Network Expansion of Regional DCIs: Optical Circuit Switching versus Electrical Packet Switching

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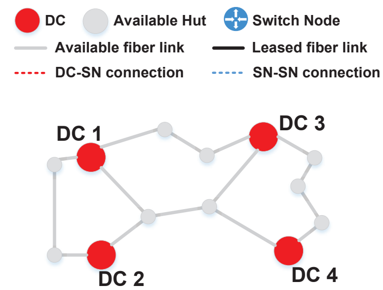
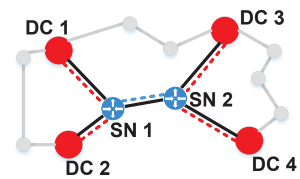
***Abstract*—Recently, the regional data center interconnect (D-CI), which is a large-capacity network data-center (DC) cluster to provide low latency and high bandwidth network services, has attracted noticeable interests from DC operators. However, the network planning for regional DCIs is challenging and existing studies only considered how to build a regional DCI from scratch. In this paper, we study how to optimize the expansion of an existing regional DCI that is based on electrical packet switching (EPS), such that the capital expenditures (CAPEX) of the network expansion can be minimized. We consider both EPS-based and optical circuit switching (OCS) based expansions to find out which one is more beneficial for CAPEX saving. Two integer linear programming (ILP) models are first formulated to tackle the EPS-based and OCS-based expansion approaches exactly, and then two heuristics are proposed by leveraging an auxiliary graph based iterative approach. Extensive simulations compare the EPS-based and OCS-based expansions in various scenarios, and our results suggest that OCS-based expansion is more cost-efficient regardless of the settings of scenarios.**

***Index Terms*—Data center interconnect (DCI), Regional DCI, Network expansion, Optical circuit switching (OCS).**



(a) Inputs of regional DCI design



(b) Output of regional DCI design

Fig. 1. Example on designing regional DCI (adapted from [11]).

I. Introduction

NOWADAYS, the rapid development of cloud computing and Big Data analytics has promoted the scaling of data-center (DC) infrastructures [1–4]. The traditional way to adapt to the scaling is to build mega-DCs globally, each of which contains numerous servers, switches and storages, and to connect them with a wide-area network (WAN) [5]. Then, by leveraging the recent advances on optical networking [6–10], flexible bandwidth provisioning can be realized for the data transfers among DCs. However, due to the difficulty of building mega-DCs in/near metro areas and the requirements of fault tolerance, large DC operators have become reluctant to pursue the mega-DC-based approach and switched to counting on a group (typically 5∼20) of smaller DCs located within metro reach (*i.e.*, tens of kilometers) to serve a large geographical area [11]. The DC group is known as a “DC region”, while the network to connect them is a regional DC interconnect (DCI). Recently, building DC regions has become a common industry practice (*e.g.*, Microsoft [11] and Facebook [12]).

Nevertheless, as it considers complex constraints from cost, latency and availability to plan unique network segments, the network design of regional DCIs is challenging and only started to attract research interests since recently. Fig. 1 shows an illustrative example to explain the design of a regional DCI. Here, the fiber map that contains all the available fiber ducts and huts, and the DC locations are given as the inputs, and the DC operator needs to determine where to place the switch nodes (SNs) and how to rent fiber links to route the data transfers for DC-SN and SN-SN connections. Meanwhile, the capacities of leased fiber links should support non-blocking communications through the DC-SN and SN-SN connections (*capacity constraint*), each DC-SN or SN-SN connection can only go through certain huts at most (*length constraint*), and the number of leased fiber links going through a same duct should not exceed an upper-limit (*availability constraint*) [11].

In [11], Dukic *et al.* proposed a new network architecture for regional DCIs, namely Iris, which leverages optical circuit switching (OCS) at fiber-level to transmit data in the optical domain completely between DCs , reducing the usage of high-speed transceivers (TRXs) effectively. Therefore, comparing with the regional DCIs that rely on electrical packet switching (EPS), Iris simplifies the network architecture and saves the capital expenditures (CAPEX) and operational expenditures (OPEX) significantly. The study in [13] designed Shoofly to optimize the capacity provisioning in the WAN that connects regional DCIs. However, all these existing studies on regional DCIs overlooked an important question: how to expand an existing EPS-based regional DCI cost-effectively? This question is relevant because other than building a regional DCI from scratch, expanding an existing one would be more reasonable in practice to protect the current investment of an operator.

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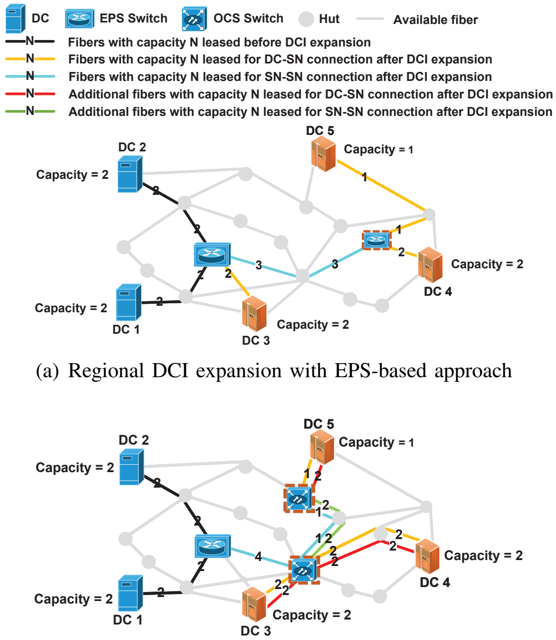


(a) Regional DCI expansion with EPS-based approach

(b) Regional DCI expansion with OCS-based approach

Fig. 2. Examples on expanding EPS-based regional DCI.

