

Recent Progress in Optical Network Design and Control towards Human-Centered Smart Society

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SUMMARY In this paper, we investigate the evolution of an optical network architecture and discuss the future direction of research on optical network design and control. We review existing research on optical network design and control and present some open challenges. One of the important open challenges lies in multilayer resource optimization including IT and optical network resources. We propose an adaptive joint optimization method of IT resources and optical spectrum under time-varying traffic demand in optical networks while avoiding an increase in 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.

key words: optical network architecture, network design, network control, traffic engineering, optimization, SFC provisioning

1. Introduction

Society 5.0 was proposed by the government of Japan in the fifth Science and Technology Basic Plan as a human-centered smart society in future [1]. In Society 5.0, the physical space is tightly integrated with the cyberspace. One of the key elements in Society 5.0 is a cyber-physical system (CPS). CPSs are rapidly becoming popular and coming into commercial use due to the recent technological advancements in 5G mobile network, internet of things (IoT), machine learning, and Big Data analysis. CPSs are engineered systems that require tighter integration of computing, communication, and control technologies to achieve the optimality, stability, performance, reliability, and robustness in dealing with physical systems [2]. For this purpose, we need to collect extremely large volume of real-time data from the physical space. Future transport network should support such requirements imposed by CPSs towards human-centered smart society in addition to those of existing network applications.

In this paper, we investigate the evolution of an optical network architecture and discuss the future direction of research on optical network design and control. We categorize the research area of optical network design and control into three aspects: i) transmission technologies, ii) network mod-

elling, and iii) optimization target. The purpose of this paper is not to provide up-to-date comprehensive survey on optical network design and control but to present how recent technological advancements in this area drive the evolution of an optical network architecture. We review existing research from the viewpoint of the above three aspects and present some of the open challenges. Future transport networks should improve energy efficiency while satisfying ever-increasing bandwidth demand. For this purpose, an architecture of future transport networks should be simplified by eliminating sophisticated electrical processing [3]. In future, the optical layer will be capable of the direct accommodation of the service layer. The key to this is tighter integration of the optical layer and service layer.

One of the important open challenges in optical network design and control lies in multilayer resource optimization across from the service-layer to the optical-layer network. Multilayer resource optimization has attracted wide research interest [4]–[12]. Here, the purpose of multilayer resource optimization is to minimize the total cost of ownership (TCO) including network cost and operational expenditure (OPEX) by efficiently utilizing various network resources consisting of multiple layers. We briefly describe the need for multilayer resource optimization in optical networks. ETSI network function virtualization (NFV) has been widely deployed in providing virtualized network services [13]. 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. Optical networks provide connectivity to transport traffic from a DC to users. Currently, optical transmission technologies are widely deployed as network connectivity for providing large-capacity and low-latency required by current network services such as 5G and high-definition (HD) video conference. To achieve a cost-efficient network service, we need to reduce TCO consisting of i) the deployment of IT and spectrum resources and ii) operation cost for providing the service. Multilayer resource optimization is essential for this purpose. Here, the key to the TCO reduction lies in the savings of OPEX [14]. However, few research has considered operational constraints in optimizing multilayer resources including IT and optical resources.

In this paper, we propose an adaptive joint optimization method of IT and optical resources under time-varying traffic demand in optical networks while avoiding the increase in operation cost. We reveal that we can maintain

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the efficiency of network resources with a limited amount of reconfigured IT and optical resources. This leads to lower operation cost when reconfiguring the network. This paper makes three main contributions: i) we discuss the future direction of research on optical network design and control and present some of the open challenges, ii) we formulate the multilayer resource optimization problem of IT and optical resources in consideration of operation cost as mixed integer linear programming (MILP), and iii) we clarify the trade-off relationship between network resource consumption and operation cost and demonstrate the proposed method reduces operation cost while maintaining the efficiency of network resources when traffic demand changes.

The rest of this paper is organized as follows; we discuss the future direction of optical network design and control, and present some of the open challenges in Sect. 2. Section 3 describes a multilayer resource optimization problem in consideration of operation cost. We propose a multilayer resource optimization method in Sect. 4 and then present some of the numerical experiments to demonstrate the effectiveness of the proposed method in Sect. 5. Finally, a brief conclusion is provided in Sect. 6.

2. Future Direction of Optical Network Design and Control

We first investigate the evolution of a transport network architecture and discuss the research direction of optical network design and control.

2.1 Evolution of Network Architecture

A current transport network architecture composes of complex layered network systems due to constraints on technologies, network operation and services, as illustrated in Fig. 1. A typical current network architecture consists of the packet transmission layer (Layer 2 and/or Layer 3) and the service layer on top of the optical layer [15]. The optical layer consists of optical-cross connects (OXCs), transponders, in-line amplifiers, and optical fibers. The packet transmission layer is constructed on top of the optical layer. The packet transmission layer provides sophisticated transport functions such as fine-grained bandwidth allocation, protection against network failures, logical separation for virtual private network

(VPN) services, service level agreement (SLA) assurance. Those functions are essential to accommodating various network services. Current optical transmission technologies are unable to support all of those functions without deploying any electrical processing.

