Adaptive Joint Optimization of IT Resources and Optical Spectrum Considering Operation Cost

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***Abstract*—We propose an adaptive joint optimization method of IT resources and optical spectrum under time-varying traffic demand in elastic optical networks while avoiding an increase in operation cost. Currently, numerous network services are provided by a service function chain (SFC). Once SFCs are provisioned, an optical path is established to connect the SFC and users. SFCs are placed in one of the candidate datacenters in the network by considering residual IT resources and the location of users. Here, the optimal placement of SFCs can vary due to service demand changes. To maintain network performance, we need to reconfigure network configuration by migrating SFCs and rerouting optical paths. However, such reconfiguration requires additional operation cost. In this paper, we consider the joint optimization problem of IT resources and optical spectrum in consideration of operation cost. We formulate the problem as mixed integer linear programming and then quantitatively evaluate the trade-off relationship between the optimality of reconfiguration and operation cost. We demonstrate that we can achieve sufficient network performance through the adaptive joint optimization while suppressing an increase in operation cost.**

***Index Terms*—elastic optical network, traffic engineering, optimization, SFC provisioning**

I. Introduction

Currently increasing numbers of 5G mobile services are provided by mobile virtual network operators (MVNOs). MVNOs do not deploy their own network infrastructure but lease those resources from infrastructure providers. ETSI network function virtualization (NFV) has been widely deployed in providing virtualized network services [1]. In NFV, network functions are represented by a virtual network function (VNF) that is operated on commodity servers shared by other services or operators. Datacenters (DCs) are geographically distributed and accommodate numerous servers. MVNOs utilize those virtualized computing resources in addition to network connectivity to transport traffic from a DC to users. Recently, optical transport technologies are widely deployed as network connectivity for providing large-capacity and low-latency required by current 5G services. An elastic optical network (EON) supports fine granularity in terms of bandwidth allocation and high efficiency of spectrum resources and is considered as a promising optical transport technology [2], [3]. Due to the fierce competition among MVNOs, they need to reduce the total cost of i) the deployment of IT and spectrum resources and ii) operation cost for providing their own services. An important thing here is how to assure adaptability of the service under time-varying service demand by optimizing the allocation of IT and spectrum resources while suppressing operation cost.

The joint optimization of IT and spectrum resources has been intensively investigated [4]–[8]. Walkowiak *et al.* proposed anycast routing algorithms in EONs to efficiently connect users to any available DC [4]. However, their proposal did not consider the optimal placement of VNFs among available DCs, which restricts the efficiency of spectrum-resource usage. Garrich *et al.* proposed the joint optimization method of IT and optical network resources [5]. However, how to reconfigure those resources in response to traffic demand changes was out of their scope. Fang *et al.* proposed joint defragmentation of IT and spectrum resources in EONs [7]. We proposed an optimal VNF placement method in optical networks [8]. However, they did not consider operation cost in reconfiguring IT and spectrum resources.

Our work was motivated by the above observation. To cope with traffic demand changes, we must deploy the joint optimization of IT and spectrum resources in EONs for cost-effective MVNO services; at the same time, we also need to minimize operation cost required for reconfiguring those resources. To improve the adaptability of traffic demand changes, we need to migrate some existing VNFs to other DCs and also reconfigure the optical path connecting newly migrated VNFs with users. However, such VNF migration as well as optical-path reconfiguration incurs additional operation cost. We thus need to avoid the increase in operation cost when optimizing IT and spectrum resources. As for traffic engineering while considering operation cost, Zheng *et al.* recently proposed routing update algorithms with operation cost in response to traffic demand changes [9]. However, their focus is on conventional packet-based IP networks, so their proposal is unable to be applied to EONs. To the best of our knowledge, few studies have investigated the adaptive joint optimization of IT and spectrum resources in consideration of operation cost.