This work tackles the question to optimize the expansion of an existing EPS-based regional DCI such that the network expansion's CAPEX can be minimized under the constraints of fiber capacity, connection length and service availability. We consider both the EPS-based and OCS-based expansions to find out which one is more beneficial for CAPEX saving. Specifically, we first formulate two integer linear programming (ILP) models to respectively optimize the EPS-based and OCS-based expansions, and then propose heuristics to improve the time-efficiency of problem-solving. Extensive simulations compare the EPS-based and OCS-based expansions in various scenarios, including the locations and capacities of newly-added DCs, the settings of the length and availability constraints, *etc*. Our results suggest that the OCS-based approach is more cost-efficient regardless of the settings of scenarios.

The rest of the paper is organized as follows. We briefly review the related work in Section II. In Section III, we define the problem of network expansion of an EPS-based regional DCI, and explain the principles of the EPS-based and OCS-based approaches for network expansion. The ILP models for optimizing the EPS-based and OCS-based approaches are formulated in Section IV, while the corresponding heuristics are designed in Section V. We discuss the simulation results in Section VI. Finally, Section VII summarizes the paper.

II. Related Work

Previous studies on DCI can be mostly categorized as those on network planning and provisioning. As for network planning, people have considered how to plan DCIs to better support network function virtualization (NFV) in [14, 15]. The NFV-related service provisioning in DCIs has been tackled in [16–18], while the network control and management (NC&M) schemes for the traffic control and scheduling in DCIs have been investigated in [19–23]. However, all of the studies mentioned above did not consider the architecture design of regional DCIs related to the choice between EPS and OCS.

The authors of [11] analyzed the practical constraints in the design of regional DCIs, proposed to architect regional DCIs completely with OCS based on a framework named Iris, and verified that compared with EPS, OCS can simplify the network structure of regional DCIs and reduce their CAPEX significantly. Xie *et al.* [24] explained the recent advances on building scalable hyperscale DCs, including the progresses on optical devices, subsystems and systems, as well as the new NC&M techniques to manage large-scale DCIs. However, these study only addressed how to build a new DCI based on OCS, but did not consider the network expansion of an existing one. As explained above, expanding an existing regional DCI would be more reasonable to protect the current investment of the DC operator. Nevertheless, to the best of our knowledge, the problem of how to expand an existing EPS-based regional DCI cost-efficiently has not been explored in the literature yet.

III. Problem Description

In this section, we first define the network model for DCI expansion, and then respectively explain the problems of EPS-based and OCS-based network expansions.

A. Network Model

We denote the physical topology for the regional DCI expansion as a graph $G(V, E)$, where V represents the set of facility huts, on which DC/SN can be placed, and E is the set of fiber ducts that can be leased by the DC operator. Fig. 2 shows examples on the regional DCI expansions considered in this work. Here, the existing DCI consists of two DCs (*DCs* 1 and 2), an EPS-based SN, and several leased fibers. As for the bandwidth capacity of each DC, we define it as the number of leased fibers that use the DC as an end node, and mark it on the leased fibers [11]. For instance, the capacities of *DCs* 1 and 2 are both 2 as marked on the leased fibers between them in Fig. 2. Note that, the capacity of each DC is obtained by summing the traffic amounts in corresponding row and column of the DC-DC traffic matrix. Therefore, the set of DC capacities represents a specific DC-DC traffic matrix. People usually refer to the network planning based on such a set of DC capacities as the network-hose planning model [25], and it is a common practice in the network planning of DCIs [11].

The regional DCI expansion then works as follows. The DC operator first specifies the locations of the new DCs, and then to expand the DCI to cover the new DCs, it needs to determine: 1) how many SNs are needed and where to place them, and 2) what are the fibers (how many and through which ducts) that need to be leased to interconnect the DCs? The optimization objective is to minimize the CAPEX of the DCI expansion, which includes the costs of fiber leasing, new TRXs, and new EPS/OCS ports. According to the study in [11], using wavelength-level switching in practical regional DCIs is more complex and costlier than necessary. Hence, we assume that the OCS in the DCI is at fiber-level. The cost of fiber leasing is in leased fibers per span between huts. Each EPS port needs to equip a TRX, and thus a DC-SN connection carrying $\mathcal{W}$ wavelengths asks for $2 \cdot \mathcal{W}$ TRXs if the SN is EPS-based. To ensure quality-of-service (QoS) of the expanded DCI, we introduce two constraints: 1) the number of leased fibers going through a same duct cannot exceed Λ (*availability constraint*), and 2) each DC-SN or SN-SN connection can go across $\mathcal{H}$ huts at most to avoid long latency (*length constraint*) [11].

