Highly efficient optical aggregation network with network functions virtualization

Takashi Miyamura¹ | Akira Misawa² | Jun-ichi Kani³

¹NTT Network Service Systems Laboratories, NTT Corporation, Musashino, Tokyo, Japan
²Chitose Institute of Science and Technology (CIST), Chitose, Hokkaido
³NTT Access Service Systems Laboratories, NTT Corporation, Yokosuka, Kanagawa, Japan

Correspondence
Takashi Miyamura, PhD, NTT Network Service Systems Laboratories, NTT Corporation, Musashino, Tokyo, Japan.
Email: taka.miyamura@hco.ntt.co.jp

Summary
Network functions virtualization enables network edge functions to be relocated from dedicated hardware to distributed pools of commodity servers. Metro aggregation networks provide transport between access gateway nodes and such servers accommodating virtual network functions (VNFs). Networks need to be designed to increase the efficiency of network resource usage and reducing network cost as well as energy consumption. However, independently placing VNFs on a server from a physical network design degrades the efficiency of resource usage and causes an increase in network cost. We can avoid such problems by adequately placing each VNF in consideration of the location of access gateway nodes and a network topology. We thus propose a method for designing an optical aggregation network with VNF placement. We successfully formulate the design method as mixed-integer linear programming and demonstrate its effectiveness through intensive mathematical experiments. The experiments showed that the proposed method reduced network cost by up to about 18% while performing almost optimally in terms of server load dispersion.

1 | INTRODUCTION

Cloud providers operate geographically distributed datacenters. To inter-connect such datacenters, they lease physical network infrastructure such as dark fibers from carriers and construct their own virtualized optical transport network.¹ Currently, virtualized cloud access has received much attention for quality of service (QoS) assurance and performance optimization.²,³ To provide their cloud service to end users, cloud providers need to aggregate sparsely distributed user traffic via a carrier’s access gateway nodes (AGNs) and transport such traffic to datacenters, as shown in Figure 1. For this purpose, they need to construct a virtualized aggregation network connecting AGNs with their datacenters. Network functions virtualization (NFV) enables network functions to be relocated from dedicated hardware to distributed pools of commodity servers.⁴,⁵ By introducing NFV into metro aggregation networks, cloud providers can construct their own virtualized metro aggregation networks. This improves QoS of their cloud services while efficiently utilizing network resources for cloud access. Due to fierce competition and increasing volume of data traffic, cloud providers must reduce

Abbreviations: AGN, access gateway node; ES, edge server; NFV, Network functions virtualization; OADM, optical add/drop multiplexer; VNF, virtual network function

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.
© 2018 The Authors. International International Journal of Network Management Published by John Wiley & Sons, Ltd.

Int J Network Mgmt. 2019;29:e2052.
https://doi.org/10.1002/nem.2052
the consumption of physical network resources to connect datacenters with carrier’s AGNs. The key to this lies in how to design the mapping of a virtual network of a cloud provider on a carrier’s physical network infrastructure.

Virtual network embedding is one of the main issues in cloud networking. The challenge in virtual network embedding is to efficiently map virtual nodes and virtual links onto physical network resources. To reduce network cost, cloud providers need to design minimum-cost mapping of their own virtual network on physical network infrastructure. Ways to map virtual networks on physical networks have been extensively investigated. Chowdhury et al. assumed conventional packet-based networks as physical network infrastructure. This assumption is restricted to network performance. To accommodate an increasing volume of data traffic, datacenters are currently inter-connected by using optical transport systems. Lin et al. investigated an integrated approach for virtual network function (VNF) placement on top of optical transport networks. They focused on establishing a virtualized core network that interconnects distributed datacenters. They assumed a point-to-point (P2P) wavelength-routed path network as an underlying physical network. However, P2P wavelength-routed network architecture is not suitable for a metro aggregation network because it has too few optical fibers. Although the volume of traffic from each AGN is relatively low, we need to efficiently aggregate traffic from numerous AGNs to a datacenter with limited wavelength and fiber resources. Their method cannot efficiently utilize wavelength resources and consumes too much wavelength resources because it uses a dedicated P2P wavelength path that directly connects numerous AGNs with a datacenter.

For cost-efficient end-to-end cloud networking, minimum-cost mapping must be found that efficiently aggregates traffic from numerous AGNs to datacenters, while reducing the consumption of physical link resources. In addition, metro/access networks account for most of the network cost. Thus, virtual network embedding problems in metro aggregation networks must be solved for cost-efficient cloud networking. Cloud providers need to find ways to efficiently embed point-to-multipoint (P2MP) paths that connect numerous AGNs with datacenters. However, few studies have investigated virtual network embedding problems while considering efficient traffic aggregation using P2MP paths.

In this paper, we thus propose a design method for solving virtual network embedding problems in consideration of efficient traffic aggregation in a metro aggregation network. Independently placing VNFs on a server from a physical network topology degrades the efficiency of physical network resources and causes an increase in network cost. We can avoid such problems by adequately placing each VNF in consideration of the location of AGNs and a physical network topology,
which enables efficient P2MP path routing in a physical network. The goal of this paper is to establish an integrated design method for VNF placement in conjunction with P2MP path routing in an optical aggregation network. The proposed method is based on mixed-integer linear programming (MILP) formulations and provides the optimal embedding that minimizes network cost while efficiently utilizing server resources in datacenters. As we discuss later, by integrating the VNF placement with physical network design, we can dramatically reduce the network cost while efficiently using server resources. To the best of our knowledge, this is the first paper to provide a design method for a metro aggregation network with NFV environments.