In this paper, we propose an adaptive joint optimization method of IT and spectrum resources under time-varying traffic demand in EONs while avoiding the increase in op-

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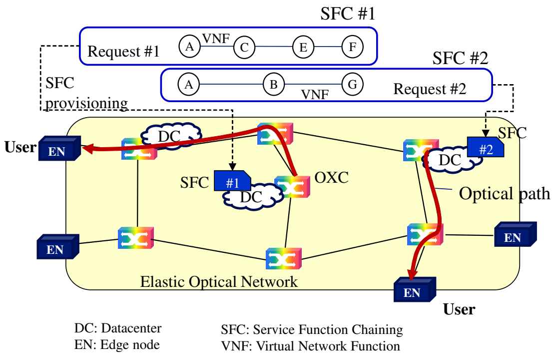

Fig. 1. Infrastructure provider's network that leases virtualized IT and spectrum resources

eration cost. Here, we define operation cost as the total amount of reconfigured optical paths and migrated VNFs. This is because operation cost is almost proportional to the amount of operations such as configuration changes. We first investigate the trade-off relationship between network resource consumption and operation cost in the case of traffic demand changes. We reveal that we can maintain the efficiency of network resources with a limited amount of reconfigured IT and spectrum resources. This leads to lower operation cost when reconfiguring the network. This paper makes three main contributions: i) we formulate the joint optimization problem of IT and spectrum resources in consideration of operation cost as mixed integer linear programming (MILP), ii) we clarify the trade-off relationship between network resource consumption and operation cost, and iii) we demonstrate the proposed method reduces operation cost while maintaining the efficiency of network resources when traffic demand changes.

II. System Model

Before presenting the proposed method, we describe the system model of the joint optimization. First, we describe an overview of the system model and then delineate the joint optimization of IT and spectrum resources in EONs. Finally, we define the cost used in the joint optimization problem.

A. Overview

First, we give an overview of the system model. Figure 1 illustrates a network of an infrastructure provider that leases virtualized IT and spectrum resources to MVNOs. The infrastructure provider operates multiple DCs consisting of commodity servers, edge nodes (ENs) accommodating numerous users, and a transport network. Regarding a transport network, an EON is deployed to connect a DC with other distant DCs or an EN. An EON consists of optical cross-connects (OXCs) and physical fiber links. In EONs, the optical spectrum in a fiber link is divided into a fixed size of frequency slots (ex., 6.25 GHz), and the number of slots allocated to each optical path is flexibly determined in accordance with the bandwidth requirement. An optical path is formed between a DC and EN.

To provide a network service over the infrastructure provider's network, we basically deploy multiple types of VNFs, and each VNF is routed sequentially in the given execution order. Such chained VNFs are referred to as a service chain or service function chain (SFC) [6], [10]. Each SFC is virtually hosted on a server in a DC and can be shared by multiple users subscribing to the same network service.

Upon a provision of a new network service, the request of SFC creation is generated by an MVNO. A request includes the description of a required SFC and the group of ENs accommodating users served by the SFC. Here, the description of a SFC includes types and the execution sequence of VNFs, required IT resources, and bandwidth. To avoid the complexity of interoperability and license problems regarding inter-domain SFC provisioning, we assume all VNFs forming the same SFC are placed in the same DC. Upon receiving a SFC request, the infrastructure provider determines the placement of the SFC by considering the required IT and network resources. Here, the placement of SFC is to determine where to place each SFC among candidate DCs.

The adequate placement of SFCs as well as the route for optical paths is highly dependent on the demand of IT and spectrum resources. However, such demand is time-varying and often indicates unexpected changes. We thus need to reconfigure IT and spectrum resources to maintain the efficiency of resource usage against demand changes. The reconfiguration requires the migration of SFCs and addition/deletion of optical paths, which incurs additional operation cost. Here, the total cost consists of operation cost in addition to network cost. Hence, we must carefully design the reconfiguration of IT and spectrum resources in consideration of operation cost to minimize the total cost.

B. Adaptive joint optimization of IT and spectrum resources

Next, we describe the adaptive joint optimization of IT and spectrum resources. Regarding IT resources, we can control the allocation of an SFC to a DC. We basically determine the placement of each SFC by considering resource requirements of an SFC and residual IT resources at a DC. Due to service demand changes, IT resources at some DCs are exhausted whereas those at other DCs are under-utilized. In this case, we migrate some SFCs from congested DCs to under-utilized DCs. To maintain the connectivity between SFCs and users, we also need to reconfigure optical paths. To minimize the service interruption during the reconfiguration phase, we add a new optical path, move traffic to the newly added path, and finally delete the original optical path. Operation cost is basically proportional to the amount of migrated SFCs and reconfigured optical paths.