B. EPS-based Regional DCI Expansion

Fig. 2(a) gives an example on expanding an EPS-based regional DCI with the EPS-based approach. We set $\Lambda = 4$ and $\mathcal{H} = 2$, and assume that the capacities of *DCs* 1-5 are $\{2, 2, 2, 2, 1\}$, respectively. First, as *DC* 3 is close to the existing SN, we can directly connect it to the SN, satisfying the latency constraint. As for *DCs* 4 and 5, we need to place a new EPS-based SN for it, lease fibers to set up the related DC-SN and SN-SN connections with enough capacities to make sure that all the DCs in the expanded DCI can communicate with each other. For example, we need to lease three fibers for the SN-SN connection between the existing and new SNs, for satisfying the capacities of *DCs* 4 and 5. The DCI expansion finally leases $2 + 3 \times 2 + 2 + 1 \times 2 = 12$ fibers, and requires $(2 + 3 + 2 + 1) \cdot 2 \cdot \mathcal{W} = 16 \cdot \mathcal{W}$ new EPS ports and TRXs.

C. OCS-based Regional DCI Expansion

Unlike the EPS-based approach, the OCS-based DCI expansion needs to lease additional fibers due to the coarse granularity of the OCS at fiber-level [11]. For instance, although the capacity of *DC* 5 is one fiber, we need to lease multiple fibers from it. This is because if only one fiber is leased from *DC* 5, an OCS-based SN at fiber-level cannot make it communicate with multiple DCs simultaneously. Fig. 3 explains the leasing of additional fibers in the OCS-based approach, to cover *DCs* 3-5 and two new OCS-based SNs. The additional fibers are calculated according to the following principle defined in [11].

***Theorem** 1:* If there are N new DCs to be covered in an OCS-based DCI expansion, $N - 1$ additional fibers need to be leased from each new DC. Moreover, additional fibers need to be leased for each connection between two OCS-based SNs ($v, u \in V$) and their number is $N_v \cdot N_u$, where N_v and N_u are the numbers of DCs connected to SNs v and u, respectively.

According to *Theorem* 1, we can obtain the number of additional fibers that need to be leased from each of *DCs* 3-5 as 2, while for the connection between the two OCS-based SNs, the number of additional fibers is $2 \times 1 = 2$, as two and one DCs are connected to the two SNs, respectively.

***Definition** 1:* Each fiber leased for a DC-SN connection to satisfy the capacity of the DC is denoted as a *DC-SN fiber (DC-SN-F)*, while an additional fiber leased for the DC-SN connection is defined as a *DC-SN additional fiber (DC-SN-AF)*. The similar definitions apply to each SN-SN connection, for *SN-SN-F* and *SN-SN-AF*, respectively.

Then, the example on OCS-based DCI expansion can be understood as follows. First of all, we have $N = 3$ new DCs, which leads to two DC-SN-AFs from each of them. Then, we place an OCS-based SN to connect *DCs* 3 and 4, lease 4 and 8 fibers for each resulting DC-SN connection, respectively, and

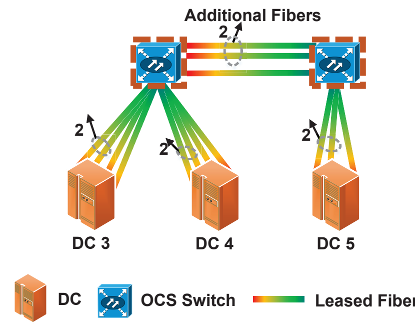


Fig. 3. Example on additional fibers needed in OCS-based DCI expansion.

lease 4 fibers to connect to the existing EPS-based SN because there are 4 fibers going into the SN from *DCs* 1 and 2. Next, we place another OCS-based SN to let *DC* 5 join the regional DCI, and lease the needed fibers. Finally, according to the expansion scheme in Fig. 2(b), the CAPEX can be calculated as follows. First, the DCI expansion leases 25 fibers. Second, as new TRXs only need to be equipped on the new DCs and the existing EPS-based SN while the DC-SN-AFs do not require any new TRXs on DCs [11], the number of new TRXs is $(4{+}2{+}2{+}1){\cdot}\mathcal{W} = 9{\cdot}\mathcal{W}$. Finally, as each DC-SN-F/DC-SN-AF needs 5 OCS ports (*i.e.*, 4 and 1 on the DC and SN sides, respectively) [11] and each SN-SN-F/SN-SN-AF requires 2 OCS ports, there are $(4 + 4 + 3) \times 5 + 3 \times 2 + 4 = 65$ new OCS ports, and $4 \cdot \mathcal{W}$ new EPS ports. By comparing with the corresponding numbers in Fig. 2(b), we can see that the OCS-based DCI expansion reduces the numbers of new TRXs and EPS ports at the cost of more leased fibers and OCS ports.

IV. ILP Formulations

This section formulates two ILP models to optimize the EPS-based and OCS-based regional DCI expansions, respectively. Specifically, we first list all the related constraints and then specify those that should be include in each optimization.