The main contributions of this paper lie in as follows:

(a) successfully formulating an integrated design for an optical aggregation network with VNF placement as MILP and,
(b) quantitatively evaluating the effectiveness of the proposed integrated design method compared with those of conventional methods.

By using the proposed method, we can reduce network cost by up to 18% while efficiently dispersing server load in datacenters.

The remainder of this paper is organized as follows. We describe an architecture of a next-generation optical aggregation network in Section 2 and then define a network design problem to be solved in Section 3. Section 4 describes a model of the optical aggregation network and presents a mathematical formulation of the design problem. Results of intensive mathematical experiments are presented in Section 5. A brief conclusion is provided in Section 6. This work was in part presented in APNOMS 2017.

2 | BACKGROUND

Before presenting the proposed design method, we briefly explain recent trends in metro/access networks and describe an architecture of the optical metro aggregation network considered in this paper.

2.1 | Recent trends in metro aggregation networks

Emerging network applications, such as Internet of things and vehicle-to-vehicle communication, are imposing unpredictable traffic variations on metro aggregation networks that connect datacenters with AGNs. Thus, metro aggregation networks must effectively transport large-volume traffic and adapt to such unpredictable traffic. In a metro aggregation network, low-speed legacy time division multiplexing (TDM) interface technologies, such as synchronous optical networking/synchronous digital hierarchy (SONET/SDH), were used to aggregate voice traffic. A metro aggregation network enables us to efficiently transport traffic by using line multiplexing between AGNs located at access networks and edge routers, which provide network edge functions, at the edge of core networks. AGNs include optical line terminals (OLTs) and radio base stations (RBSs). Currently, the majority of traffic is packet based, so electrical Layer 2 switches with wavelength division multiplexing (WDM) transmission systems are commonly used for aggregating such traffic. A metro aggregation network uses electrical Layer 2 switches to aggregate low-speed packet-based traffic from numerous AGNs. This increases network cost as well as energy consumption because WDM transponders in conjunction with electrical switches are required at each transit node. Metro and access network convergence is one of the most important recent trends. A passive optical network (PON) has been widely deployed in access networks. There have been extensive investigations to expand the applicability of PON-based technologies. Davey et al. presented long-reach PON technologies that extend the reach of a PON by using optical amplifiers. The concept of long-reach PON simplifies a metro/access network architecture and reduces network cost by eliminating electronic aggregation switches. To further enhance network throughput of the PON, WDM-based PON technologies have been developed and are already commercially available. Currently, a time division multiplexing-wavelength division multiplexing (TDM-WDM) based PON has been standardized as NG-PON2 to achieve throughput of 40 Gbps.

Over the past decade, TDM-WDM-based metro/access network architectures have been extensively investigated on the basis of emerging PON-based technologies. Kotsugai et al. developed a highly efficient TDM-based optical access/aggregation network architecture on the basis of variable bandwidth wavelength technologies. Ruffini et al. proposed a dynamically reconfigurable TDM-WDM-based ring architecture using PON technologies. To efficiently accommodate bursty traffic from numerous AGNs, these aggregation network architectures enable a common wavelength channel to be shared by multiple AGNs through optical TDM technologies such as dynamic bandwidth allocation (DBA) used in PON. In those architectures, a logical layout is basically a tree topology constructed on top of ring-based phys-
tical networks. Thus, a path topology in such networks forms P2MP connectivity. The architecture is suitable for traffic aggregation because a common wavelength channel can be shared by multiple AGNs, which can reduce network cost. The details are described in the next subsection.

2.2 Related work

We briefly review related work on (a) an architecture for a TDM-WDM-based optical aggregation network, (b) the optimization of optical multicast networks, and (c) the virtual network embedding problem. Here, we consider a TDM-WDM-based network as an aggregation network, which connects an AGN (i.e., an OLT) with a corresponding server accommodating VNFs using a shared P2MP wavelength path.

As for an optical aggregation network architecture, our research group proposed a system architecture for optical TDM-based aggregation networks. Kotsugai et al. proposed a highly-efficient TDM-based optical access/aggregation network architecture based on variable bandwidth wavelength technologies. Recently, Carey et al. proposed a dynamically reconfigurable TDM-WDM ring architecture using PON technologies. Previous studies mainly focused on developing and demonstrating network and system architectures, but few have investigated the design of TDM-WDM-based optical aggregation networks.

To design a multicast network, a mathematical formulation of multicast trees in network cording was presented by Ahlswede et al. Köksal and Ersoy and Hachisuka et al. produced related work on optical multicast network design algorithms. Their work considers optical multicast that simply splits optical signals at intermediate nodes, so their models did not cover the sharing of a P2MP wavelength path with multiple destination nodes through DBA. In aggregation networks, as we described earlier, such capability is essential to efficiently accommodate bursty traffic from OLTs by using oversubscription or statistical multiplexing.

