Optimal Load Balancing Method for Symmetrically Routed Hybrid SDN Networks

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***Abstract*—Software Defined Networking (SDN) makes load balancing efficient and intelligent. However, fully deploying an SDN presents economical, organizational and technical challenges. Therefore, load balancing in hybrid SDN networks where the routing protocol parameters are designed through an SDN channel is one of the hottest topics in the field. In addition, symmetrically routing is a practical requirement for network operators since asymmetrically routed flows make the network too complex to manage. In this paper, we propose a load balancing method for symmetrically routed hybrid SDN networks that can handle existing distributed routing parameters, link cost and path selection. The proposed method optimizes link cost and path selection simultaneously under a symmetrically routed condition, while traditional methods optimize them individually. In a numerical simulation, the load balancing performance of the proposed method is better and more stable than any of the traditional methods. Furthermore, the proposed method has high versatility, and provides the best performance even in networks without distributed routing protocols.**

Keywords—load balancing; traffic engineering; hybrid SDN; routng; link cost; path selection

I. INTRODUCTION

The Software Defined Networking (SDN) is an emerging paradigm that is expected to ease the complexities of traditional IP networks [1]. The visibility, programmability and openness of the SDN make load balancing in networks efficient and intelligent [2]. However, fully deploying an SDN presents economical, organizational and technical challenges. Many studies have proposed the hybrid deployment of an SDN with distributed routing protocols [1]. Dominant SDN controllers [3] are designed to integrate traditional IP technologies, such as Open Shortest Path Bridging (OSPF) and Intermediate System to Intermediate System (IS-IS), with SDN interfaces. However, load balancing in hybrid SDN networks where the protocol parameters are adjusted through an SDN channel is an open question in the field [4].

Load balancing with s*ymmetrically routed* flows is another practical topic that requires study. When flows between two endpoints follow the same path in both forward and reverse directions, they are called *symmetrically routed*. Even though traditional load balancing methods may result in asymmetrically routed flows [5], such flows make the network practically impossible for operators to manage. Operators are required to monitor twice as many nodes to manage asymmetrically routed flows as symmetrically routed flows. Asymmetrically routed flows will increase OPEX.

Therefore, we focus on a load balancing method for symmetrically routed hybrid SDN networks that can handle existing distributed routing parameters, such as link cost and path selection. The distributed routing parameters enable operators to apply the method to both the traditional and SDN parts of hybrid SDN networks. Furthermore, the symmetrically routed condition can mitigate the difficulties involved in managing networks as described above. Fig. 1 shows an example of a symmetrically routed hybrid SDN network. Each node adopts distributed routing protocols, e.g. OSPF or IS-IS, and has an interface with the SDN control channel. Nodes share link state information via distributed routing protocols. The value of the link cost in the link state information represents the cost of transporting packets through the link. Nodes use a set of link costs to calculate the shortest path. Packets are routed symmetrically over the shortest paths from source nodes to destination nodes. When a node receives a packet, the node arbitrarily selects one of the shortest paths over which to send the packet. Through the SDN control channel, operators can design link costs to control the geometry of the shortest paths. They can also design the path selection at each node.

Although many load balancing methods have been reported for link cost [6] and path selection [7], these methods cannot handle link cost and path selection simultaneously under a symmetrically routed condition. Therefore, these methods may result in the paths of high rate flows overlapping on specific links and thus degrade the utilization efficiency and quality of service in the network.

In this paper, we propose a load balancing method that optimizes link cost and path selection simultaneously under a symmetrically routed condition. The proposed method newly formulates link cost of symmetrically routed networks as a Linear Programming (LP) problem and path selection probability as simultaneous equations. The distributed routing parameters derived from the proposed method are expected to minimize the Maximum Link Utilization (MLU). MLU is one of the most common metrics for evaluating the load balancing method [8]. With minimized MLU, network carriers are expected to reduce CAPEX thanks to high user accommodation in their networks.

The paper is organized as follows. Section II shows an overview of related work. Section III describes the problem and the proposed method. Section IV describes the setting and results of a computer simulation. Section V concludes the paper.