In view of recent progress in optical transmission technologies, the optical layer will support the majority of those functions currently provided by the packet transmission technologies. In near future, a transport network will migrate to all-photonics networks, where the packet transmission layer is integrated into the optical layer [3]. For example, we can convert a wavelength of an optical path without using any electrical processing by deploying all optical wavelength converters [16], and photonic-electronic integration devices were proposed for energy-saving data processing and electrical-to-optical conversion [17]. Those newly developed technologies lead to the reduction in electrical processing in transport networks. Thus, the optical layer will evolve to directly accommodate the service layer [18]. This causes new technological challenges. The key is tighter integration of the optical layer and service layer. Considering recent progress in optical network control and management such as software-defined networking (SDN) [19] and OpenFlow [20], we can develop optical network control triggered by network services and applications. However, the granularity and scalability of service-layer control are totally different from the optical layer. So, we need to fill the technological gap by fostering research on optical network design and control. In view of the above consideration, requirements of future optical networks can be summarized as follows:

- *Hyper-parallel*: optical networks should support the massive number of parallel optical channels/fibers to support VPNs and other network services in addition to ultra-high capacity.
- *Flexibility*: optical networks should retain sufficient flexibility and adaptability in terms of bandwidth allocations to support wide range of services such as IoT, CPS, extended reality (XR), and digital twin computing (DTC) [21], [22].
- *Agility*: optical networks should offer agility and resilience in response to network failures and changes in service usage in order to directly accommodate the service layer while assuring the quality of experience

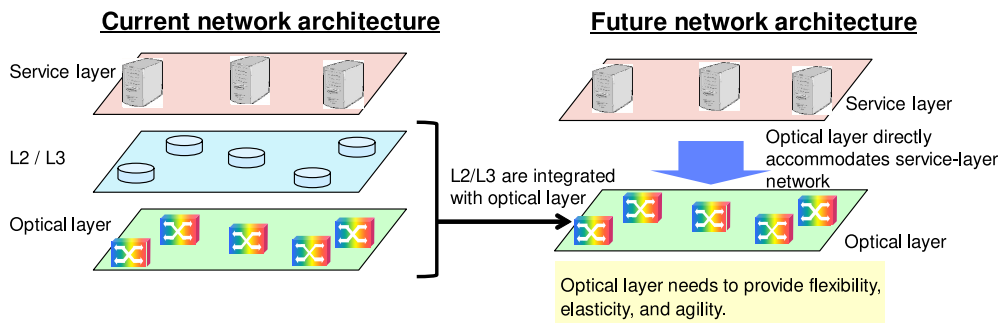


Fig. 1 Evolution of optical transport network architecture.

(QoE).

Such emerging requirements will accelerate innovations in optical network design and control in conjunction with newly developed optical transmission technologies.

2.2 Latest Trend in Optical Network Design and Control

We briefly summarize the latest trend and progress in research on optical network design and control, and the discuss the research direction of this area.

2.2.1 Overview

We first present an overview of recent research trend in optical network design and control. Optical network design and control technologies play a crucial role in the reduction of TCO by efficiently allocating network resources in response to changes in service demand and network environment. Here, the optical network design computes a required amount of spectrum resources according to bandwidth demand and allocates those resources in order to establish optical paths in the static manner, while the optical network control dynamically reconfigures allocated resources in response to demand changes and network failures. For simplicity, we use the term “optical network design and control” hereafter.

Currently, 400-Gbps transmission systems have been already deployed in production networks [15] and systems with a channel capacity of 800 Gbps are commercially available [23]. However, due to the physical limitation such as the fiber nonlinear effect and fiber fuse phenomenon, it is difficult to drastically expand the capacity of an existing single mode fiber (SMF) [24]. Optical networks are required to accommodate ever-increasing traffic demand in consideration of such limitation. We thus need to deploy *hyper-parallel* transmission links to further expand the total system capacity and also support massive numbers of logical channels required for VPNs and various network services. To achieve such hyper-parallelism, we can deploy i) multiband transmission [16], ii) multi-mode transmission [25] and iii) multi-core fibers (MCFs) [26], [27]. From the viewpoint of network design and control, it is remarkably important to efficiently utilize such hyper-parallel spectrum resources.