Recently, virtual network embedding problems have been intensively investigated. The optimization of VNF chaining problems in a packet-based network has been proposed. The mapping of virtual networks on physical networks has also been investigated, and heuristic algorithms for VNF placement have been proposed. However, those literatures did not consider a shared optical P2MP path network as a physical network. Zhang et al. investigated virtual network embedding problems for WDM and flexible-grid networks and formulated the problems as MILP. Their work also assumed a conventional P2P wavelength path network, so their method is unable to apply in TDM-WDM-based networks considered in this paper.

Software-defined networking (SDN)-based metro/access aggregation network and node architectures have been intensively studied. Cvijetic et al. proposed an optical aggregation network architecture based on SDN and OpenFlow. They performed experimental demonstration of the proposed architecture. Kondepu et al. proposed an aggregation node architecture supporting time and wavelength division multiplexed (TWDM)-PONs using SDN control. They implemented a prototype system and demonstrated the effectiveness of their architecture. Those literatures focused on system implementation and experimental demonstration of the proposed network architecture, and network optimization problems were out of their scope. Moreover, they did not consider NFV of network edge function considered in this paper.

In summary, TDM-WDM-based optical aggregation network architectures have been intensively investigated and already demonstrated in experimental networks. However, few literatures has investigated virtual network embedding problems as well as optimal VNF placement for those networks. For efficient aggregation networks, we must establish an optimal design method for virtual network embedding problems in P2MP wavelength path networks.

2.3 Architecture of optical aggregation network

We describe an architecture of TDM-WDM-based optical aggregation networks in a NFV environment. An overview of the architecture is illustrated in Figure 1. In a conventional metro aggregation network, each edge router accommodates a group of AGNs. Edge routers, which are based on dedicated hardware, provide various network edge functions such as an access control list, flow identification, and security functions to offer cloud services to customers. Before entering datacenters of a cloud provider, network edge functions are executed to all incoming traffic by an edge router. In NFV, edge routers are replaced with edge servers (ESs) that have VNFs. A VNF, which runs on a commodity-server-based ES, supports the network edge functions. By introducing NFVs, we can efficiently accommodate unpredictable demand changes with limited network resources. In the optical aggregation network architecture with VNF, resources are reallocated in accordance with the addition or withdrawal of subscribers and the variation in bandwidth usage for each user.
This improves resource utilization in accordance with unexpected traffic-demand changes, which eventually reduces network cost and energy consumption.

An optical aggregation network consists of AGNs, optical add/drop multiplexers (OADMs), WDM links connecting two adjacent physical nodes, and ESs accommodating VNFs. The important feature of the architecture is that each VNF has one-to-one correspondence to a specific AGN. For VNF placement, each VNF must be placed on an adequate ES in consideration of bandwidth demand as well as wavelength resource consumption and be able to communicate with a corresponding AGN. Thus, the architecture requires a mechanism for providing connectivity between an ES with VNFs and corresponding AGNs. For this purpose, we consider a TDM-WDM-based optical aggregation network that only requires a set of multicast-capable OADM modules for an intermediate node. A group of OADMs has a ring topology, and each wavelength in the network forms a P2MP wavelength path shared by multiple AGNs that have the same target ES. This P2MP path is called a “shared P2MP wavelength path” in this paper. Thus, we can eliminate any electrical packet processing at intermediate nodes, which reduces network cost as well as energy consumption.

Now we introduce the concept of a “shared P2MP wavelength path.” The shared P2MP wavelength path is just a version of NG-PON2 generalized to make it applicable to ring-based physical network topologies. Each ES communicates with a specific group of AGNs via a P2MP wavelength path. The bandwidth of each P2MP wavelength path can be shared by multiple AGNs in accordance with DBA; thus, we can improve the resource utilization of each wavelength channel through statistical multiplexing as well as reduce the consumption of wavelength resources. This wavelength sharing is crucially important in efficiently aggregating bursty traffic from numerous AGNs with limited wavelength resources. Optical burst contention resolution in the same wavelength channel is carried out through a DBA mechanism. DBA mechanisms are implemented on burst senders/receivers at ESs and AGNs. Enabling technologies for TDM-based shared P2MP wavelength paths have been developed and demonstrated by Carey et al. and Nakagawa et al. All wavelength channels are transmitted through the shared TDM-WDM-based ring topology. Intermediate OADMs just drop, split, or pass through wavelength signals without any packet processing. The resource demand of each VNF also varies depending on the number of subscribers on an AGN and the duration of service usage. From the viewpoint of resource management, each VNF needs to be placed to an adequate ES among server pool, while considering bandwidth requirements and resource consumption in the TDM-WDM-based optical aggregation network.

An optical aggregation network must connect an ES accommodating VNFs with corresponding AGNs via a P2MP wavelength path for end-to-end cloud networking. Thus, VNF placement greatly affects the efficiency of network resource usage. To design highly efficient networks, we must consider optical network topology information in placing VNFs to each ES. Designing VNF placement independently of an optical network topology increases consumption of wavelength paths because of the lower utilization of the paths. The details of a network design problem are described in the next section.

### 3 | OPTICAL AGGREGATION NETWORK DESIGN

#### 3.1 | Use cases

Next, we describe use cases of our network design. We mainly consider two use cases, as illustrated in Figure 2: (a) initial network design and (b) network reconfiguration design in operation.

