Enhancing survivability of inter-datacenter networks using cross-layer approaches

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***Abstract*—In this paper, we consider network design principles for highly reliable datacenter interconnection in multilayer optical and packet transport networks. To address a wide range of traffic demands while ensuring high reliability, it is crucial to effectively integrate packet-layer switching and optical-layer transmission technologies for datacenter interconnection. However, few literature has investigated the applicability of the packet layer and optical layer with respect to network survivability. In this paper, we investigate the applicability of cross-layer approaches to enhance network survivability while avoiding the increase in network cost, and also present methods for availability analysis. To clarify the applicability and effectiveness of the proposed approaches, we conducted extensive numerical experiments. When the average traffic demand exceeds approximately 150 Gbps, a direct optical connectivity approach among distant datacenters offers improved performance in terms of availability and network cost. Conversely, when traffic demand is relatively small, a cross-layer approach that integrates packet switching with optical transmission technologies can efficiently reduce network cost by improving the efficiency of optical network resources through packet multiplexing.**

***Index Terms*—datacenter network, optical networking, survivability, network optimization**

I. Introduction

Due to the rapid proliferation of AI and IoT (Internet of Things) services, the total volume of datacenter traffic has been increasing exponentially. Currently, a cloud-based service supports not only conventional web-based services but also mission-critical services and data-intensive applications. Given the evolving nature of datacenter usage, there is an urgent need to develop transport technologies that efficiently connect geographically distributed datacenters while ensuring high reliability. Reliability in datacenter interconnection is critically important, as the growing number of cloud applications demands high availability.

All-optical network architectures are deployed in datacenter interconnection for hyperscalers such as Google and Microsoft [1], [2]. These hyperscale datacenters are often connected via ultra-high-speed transmission links, such as 100 Gbps or higher, to manage the substantial volume of inter-datacenter traffic. However, for scenarios with relatively lower traffic demands, packet-based datacenter interconnection can be more cost-effective. Tan *et al.* investigated the applicability of IP switching and optical transport network (OTN) switching for connecting geographically distributed datacenters and found that IP switching was more advantageous than OTN switching when the average traffic demand was below 600 Mbps [3]. However, they did not consider reliability of those two transport technologies. Although technologies for highly reliable datacenter interconnection have been widely investigated [4], [5], but few studies have investigated the survivability of multilayer transport networks that include both IP and optical layers. To address a wide range of traffic demands while ensuring high reliability, it is essential to effectively integrate packet-layer switching with optical transmission technologies for datacenter interconnection.

Motivated by this observation, our work aims to establish network design principles for multilayer transport networks used in datacenter interconnection, with a focus on service availability. The important thing here is how to combine IP switching and optical transmission technologies to meet specific traffic demands and ensure high availability. In this paper, we investigate the applicability of IP switching technologies and optical transmission technologies for inter-datacenter networks in terms of network cost and availability, and propose cross-layer approaches for highly reliable datacenter interconnection in consideration of network cost.

II. Related Work

Approaches for designing highly reliable transport networks have been extensively investigated [6]–[8]. Clouqueur *et al.* developed a theoretical framework for the availability analysis of wavelength division multiplexing (WDM)-based span-restorable mesh networks [6]. They presented models for availability analysis focused on restoration and evaluated the restorability of connections in the event of single and

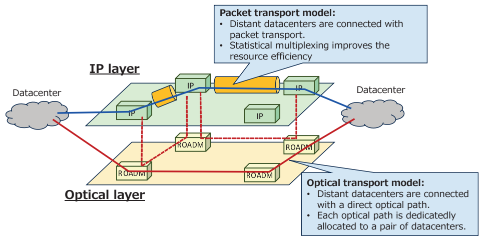

Fig. 1. Overview of multilayer transport network for datacenter interconnection

dual failures. However, their research is limited to WDM networks and does not address multi-layer networks including the IP layer. Verbrugge *et al.* investigated an availability model of multilayer transport networks [8]. They gathered general availability statistics for IP and synchronous digital hierarchy (SDH) equipment and conducted several case studies. Their investigation into survivability mechanisms was confined to protection schemes in the optical layer, with packet-layer restoration mechanisms not considered. In terms of transport architectures for inter-datacenter networks, we proposed optical aggregation networks using point-to-multipoint optical paths for software-defined datacenters [9]. Although our previous work efficiently handled inter-datacenter traffic, it did not address failure protection.