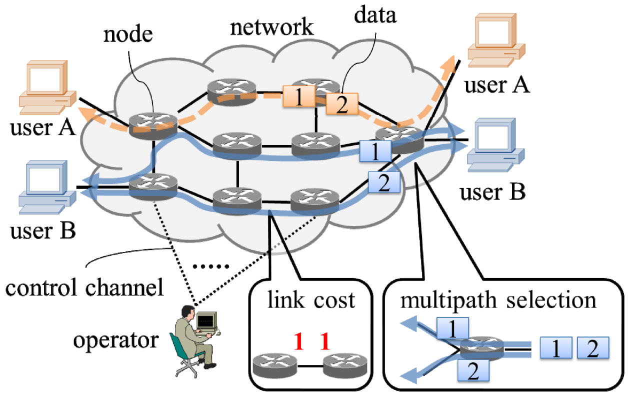


Fig. 1. System configuration

TABLE I. VARIABLES

Variable	**Definition**
$G = (V, E)$	Directed graph representing network topology
V	Set of nodes
$V_{w/o} \subset V$	Subset of nodes that adopt no distributed routing protocols
E	Set of directed links
$c_{i,j} > 0$	Capacity of link $(i, j) \in E$
$X_{i,j}^{k} \geqq 0$	Planned traffic from $i \in V$ to $j \in V$ for demand $k \in K$
K	Traffic demand in network or set of point-to-point demands
$K_{1/2} \subset K$	Subset of K such that; if $k_0 \in K_{1/2}$, then $k_1 \in K \backslash K_{1/2}$ exists such that $X_{i,j}^{k0} = X_{j,i}^{k1}$
α	Maximum link utilization rate of entire network, or MLU
$r > 0$	Parameter for tuning objective function
$d_k \geqq 0$	Guaranteed bandwidth for demand $k \in K$
$s_k \in V$	Source node for demand $k \in K$
$t_k \in V$	Destination node for demand k∈K
$M_{i,j} \geqq 0$	Variable allocated to link $(i, j) \in E$ employed in link cost calculation
$U_i^k \geqq 0$	Variable allocated to node $i \in V$ employed in link cost calculation
N_k	Set of shortest paths from s_k to d_k for demand $k \in K$
$0 \leqq p_n \leqq 1$	Selection probability of path n
$z_{i,j}^{n} \in \{0, 1\}$	Indicator of state of path n at link $(i, j) \in E$; if path n uses link $(i, j) \in E$, $z_{i,j}^{n} = 1$. Otherwise $z_{i,j}^{n} = 0$.

II. RELATED WORK

Many studies have looked at methods for optimizing the link cost for load balancing [6]. Wang, et al. developed an optimal method based on LP and proved its optimality in load balancing [9]. However, an LP-based method can result in asymmetrically routed flows. We cannot apply the LP-based method to symmetrically routed hybrid SDN networks. Heuristic-based methods have also been proposed, namely a local search algorithm, a genetic algorithm, and a simulated annealing algorithm. However, heuristic-based methods may provide us with an inappropriate link cost as a result of local minima and late convergence [6].

A number of path selection methods have also been reported. Prabhavat et al. [7] categorized them into non-adaptive models, such as Packet-By-Packet Round Robin (PBP-RR) [10], and adaptive models, such as Rate-Based Path Selection (RBPS) [11]. When the flow size is sufficiently small compared with the wire rate, and all the traffic and network information is given without delay, RBPS optimizes path selection for load balancing.

However, these methods cannot optimize link cost and path selection simultaneously. To make matters worse, these methods can output asymmetrically routed flows. Therefore, these methods may result in traffic concentrate on specific links, and degrade user accommodation in a network.

III. PROPOSED METHOD

We propose an optimal load balancing method for symmetrically routed hybrid SDN networks. The proposed method can optimize link cost and path selection simultaneously under a symmetrically routed condition. The proposed method newly formulates link cost as an LP problem and path selection probability as simultaneous equations.

The proposed method has four steps. First, as described in III-B, it calculates the load-balanced traffic in the entire network based on the Multi Commodity Flow (MCF) model [12]. Second, as described in III-C, it calculates the link cost consistent with the load-balanced traffic obtained in III.A. Third, as described in III-D, it calculates the path selection probability consistent with the load-balanced traffic, obtained in III.A. Finally, as described in III-E, it configures each node according to the optimized link cost and path selection.

A. Problem Description

Before proposing the method, we define the load balancing problem as in a previous study [9]. Table I defines the variables employed in this paper.