C. Definition of Cost

Finally, we present the definition of network cost and operation cost. For the first term, we simply define network cost as the total occupancy of spectrum resources used for establishing all optical paths in the network. Next, we define operation cost as the total number of migrated SFCs and length of added/deleted optical paths at each reconfiguration period. In the joint optimization, we aim at optimizing the summation of network cost and operation cost.

III. Proposed Method

Now we present a proposed joint optimization method for optimizing IT and spectrum resources while avoiding the increase in operation cost. We first define the problem we are solving and then describe the network model. Finally, we present the proposed joint optimization method.

A. Problem Statement

Before presenting the problem statement, we describe the motivation of our work with an illustrative example as shown in Fig. 2. The left-hand side of the picture corresponds to an example of the conventional reconfiguration scheme without considering operation cost. At time T_1, an SFC (blue one) is placed on a DC attached with OXC2 and the requesting user is accommodated by OXC1. A single optical path is established between OXC1 and OXC2. A new SFC request (red one) arrives at time T_2. Requesting users are accommodated by OXC1 and OXC8. To minimize network cost (i.e., the total consumption of spectrum resources), the new SFC is placed in a DC attached with OXC7. To connect the new SFC and two users, we newly add two optical paths. Finally, at time T_3, a requesting user at OXC1 (served by the blue SFC) and OXC8 (served by the red SFC) is disconnected due to demand changes. Thus, there is just one user that is accommodated by OXC1 and is served by the red SFC. To optimize the usage of spectrum resources, the red SFC is migrated to a DC attached with OXC2. To complete the whole reconfiguration process, we need to change three SFCs and four optical paths in total. On the other hand, by introducing the proposed method in consideration of operation cost, we can minimize the total number of migrated SFCs and reconfigured optical paths (the right-hand side of Fig. 2). At time T_2, to avoid unnecessarily adding optical paths, a newly added SFC (red one) is placed in a DC attached with OXC2, and just one optical path is newly added to connect the SFC with a user at OXC8. Finally, at time T_3, we remove the blue SFC and one optical path between OXC2 and OXC8. In total, we just change two SFCs and two optical paths. Thus, the proposed method can reduce operation cost by about 40% in this simple example.

Now, we define the problem we are solving. We want to find a new network configuration consisting of SFCs to be migrated and reconfigured optical paths for a given traffic demand and current network configuration so as to minimize the weighted sum of network cost and operation cost.

B. Mathematical Model

We now present the mathematical model of the joint optimization problem. The network is composed of DCs, ENs, OXCs, and fiber links. We assume the following inputs given to the problem:

- DCs that provide IT resources to host SFCs
- ENs that accommodate users served by an SFC

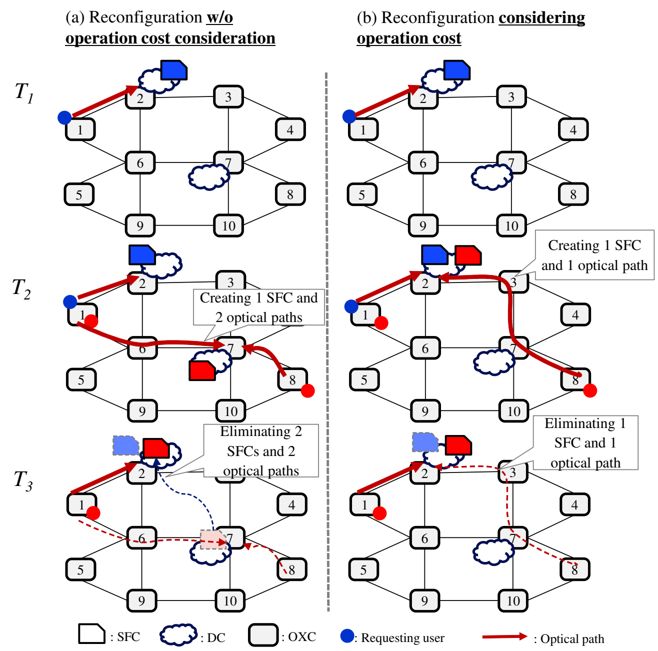

Fig. 2. Motivating example. If we reconfigure IT and network resources without considering operation cost, resources may be unnecessarily added/deleted resources.