Liu *et al.* investigated the survivability of inter-datacenter networks with a focus on disaster protection and proposed a disaster-resilient provisioning mechanism using cooperative storage systems [4]. Their work concentrated on elastic optical networks (EONs), and multilayer transport networks that include the IP layer were not considered. To cope with dynamically time-varying inter-datacenter traffic, flexibility and adaptability of IP switching are crucial for enhancing resource efficiency. Tan *et al.* assessed the applicability of IP switching and OTN switching for inter-datacenter networks [3], but their model did not address the survivability against failures. Regarding multilayer transport networks for datacenter interconnection, Wu *et al.* evaluated cross-layer protection schemes in Flex Ethernet (FlexE) over EONs [10]. Their study focused on data-rate mismatch problems between FlexE and EONs, without investigating the availability of the proposed protection schemes.

Few studies have investigated the availability of multilayer transport networks that include both IP and optical layers. It is notable that IP switching can enhance the efficiency of optical transport resources for relatively low traffic demands [3]. To the best of our knowledge, this is the first paper presenting cross-layer approaches for achieving highly reliable datacenter interconnection and methods for availability analysis of multi-layer transport networks in consideration of packet restoration and optical protection schemes.

III. Survivability of Inter-datacenter Networks

Here, we describe the architecture of a multilayer transport network that provides datacenter interconnection and introduce approaches for network survivability. Finally, we present the problem definition.

A. Architecture of Multilayer Transport Network

First, we outline the architecture of a multilayer transport network that provides connectivity among geographically distributed datacenters. A multilayer transport network comprises both the IP and optical layers, as illustrated in Fig. 1. The IP-layer network consists of IP routers and logical links connecting two adjacent IP routers, while the optical-layer network includes reconfigurable add-drop modules (ROADMs), optical transponders, and fiber links. We consider two models for survivable datacenter interconnection: i) a packet transport model and ii) an optical transport model. For hyperscale datacenters, which require the transport of substantial traffic volumes, all-optical network architectures are typically deployed. In the optical transport model, a dedicated optical path with a capacity of 100 Gbps or higher per channel is allocated to connect a pair of distant datacenters. When traffic demand is sufficiently high, the optical transport model offers efficient and low-latency connectivity among datacenters. In contrast, packet-based transport technologies are widely deployed for interconnection among datacenters with lower traffic demands. Packet transport technologies such as IP, multi-protocol label switching (MPLS), and Ethernet are widely deployed to connect distant datacenters. In this paper, we focus on MPLS-based packet technologies because current commercial IP routers support MPLS, which provides various restoration schemes for failure recovery. A label switched path (LSP) is established between pairs of source and destination IP routers that accommodate datacenters. In the packet transport model, each IP link corresponds to an optical path connecting two adjacent IP routers. The bandwidth of each optical path (e.g., IP link) can be shared by multiple LSPs allocated to different datacenter users. Thus, optical-layer resource efficiency can be improved by packet multiplexing when inter-datacenter traffic demands are relatively low. The packet transport model tends to offer more cost-effective performance when traffic volumes are smaller. Therefore, it is essential to investigate the applicability of both the optical and packet transport models across varying traffic demand to establish network design principles for survivable datacenter interconnection.

B. Cross-layer approaches for network survivability

Next, we introduce approaches for network survivability in the multilayer transport network. We consider two approaches corresponding to the above two transport models; the 3-stage packet transport model and the direct optical transport model, as illustrated in Fig. 2.

In the 3-stage packet transport model, a pair of LSPs is established between source and destination nodes, with one LSP serving as the primary path and the other as a backup path. We implement an MPLS restoration scheme for failure recovery. Each IP link along these LSPs corresponds to an optical path established in the optical layer. In the optical layer, no protection schemes are deployed. To enhance the efficiency

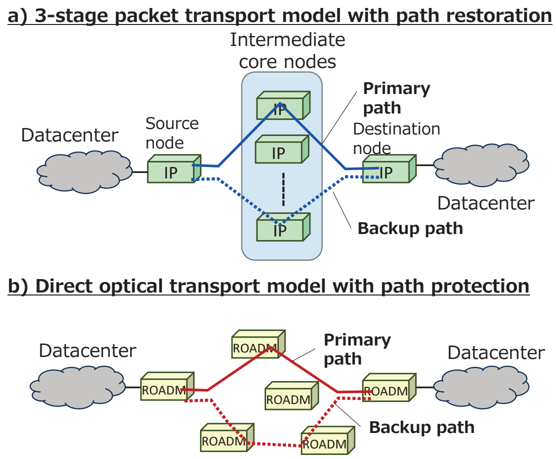

Fig. 2. Overview of cross-layer approaches for network survivability in multilayer transport network.