In the first use case, we create a logical network on an optical aggregation network. In the initial state, we need to design a logical network, which includes VNF placement on an adequate server and wavelength path routing, in consideration of traffic demand requirements on a given physical network. Our design method basically provides a solution to this initial network design.

The network reconfiguration design maintains network performance in accordance with unpredictable traffic demand changes after the initial network design. In the initial network design, we usually allocate redundant network resources to accommodate growing traffic demand on the basis of predictions for three or six months ahead to avoid frequent infrastructure expansions. However, long-term traffic prediction often overestimates as well as underestimates future traffic demand. Underestimating traffic demand causes network congestion and service-quality degradation. In such a case, we can alleviate the impact of prediction errors by reconfiguring a logical network on the basis of actual measured traffic. Network reconfiguration design has been intensively studied and demonstrated. In the optical aggregation network, a prediction error causes over/under-utilized ESs and wavelength paths. By reconfiguring the VNF placement, we can efficiently avoid such problems.
In summary, to efficiently operate an optical aggregation network with network edge VNF, a design method must be developed that determines VNF placement and shared P2MP wavelength path routing in consideration of traffic demand requirements and physical network resource utilization.

### 3.2 Problem definition

Now, we describe a problem we are solving. By adequately designing VNF placement in consideration of resource consumptions of shared P2MP wavelength paths, we can reduce network cost and improve robustness against unpredictable demand changes by allocating sufficient residual resources among ESs. Figure 3 illustrates an example of an optical aggregation network design with VNF placement. The network provides a physical path connecting each ES accommodating VNFs with corresponding AGNs via wavelength paths. In Case A, three pairs of VNFs and AGNs are connected via two P2MP wavelength paths. On the other hand, in Case B, the three VNFs, located at the same ES, are connected with the corresponding AGN via a common P2MP wavelength path. Case A consumes more wavelength-link resources than Case B.
because VNF placement is independently designed from physical path routing. However, designing VNF placement independently of wavelength path routing increases consumption of wavelength paths due to lower utilization of the paths. To cope with accelerating traffic demand growth, we must improve the utilization of limited physical network resources by designing an efficient logical network. Moreover, server load must be dispersed to cope with sudden increases in resource consumption by VNFs. Thus, the network design must minimize the maximum server load among server pools. The key to this is to establish an integrated design method for VNF placement in conjunction with P2MP wavelength path routing in an optical aggregation network.

What is important is how to place each VNF on an adequate server among pools in consideration of efficient route selection between ESs and AGNs. We now describe the problem we are attempting to solve: how to place VNFs and allocate network resources to minimize network resource consumption on a given physical network while adequately dispersing server load.

4 | PROPOSED DESIGN METHOD

4.1 | Network model

First, we give an overview of an optical aggregation network model. The network consists of ESs, AGNs, intermediate nodes (OADMs), and physical WDM links connecting two adjacent nodes. We assume the following input given to the problem:

- ESs accommodating VNFs,
- AGNs generating traffic demand,
- VNFs corresponding to each AGN,
- Intermediate nodes (OADMs),
- Physical WDM links,
- Traffic demand of each AGN.

Figure 4 shows an example that explains the relationship between physical and logical networks. In this example, two pairs of ESs and AGNs are attached with a TDM-WDM-based ring network, and two VNFs are accommodated in ES 0. A shared P2MP wavelength path is established between ES 0 and AGNs 1 and 2 in the physical network. The bandwidth of the wavelength path is shared by two AGNs through the optical TDM. Thus, each AGN can occupy up to the full bandwidth of the path, but the sum of average traffic from the two AGNs does not exceed the bandwidth. This enables a wavelength channel to be efficiently used by statistically multiplexing bursty traffic from AGNs.

Second, we describe notations used in our mathematical formulation before presenting it. Mathematical formulations of optical multicast path trees have been studied by Köksal and Ersoy, but their model cannot be applied to the variable source-node locations derived from VNF placement and shared P2MP wavelength paths considered in this paper. In a basic network optimization problem, source and destination nodes are predetermined. However, in our model, the source-node (ie. VNF) location changes depending on VNF placement. We previously proposed mathematical formula-
tions considering some of these requirements. We extend our previous formulations to apply them to shared P2MP wavelength path networks. The basic idea of the formulation is to define a multipoint-to-point flow from candidate ESs to each AGN and selecting the optimal ES among the candidates. We introduce the following notations:

- $m$ and $n$ denote end points of a physical link in the physical network,
- $i$ and $j$ denote source and destination nodes in the logical/physical network, respectively.

**Given:**

- $N$: number of nodes in the network
- $E$: set of physical links
- $V$: set of physical nodes
- $V_{agn}$: set of AGNs
- $V_{es}$: set of ESs
- $V_{in}$: set of intermediate nodes
- $E_{i}$: maximum number of wavelengths per physical link
- $D_{j}$: Traffic demand generated at AGN $j$
- $C_{\lambda}$: capacity of a wavelength channel (in Gbps)
- $C_{es}$: capacity of each ES

**Variables:**

- $L_{ij}$: traffic demand on logical link $ij$,
- $C_{mn}^{i}$: number of wavelengths occupied by a P2MP path originating at ES $i$ on link $mn$,
- $p_{mn}^{ij}$: physical path routing from node $i$ to node $j$
- $x_{ij}^{k}$: traffic routing from node $i$ to node $j$ regarding VNF $k$