Next, we investigate the requirement of *flexibility* and *agility* in optical network design and control. A conventional optical path often forms a point-to-point link connecting a pair of routers and switches in the packet transmission layer. Once establishing an optical path, the path is usually active for more than a ten year and the dynamic reconfiguration of the path is merely performed due to the stability of network operation and services. However, in emerging network applications such as CPSs, XR and DTC, various parameters such as connection end points and bandwidth demand vary from time to time; at the same time, the variation of such parameters is unable to predict in advance. The important thing here is optimizing TCO while assuring QoE in response to unpredictable time-varying service demand. More specifically,

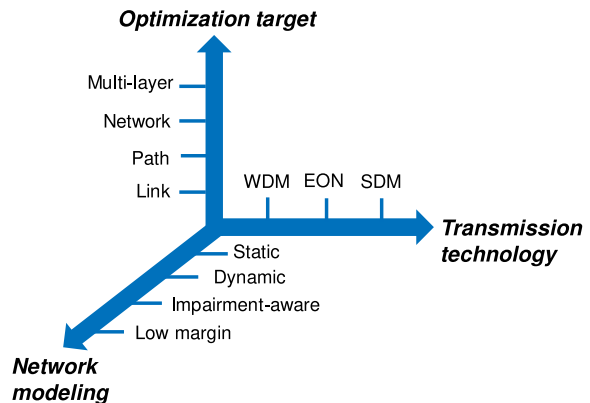


Fig. 2 Research direction of optical network design and control.

we need to maintain the efficiency of resource utilization by dynamically allocating and reconfiguring network resources in response to time-varying traffic demand induced by the service layer.

The research direction of optical network design and control is illustrated in Fig. 2. The research direction can be categorized into three aspects: i) transmission technologies, ii) network modeling, and iii) optimization target. First, the transmission technologies simply indicate types of optical transmission technologies deployed in underlying optical networks. Second, the network modeling is defined as modeling techniques in consideration of actual network systems, physical-layer impairments, and various operational requirements. Finally, the optimization target indicates the scope of optimization in designing and controlling optical networks.

2.2.2 Research Direction and Open Challenges

Here, we discuss research direction of optical network design and control, and present some of the open challenges. We briefly survey related work on optical network design and control based on the above categorization.

First, regarding the transmission technologies, wavelength division multiplexing (WDM)-based wavelength routed networks have been widely deployed in conventional transport networks. To improve the efficiency of spectrum resources, elastic optical networks (EONs) were proposed [28], [29]. EONs support granular bandwidth allocation and improve spectral resource efficiency by utilizing an advanced modulation format. Recently, to further expand the total capacity of an optical fiber cable, space-division multiplexing (SDM) has been intensively investigated [25]–[27], [30]–[32]. Here, SDM transmission systems aim at overcoming the theoretical capacity limit of SMFs to utilize the additional spatial dimension such as MCFs or multi-mode transmission. MCFs contain multiple single-mode cores in a fiber cladding. We can expand the total capacity of a single fiber by utilizing multiple cores.

In SDM, inter-core crosstalk (XT) causes signal degradation, which can severely impact the quality of transmission (QoT). Klinkowski et al. proposed dynamic XT-aware opti-

cal provisioning algorithms in order to ensure the QoT in MCF-based optical networks [26]. Additionally, fragmentation is one of the major obstacles in deploying SDM-based networks as well as EONs. When optical path requests are accepted and released dynamically and repeatedly, spectrum resources can be scattered and isolated into segments. Such phenomena are called fragmentation, which often deteriorates the utilization of spectrum resources. Chatterjee *et al.* proposed a proactive fragmentation management scheme in SDM-based networks [32]. In the proposed scheme, both inter-core and inter-mode XTs are efficiently avoided in provisioning optical paths in order to improve resource utilization.

An optical node architecture regarding the switching capability of core nodes must be one of the most important research topics on SDM transmission systems. Jinno *et al.* proposed a spatial channel network (SCN) architecture, where the SDM layer is defined as a new networking layer that supports the SDM-based multiplexing technologies [27]. In SCNs, a spatial cross-connect handles a spatial channel accommodating optical channels, while a conventional wavelength cross-connect provides the spectral grooming. In [30], the effectiveness of spectral grooming and spatial bypass was quantitatively evaluated.

Next, we elaborate on the network modeling aspect. Network modeling, which is the basis on network design and control, has made remarkable progress and evolution in order to satisfy various design requirements. In a conventional network design problem, we just compute the static configuration of optical paths for a given physical network topology and bandwidth demand. To cope with time-varying traffic demand and bandwidth-on-demand services, approaches for dynamically establishing optical paths or reconfiguring existing paths have been widely investigated [34]–[38]. One of the major difficulties in designing optical paths and networks lies in physical-layer impairments. Impairment-aware routing algorithms and network design methods were proposed in [39], [40]. Soumplis *et al.* investigated key factors that affected the degradation of QoT and presented the ageing model of transmission systems and links [40]. They also proposed routing and spectrum assignment (RSA) algorithms in consideration of actual network conditions including ageing in order to ensure QoT at the end of life.

To minimize the total network cost, low-margin network design has been intensively investigated [41]–[43]. Once establishing an optical path, the path is often active for more than a ten year. During the active period, we need to maintain the QoT for the path. For this purpose, we allocate a certain amount of margin in designing an optical path, which leads to an increase in network cost. In the low-margin network design, we aim at minimizing the margin in order to maximize the efficiency of spectrum resources.