of optical transport resources, the 3-stage packet transport model is designed such that each LSP passes through a single intermediate core node, thereby improving the effectiveness of packet multiplexing. Here, each LSP does not pass through two or more intermediate core nodes.

The direct optical transport model provides optical connectivity between two distant datacenters without any packet processing. In this model, a path protection scheme is employed for failure recovery. We establish a pair of primary and backup optical paths between source and destination nodes. In the event of a failure along the primary path, the failed path is switched over to the backup path. The bandwidth of each optical path is dedicatedly allocated to a specific datacenter user and cannot by shared by others. Consequently, when traffic demand is relatively low, the efficiency of the optical path may decline.

Those two transport models can adequately handle failure occurrence, but there is a difference in reliability between the two models. The details of availability calculations for those two models are described in the next section. Here, we briefly explain the difference in availability between the two models. The 3-stage packet transport model, which is a cross-layer approach, requires each LSP connecting source and destination nodes to traverse three IP routers and two IP links. An IP links consists of an optical path in the optical layer. In contrast, the direct optical transport model uses a pair of optical paths for handling traffic between two datacenters. As a result, the 3-stage packet transport model may have lower availability due to the additional nodes and physical links traversed in both the IP and optical layers, compared to the direct optical transport model.

C. Problem definition

Finally, we define the problem addressed in this paper. In terms of availability, the direct optical transport model generally outperforms the 3-stage packet transport model. However, the 3-stage packet transport model can provide more advantageous performance in terms of network cost when traffic demand is relatively low. To design cost-efficient inter-datacenter networks while ensuring adequate reliability, we need to effectively integrate packet switching with optical transmission technologies. We thus aim to clarify the applicability of the packet transport model and optical transport model in terms of network cost and reliability, considering varying traffic demands.

IV. Mathematical Formulation

We now provide an overview of the mathematical models and methods for calculating availability in each transport model, followed by MILP formulations for cross-layer approaches to network survivability.

A. Overview

We present an overview of our mathematical models developed for the proposed cross-layer approaches aiming at ensuring network survivability. A transport network accommodates multiple datacenters and provides connectivity between pairs of datacenters. The physical network topology and traffic demands generated by the datacenters are predefined. Our goal is to determine the most efficient routing for paths in each transport model and calculate the availability of those paths.

In the 3-stage packet transport model, we compute a pair of link-disjoint paths connecting source and destination nodes at the packet layer. Bandwidth is allocated to both the primary and backup paths based on the traffic demand between the two datacenters. To transport traffic between intermediate core nodes and source/destination nodes, an optical path is established at the optical layer. The bandwidth of an optical path can be shared across multiple datacenter users (i.e., multiple LSPs).

In the direct optical transport model, a pair of link-disjoint optical paths is computed between the source and destination nodes at the optical layer, without utilizing packet-layer resources. In this paper, two types of an optical path are considered: 100 Gbps and 400 Gbps. The bandwidth of an optical path is determined by the traffic demand between datacenters. For example, if the traffic demand is 180 Gbps, two 100 Gbps optical paths are allocated for both primary and backup paths to satisfy the bandwidth requirement.

B. Computation of availability

Here, we present the methodology for availability analysis in the two transport models. An example of availability computation for the 3-stage packet transport model is illustrated in Fig. 3. Previous studies, such as [6], have investigated the availability of protection paths. In this paper, we extend their model to apply to our cross-layer approaches. Here, availability is defined as the probability that a connection (a pair of primary and backup paths) can be seen at operational state (or in service) at a random period in the future [6]. The availability of a connection depends on failure probability of its component. To compute availability, we use the following notations.

- p_{ip}: probability that an IP router is in the failed state at a random period in the future.
- p_o: probability that a node (e.g., ROADM) in the optical layer is in the failed state.
- p_f: probability that a physical fiber link is in the failed state.
- $p_{primary\_path}$: probability that a primary path is in the failed state.
- p_{backup_path}: probability that a backup path is in the failed state.
- hop^p_{opt}: number of hop counts in optical path p.