Parameters:

- $G(V, E)$: the physical topology for the DCI expansion.
- V_{ce}/V_{cn}: the sets of huts that carry existing and new DCs, respectively ($V_{ce} \neq V_{cn},\ V_{ce} \subset V,\ V_{cn} \subset V$).
- V_e: the set of huts that carry existing EPS-based SNs in the original DCI ($V_e \subset V$).
- V_{un}: the set of unused huts.
- P: the set of feasible routing paths in $G(V, E)$, *i.e.*, for each pair of huts $u, v \in V$, we pre-calculate K shortest paths to put in P, and $p^k_{u,v}$ denotes the k-th path.
- Φ: the number of fiber paths[1] leased in the original DCI.
- Ψ: the number of fibers leased in the original DCI.
- $h^k_{u,v}$: the hop-count of path $p^k_{u,v} \in P$.
- B: the set of capacities of DCs or total throughputs of existing SNs. Specifically, if hut $v \in V$ carries a DC, $B_v \in B$ refers to the DC's capacity in fibers, or if v carries an existing SN, B_v is its total throughput before the expansion, also in fibers. For instance, in Fig. 2(a), the

[1]Here, we define a fiber path as an end-to-end fiber connection for DC-SN or SN-SN. For example, in Fig. 2(a), there are two fiber paths between *DC* 1 and the existing EPS-based SN in the original regional DCI.

capacity of *DC* 1 is 2, while the total throughput of the existing EPS-based SN is $2+2=4$ before the expansion.

- $Y^k_{u,v,e}$: the boolean indicator that equals 1 if path $p^k_{u,v} \in P$ uses duct $e \in E$, and 0 otherwise.
- $F^k_{u,v,w}$: the boolean indicator that equals 1 if path $p^k_{u,v} \in P$ uses hut $w \in V$, and 0 otherwise.
- Λ: the most fibers that can be leased on a duct.
- $\mathcal{H}$: the hop-count limit for a DC-SN/SN-SN connection.
- $\mathcal{W}$: the wavelength channels that each fiber carries.
- $\mathcal{M}$: a large positive number.
- C_f/C_t/C_e/C_o: the unit cost of leasing a fiber, or adding a new TRX/EPS port/OCS port, respectively.

Decision Variables:

- $\gamma^k_{u,v}$/$\eta^k_{u,v}$: the boolean variable that equals 1 if path $p^k_{u,v} \in P$ is used by the DCI expansion for a DC-SN-F/SN-SN-F or DC-SN-AF/SN-SN-AF, respectively, and 0 otherwise.
- $\phi^k_{u,v}$/$\varphi^k_{u,v}$: the number of fibers leased on path $p^k_{u,v} \in P$ after the DCI expansion for a DC-SN-F/SN-SN-F or DC-SN-AF/SN-SN-AF, respectively.
- $y^{u',v'}_{u,v}$: the boolean variable that equals 1 if hut u can reach hut v by passing through huts u' and v' in sequence ($u, v, u', v' \in (V_e \cup V_{un})$), and 0 otherwise.
- $b_{u,v}$: the boolean variable that equals 1 if huts u and v both carry SNs ($u, v \in V_e \cup V_{un}$), and 0 otherwise.
- $\pi_{u,v}$: the boolean variable that equals 1 if a pair of EPS- and OCS-based SNs are on huts u and v, and 0 otherwise.
- $\lambda_{u,v}$: the boolean variable that equals 1 if there exists a DC-SN-AF between huts u and v, and 0 otherwise.
- $\mu^{m,n}_{u,v}$: the boolean variable that equals 1 if the additional fibers between DCs m and n ($m, n \in V_{cn}$) use SN-SN connection between huts u and v, and 0 otherwise.
- $\omega_{u,v}$: the integer variable that indicates the number of additional fibers between huts u and v.
- T_v: the DC capacity if hut v carries a DC, or the total SN throughput if hut v carries an SN.
- α_v: the boolean variable that equals 1 if hut v carries a DC or an SN, and 0 otherwise.
- $\varepsilon_{u,v}$/$\tau_{u,v}$/$\rho^k_{u,v}$/$\chi^k_{u,v}$: the auxiliary boolean variables that are introduced for linearization.

Objectives:

The optimization objective is to minimize the CAPEX of the DCI expansion, where the CAPEX of an EPS-based expansion includes the costs due to newly-added fibers, TRXs, and EPS ports, and that of an OCS-based expansion contains the costs of newly-added fibers, TRXs, EPS ports, and OCS ports. Hence, we define the CAPEX of an EPS-based expansion as

$$\mathcal{Q}_e = \Omega_e \cdot C_f + 2 \cdot \Theta \cdot \mathcal{W} \cdot (C_e + C_t), \tag{1}$$

where Θ is the number of newly-leased fiber paths for DC-SN and SN-SN connections, and Ω_e is the total number of newly-leased fibers, which can be calculated as

$$\begin{cases} \Theta = \dfrac{1}{2} \cdot \displaystyle\sum_{k=1}^{K} \sum_{u,v \in V} \phi^k_{u,v} - \Phi, \\ \Omega_e = \dfrac{1}{2} \cdot \displaystyle\sum_{k=1}^{K} \sum_{u,v \in V} \phi^k_{u,v} \cdot h^k_{u,v} - \Psi. \end{cases} \tag{2}$$