To calculate solutions in a given network design problem, integer linear programming (ILP) and meta heuristics have been widely used in existing research [4], [7], [35]. Recently, deep reinforcement learning (DRL)-based RSA algorithms were investigated to cope with the uncertainty of

future traffic demand [44]. One of the important questions is the effectiveness and applicability of machine-learning (ML)-based or AI-based approaches for RSA problems. Martin *et al.* designed ML-based algorithms for routing and wavelength assignment problems and evaluated their effectiveness [47]. ML-based algorithms produced feasible solutions much faster than ILP in the five-node network. The scalability of ML-based algorithms was not investigated in their work. They concluded the effectiveness of ML-based approaches was controversial. One of the major difficulties in ML-based approaches is the collection of huge training datasets, especially for RSA problems. In consideration of dataset issues, the estimation of QoT can be suitable for ML-based approaches. Salani *et al.* proposed an RSA method integrating ML-based QoT estimation [48]. In their method, ILP was used for solving RSA problems, while QoT estimation was performed based on ML-based approaches.

Finally, we review existing research related to the optimization target. The optimization target has gradually developed and evolved in order to improve the efficiency of entire network resources by expanding the scope from link-level to network-level optimization. In a classic network design problem, we compute an optimal link capacity or an optimal route for an optical path in the static manner. In EONs, RSA algorithms for a given bandwidth demand and a physical topology were widely investigated [35]. A set of optical paths forms a virtual network topology (VNT), which can be seen as a logical topology of an upper-layer network (ex. an IP network) [37]. Approaches for optimizing a logical configuration of an optical network including a VNT have been intensively studied [37], [38]. By optimizing a VNT, we can further reduce the usage of optical resources for a given upper-layer traffic demand compared with single-layer optimization.

Considering the evolution of an optical network architecture, multilayer resource optimization including the service-layer resources is one of the most important research topics in optical network design and control [4]–[12]. In conventional network design problems, we compute the configuration of optical paths to reduce optical-layer network cost for a given volume of upper-layer traffic demand [34]. In provisioning service-layer resources such as VNFs, we mainly try to find the optimal allocation of such resources without performing any reconfiguration of given optical paths [49], [50]. Such limited optimization scope often deteriorates the efficiency of entire network resources across from the service layer to optical layer. In multilayer resource optimization, we optimize an allocation of upper-layer resources (ex. IT resources, VNFs, and content) and optical resources at the same time in order to improve the efficiency of the entire network resources. This leads to the TCO reduction.

Now we investigate open challenges on the basis of the above observation. From the viewpoint of the transmission technologies, network design problems in EONs and SDM networks have been intensively studied so far. Additionally, in SDM, various approaches have been proposed and investigated. For example, we can rely on massive numbers of

parallel SMF-based transmission links instead of MCFs [27]. In SDM, we need to carefully observe the direction of technological advancements. Regardless of whether or not MCFs are deployed, we need to handle massive numbers of parallel transmission links in optimizing optical resources. So, approaches for optical network design and control should be scalable and lightweight regarding the number of allocated resources.

In reviewing the aspects of the network modeling and optimization target, we need to consider service-specific requirements and spatio-temporal dynamics. The ultimate goal of optical network design and control is to maintain the efficiency of resource utilization for the TCO reduction in accordance with network dynamics. Currently, the duration of an optical path is relatively longer, so we need to allocate a certain amount of the margin for the path to assure QoT. In future, optical paths can be dynamically established by emerging applications. Such optical paths will be of short duration. Low margin network design for such short-duration optical paths may be one of the important open issues. It is difficult to precisely model the dynamics of future traffic demand generated by emerging applications. Thus, we need some adaptability and agility in optical network design and control to cope with the uncertainty of future traffic demand. Additionally, tighter integration of the service layer and optical layer is essential in optimizing the entire network resources. So, we need to further investigate dynamic multilayer resource optimization to achieve the TCO reduction and the direct accommodation of service-layer networks onto the optical layer.

2.3 Multilayer Resource Optimization

Here, we review existing research on multilayer resource optimization that aims at improving the efficiency of the entire network resources across from the service layer to the optical layer. Before presenting our survey, we briefly describe background information related to this research topic.

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. MVNOs utilize those virtualized computing resources in addition to network connectivity to transport traffic from a DC to users. Optical transport technologies are widely deployed as network connectivity for providing large-capacity and low-latency required by current 5G services. 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. 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.

Furthermore, emerging services such as DTC, we need to obtain extremely large volume of real-time data from the physical space and forward such data to a digital twin platform. Obtained data is processed based on ML or AI-based approaches for the applications of DTC [22]. In deploying DTC, we need a massive amount of IT resources at DCs in addition to transport resources connecting real systems in the physical space and the digital twin platform at DCs. To enable a cost-efficient DTC service, we need to efficiently allocate multilayer resources including IT resources to the DTC service in response to time-varying traffic demand.