To compute availability, we need to determine the failure probability of each IP link, which corresponds to an optical path in the optical layer. The availability of each IP link depends on the hop count of the associated optical paths. For example, if optical path $p1$ has two hops, its availability is calculated as $1 - p_f^2 \cdot p_o^3$. This process is applied to compute the availability of all IP links in the connection.

In the direct optical transport model, the primary and backup optical paths are denoted as $f1$ and $f2$, respectively. The availability of the corresponding connection is calculated as

$$1-\left(1-p_o^{hop^{f1}_{opt}+1}\cdot p_f^{hop^{f1}_{opt}}\right)\cdot\left(1-p_o^{hop^{f2}_{opt}+1}\cdot p_f^{hop^{f2}_{opt}}\right) \quad (1)$$

Similarly, we can compute the availability of the packet transport model.

C. Notations

Before presenting the MILP formulations for both transport models, we introduce some of the notations and assumptions. Important notations used in the MILP formulations are summarized in Table I.

We assume the following inputs given to the problem:

- ROADMs
- Fiber links connecting two adjacent nodes
- IP routers
- Traffic demand between a pair of source/destination nodes accommodating datacenters

We describe the notations used in the MILP formulations. In our network model, traffic demand of each source-destination pair is given in advance, so we can solve an RSA problem to find the optimal configuration of optical paths.

The physical network is modeled as a directed graph $G = (V, E)$. $p^{f,ij}_{mn}$ represents the number of optical paths from node i to j with type f occupying fiber link mn, and it is a non-negative integer. A logical link is defined as a virtual link connecting two distant edge nodes that accommodate datacenters, used to compute the total bandwidth between those nodes. v_{ij} holds non-negative integers indicating virtual links with any types of optical paths (e.g., 100 Gbps and 400 Gbps), while v^f_{ij} represents virtual links composed of optical paths with type f. Traffic demand from node i to j is denoted by D_{ij}.

TABLE I
IMPORTANT NOTATIONS

Given:	
E	set of fiber links
V	set of physical nodes (both ROADMs and IP routers)
V_{en}	set of edge nodes in the packet layer
V_{ic}	set of intermediate core nodes in the packet layer (subset of V)
V_{opt}	set of ROADMs in the optical layer
S_{mn}	set of spectrum slots on fiber link mn 100 Gbps with 37.5 GHz grid)
C^f_{bw}	bandwidth of optical path type $f \in F_{opt}$ (in Gbps)
C^f_{slot}	number of required spectrum slots for optical path type f
D_{ij}	traffic demand between edge node i and j (in Gbps)
Variables:	
$p^{f,ij}_{mn}$	occupancy of fiber link mn used for a set of primary optical paths from node i to j with type f
$pb^{f,ij}_{mn}$	occupancy of fiber link mn used for a set of primary optical paths from node i to j with type f
$pc^{f,ij}_{mn}$	occupancy of fiber link mn used for a set of optical paths connecting edge/core node i with core/edge node j with type f
v_{ij}	logical link from nodes i to j
v^f_{ij}	logical link from nodes i to j using optical paths with type f
vc_{ij}	logical link connecting edge/core node i with core/edge node j
vc^f_{ij}	logical link connecting edge/core node i with core/edge node j with optical paths of type f
x^{ij}_{kl}	occupancy of logical link kl used for a set of primary paths from node i to j in the IP layer
xb^{ij}_{kl}	occupancy of logical link kl used for a set of backup paths from node i to j in the IP layer

D. MILP formulations

Now we present the MILP formulations for both transport models in consideration of network survivability. Due to the limitation of the space, we provide only a brief overview of the formulations.