- OXCs
- fiber links connecting two adjacent nodes
- demand of each SFC generated by users at an EN

We present the notations used in the MILP formulations. In our network model, the location of source nodes (i.e., a DC hosting SFCs) varies depending on the result of SFC provisioning. We assume time-varying traffic demand, so we need to reconfigure SFC placement and optical-path routing in response to traffic demand changes to maintain the efficiency of network resources. We previously proposed mathematical formulations considering some of these requirements [11]. However, the adaptive reconfiguration in response to demand changes was out of our scope. We thus extend the previous formulations so as to support adaptive reconfiguration. We consider a discrete time series where $t = 0, 1, \ldots$ to incorporate time-varying traffic demand into our model. At the end of each epoch, we perform adaptive reconfiguration on the basis of the collected traffic demand.

Key variables and parameters used in our model are summarized in Table I. A physical network is modeled as a directed graph $G = (V, E)$. To compute operation cost, we need to keep both the existing network configuration (i.e., SFC placement and route for optical paths) and future network configuration to be computed in the optimization problem. The previous network configurations are given by variables $l_{ij}(t-1)$, $p^{ij}_{mn}(t-1)$, $s^{ij}_{mn,h}(t-1)$, and $x^k_{ij}(t-1)$. Those variables are obtained from the results in the previous reconfiguration period.

As for variables, $l_{ij}(t)$ holds a non-negative integer variable whereas both $p^{ij}_{mn}(t)$ and $s^{ij}_{mn,h}(t)$ are binary variables. A

TABLE I
IMPORTANT NOTATIONS

Given:	
E	set of fiber links
V	set of physical nodes (both ENs and OXCs)
K_{sfc}	set of SFCs requested by users
V_{en}	set of ENs (subset of V)
V_{dc}	set of DCs connected to OXCs (subset of V)
V_{in}	set of OXCs (subset of V)
S_{mn}	set of spectrum slots on fiber link mn
E_{slot}	maximum number of spectrum slots per fiber link
C_{slot}	spectrum-slot bandwidth (in Gbps)
C_{dc}	capacity of IT resources at each DC
D_j^k(t)	traffic demand generated by SFC k at EN j
Variables:	
$l_{ij}(t)$	summation of traffic volume on logical link ij
$p_{mn}^{ij}(t)$	route for an elastic optical path from nodes i to j
$s_{mn,h}^{ij}(t)$	usage of slot h on link mn for an optical path from nodes i to j
$x_{ij}^k(t)$	route on a virtual topology from nodes i to j regarding SFC k at the next reconfiguration period
$c_{op}(t)$	operation cost

logical link is defined as a virtual link connecting a DC with an EN and is used for computing the total bandwidth between those two nodes. Regarding the physical-network model, the routing and spectrum-slot assignment of each optical path are provided by variables $p_{mn}^{ij}(t)$ and $s_{mn,h}^{ij}(t)$. If $p_{mn}^{ij}(t)$ is identical to 1, an optical path from nodes i to j uses fiber link mn. In addition, the allocation of spectrum slot h on link mn is determined by variable $s_{mn,h}^{ij}(t)$. The number of assigned spectrum slots for an optical path between nodes i and j is denoted by $l_{ij}(t)$.

In the logical network design, $x_{ij}^k(t)$, which is a binary variable, indicates the location of SFC k requested from users at EN j. If $x_{ij}^k(t)$ is equal to 1, the SFC k requested by users at EN j is stored at DC i. Traffic demand of SFC k is denoted by $D_j^k(t)$, and we assume $D_j^k(t)$ is identical to IT resources required by SFC k for simplicity. We assume both strict spectrum-slot continuity and strict spectrum-slot contiguity. The same spectrum slots must be allocated along fiber links traversed by an optical path; at the same time, contiguous slots must be assigned to one optical path.