Multilayer resource optimization of IT and spectrum resources has been intensively investigated [4]–[12]. Lin et al. investigated an integrated approach for VNF placement on top of optical transport networks [4]. They focused on establishing a virtualized core network that interconnects distributed DCs. However, they assumed conventional WDM-based transport networks, not EONs, as underlay networks. Walkowiak et al. proposed anycast routing algorithms in EONs to efficiently connect users to any available DC [34]. 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]. Here, the goal of multilayer resource optimization is to minimize TCO including operation cost in response to time-varying traffic demand. However, those existing research did not consider operation cost in reconfiguring multilayer resources across from the service layer to the optical layer.

Our work was motivated by the above observation. To cope with traffic demand changes while maintaining the efficiency of resource usage, we must deploy multilayer resource optimization including IT and spectrum resources in optical networks for cost-effective network services; at the same time, we also need to minimize operation cost required for reconfiguring those resources. To improve the flexibility and adaptability of traffic demand changes, we need to migrate some existing VNFs to other DCs and also reconfigure some of the existing optical path in order to connect 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 re-optimizing IT and spectrum resources. As for traffic engineering in consideration of operation cost, Zheng et al. recently proposed routing update algorithms with operation-cost constraints in response to traffic demand changes [33]. However, their focus is on the conventional packet transmission layer, so their proposal is unable to be applied to the optical layer. To the best of our knowledge, few studies have investigated the multilayer resource optimization including IT and optical resources in consideration of operation cost. In this paper, we thus propose a joint optimization method of

IT and optical resources under time-varying traffic demand in optical networks while avoiding the increase in operation cost. We believe the proposed multilayer resource optimization method will contribute to not only the TCO reduction but also the realization of a future network architecture where the optical layer directly accommodates the service layer.

3. Multilayer Resource Optimization with Operational Constraints

Now we study multilayer IT and optical resource optimization in consideration of operation cost in optical networks. Before presenting the proposed method, we first describe an overview of the system model and then delineate the joint optimization of IT and spectrum resources in optical networks. Finally, we define the cost used in the joint optimization problem.

3.1 Overview of System Model

First, we give an overview of the system model. Figure 3 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], [50]. 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.

3.2 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 each 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.

3.3 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.

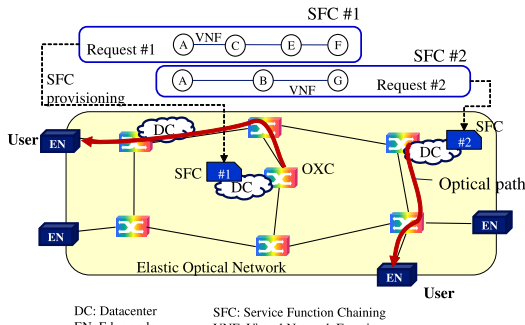


Fig. 3 Infrastructure provider's network that leases virtualized IT and spectrum resources.

4. Proposed Method

We present a proposed multilayer resource 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.

4.1 Problem Statement

Before presenting the problem statement, we describe the motivation of our work with an illustrative example as shown in Fig. 4. 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. 4). 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.

4.2 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
- 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 [9]. 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 $t = 0, 1, \dots$ 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. Before presenting our formulation, we introduce some notations:

- m and n indicate the end nodes of a fiber link in the EON,
- i and j indicate the origin and destination nodes in the EON, respectively.

Key variables and parameters used in our model are summarized in Table 1. 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 $l_{ij}(t-1)$, $p_{mn}^{ij}(t-1)$, $s_{mn,h}^{ij}(t-1)$, and $x_{ij}^k(t-1)$. Those variables are obtained from the results in the previous

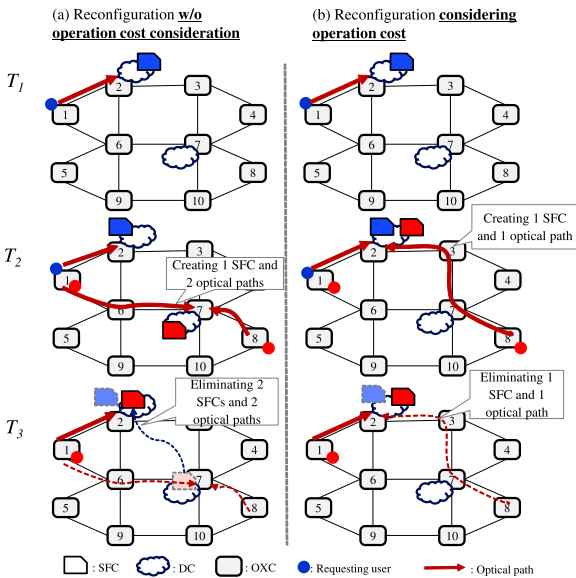


Fig. 4 Motivating example. If we reconfigure IT and network resources without considering operation cost, resources may be unnecessarily added/deleted resources.