We define the link utilization rate as the sum of the traffic at the link divided by the link capacity. The goal of load balancing is to average the link utilization rate among all the links in a network. So we represent the load balancing problem as the problem of minimizing the MLU in a network, in accordance with previous work [9]. As the performance of a method improves, the MLU decreases. As Table I shows, α denotes the MLU in this paper.

We assume that any link has a symmetrical capacity independent of its orientation. In other words, $c_{i,j} = c_{j,i}$ holds for any $(i, j) \in E$. In addition, we focus on users with guaranteed bandwidth because they are the most important users as regards operators improving user accommodation in their networks. In this paper, each *demand* represents guaranteed bandwidth from source node to destination node. We assume that operators guarantee the same amount of point-to-point bandwidth for up and down paths, which is a common guarantee for enterprise users. For example, users want to connect between their branches over a network.

Because of the second assumption and the symmetrically routed condition, each planned item of traffic $X_{i,j}^{k}$ flows symmetrically on each link $(i, j) \in E$, and there is a subset $K_{1/2}$

as defined in Table I. Fig. 2 shows the concept of demand subset $K_{1/2}$.

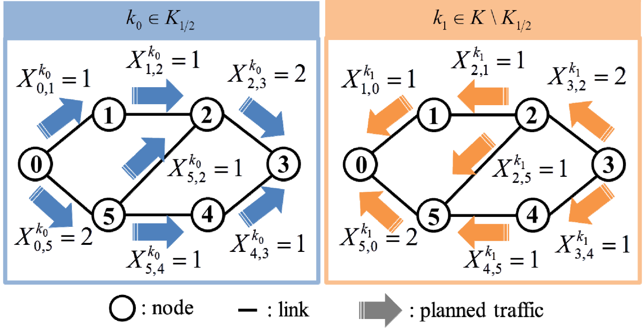


Fig. 2. Concept of demand subset $K_{1/2}$

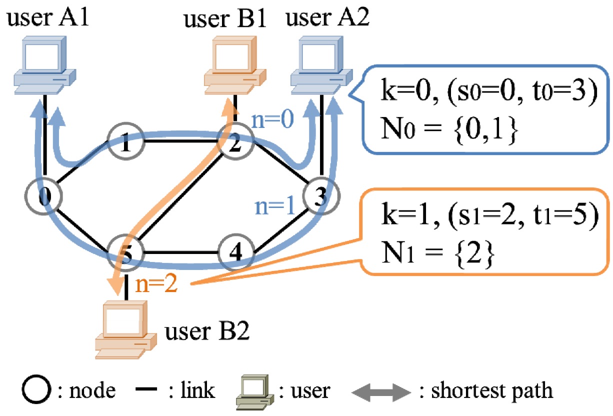


Fig. 3. Example of variables employed in (13) and (14)

B. Calculation of Load-Balanced Traffic Distribution

First, the proposed method calculates the load-balanced traffic in the entire network based on the MCF model [12]. An LP problem for planned traffic $X_{i,j}^k$ as defined below outputs the load-balanced traffic distribution. In this paper, we denote the LP problem as (*P*).

$$\text{minimize:}\quad \alpha + r\sum_{k\in K}\sum_{(i,j)\in E} X_{i,j}^k \tag{1}$$

$$\text{subject to:}\quad \sum_{j:(i,j)\in E} X_{i,j}^k - \sum_{j:(j,i)\in E} X_{j,i}^k = 0, \quad k\in K,\ i\neq s_k, t_k, \tag{2}$$

$$\sum_{(i,j)\in E} X_{i,j}^k = d_k, \quad k\in K,\ i = s_k, \tag{3}$$

$$\sum_{k\in K} X_{i,j}^k \le c_{i,j}\alpha, \quad (i,j)\in E, \tag{4}$$

$$X_{i,j}^{k_0} = X_{i,j}^{k_1}, \quad k_0\in K_{1/2},\ k_0\in K\backslash K_{1/2},\ (i,j)\in E, \tag{5}$$

$$0 \le X_{i,j}^k \le d_k, \quad k\in K,\ (i,j)\in E, \tag{6}$$

Table I defines variables *α*, and $X_{i,j}^k$, balancing parameter *r*, and given information *E*, *K*, (s_k, t_k, d_k), and $c_{i,j}$.