The CAPEX of an OCS-based expansion is defined as

$$\begin{aligned} \mathcal{Q}_o =& \Omega_o \cdot C_f + (\mathcal{R}_{co} + \mathcal{R}_{oo} + \mathcal{R}_{eo}) \cdot C_o + \mathcal{R}_{eo} \cdot \mathcal{W} \cdot C_e \\ &+ \mathcal{W} \cdot C_t \cdot \left(\mathcal{R}_{eo} + \sum_{u \in V_{cn}} B_u \right), \end{aligned} \tag{3}$$

where Ω_o is the number of newly-leased fibers, $\mathcal{R}_{co}$ is the number of new OCS ports required by the DC-SN connections between new DCs and newly-added OCS-based SNs, $\mathcal{R}_{oo}$ is the number of new OCS ports for the SN-SN connections between newly-added OCS-based SNs, and $\mathcal{R}_{eo}$ is the number of EPS/OCS ports for the SN-SN connections between newly-added OCS-based SNs and existing EPS-based SNs:

$$\begin{cases} \Omega_o = \dfrac{1}{2} \cdot \displaystyle\sum_{k=1}^{K} \sum_{u,v \in V} \left(\phi^k_{u,v} + \varphi^k_{u,v} \right) \cdot h^k_{u,v} - \Psi, \\ \mathcal{R}_{co} = 5 \cdot \displaystyle\sum_{k=1}^{K} \sum_{u \in V_{cn}, v \in V_{un}} \left(\phi^k_{u,v} + \varphi^k_{u,v} \right), \\ \mathcal{R}_{oo} = \displaystyle\sum_{k=1}^{K} \sum_{u,v \in V_{un}} \left(\phi^k_{u,v} + \varphi^k_{u,v} \right), \\ \mathcal{R}_{eo} = \displaystyle\sum_{k=1}^{K} \sum_{u \in V_e, v \in V_{un}} \phi^k_{u,v}. \end{cases} \tag{4}$$

Constraints:

1) Constraints related to the existing regional DCI:

$$\begin{cases} \alpha_v = 1, \\ T_v = B_v, \end{cases} \quad \forall v \in V_{ce} \cup V_{cn}. \tag{5}$$

Eq. (5) marks the location and capacity of each DC correctly.

$$\alpha_v = 1, \quad \forall v \in V_e. \tag{6}$$

Eq. (6) marks locations of existing EPS-based SNs correctly.

2) Constraints on fiber leasing in EPS-based expansion:

$$T_u = \sum_{k=1}^{K} \sum_{v \in V_e \cup V_{un}} \phi^k_{u,v}, \quad \forall u \in V_{cn}. \tag{7}$$

Eq. (7) ensures that the capacity of each new DC is satisfied in the expanded DCI, by connecting to existing/new SN(s).

3) Constraints on fiber leasing in OCS-based expansion:

$$T_u = \sum_{k=1}^{K} \sum_{v \in V_{un}} \phi^k_{u,v}, \quad \forall u \in V_{cn}. \tag{8}$$

Eq. (8) ensures that the capacity of each new DC is satisfied in the expanded DCI, by connecting to new OCS-based SN(s).

$$|V_{cn}| - 1 = \sum_{k=1}^{K} \sum_{v \in V_{un}} \varphi^k_{u,v}, \quad \forall u \in V_{cn}. \tag{9}$$

Eq. (9) ensures that the additional fibers needed by each new DC are leased and they only connect to new OCS-based SNs.

4) Constraints related to SN-SN connections:

$$\sum_{u',v' \in V_e \cup V_{un}} \left(y^{u',v'}_{u,v} - y^{v',u'}_{u,v} \right) = \begin{cases} b_{u,v} & , u' = u, \\ -b_{u,v} & , u' = v, \\ 0 & , \text{otherwise}, \end{cases} \quad \{u, v : u \neq v,\ u, v \in V_e \cup V_{un}\}. \tag{10}$$

Eq. (10) ensures that any two feasible huts for SNs are not disconnected in the physical topology.

$$\begin{cases} b_{u,v} \le \alpha_u, \\ b_{u,v} \le \alpha_v, \\ b_{u,v} \ge \alpha_u + \alpha_v - 1, \end{cases} \{u, v : u \ne v,\ u, v \in V_e \cup V_{un}\}. \quad (11)$$

Eq. (11) ensures that the value of $b_{u,v}$ is correctly set according to the scheme of SN deployment on huts u and v.

$$y_{u,v}^{u',v'} \le b_{u,v},\ \{u, v, u', v' : u \ne v,\ u, v, u', v' \in V_e \cup V_{un}\}. \quad (12)$$

Eq. (12) ensures that the value of $y_{u,v}^{u',v'}$ is correctly set according to the scheme of SN deployment on u and v.

$$y_{u,v}^{u',v'} = y_{v,u}^{v',u'},\ \{u, v, u', v' : u \ne v,\ u, v, u', v' \in V_e \cup V_{un}\}. \quad (13)$$

Eq. (13) ensures that the bi-directional SN-SN connections between two SNs use the same routing path.