Table 1 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
$y_{mn}^{max}(t)$	maximum number of assigned spectrum slots on fiber link mn
$y_{mn}^{min}(t)$	minimum number of assigned spectrum slots on fiber link mn
$z_{mn}(t)$	difference value between maximum and minimum numbers of assigned spectrum slots on fiber link mn

reconfiguration period.

As for variables, $l_{ij}(t)$ holds a non-negative integer variable whereas both $p_{mn}^{ij}(t)$ and $s_{mn,h}^{ij}(t)$ are binary variables. A 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. As for spectrum-slot continuity and contiguity constraints, we introduce the following variables: $y_{mn}^{max}(t)$, $y_{mn}^{min}(t)$, and $z_{mn}(t)$. 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.

4.3 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

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

Constraints: optical network design (optical-path routing)

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

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

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

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

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

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

Constraints: optical network design (spectrum-slot assignment)

$$c_{ij,lh}(t) \geq p_{mn}^{ij}(t) + p_{mn}^{lh}(t) - 1, \quad \forall i, l \in V_{dc}, j, h \in V_{en} \quad (8)$$

$$o_{ij,lh}(t) + o_{lh,ij}(t) = 1, \quad \forall i, l \in V_{dc}, j, h \in V_{en}, (i, j) \neq (l, h) \quad (9)$$

$$z_{lh}(t) + w_{ij}(t) + 1 \leq E_{slot} \cdot (1 + o_{ij,lh}(t) - c_{ij,lh}(t)), \quad \forall i, l \in V_{dc}, \forall j, h \in V_{en}, (i, j) \neq (l, h) \quad (10)$$

$$z_{ij}(t) - w_{lh}(t) + 1 \leq E_{slot} \cdot (2 - o_{ij,lh}(t) - c_{ij,lh}(t)), \quad \forall i, l \in V_{dc}, \forall j, h \in V_{en}, (i, j) \neq (l, h) \quad (11)$$

$$z_{ij}(t) - w_{ij}(t) + 1 \geq y_{ij}(t), \quad \forall i \in V_{dc}, \forall j \in V_{en}, \quad (12)$$

$$z_{ij}(t), w_{ij}(t), y_{ij}(t) \in (0, E_{slot}], \quad \forall i \in V_{dc}, \forall j \in V_{en}, \quad (13)$$

$$Z_{ij}(t) \leq u, \quad \forall i \in V_{dc}, \forall j \in V_{en}. \quad (14)$$

Constraints: Operation cost

$$c_{op}(t) = \sum_{ij, mn} |p_{mn}^{ij}(t-1) - p_{mn}^{ij}(t)| + \sum_{ij, k} |x_{ij}^k(t-1) - x_{ij}^k(t)| \quad (15)$$

Constraints: Logical network design

$$\sum_i x_{ij}^k(t) = \begin{cases} 1, & \text{if } D_j^k(t) > 0 \\ 0, & \text{else} \end{cases} \quad (16)$$

$$\sum_k D_j^k(t) \cdot x_{ij}^k(t) \leq C_{slot} \cdot l_{ij}(t), \quad \forall i \in V_{dc}, \forall j \in V_{en} \quad (17)$$

$$\sum_k \sum_j D_j^k(t) \cdot x_{ij}^k(t) \leq C_{dc}, \quad \forall i \in V_{dc} \quad (18)$$

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 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 node i and j is expressed in Eq. (7).

Spectrum-slot-contiguity constraints are determined from Eqs. (8), (9), (10), (11), (12), and (13). Equation (8) computes whether or not two different optical paths share the common fiber link on the route. Equations (9), (10), and (11) ensure the spectrum-slot assignment of any two different optical paths do not overlap. The total number of spectrum slots allocated to an optical path is provided in Eq. (12).

Operation cost is given by Eq. (15). 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. Equation (16) shows that SFC k can be located at one candidate DC, but the sum of traffic flows must equal 1. Equations (17) and (18) are constraints on the capacity of logical links and DCs. Due to space limitations, we omit the description of some constraints.

5. Numerical Experiments

We performed intensive numerical experiments to demonstrate the effectiveness of the proposed method. In this section, we first investigate the trade-off between operation cost and the optimality of network reconfiguration. On the basis of this investigation, we compare the performance of the proposed method with conventional methods.

5.1 Aims and Conditions

We first describe the aims and conditions of the numerical experiments. We used the 11-node 15-link Abilene network topology and 12-node 17-link JPN12 network topology [51] as illustrated in Figs. 5 and 6. The network is attached with four ENs and four DCs in the Abilene topology, while the JPN12 topology has four ENs and three 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

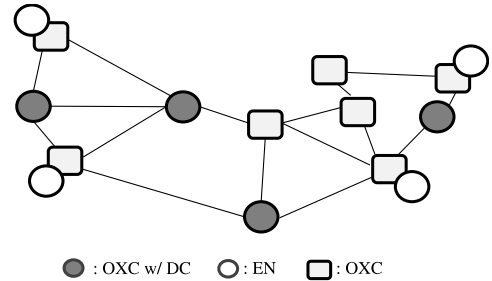


Fig. 5 11-node 15-link Abilene network topology with 4 ENs and 4 DCs.

