as an input, the sum of traffic volume passing a link before the reconfiguration simply represents a utilization of the link, i.e., it contains no estimation error. Consequently, the sum of estimation errors for passing a link after reconfiguration is the sum of estimation errors of traffic whose routes are changed by the reconfiguration. In the tomogravity model, there is a weak correlation between the property of path and the amount of estimation error when the traffic volumes are randomly given. Therefore, the estimation error of the link is relative to the number of routes passing the link changed by the reconfiguration.

From the viewpoint of the degree of route changes (i.e., how many routes are changed by TE) after reoptimization for each TE, Approach 2 changes only packet-layer routing and has a smaller number of logical links compared to Approaches 3 and 4. That is, Approach 2 has less alternative routes than Approaches 3 and 4. Approach 3 also configures the VNT, however, this approach only performs the minimum hop routing in the packet-layer. From these comparison, Approach 4 may have more route changes compared to Approaches 2 and 3, and therefore it may have more estimation errors.

From Table 2, we can also see that Approach 4 can accommodate the highest amount of traffic despite being the most sensitive to estimation errors. In this way, Approach 4 can work well if we use the estimated traffic matrix, although the impact of estimation errors on it is the greatest among four TE approaches. If we could reduce the impact of estimation errors, Approach 4 would work even better. Accordingly, we propose a method to reduce such impact in the next subsection.

3. 2 Proposed method for reducing impacts of estimation errors

In this subsection we propose a method to reduce the impact of estimation errors on VNT reconfiguration performance. Our method is based on the *reestimation* of part of the traffic matrix in order to better approximate the traffic demand. More specifically, we reestimate entries of the traffic matrix by changing a part of the route of packet LSP l so that it passes through optical path p. As the result of changing the route, the amount of traffic on optical path p is changed by the amount of traffic, r_l , of packet LSP l, i.e.,

$$r_l = x'_p - x_p, \tag{12}$$

where x_p and x'_p are the rates of traffic on optical path p monitored before and after changing the route, respectively.

Increasing the number of edge-to-edge paths reestimated by setting new LSPs raises the accuracy of traffic matrix estimation. Here,

Table 3 Results of reconfiguration using the reestimated traffic matrix

Method	Pr	Vo
True traffic matrix	N/A	142 Gbps
Tomogravity	1.21	119 Gbps
M1	1.49	99 Gbps
M2	1.30	106 Gbps
M3	1.00	110 Gbps
M4	1.14	130 Gbps

the main issue of the proposed method is how to decide which paths should be re–estimated. We propose four methods as follows.

M1 Select the entries randomly from the set of entries

M2 Select the entries in descending order of the number of hops for each traffic demand

M3 Select the entries in descending order of the underestimation error value

M4 Select the entries in descending order of absolute error value

M2 is based on the fact that errors in a path having a larger number of hops have impacts to more logical links. M3 is based on the fact that the logical link, whose true link loads is high, is caused by underestimation and the high load link reduce the amount of traffic the network can accommodate. M4 is the method which can reduce the estimation errors optimally irrespective of underestimated entry or overestimated entry.

Note here that our purpose on proposed selection methods is to investigate the possibility of improvement of the accuracy by the partial matrix reestimation. We therefore assume that routers can collect the amount of overestimate/underestimate errors for the next traffic matrix estimation, while it is difficult to obtain the exact values in the real environment.

3. 3 Evaluation

We examined the VNT reconfigurations with Approach 4 yielded by the traffic matrices reestimated by M1 through M4. In this simulation, we used the backbone topology of NSFnet and set the maximum number of wavelengths to 4. We reestimate 40 % of all traffic matrix entries. We evaluate the effect of reestimation by using Vo and Pr.

Table 3 compares Pr and Vo among four selection methods. We also show the results in true traffic matrix and tomogravity cases for comparison purpose. From this table, an interesting observation is shown that reestimation to obtain the actual traffic demand is not always improve the accuracy of the estimation. For example, the result of M1 shows that the reestimation gives worse accuracy compared to the tomogravity model (i.e., without reestimation) even if 40% of edge-to-edge paths are obtained true traffic demands. Another observation is that reducing the value of Pr cannot always give an improvement of accommodative traffic on TE. It is because reducing underestimaed entries increases the overestimated link utilization which reserves unnecessary bandwidth, though reducing underestimaed entries can reduce the value of Pr. On the other hand, Pr in M4 is smaller, and can accommodate more traffic than the tomogravity model. That is, one important issue on reestimating true traffic demand is not only the amount of estimation error, but also the balance between total of underestimate and overestimate errors which would be relaxed by the reestimation.

4 Concluding Remarks

We considered multilayer traffic engineering (TE) strategies for IP and Optical networks. Since it is infeasible to collect a comprehensive traffic matrix information for a large-scale network due the N-square problem, hence we developed a traffic matrix estimation method suitable for multilayer TE. In this method, we reestimate entries of the traffic matrix by changing a part of the route. We investigated its performance through extensive simulations. The result shows that we can significantly reduce the impact of estimation errors by reestimating the 40 % of all traffic matrix entries.

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