Here, $L_{ij}$ is a nonnegative real variable while variables $C_{mn}^{i}$ and $p_{mn}^{ij}$ hold nonnegative integers. We model a physical network as a directed graph $G = (V, E)$. For the physical network design, the route and capacity of shared P2MP wavelength paths are determined by variables $C_{mn}^{i}$ and $p_{mn}^{ij}$. In designing the logical network, $x_{ij}^{k}$ is a binary variable that expresses the location of VNF $k$,

$$x_{ij}^{k} = \begin{cases} 
1 & \text{if VNF } k \text{ associated with AGN } j \\
0 & \text{otherwise}
\end{cases}$$

Here, traffic demand is defined to each AGN not VNF, and the traffic demand of VNF $k$ is identical to that of the corresponding AGN $i$ ($D_{i}$). A mathematical formulation based on the above notations is presented in the next subsection.

### 4.2 Mathematical formulation

Finally, we present a mathematical formulation of shared P2MP wavelength path networks with VNF placement. The objective for our design is to minimize network resource consumption while avoiding an increase in the maximum load of ESs on a given physical network. In the logical network design, we need to determine how to do the following:

- Place a VNF to adequate ESs considering bandwidth requirement and the capacity of ESs.
- Find routes for P2MP wavelength paths that minimize physical network resource consumption.
- Define a group of AGNs accommodated by the same P2MP path.

An outline of the MILP formulation is described below.

**Objective:** Minimizing network cost and maximum server load

$$\min \left( \sum_{k} \sum_{mn} C_{mn}^{k} + \alpha \max_{l} \sum_{k} \sum_{j} D_{j} \cdot x_{ij}^{k} \right)$$

**Constraints:** Physical network design:

$$\sum_{l} p_{ml}^{ij} - \sum_{l} p_{ln}^{ij} = \begin{cases} 
-\lfloor L_{ij} \rfloor & l \in V_{es} \\
\lceil L_{ij} \rceil & l \in V_{agn} \\
0 & l \in V_{in}
\end{cases}$$

In Equation 1, the first term corresponds to the sum of wavelength resource consumption and the second term indicates the maximum load of ESs. The two terms have different scales, so we introduce parameter α to adjust the scale. Equation 2 shows a flow conservation law regarding physical path routing between ESs and AGNs. Note that a P2P path \( p_{mn} \) is not actually established in the physical network, but the variable indicates a conceptual flow.\(^{23}\) The term \( C_{mn} \) is used for computing the route and capacity for P2MP path in conjunction with \( p_{mn} \). Equations 3-5, and 6 constrain link capacity considering shared P2MP paths. Equation 5 shows that the capacity of a P2MP path exceeds the traffic demand on the corresponding logical link. Equation 6 is constraint on the capacity of physical links. Equation 7 shows that VNFs can be located at one candidate ES, but the sum of traffic flows must equal to 1. Equations 8 and 9 are constraints on the capacity of logical links and ESs.

### 5 PERFORMANCE EVALUATION

#### 5.1 Aims and conditions

We conducted intensive mathematical experiments to quantitatively evaluate the effectiveness of the proposed method. More specifically, we demonstrated that the proposed method can more effectively reduce network cost while maintaining server utilization than an independent design method. With the independent design method, VNF placement is determined independently of physical network information including a network topology and wavelength path routing. The objectives are summarized below:

- to clarify the trade-off between network cost and maximum server load and how to determine control parameter \( \alpha \) in the proposed method.
- to demonstrate the effectiveness of the proposed method compared with that of the conventional independent design method in terms of reducing network cost as well as dispersing server load.

We describe the conditions used in the experiments. We implemented our formulation on GNU linear programming kit (GLPK),\(^{37}\) which is an open-source linear programming solver. Table 1 summarizes the specifications of our evaluation environment. A 10-node multi-ring network topology and 12-node torus-form network topology were used in the experiments, as shown in Figures 5 and 6, respectively. Traffic demand of AGNs was generated in accordance with the Zipf distribution:\(^{38}\)

\[
d(x) = b \cdot x^{-\beta} \quad (x = 1, \ldots, ||V_{agn}||).
\]  

(10)

Traffic demand \( D_i \) was determined by the above \( d(x) \) and parameter \( \beta \) was set to 1.0 in our experiments.\(^{39}\) We generated the same number of \( d(x) \) as that of AGNs, and we randomly assigned \( d(x) \) with traffic demand \( D_i \). The experiments had three shared conditions as follows:
### TABLE 1  Evaluation environment

| Spec.          |         |
|----------------|---------|
| **OS**         | CentOS 7.2 |
| **CPU**        | Intel Xeon E3-1260L 2.9GHz |
| **Memory**     | 16GB (DDR4-2133) |
| **LP Solver**  | GLPK v4.64 |

Abbreviations: CPU, central processing unit; OS, operating system.