Objective in the direct optical transport model:

$$\min\left(\sum_{ij}\sum_{mn,f}(C^f_{slot}\cdot p^{f,ij}_{mn}+C^f_{slot}\cdot pb^{f,ij}_{mn})+W_{opt}\cdot v_{ij}\right) \quad (2)$$

Objective in the 3-stage packet transport model:

$$\min\left(\sum_{ij}\sum_{mn,f}(C^f_{slot}\cdot pc^{f,ij}_{mn}+W_{opt}\cdot v_{ij}+2W_{ip}\cdot vc_{ij}\right) \quad (3)$$

Constraints in the direct optical transport model:

$$\sum_m p^{f,ij}_{mk}-\sum_n p^{f,ij}_{kn}=\begin{cases}-v^f_{ij}, & \text{if } k=i\\ v^f_{ij}, & \text{if } k=j\\ 0, & k\in V_{opt}\end{cases}, \quad (4)$$

$$\sum_m p^{ij}_{mk}-\sum_n p^{ij}_{kn}=\begin{cases}-v_{ij}, & \text{if } k=i\\ v_{ij}, & \text{if } k=j\\ 0, & k\in V_{opt}\end{cases}, \quad (5)$$

$$p^{ij}_{mn}=C^f_{bw}\cdot\sum_f p^{f,ij}_{mn} \quad \forall m,n\in E,\ i,j\in V_{en} \quad (6)$$

$$\mathbb{1}_{\{p^{f,ij}_{mn}>0\}}+\mathbb{1}_{\{pb^{f,ij}_{mn}>0\}}=\mathbb{1}_{\{v^f_{ij}>0\}} \quad \forall m,n\in E \quad (7)$$

$$v_{ij}\geq D_{ij} \quad \forall i,j\in V_{en} \quad (8)$$

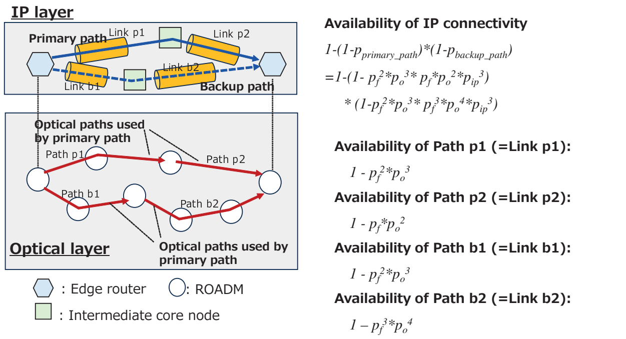

Fig. 3. Example of availability computation in the 3-stage packet transport model

Constraints in the 3-stage packet transport model:

$$pc_{mn}^{ij} = C_{bw}^{f} \cdot \sum_{f} pc_{mn}^{f,ij} \tag{9}$$

$$\sum_{h \in V_{ic}} x_{ih}^{ij} - \sum_{h \in V_{ic}} x_{hj}^{ij} = 0, \quad \text{if } D_{ij} > 0 \tag{10}$$

$$\sum_{h \in V_{ic}} xb_{ih}^{ij} - \sum_{h \in V_{ic}} xb_{hj}^{ij} = 0, \quad \text{if } D_{ij} > 0 \tag{11}$$

$$x_{il}^{ij} + xb_{il}^{ij} \leq 1 \quad \forall i \in V_{ic}\ (V_{en}),\ \ l \in V_{en}\ (V_{ic}) \tag{12}$$

$$vc_{ij} \geq D_{ij} \quad \forall i,\ j \in V_{en} \tag{13}$$

The objective functions in the direct optical transport model and 3-stage packet transport model are given by Eqs. (2) and (3), respectively. Equation (4) and (5) correspond to the flow conservation law in the optical layer. Equation (7) delineates link-disjoint constraints. The bandwidth requirements of virtual links is given by (8). In the 3-stage packet transport model, constraints are similar to those in the direct optical transport model. So, we omit the description of several constraints. The flow conservation law in the packet layer is denoted by Eqs. (10) and (11), while constraints on link-disjoint paths are provided by Eq. (12). As for other constraints, we omit the description of spectrum-slot continuity and contiguity constraints due to the limitation of the space. Please refer to our previous work [11].

V. Performance Evaluation

To investigate the applicability of the optical transport model and packet transport model for network survivability, we conducted extensive numerical experiments. The key results of these experiments are presented below.

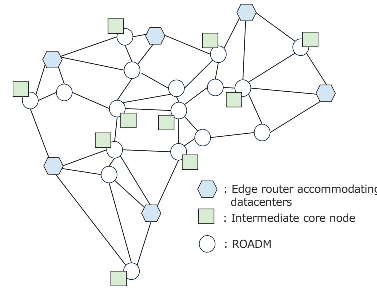

Fig. 4. The 23-node and 43-link Tokyo metropolitan area network (TMN23) topology

A. Aims and conditions

We first outline the aims and conditions of the performance evaluation. Our goal is to assess the viability of the two transport models and to establish a design principle for network survivability in multilayer transport networks. To achieve this, we evaluated total consumption of spectrum slots, network cost, and availability in each model, considering the given traffic demand and physical network topology. Here, network cost is defined as the total cost of IP router interface and optical transponders used for established all the paths in the network. Here, we used the following relative interface cost [12].