$\sum_{k\in K}\sum_{(i,j)\in E} X_{i,j}^k$ is a penalty term for a roundabout path. As the number of links through which packets flow increases, the penalty term increases. Without the penalty term, (*P*) may output an infeasible traffic distribution with non-negative link metrics [9]. Therefore, the objective is set as (1). Except when $i = s_k$ or $i = t_k$, the sum of the planned traffic flowing into *i* is equal to that flowing from *i*, as stated in (2). The sum of the planned traffic flowing from s_k is equal to the guaranteed bandwidth d_k, as stated in (3). By definition, *α* exceeds any link utilization rate, as stated in (4). (5) is a constraint derived from the symmetrically routed condition, as described in III-A. By definition, $X_{i,j}^k$ is more than zero and less than d_k, as reported in (6).

Fig. 2 shows a traffic example that satisfies (2) and (3). Let us consider a point-to-point demand k_0 such that $s_{k0} = 0$, $t_{k0} = 3$, and $d_{k0} = 3$. When $i = 2$, (2) states that ($X_{2,3}^{k0}$) - ($X_{1,2}^{k0} + X_{5,2}^{k0}$) = 2 - (1+1) = 0 holds. When i = 0 = s_{k0}, (3) states that ($X_{0,1}^{k0}$ + $X_{0,5}^{k0}$) = 3 = d_{k0} holds.

After obtaining load-balanced traffic $X_{i,j}^k$ from (*P*) problem, the proposed method calculates the link cost and the path selection probability consistent with the load-balanced traffic.

C. Calculation of Link Cost

The LP problem defined below calculates the link cost consistent with the load-balanced traffic. In this paper, we call the LP problem (*D*). (*D*) is a dual problem automatically derived from (*P*). With the link cost set as $M_{i,j} + 2r$ obtained from (*D*), the load-balanced traffic obtained from (*P*) flows through the shortest paths. We have omitted the detailed proof due to space limitations.

$$\text{maximize:}\quad \sum_{k\in K_{1/2}} d_k U_{t_k}^k\ , \tag{7}$$

$$\text{subject to:}\quad U_j^k - U_i^k \le M_{i,j} + 2r\ , \quad k\in K_{1/2},\ i\neq s_k, t_k, \tag{8}$$

$$\sum_{(i,j)\in E} c_{i,j} M_{i,j} = 2\ , \tag{9}$$

$$M_{i,j} = M_{j,i}\ , \quad (i,j)\in E, \tag{10}$$

$$M_{i,j} \ge 0\ , \quad (i,j)\in E, \tag{11}$$

$$U_{s_k}^k = 0\ , \quad k\in K_{1/2}, \tag{12}$$

U_i^k and $M_{i,j}$ are variables as defined in Table I. *r* is the same value as employed in (*P*). *E*, $K_{1/2}$, (s_k, t_k, d_k), and $c_{i,j}$ are given information as defined in Table I. (10) is a constraint that ensures the symmetry of the link cost, which results in symmetrically routed flows.

D. Calculation of Path Selection Probability

The proposed method employs the simultaneous equations defined below to obtain the path selection probability p_n that is consistent with the load-balanced traffic.

$$\sum_{n\in N_k} d_k p_n z^n_{i,j} = X^k_{i,j}, \qquad k\in K \quad (i,j)\in E, \qquad (13)$$

$$\sum_{n\in N_k} p_n = 1, \qquad k\in K, \qquad (14)$$

p_n is a variable as defined in Table I. $X_{i,j}^k$ is the planned traffic obtained from (P). E, K, N_k, d_k, and $z_{i,j}^n$ are given information as defined in Table I.

From the definition, variable p_n satisfies $0 \leqq p_n \leqq 1$. $d_k p_n z_{i,j}^n$ represents the guaranteed bandwidth for a demand k flowing through a path n at link (i, j). The total guaranteed bandwidth for a demand k at a link (i, j) is equal to the planned traffic, as stated in (13). Since one path is selected from the shortest path set N_k, (14) is satisfied.

Fig. 3 shows an example of the variables employed in (13) and (14). Let us consider a point-to-point demand $k = 0$ such that $s_0 = 0$ and $t_0 = 3$. The set of the shortest paths from $s_0 = 0$ to $t_0 = 3$ is $N_0 = \{0, 1\}$. Then, $\sum_{n\in N0} p_n = p_0 + p_1 = 1$ holds. Let us consider a point-to-point demand $k = 1$ such that $s_1 = 2$ and $t_1 = 5$. The set of shortest paths from $s_1 = 2$ to $t_1 = 5$ is $N_1 = 2$. Then, $\sum_{n\in N1} p_n = p_2 = 1$ holds.