C. MILP Formulations

Next, we briefly describe MILP formulations of the joint optimization problem. The objective of our joint optimization problem is to minimize the total number of allocated spectrum slots while minimizing operation cost in a given network and traffic conditions. With this optimization problem, we need to solve the following issues:

- Place an SFC in one candidate DC in consideration of bandwidth requirement and residual IT resources at each DC while minimizing operation cost.
- Find route and spectrum-slot assignment for each elastic optical path in order to minimize network resource consumption in consideration of spectrum-slot constraints.

The formulation is outlined below.

Objective: Minimizing network resource consumption and operation cost

$$\min\Bigg(\sum_{ij}\sum_{mn,h} s_{mn}^{ij}(t) + \alpha\cdot\max_{ij}\sum_{k} D_j^k\cdot x_{ij}^k(t) + u + W_o * c_{op}(t)\Bigg) \tag{1}$$

Constraints: optical network design (optical-path routing)

$$\sum_{l} p_{ml}^{ij}(t) - \sum_{l} p_{ln}^{ij}(t) = \begin{cases} -1, & l\in V_{dc} \;\; l_{ij}(t)>0 \\ 1, & l\in V_{en} \;\; l_{ij(t)}>0 \\ 0, & l\in V_{in}\end{cases}, \tag{2}$$

$$\sum_{m} s_{mr,h}^{ij}(t) - \sum_{n} s_{rn,h}^{ij(t)} = \begin{cases} -y_{ij}(t), & r\in V_{dc} \\ y_{ij}(t), & r\in V_{en} \\ 0, & r\in V_{in}\end{cases}, \tag{3}$$

$$s_{mn,h}^{ij}(t) \le E_{slot},\quad \forall i\in V_{dc},\ j\in V_{en},\ h\in S_{mn} \tag{4}$$

$$p_{mn}^{ij}(t) \le s_{mn,h}^{ij}(t),\quad \forall i\in V_{dc},\ j\in V_{en},\ h\in S_{mn} \tag{5}$$

$$p_{mn}^{ij}(t) \ge s_{mn,h}^{ij}(t)/E_{slot},\quad \forall i\in V_{dc},\ j\in V_{en},\ h\in S_{mn} \tag{6}$$

$$l_{ij}(t) = y_{ij}(t),\ \forall i\in V_{dc},\ \forall j\in V_{en} \tag{7}$$

Constraints: Operation cost

$$c_{op}(t) = |p_{mn}^{ij}(t-1) - p_{mn}^{ij}(t)| + |x_{ij}^k(t-1) - x_{ij}^k(t)| \tag{8}$$

Constraints: Logical network design

$$\sum_{i} x_{ij}^k(t) = \begin{cases} 1, & \text{if } D_j^k(t)>0 \\ 0, & \text{else}\end{cases} \tag{9}$$

$$\sum_{k} D_j^k(t)\cdot x_{ij}^k(t) \le C_{slot}\cdot l_{ij}(t),\quad \forall i\in V_{dc},\ \forall j\in V_{en} \tag{10}$$

$$\sum_{k}\sum_{j} D_j^k(t)\cdot x_{ij}^k(t) \le C_{dc},\quad \forall i\in V_{dc} \tag{11}$$

The first term in Eq. (1) corresponds to the total spectrum-slot consumption, and the second term denotes the maximum load of DCs. As the two terms can have different scales, we deploy parameter α to adjust the different scale. Additionally, the third term corresponds to constraints on spectrum-slot contiguity and continuity. Operation cost is represented by the fourth term, and we introduce parameter W_o to reflect the importance of operation cost in the optimization. Equation (2) indicates a flow-conservation law with regard to optical-path routing between DCs and ENs. Note that a point-to-point optical path p_{mn}^{ij} just indicates whether the path passes through fiber link mn. The term $s_{mn,h}^{ij}$ is used for computing the slot allocation and capacity for an optical path in conjunction with