**FIGURE 5**  Ten-node 3-ring network topology with four edge servers (ESs) and six access gateway nodes (AGNs)

**FIGURE 6**  Twelve-node torus-form network topology with four edge servers (ESs) and eight access gateway nodes (AGNs)

- number of wavelengths per link $E_i$: 16
- capacity of a wavelength channel $C_{\lambda i}$: 100 Gbps
- capacity of each ES $C_{es}$: 500 Gbps

### 5.2  Reference methods

We compared the performance of the proposed method (Proposed) with those of two conventional server selection methods (MinHop and RoundRobin)\(^3^6\) and with that of the independent design method (OptVNF). In MinHop, VNFs are always placed on the ES nearest to an AGN among ESs on the basis of hop counts from each AGN. Thus, MinHop...
FIGURE 7  Trade-off between network cost and maximum server load

can basically provide the lowest network cost of the three comparison methods. The network cost is defined as the total amount of WDM links occupied by all P2MP wavelength paths established on the physical network. With RoundRobin, each VNF is placed among four ESs in round robin order without taking into account network cost, which can efficiently distribute server load among the ESs. With OptVNF, we first optimize VNF placement to minimize the maximum server load without considering the minimization of network cost. After determining VNF placement, we optimize network cost. Thus, OptVNF can be used for a benchmark to evaluate the effectiveness of the proposed integrated design method. We evaluated network cost and maximum server load while varying traffic demand in two different network topologies.

5.3 Relationship between network cost and server load

First, we investigated how optimization parameter \( \alpha \) affects the network cost and maximum server load. Both the network cost and maximum server load are derived from Equation 1, and the value of two objectives is normalized by that in the traffic demand of 0.1. Parameter \( \alpha \), which is given in Equation 1, indicates the optimization weight of two objectives. If we set \( \alpha \) as 0, the proposed method just minimizes network cost without taking into account the maximum server load. The greater value of \( \alpha \) indicates the increased weight of the maximum server load in the optimization.

We compared both performance indices while varying \( \alpha \) from 0 to 1000. The average traffic demand of each AGN was set as 40 Gbps. The results are shown in Figure 7. When \( \alpha \) was relatively low, our proposed method tended to optimize network cost instead of minimizing the maximum server load. As \( \alpha \) increased, our method tended to optimize the maximum server load. By choosing \( \alpha \) between 0.1 and 1, we could efficiently reduce network cost while adequately dispersing server load.

5.4 Effectiveness of integrated design method

Second, we evaluated the effectiveness of the proposed integrated design method in terms of reducing both network cost and maximum server load. On the basis of the above investigation into \( \alpha \), we set \( \alpha \) as 0.5 in this experiment. We compared the performance of our proposed method (Proposed) with those of three conventional methods (MinHop, RoundRobin, and OptVNF).

We evaluated network cost and maximum server load while varying traffic demand in two types of network topologies. The results of the multi-ring topology are shown in Figures 8 and 9. The horizontal line in both figures is relative traffic demand normalized by the capacity of wavelength channel. Traffic demand 0.5 means 50 Gbps of average traffic demand from each AGN. Proposed had up to 12% and 13% lower maximum server load and network cost, respectively, than RoundRobin. Moreover, Proposed had only about 12% higher network cost than MinHop, which was used as a benchmark of network cost in our evaluation.

The proposed method had almost the same maximum server load (less than 1% higher) as the independent design method OptVNF, which was the best at finding the optimal solutions in terms of the maximum server load among the four methods. Moreover, the proposed method had 18% lower network cost than OptVNF. To investigate the dependence of a network topology on performance, we also evaluated performance in the torus-form topology. The results are shown in Figures 10 and 11 and indicate almost the same tendency. The proposed method had 11% lower network cost than...
OptVNF while maintaining almost the same performance of server load dispersion. Thus, we concluded that network cost can be reduced by integrating VNF placement with wavelength path routing.

5.5 Discussion

Finally, we discuss the results of our numerical experiments and present future prospects of deployment into production. We demonstrated the effectiveness of an integrated design method for VNF placement in conjunction with wavelength
path routing through extensive numerical experiments. We considered two deployment scenarios: (a) network planning and optimization for carrier networks and (b) virtual network embedding for cloud providers. In the first scenario, by deploying the proposed method in network planning, telecom operators are able to reduce network cost as well as energy consumptions of their own network infrastructures. Furthermore, we quantitatively demonstrated the effectiveness of TDM-WDM-based network technologies on network cost reduction. We believe such results will contribute to deployment decision on the technologies. In the second scenario, cloud providers can reduce the amount of network resources that are leased from telecom operators. The proposed scheme can find minimum-cost mapping of their own virtual network on a carrier’s physical network infrastructure. If cloud providers own edge datacenters, we can further reduce the usage of physical network resources by adjusting control parameter $\alpha$. Significant findings of our performance evaluation are that the proposed integrated design method improves the efficiency of network and server resource usage for various network conditions, and also, we can control the trade-off between the network cost and maximum server load.

To deploy the proposed method into production networks, we need to further study (a) the scalability of the proposed method and (b) network reconfiguration design for VNF replacement. Regarding the scalability, we investigated the computation time of the proposed method and found out that the bottleneck lies in the VNF placement calculation instead of P2MP-path computation. The computational overhead of P2MP-path routing is relatively light-weight, so we will develop a heuristic VNF placement algorithms for improving scalability in terms of the number of VNFs. To develop a method for network reconfiguration, we need to investigate network control and virtual machine (VM) management mechanisms that include hitless VM live-migration and on-line wavelength path reconfiguration.