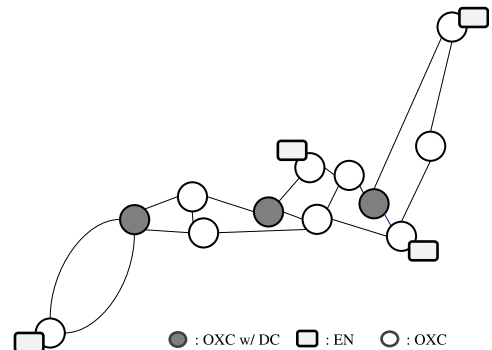


Fig. 6 12-node 17-link JPN12 network topology with 4 ENs and 3 DCs.

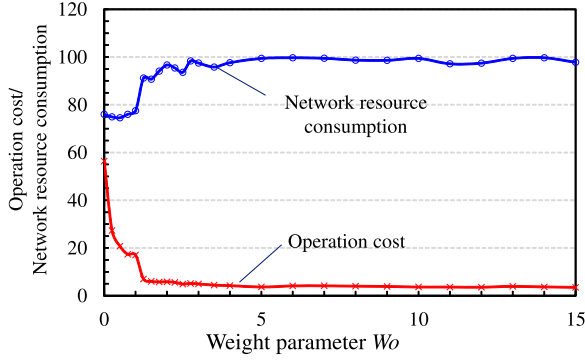


Fig. 7 Relationship between operation cost and network resource consumption while varying weight parameter W_o .

each source/destination pair [52], which is given by

$$D_j^k(t) = A \cdot N_k \cdot \left(\sin(2\pi t/T + \theta_j^k) + 1 \right) \quad (19)$$

Here, A is a normalized parameter that determines the magnitude of generated traffic while N_k is the number of VNFs in SFC k . T and θ_j^k correspond to cycle length and phase difference. We set T as 24 hours while θ_j^k was randomly chosen from 0 to 2π . At the end of each epoch (i.e., every hour), network reconfiguration is performed.

5.2 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 in the Abilene topology. The results are shown in Fig. 7. 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 with 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.

5.3 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 four conventional methods Full, Random, RoundRobin and Peak. 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, while RoundRobin corresponds to the method where SFC placement is determined in accordance with the round robin order among candidate DCs. Finally, Peak corresponds to the method where SFC placement as well as optical path routing is determined in advance in consideration of the peak traffic demand within the 24 hours. So, in Peak, we do not perform any reconfiguration in response to traffic demand changes.

In Proposed, we computed solutions by using the MILP formulation described in Sect. 4. We deployed SCIP [53], which was one of the fastest non-commercial linear programming solver. In RoundRobin and Random, the optical network design phase was performed by using the MILP formulation. In each experiment, we could obtain the optimal solutions by using SCIP.

We compared network resource consumption and operation cost of the proposed method with the three conventional methods. The results in the Abilene topology are shown in Figs. 8 and 9. 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. 9. 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. Furthermore, the proposed method reduced network resource consumption by about 15% in average compared with Peak. This also indicates that dynamic reconfiguration is highly effective under time-varying traffic demand to reduce TCO and such capability should be supported in future optical networks.

We also performed the same experiments in the JPN12 topology. The results are shown in Figs. 10 and 11. 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 25% compared with Peak. However, Proposed adequately avoided the increase

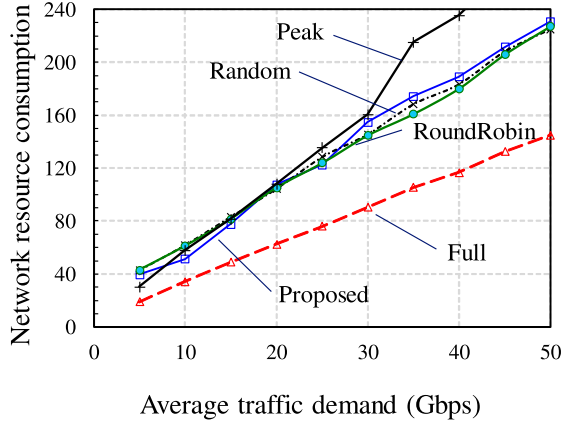


Fig. 8 Comparison of network resource consumption in Abilene topology.

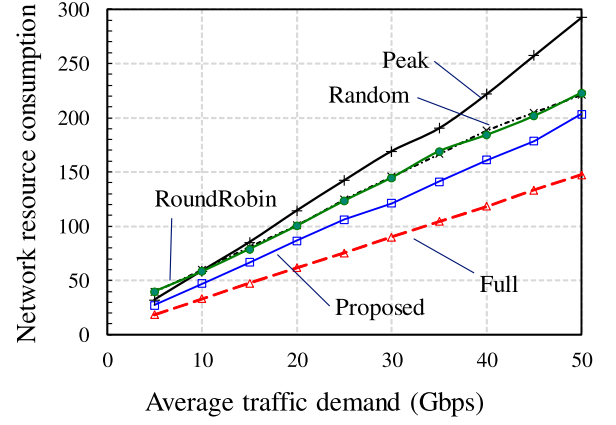


Fig. 10 Comparison of network resource consumption in JPN12 topology.