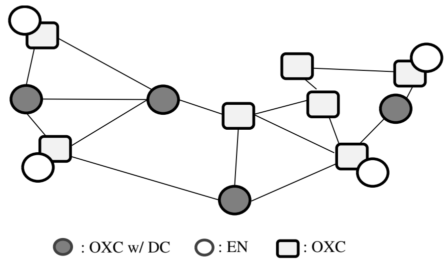

Fig. 3. 11-node 15-link Abilene network topology with 4 ENs and 4 DCs

p_{mn}^{ij}. Equations (3) and (4) constrain spectrum-slot allocation considering physical requirements on continuity and the maximum number of spectrum slots, respectively. Equations (5) and (6) describe the relationship between optical-path routing p_{mn}^{ij} and the route with capacity $s_{mn,h}^{ij}$, respectively. The capacity of a logical link between nodes i and j is expressed in Eq. (7).

Operation cost is given by Eq (8). The first term of the right-hand side is related to the amount of spectrum resources to be reconfigured while the second term corresponds to the number of migrated SFCs. For the details of the mathematical formulations related to spectrum-slot contiguity/continuity, please refer to [11].

IV. Numerical Experiments

A. Aims and conditions

We first describe the aims and conditions of the numerical experiments. We used the 11-node 15-link Abilene network topology as illustrated in Fig. 3. The network is attached with four ENs and four DCs. Each SFC consists of up to five VNFs. The number of VNFs per SFC was determined randomly in accordance with the uniform distribution. The bandwidth requirement per VNF was adjusted in accordance with the condition of each experiment. The location of users served by an SFC was randomly chosen among four ENs. We had the following common conditions in the experiments:

- number of spectrum slots per link E_{slot}: 64
- bandwidth of each spectrum slot C_{slot}: 12.5 Gbps
- capacity of IT resources at each DC: 600
- number of SFCs in the network $|K_{sfc}|$: 15

We assumed 24-hour cyclic-stationary traffic demand for each source/destination pair [12], which is given by

$$D_j^k(t) = A \cdot N_k \cdot \left(\sin(2\pi t/T + \theta_j^k) + 1\right) \qquad (12)$$

We set T as 24 hours while θ_j^k was randomly chosen from 0 to 2π. At the end of each epoch, network reconfiguration is performed.

B. Trade-off between optimality and operation cost

To deploy the proposed method, we need to determine parameter W_o in Eq. (1) that determines the weight of operation cost against network resource consumption in the optimization. As parameter W_o grows, the proposed method tends to decrease operation cost rather than network resource consumption. We thus investigate the trade-off between operation cost and network resource consumption to clarify the optimal value of W_o while varying W_o from 0.001 to 15.0. The results are shown in Fig. 4. The vertical line indicates both operation cost and network resource consumption, while the horizontal line corresponds to weight parameter W_o. As W_o increases, operation cost tends to decrease. However, the decrease was saturated around 3.0 of W_o. On the other hand, network resource consumption tends to increase in accordance on the growth of W_o, and the increase in network resource consumption was also saturated around 3.0 of W_o. Based on those experimental results, by setting parameter W_o as around 3.0, the proposed method can effectively reduce network resource consumption while avoiding the increase in operation cost.

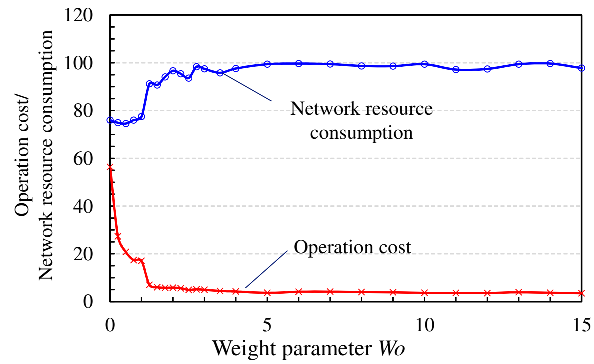

Fig. 4. Relationship between operation cost and network resource consumption while varying weight parameter W_o