$$\begin{aligned} & y_{u,v}^{u',v'} \le \sum_{k=1}^{K} \gamma_{u',v'}^{k} + \mathcal{M} \cdot (2 - \alpha_u - \alpha_v), \\ & \{u, v, u', v' : u \ne v,\ u, v, u', v' \in V_e \cup V_{un}\}. \end{aligned} \quad (14)$$

Eq. (14) ensures that two SNs can talk with each other either through a direct SN-SN connection or relayed by other SNs.

$$\pi_{u,v} \ge \gamma_{u,v}^{k}, \quad \forall u \in V_e, v \in V_{un}, k \in [1, K], \quad (15)$$

$$\sum_{u \in V_e, v \in V_{un}} \pi_{u,v} = 1. \quad (16)$$

Eqs. (15) and (16) ensure that the existing and new DCs can communicate with each other after the DCI expansion.

5) Constraints on communications among DCs and SNs:

$$\sum_{k=1}^{K} \sum_{v \in V_{ce} \cup V_{cn}} \phi_{u,v}^{k} \ge 1 - \mathcal{M} \cdot (1 - \alpha_u), \quad \forall u \in V_{un}, \quad (17)$$

$$\sum_{k=1}^{K} \sum_{v \in V_{ce} \cup V_{cn}} \varphi_{u,v}^{k} \ge 1 - \mathcal{M} \cdot (1 - \alpha_u), \quad \forall u \in V_{un}. \quad (18)$$

Eq. (17) ensures that each new SN is connected to at least one DC after the EPS-based expansion, while Eqs. (17) and (18) ensure that each new SN is connected with both DC-SN-F(s) and DC-SN-AF(s) after the OCS-based expansion.

$$T_u = \sum_{k=1}^{K} \sum_{v \in V_{ce} \cup V_{cn}} \phi_{u,v}^{k}, \quad \forall u \in V_e \cup V_{un}. \quad (19)$$

Eq. (19) calculates the total throughput of each SN, which equals to the total number of the fibers that connect with the SN and are for DC-SN connections.

$$\begin{aligned} & \sum_{k=1}^{K} \phi_{u,v}^{k} \ge \gamma_{u,v}^{k'} \cdot \min(T_u, T_v), \\ & \{u, v : u \ne v,\ u, v \in V_e \cup V_{un}\},\ k' \in [1, K]. \end{aligned} \quad (20)$$

Eq. (20) ensures the leased fibers in the expanded DCI can realize non-blocking communication between two SNs.

$$\begin{cases} T_u \ge \varepsilon_{u,v}, \\ T_v \ge \varepsilon_{u,v}, \\ \varepsilon_{u,v} \ge T_u - \mathcal{M} \cdot (1 - \tau_{u,v}), \\ \varepsilon_{u,v} \ge T_v - \mathcal{M} \cdot \tau_{u,v}, \end{cases} \quad (21)$$
$$\{u, v : u \ne v,\ u, v \in V_e \cup V_{un}\}.$$

$$\begin{cases} \rho_{u,v}^{k'} \le \mathcal{M} \cdot \gamma_{u,v}^{k'}, \\ \rho_{u,v}^{k'} \le \varepsilon_{u,v}, \\ \rho_{u,v}^{k'} \ge \varepsilon_{u,v} - \mathcal{M} \cdot \left(1 - \gamma_{u,v}^{k'}\right), \end{cases} \quad (22)$$
$$\{u, v : u \ne v,\ u, v \in V_e \cup V_{un}\}, k' \in [1, K].$$

$$\sum_{k=1}^{K} \phi_{u,v}^{k} \ge \rho_{u,v}^{k'},\ \{u, v : u \ne v,\ u, v \in V_e \cup V_{un}\}, k' \in [1, K]. \quad (23)$$

Eqs. (21)-(23) linearize the nonlinear constraint in Eq. (20).

6) Constraints on leasing additional fibers:

$$\sum_{k=1}^{K} \eta_{u,v}^{k} \ge \gamma_{u,v}^{k'},\ \{u, v : u \ne v,\ u, v \in V_{un}\},\ k' \in [1, K]. \quad (24)$$

Eq. (24) ensures that additional fibers are correctly leased for each SN-SN connection between two OCS-based SNs.

$$\lambda_{u,v} \ge \eta_{u,v}^{k},\ \forall u \in V_{cn}, v \in V_{un}, k \in [1, K]. \quad (25)$$

Eq. (25) ensures that the value of $\lambda_{u,v}$ is correctly set to denote the DC-SN-AFs between the DC on u and SN on v.

$$\begin{aligned} & \mu_{u',v'}^{m,n} \ge 1 - \mathcal{M} \cdot \left(3 - \lambda_{u,m} - \lambda_{v,n} - y_{u,v}^{u',v'}\right), \\ & \forall m, n \in V_{cn}, \{u, v, u', v' : u \ne v,\ u' \ne v',\ u, v, u', v' \in V_{un}\}. \end{aligned} \quad (26)$$

Eq. (26) ensures that the additional fibers between new DCs m and n pass through a pair of OCS-based SNs u' and v'.