E. Configuration

The proposed method configures nodes in hybrid SDN networks according to the optimized link cost and path selection. Through the SDN control channel, the method sets the link cost $M_{i,j} + 2r$ to the interface toward node j at node i, and its counterpart at node j, for each link $(i,j)\in E$. There are various ways to realize the path selection probability p_n for each path $n\in N_k$, and for each demand $k\in K$. One example is to construct a logical end-to-end path $n\in N_k$ and hash the packets for demand $k\in K$ at a rate of p_n at the source node s_k.

The proposed method can be employed even when some nodes in the hybrid SDN networks adopt no distributed routing protocols ($V_{w/o} \neq \varnothing$), and it provides the best performance. The method balances the traffic in the entire network by adding entries in the routing table at each node $i\in V_{w/o}$ according to the optimal traffic $X_{i,j}^k$ toward each node $j\in V$ derived from (P).

The proposed method automatically controls all flows in a network through the SDN control channel. It will make hybrid SDN networks easy for operators to configure.

IV. NUMERICAL SIMULATION

We used a computer simulation to evaluate the load balancing performance of the proposed method. The MLU of the proposed method was compared with those of traditional methods. IV-A describes the simulation model and setting. IV-B presents the simulation result and the corresponding discussion.

A. Simulation Model and Setting

We employed cost239 topology and nsfnet topology as shown in Fig. 5a and b, respectively. Cost239 and nsfnet are network topologies familiar in Europe and the U.S., respectively. The capacities of all the links were assumed to be 10 Gbps. Dual 1 Gbps point-to-point communication is guaranteed for each user. The source and the destination node corresponding to each demand were randomly selected. Each network accommodated from one to 100 users. 5 000 sets of traffic demand K were employed in the simulation.

The proposed method was compared with two traditional path selection methods. Both types of models mentioned in II-C, namely non-adaptive models and adaptive models, were used in the simulation. We employed the optimum method for the conditions, namely RBPS [11], from the adaptive models. We call the method trad 1. We also employed the simplest method, PBP-RR [10] from the non-adaptive models. We call the method trad 2. We assumed that all link costs were set at 1 when employing trad 1 and trad 2, since no traditional method can stably optimize the link cost under the symmetrically routed condition. Since we prioritized the load balancing performance rather than the avoidance of a roundabout path in the simulation, we set r = 0.001 when employing the proposed method. We used the GNU Linear Programming Kit (GLPK) [13] to solve the LP problems. The MLU was measured using the above conditions, and it decreased as the load balancing improved.

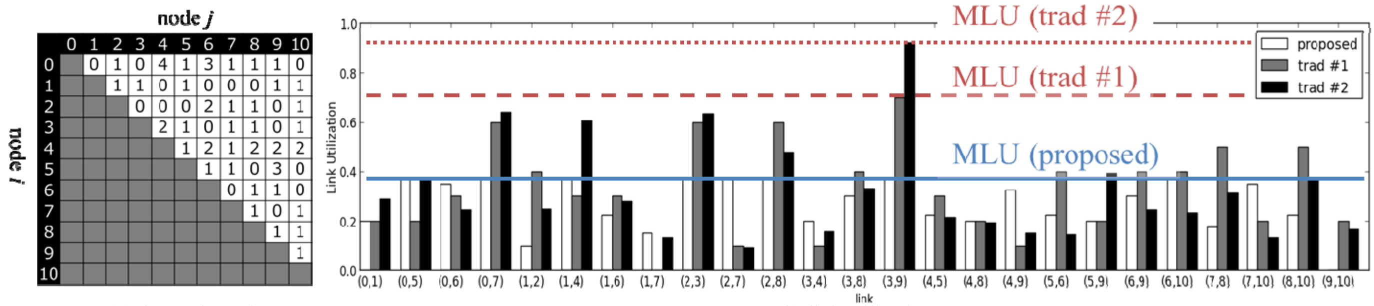
B. Results and Discussion

Fig. 5c and d show the average MLUs with each method. The margin of the average MLUs between methods became larger as the number of users increased. The average MLU with the proposed method was 0.20 points less than with the trad 1 method and 0.44 points less than with the trad 2 method when using cost239 topology accommodating 112 users, and 0.44 points less than with the trad 1 method and 0.68 points less than with the trad 2 method when using nsfnet topology accommodating 66 users. The proposed method always performed the best of the three methods with all 5 000 traffic demand sets in each topology. Moreover, the maximum standard deviations of the MLU with the proposed, trad 1, and trad 2 methods were 0.15, 0.32, and 0.36, respectively.