6  |  CONCLUDING REMARKS

We proposed an integrated design method for highly efficient optical aggregation networks with VNFs, where a P2MP wavelength path is shared by multiple AGNs through optical TDM technologies, and the location of VNFs can be selected flexibly among commodity server pools. By using the proposed method, cloud providers can construct a minimum-cost network that efficiently aggregates geographically distributed user traffic to their central datacenters. Designing VNF placement independently of wavelength path routing increases consumption of wavelength paths due to the lower utilization of the paths. In this study, we successfully formulated the proposed integrated design method as MILP and quantitatively evaluated its effectiveness through intensive mathematical experiments.

This is the first paper providing a design method for a metro aggregation network in NFV environments. Our work expands the applicability of virtual network embedding problems into metro/access networks, which account for the most of the network cost in current commercial carrier networks. The keys to the proposed method lie in (a) an integrated approach for VNF placement in consideration of physical network design and (b) a sophisticated mathematical formulation of TDM-WDM-based optical aggregation networks with VNF placement. Our MILP formulation can be also applied to network design of NG-PON2, which is a promising next-generation access network technology.

The performance evaluation revealed that the independent design method is liable to increase network cost due to lower efficiency of wavelength paths. The proposed method improves utilization by adequately determining VNF placement in
consideration of wavelength path routing, which eventually reduces network cost. Our mathematical experiments showed that the proposed method can reduce network cost by about 18% while achieving nearly-optimal server utilization.

Future work will include the development of a heuristic algorithm. As the proposed method fully depends on the MILP formulation, it provides optimal solutions. However, it may fail to provide scalability and quick responsiveness in a large-scale network. To avoid scalability problems, we will develop a heuristic algorithm on the basis of the observations in our experiments.

**orcID**

Takashi Miyamura [http://orcid.org/0000-0003-1520-9686](http://orcid.org/0000-0003-1520-9686)

**REFERENCES**

1. Vusirikala V. A Decade of Software Defined Networking at Google, ECOC 2017; 2017.
2. Simeone O, Maeder A, Peng M, Sahin O, Wei Y. Cloud radio access network: virtualizing wireless access for dense heterogeneous systems. *J Commun Netw*. 2016;18(2):135-149.
3. Yamanaka N, Takeshita H, Okamoto S, Sato T, Zhang S. Energy efficiency of future central and/or linked distributed function network using optical technologies. In: Proc. 19th European Conference on Networks and Optical Communications (NOC); Milan, Italy, 2014:97-101.
4. ETSI GS. NFV001, Network Functions Virtualisation (NFV); Use Cases, 1 V1.1.1. [http://www.etsi.org/standards](http://www.etsi.org/standards); 2013.
5. Mosharaf Kabir Chowdhury NM, Rahman MR, Boutaba R. Virtual network embedding with coordinated node and link mapping. *INFOCOM*. 2010;2009:783-791.
6. Addis B, Belaben D, Bouet M, Secchi S. Virtual network functions placement and routing optimization. *CloudNet 2015 - IEEE 4th International Conference on Cloud Networking*. Niagara Falls, ON, Canada: IEEE; 2015:171-177.
7. Otokura M, Leibnitz K, Koizumi Y, Kominami D, Shimokawa T, Murata M. Application of evolutionary mechanism to dynamic virtual network function placement. The *IEEE 24th International Conference on Network Protocols (ICNP)*. Singapore: Workshop: Control Operation and Application in SDN protocols (CoolSDN Workshop); 2016.
8. Lin T, Zhou Z, Tornatore M, Mukherjee B. Demand-aware network function placement. *IEEE J Lightwave Technol*. 2016;34:2590-2600.
9. Miyamura T, Misawa A, Kani J-I. Design of optical aggregation network with carrier edge functions virtualization. In: Proc APNOMS 2017; Seoul, Korea, 2017:88-93.
10. Yetginer E, Karasan E. Dynamic wavelength allocation in IP/WDM metro access networks. *IEEE J Lightwave Technol*. 2009;27(3):273-291.
11. Misawa A, Katayama M. Resource management architecture of metro aggregation network for IoT traffic. *IEICE Trans Commun*. 2018;101(3):620-627. [https://doi.org/10.1587/transcom.2017NRI002](https://doi.org/10.1587/transcom.2017NRI002)
12. Miyamura T, Misawa A, Kani J-I. Design of optical aggregation network with carrier edge functions virtualization. In: Proc APNOMS 2017; Seoul, Korea, 2017:88-93.
13. Kotsugai A, Sato T, Takeshita H, Okamoto S, Yamanaka N. TDMA-based OLT sharing method to improve disaster tolerance in elastic lambda aggregation network. In: Proc ECOC 2014; Cannes, France, 2014:1-3.
14. Carey D, Brandonisio N, Porto S, et al. Dynamically reconfigurable TDM-DWDM PON ring architecture for efficient rural deployment. In: Proc ECOC 2016; Düsseldorf, Germany, 2016:171-177.
15. Hattori K, Homemoto T, Nakagawa M, Kimishima N, Katayama M, Misawa A. Optical layer 2 switch network with bufferless optical TDM and dynamic bandwidth allocation. *IEICE Trans Electron*. 2016;E99.C(2):189-202.
16. Ahlswede R, Cai N, Li S-YR, Yeung RW. Network information flow. *IEEE Trans Inf Theory*. 2000;46.
17. Koitsuka Y, Hasegawa H, Sato K. Impairment-aware multicast tree design for hierarchical optical path networks. *Photonics in Switching*. 2012; 2012 (PS, 2012), Th-S33-O08.
18. Zhang S, Shi L, Vadevru CSK, Mukherjee B. Network virtualization over WDM and flexible-grid optical networks. *Opt Switching Netw*. 2013;10(4):291-300.
19. Cvetic J, Tanaka A, Ji PN, Sethuraman K, Murakami S, Wang T. SDN and openflow for dynamic flex-grid optical access and aggregation networks. *IEEE J Lightwave Technol*. 2014;32(4):864-870.
28. Kondepu K, Sgambelluri A, Valcarenghi L, Cugini F, Castoldi P. An SDN-based integration of green TWDM-PONs and metro networks preserving end-to-end delay. In: Proc OFC 2015; Los Angeles, United States, 2015:Th2A-62.
29. Kang J-M, Bannazadeh H, Rahimi H, Lin T, Faraji M, Leon-Garcia A. Software-defined infrastructure and the future central office. In: Proc. 2013 IEEE International Conference on Communications Workshops (ICC); Budapest, Hungary, 2013:225-229.
30. Misawa A, Mochizuki K, Tsuchiya H, et al. Virtual edge architecture with optical bandwidth resource control. *IEICE Trans Commun*. 2016;E99.B(8):1805-1812.
31. Nakagawa M, Masumoto K, Hattori K, et al. Flexible and cost-effective optical metro network with photonic-sub-lambda aggregation capability. In: Proc OECC/PS2016; Niigata, Japan, 2016:1-3.
32. Papagiannaki K, Taft N, Zhang Zhi-Li, Diot C. Long-term forecasting of internet backbone traffic: observations and initial models. In: Proc INFOCOM 2003; San Francisco, United States, 2003:1178-1188.
33. Miyamura T, Kurimoto T, Hayashi R, Inoue I, Shimomoto K, Urushidani S. Demonstration of PCE-controlled dynamic traffic engineering for GMPLS-based multilayer service network. Proc ECOC2005; Turin, Italy, 2005;2:269-270.
34. Koizumi Y, Miyamura T, Arakawa S, Oki E, Shimomoto K, Murata M. Adaptive virtual network topology control based on attractor selection. *IEEE J Lightwave Technol*. 2010;28(11):1720-1731.
35. Miyamura T, Shimazaki D, Arakawa S, et al. Experimental demonstration of adaptive virtual network topology control mechanism based on SDTN architecture. In: Proc ECOC 2013; London, United Kingdom, 2013:1-3.
36. Yamashita S, Imachi D, Yamamoto M, Miyamura T, Kamamura S, Sasayama K. A new content-oriented traffic engineering for content distribution: CAR (Content Aware Routing). *IEICE Trans Commun*. 2015;E98-B(4):575-584.
37. GNU Linear Programming Kit. https://www.gnu.org/software/glpk/
38. Breslau L, Cao P, Fan L, Phillips G, Shenker S. Web caching and Zipf-like distributions: Evidence and implications. In: Proc. of INFOCOM’99; New York, United States, 1999:126-134.
39. Gabaix X. Zipf's law for cities: An explanation. *Q J Econ*. 1999;114(3):739-767.