$$\omega_{u,v} = \frac{1}{2} \cdot \sum_{m,n \in V_{cn}} \left(\mu_{u,v}^{m,n} + \mu_{v,u}^{m,n}\right),\ \{u, v : u \ne v,\ u, v \in V_{un}\}. \quad (27)$$

Eq. (27) ensures that the value of $\omega_{u,v}$ is correctly set to denote the additional fibers leased for the SN-SN connection between two OCS-based SNs on huts u and v.

$$\sum_{k=1}^{K} \varphi_{u,v}^{k} \ge \eta_{u,v}^{k'} \cdot \omega_{u,v},\ \{u, v : u \ne v, u, v \in V_{un}\},\ k' \in [1, K]. \quad (28)$$

Eq. (28) ensures that additional fibers are leased to realize non-blocking communication between new OCS-based SNs.

$$\begin{cases} \chi_{u,v}^{k'} \le \mathcal{M} \cdot \eta_{u,v}^{k'}, \\ \chi_{u,v}^{k'} \le \omega_{u,v}, \\ \chi_{u,v}^{k'} \ge \omega_{u,v} - \mathcal{M} \cdot \left(1 - \eta_{u,v}^{k'}\right), \end{cases} \quad (29)$$
$$\{u, v : u \ne v,\ u, v \in V_{un}\},\ k' \in [1, K].$$

$$\sum_{k=1}^{K} \varphi_{u,v}^{k} \ge \chi_{u,v}^{k'},\ \{u, v : u \ne v, u, v \in V_{un}\},\ k' \in [1, K]. \quad (30)$$

Eqs. (29)-(30) linearize the nonlinear constraint in Eq. (28).

7) Global constraints for DCI expansion:

$$\begin{cases} \phi_{u,v}^{k} \le \Lambda \cdot \gamma_{u,v}^{k}, \\ \phi_{u,v}^{k} \ge \gamma_{u,v}^{k}, \end{cases} \{u, v : u \ne v,\ u, v \in V\}, k \in [1, K], \quad (31a)$$

$$\begin{cases} \varphi_{u,v}^{k} \le \Lambda \cdot \eta_{u,v}^{k}, \\ \varphi_{u,v}^{k} \ge \eta_{u,v}^{k}, \end{cases} \{u, v : u \ne v,\ u, v \in V\}, k \in [1, K]. \quad (31b)$$

Eq. (31) ensures that fibers have to be leased on selected paths.

$$\begin{cases} \alpha_u \ge \gamma_{u,v}^{k}, \\ \alpha_v \ge \gamma_{u,v}^{k}, \end{cases} \{u, v : u \ne v,\ u, v \in V\}, k \in [1, K], \quad (32a)$$

$$\begin{cases} \alpha_u \ge \eta_{u,v}^{k}, \\ \alpha_v \ge \eta_{u,v}^{k}, \end{cases} \{u, v : u \ne v,\ u, v \in V\}, k \in [1, K]. \quad (32b)$$

Eq. (32) ensures that if path $p_{u,v}^k$ is selected for fiber leasing, each of huts u and v has to carry a facility (a DC or an SN).

$$\begin{cases} \gamma_{u,v}^k \cdot h_{u,v}^k \leq \mathcal{H}, \\ \eta_{u,v}^k \cdot h_{u,v}^k \leq \mathcal{H}, \end{cases} \quad \forall u, v \in V, \ k \in [1, K]. \tag{33}$$

Eq. (33) ensures that the hop-count of any DC-SN/SN-SN connection does not exceed the upper-limit $\mathcal{H}$.

$$\sum_{k=1}^{K} \sum_{u,v \in V} Y_{u,v,e}^k \cdot \left(\phi_{u,v}^k + \varphi_{u,v}^k\right) \leq \Lambda, \forall e \in E. \tag{34}$$

Eq. (34) ensures that the number of leased fibers through each duct in the physical topology does not exceed its capacity Λ.

$$\begin{cases} \gamma_{u,v}^k + \alpha_w \cdot F_{u,v,w}^k \leq 1, \\ \eta_{u,v}^k + \alpha_w \cdot F_{u,v,w}^k \leq 1, \end{cases} \tag{35}$$
$$\{u, v, w : u \neq v, w \neq u, w \neq v, \ u, v, w \in V\}, k \in [1, K].$$

Eq. (35) ensures that there is no DC or SN on any intermediate hut of a DC-SN/SN-SN connection.

Finally, the optimizations of the EPS-based and OCS-based expansions are formulated as follows.

Optimization for EPS-based DCI Expansion:

Minimize $\mathcal{Q}_e$,
s.t. Eqs. (1), (2), (5)-(7), (10)-(14), (17), (19)-(23), (31)-(35).

Optimization for OCS-based DCI Expansion:

Minimize $\mathcal{Q}_o$,
s.t. Eqs. (3)-(6), (8)-(35).