Fig. 4 shows the result obtained for the methods with a set of demand K_0 (accommodating 50 users) with the cost239 topology. Because of the symmetry, the demand matrix is simplified as the upper triangular matrices shown in Fig. 4a. The traditional methods were unable to reduce the MLU in Fig. 4b. In contrast, by optimizing the link metric and path selection simultaneously, the proposed method reduced the MLU well.

V. CONCLUSION

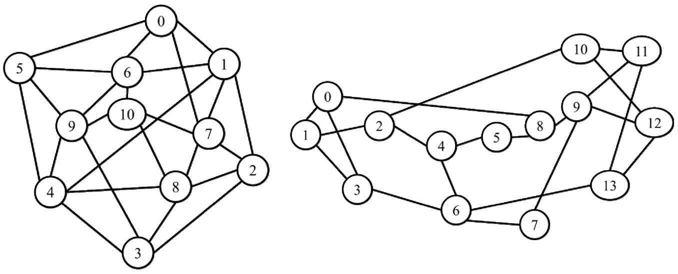
We proposed a load balancing method for hybrid SDN networks that can optimize path construction and path selection under a symmetrically routed condition. The proposed method newly formulates path construction of symmetrically routed networks as an LP problem and path selection probability as simultaneous equations. Our approach can avoid the concentration of traffic at a certain link by optimizing path



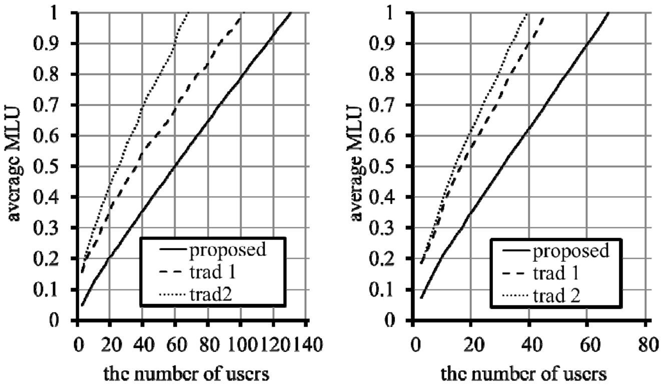
node *i* \ node *j*	0	1	2	3	4	5	6	7	8	9	10
0		0	1	0	4	1	3	1	1	1	0
1			1	1	0	1	0	0	0	1	1
2				0	0	0	2	1	1	0	1
3					2	1	0	1	1	0	1
4						1	2	1	2	2	2
5							1	1	0	3	0
6								0	1	1	0
7									1	0	1
8										1	1
9											1
10											

(a) demand matrix (b) link utilization

Fig. 4. Demand matrix and link utilizations in cost239 topology with traffic demand K_0



(a) cost239 topology (b) nsfnet topology



(c) cost239 results (d) nsfnet results

Fig. 5. Simulation topologies and results

construction and path selection simultaneously, whereas traditional methods cannot avoid it since they optimize them individually. To realize optimized path construction, through the SDN control channel, the proposed method sets the optimized link cost to nodes adopting distributed routing protocols, and sets explicitly the optimized routing tables to nodes not adopting them. The proposed method has high versatility, and can be employed and provides the best performance even in networks without distributed routing protocols.

We confirmed the load balancing performance of the proposed method with a computer simulation. In the simulation, we evaluated the MLUs of methods with 5 000 sets of traffic demand in two topologies, namely cost239 and nsfnet. The proposed method always outperformed the traditional methods, e.g., the average MLU with the proposed method was 0.44 points less than with the trad 1 method and 0.68 points less than with the trad 2 method when using nsfnet topology accommodating 112 users. Furthermore, the MLUs of the traditional methods were too large with some sets of traffic demand. In contrast, the MLU of the proposed method was stably small with any set of traffic demand. The maximum standard deviations of the MLUs with the proposed, trad 1, and trad 2 methods ware 0.15, 0.32, 0.36, respectively.

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