**AUTHOR BIOGRAPHIES**

**Takashi Miyamura** is a senior researcher of Nippon Telegraph and Telephone Corporation (NTT) Network Service Systems Laboratories, Tokyo Japan. He received the BS and MS degrees from Osaka University, Osaka, Japan in 1997 and 1999, respectively, and PhD degree from Hokkaido University in 2018. In 1999, he joined NTT, where he engaged in research and development of a high-speed internet protocol switching router. He is now researching future optical transport network architectures and an optical switching system. He received paper awards from the 7th Asia-Pacific Conference on Communications (APCC 2001), and best paper award from the 19th Asia-Pacific Network Operations and Management Symposium (APNOMS 2017). He is a senior member of IEICE and a member of IEEE.

**Akira Misawa** received his B.E and ME degrees in electronics engineering and PhD degree in information science and technology from Hokkaido University, Sapporo, Japan, in 1988, 1990, and 2016. In 1990, he joined the Nippon Telegraph and Telephone Corporation, Japan, where he has been engaged in research on photonic switching systems, optical cross connect systems, and IP router system architecture. Since 2017, he has been Professor of Information Systems Engineering, Chitose Institute of Science and Technology. He is a Member of IEEE ComSoc and Senior Member of IEICE, from which he received the 1997 Young Engineers Award.

**Jun-ichi Kani** received the BE, ME, and PhD degrees from Waseda University, Tokyo, Japan, in 1994, 1996, and 2005, respectively, all in applied physics. In 1996, he joined Nippon Telegraph and Telephone Corporation (NTT) Optical Network Systems Laboratories, where he was engaged in research on optical multiplexing and transmission technologies. Since 2003, he has been with NTT Access Network Service Systems Laboratories, where he is engaged in the research and development of optical communication systems for metro and access applications, and currently heads Access Systems Technology Group. He is Member of IEEE and Senior Member of IEICE.

**How to cite this article:** Miyamura T, Misawa A, Kani J. Highly efficient optical aggregation network with network functions virtualization. *Int J Network Mgmt*. 2019;29:e2052. https://doi.org/10.1002/nem.2052