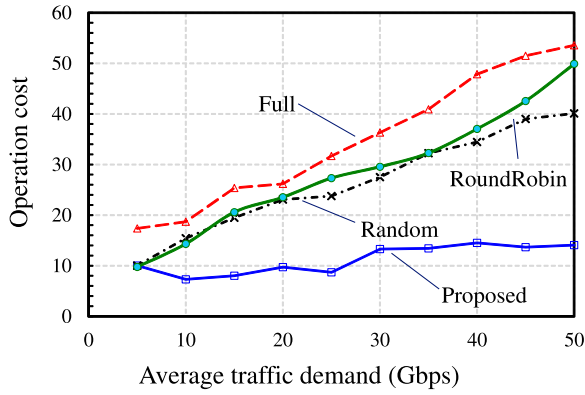


Fig. 9 Comparison of network operation cost in Abilene topology.

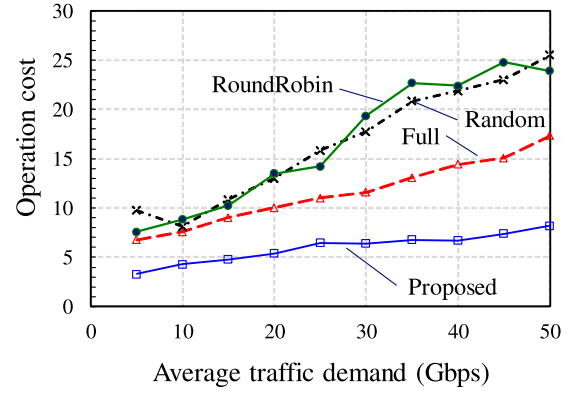


Fig. 11 Comparison of network operation cost in JPN12 topology.

in operation cost and outperformed the three conventional methods in terms of network operation cost, as shown in Fig. 11. The proposed method reduced operation cost by about 48% on average compared with Full. Although Full efficiently reduced network cost, it completely failed to reduce total cost.

In conclusion, we can reduce operation cost while maintaining the efficiency of resource usage by using the proposed method for various network conditions.

5.4 Computation Overhead

Regarding the computation overhead, we investigated the computation time of the proposed method. Here, we performed 240 experiments at the average traffic volume of 25 Gbps. The evaluation environment used in our experiments is as follows:

- CPU: Core i5 1135G7 2.40 GHz
- Memory: 16 GB
- OS: Ubuntu 22.04
- LP Solver: SCIP 8.0.3

The results are shown in Table 2. The average computation time of the proposed method at one reconfiguration

Table 2 Comparison of average computation time in Abilene topology and JPN12 topology.

	Abilene	JPN12
Proposed	1.04 s	0.95 s
RoundRobin	3.76 s	1.74 s

epoch was about 1.04 seconds in the Abilene network topology, whereas that in RoundRobin was about 0.95 seconds. In the JPN12 topology, the average computation time of the proposed method was about 3.76 seconds, while that in RoundRobin was about 1.74 seconds. Because the proposed method takes the operation cost into consideration, the average computation time tends to be relatively longer compared with the baseline method (i.e., RoundRobin). According to the results, the proposed method can obtain the optimal solutions with operational constraints in practical computation time. The computation time of the proposed method is mainly dependent on the number of physical nodes and SFCs. Even though the computation overhead was relatively low according to the results, our problem was still NP-hard. So, we need to develop a heuristic algorithm for improving scalability, which will be investigated in our future work.

6. Conclusion

In this paper, we investigated the evolution of a transport network architecture and discussed the research direction of optical network design and control. We reviewed existing research on optical network design and control, and presented some open research challenges. An architecture of future transport networks will be simplified by eliminating sophisticated electrical processing in order to improve energy efficiency while satisfying ever-increasing bandwidth demand. In future, the optical layer should be capable of the direct accommodation of the service layer. Tighter integration of the service-layer and optical-layer drives research on this area. One of the important open challenges lies in multilayer resource optimization including IT and optical network resources. We considered an adaptive multilayer resource optimization of IT resources and optical spectrum while minimizing operation cost for providing cost-efficient network services. To maintain the efficiency of resource usage under time-varying traffic demand, 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 issue, 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 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 while avoiding an increase in operation cost. We also confirmed that adaptive reconfiguration was highly effective under time-varying traffic demand while a static network configuration failed to ensure the efficiency of resource utilization. We believe the proposed method will contribute to not only the TCO reduction but also the realization of a future network architecture where the optical layer directly accommodates the service layer.

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