C. Performance comparison while varying traffic demand

Next, we compared the performance of the proposed method with conventional methods while varying the average traffic demand. Here, the average traffic demand is defined as the average traffic generated by a single ENs. Therefore, we adequately adjusted traffic demand per VNF in accordance with the condition. On the basis of the above observation, we set parameter W_o as 3.0. We compared three conventional methods $Full$, $Random$, and $RoundRobin$. First, $Full$ indicates a full reconfiguration method, which optimizes the set of optical paths as well as the placement of SFCs without considering operation cost at each reconfiguration period. Thus, $Full$ basically produces the minimum network resource consumption among four methods, and we deploy $Full$ as the benchmark of efficiency in terms of spectrum-resource usage. Next, $Random$ means the placement of each SFC is randomly chosen among four candidate DCs. Finally, $RoundRobin$ corresponds to the method where SFC placement is determined in accordance with the round robin order among candidate DCs.

We compared network resource consumption and operation cost of the proposed method with the three conventional

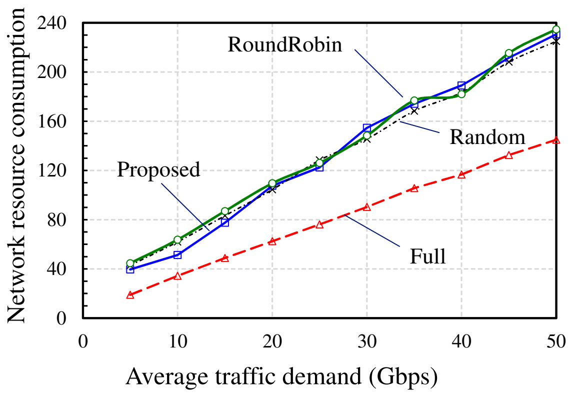

Fig. 5. Comparison of network resource consumption in Abilene topology

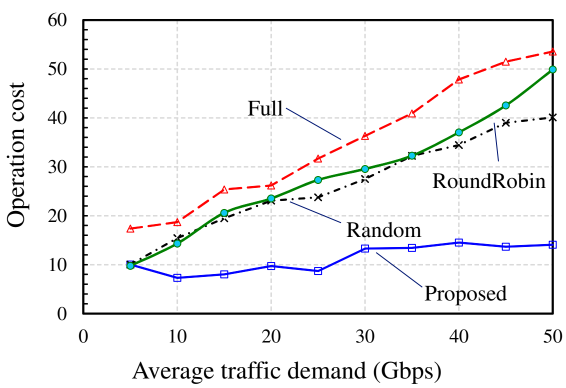

Fig. 6. Comparison of network operation cost in Abilene topology

methods. The results are shown in Figs. 5 and 6. Regarding network resource consumption, $Full$ outperformed the other three methods, as it does not consider operation cost in network reconfiguration. The proposed method reduced network resource consumption by about 4% compared with $RoundRobin$. However, $Proposed$ adequately avoided the increase in operation cost and outperformed the three conventional methods in terms of network operation cost, as shown in Fig. 6. The proposed method reduced operation cost by about 60% on average compared with $Full$. Although $Full$ efficiently reduced network cost, it completely failed to reduce total cost. Additionally, the number of reconfigured optical paths in $Full$ is proportional to the average traffic demand, which deteriorates the scalability of network reconfiguration. The proposed method achieved about 8% reduction of the total cost (i.e., the sum of network resource consumption and operation cost) compared with $Full$. In conclusion, we can reduce operation cost while maintaining the efficiency of resource usage by using the proposed method.

V. Conclusion

We considered an adaptive joint optimization of IT resources and optical spectrum while minimizing operation cost for providing cost-efficient mobile virtual network operator (MVNO) services. To maintain the efficiency of resource usage under time-varying demand changes, we need to reconfigure network configuration including service function chain (SFC) placement and optical-path rerouting. However, such reconfiguration incurs additional operation cost. To cope with this, we proposed an adaptive joint optimization method that finds adequate solutions for network reconfiguration while suppressing the increase in operation cost. We formulated the joint optimization problem as mixed integer linear programming (MILP) and investigated the trade-off between network cost and operation cost. The proposed method computes where to migrate existing the placement of SFCs and the route for optical paths in response to traffic demand changes. We demonstrated that the proposed method reduced sufficient network resource consumption under time-varying traffic demand changes while avoiding an increase in operation cost.

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