100G-Optical : 400G-Optical : 100G-IP $= 1 : 1.37 : 0.72$

In the experiments, we deployed the 23-node Tokyo metropolitan area network topology (TMN23), which is a metro network topology in Japan, as illustrated in Fig. 4. As for the spatial distribution of traffic demand, we deployed the uniform distribution model where traffic demand between every pair of nodes is equally distributed. The average traffic demand of each source-destination pair is varied from 25 Gbps to 250 Gbps. Other common conditions used in the experiments are listed below.

- Types of an optical path: 100 Gbps and 400 Gbps
- Interface speed of an IP router: 100 Gbps
- Number of spectrum slots per optical path: 3 slots for 100 Gbps and 7 slots for 400 Gbps
- Maximum spectrum slots in each fiber: 160

B. Key results

First, we compared the total consumption of spectrum slots between the packet transport model and the optical transport model, as shown in Fig. 5. As the average traffic demand increased, the total consumption of spectrum slots in both models also increased. The packet transport model reduced spectrum slot consumption by about 67 % on average compared to the optical transport model, primarily due to bandwidth sharing of the optical path via packet multiplexing.

Next, we evaluated network cost in each model, as illustrated in Fig. 6. When traffic demand was below 100 Gbps, the packet transport model outperformed the optical transport model in terms of the network cost. However, as

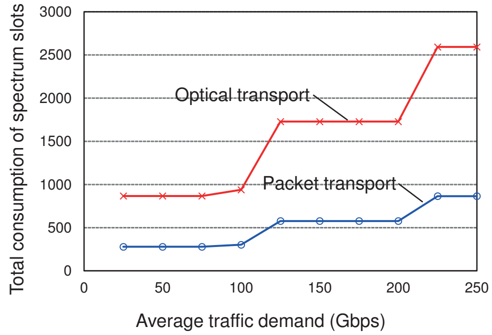

Fig. 5. Comparison of total spectrum slot consumption

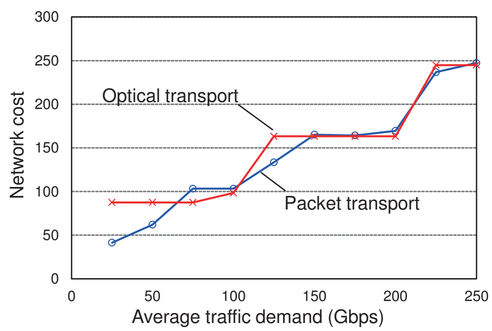

Fig. 6. Comparison of total spectrum slot consumption

traffic demand exceeded 150 Gbps, the network cost of both models converged. At higher traffic demands, the benefits of packet multiplexing diminished.

Finally, we evaluated the availability of the two models. To compute the availability, we set p_{ip} and p_o as 0.001, and p_f as 0.0005. The results are summarized in Table II. The packet transport model achieved an availability of 0.99925, while the optical transport model achieved 0.99995, consistently outperforming the packet transport model in terms of availability.

In summary, the optical transport model demonstrates advantageous performance in terms of both availability and network cost when the traffic demand exceeds 150 Gbps. For smaller traffic demands, the packet transport model can reduce network cost due to the benefit of packet multiplexing.

TABLE II
COMPARISON OF AVAILABILITY

	Availability
Packet transport model	0.99925
Optical transport model	0.99995

VI. CONCLUDING REMARKS

In this paper, we investigated the applicability of IP switching and optical transmission technologies in inter-datacenter networks, focusing on network cost and availability. We also proposed cross-layer approaches to achieve highly reliable datacenter interconnection in consideration of network cost. To validate the effectiveness of these approaches, we conducted extensive numerical experiments. When the average traffic demands exceed about 150 Gbps, the optical transport model provides advantageous performance in terms of availability and network cost. For lower traffic demands, the packet transport model offers better resource efficiency due to packet multiplexing.

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