Complexity Analysis: We can easily verify that the optimizations for EPS-based and OCS-based DCI expansions are both $\mathcal{NP}$-hard, because if we set $C_t = C_e = C_o = 0$ and make the optimizations only concern the cost of fiber leasing, they can be reduced to the k-minimum spanning tree problem, which is known to be $\mathcal{NP}$-hard [26]. Then, the complexity of the ILP models depend on the numbers of their variables and constraints. The ILP for EPS-based expansion has $2 \cdot |V| \cdot (|V_e \cup V_{un}| \cdot K + 1) + |V_e \cup V_{un}|^2 \cdot (3 + K + |V_e \cup V_{un}|^2)$ variables and $2 \cdot |V_{ce} \cup V_{cn}| + |V_e| + |V_{cn}| + |V_{un}| + |V_e \cup V_{un}| + |V_e \cup V_{un}|^2 \cdot (8 + 4 \cdot K + 3 \cdot |V_e \cup V_{un}|^2) + |E| + |V|^2 \cdot K \cdot (5 + |V|)$ constraints, while the variables and constraints in the ILP for OCS-based expansion respectively are $2 \cdot |V| \cdot (|V_e \cup V_{un}| \cdot 2 \cdot K + 1) + |V_{un}| \cdot |V_e| + |V_{un}|^2 \cdot (2 + K + |V_{cn}|^2) + |V_e \cup V_{un}|^2 \cdot (3 + K + |V_e \cup V_{un}|^2)$ and $2 \cdot |V_{ce} \cup V_{cn}| + |V_e| + 2 \cdot |V_{cn}| + 4 \cdot |V_e \cup V_{un}| + |V_e \cup V_{un}|^2 \cdot (5 + 4 \cdot K + 3 \cdot |V_e \cup V_{un}|^2) + |V_{un}| \cdot (2 + |V_e| \cdot (K+1) + |V_{cn}| \cdot K) + |V_{un}|^2 \cdot (1 + 5 \cdot K + |V_{un}|^2 \cdot |V_{cn}|^2) + |E| + |V|^2 \cdot K \cdot (10 + 2 \cdot |V|)$.

V. Heuristic Algorithms

Even though by solving the optimizations in the previous section directly, we can get the exact solutions of regional DCI expansions, the time complexity can be prohibitively high, especially for large-scale problems. Therefore, we design two time-efficient heuristics in this section, to tackle the EPS-based and OCS-based DCI expansions, respectively.

Algorithm 1: Heuristic for EPS-based DCI Expansion

Input: Physical topology $G(V, E)$, locations of DCs V_{ce}/V_{cn} and existing SNs V_e, and Λ and $\mathcal{H}$.
Output: DCI expansion scheme $\mathbb{R}^*$ and its CAPEX $\mathcal{Q}_e^*$.
1 $\mathcal{Q}_e^* = \mathcal{M}$;
2 **for** *each* $i \in [1, N_{\max}]$ **do**
3     $\tilde{V}_e = V_e$, restore $\{B_v, \forall v \in V_{cn}\}$ to original values;
4   **for** *each new DC* $v \in V_{cn}$ **do**
5   **for** *each SN* $u \in \tilde{V}_e$ **do**
6   try to satisfy capacity of DC v by connecting to SN u and update B_v as remaining capacity;
7   **end**
8   **if** $B_v > 0$ **then**
9   run *Algorithm* 2 to deploy new SN(s) to satisfy B_v and insert the new SNs in $\tilde{V}_e$;
10   **end**
11   **end**
12   initialize SN-SN connection matrix $\mathbf{J}_{|\tilde{V}_e| \times |\tilde{V}_e|}$ as $\mathbf{0}$;
13   **for** *each SN* $u \in \tilde{V}_e$ **do**
14   calculate total throughput of SN u to put in T_u;
15   find all the SNs in $\tilde{V}_e$ that can connect to SN u within hop-count of $\mathcal{H}$, and put them in V_u;
16   **for** *each SN* $v \in V_u$ **do**
17             $\mathbf{J}(u, v) = 1$;
18   **end**
19   **end**
20   initialize AG $G_a(V_a, E_a)$ as $V_a = \tilde{V}_e$ and $E_a = \emptyset$;
21   **for** *each element* $\mathbf{J}(u, v) \in \mathbf{J}$ **do**
22   **if** $\mathbf{J}(u, v) = 1$ **then**
23             $w_{u,v} = \min(T_u, T_v)$;
24   connect u and v in G_a with a link (u, v) whose weight is $w_{u,v}$ and add (u, v) in E_a;
25   **end**
26   **end**
27   compute the minimum weight spanning tree $\mathcal{T}$ in G_a;
28   set up SN-SN connections according to $\mathcal{T}$;
29   get DCI expansion scheme $\mathbb{R}$ by combining $\tilde{V}_e$ with DC-SN/SN-SN connections, and get its CAPEX $\mathcal{Q}_e$;
30   **if** $\mathcal{Q}_e < \mathcal{Q}_e^*$ **then**
31         $\mathcal{Q}_e^* = \mathcal{Q}_e$, $\mathbb{R}^* = \mathbb{R}$;
32   **end**
33 **end**

A. Algorithm Design for EPS-based DCI Expansion

Algorithm 1 shows our iterative auxiliary graph (AG) based heuristic for EPS-based regional DCI expansion (I-AG-EPS). *Line* 1 initializes the minimal CAPEX $\mathcal{Q}_e^*$ as a large value $\mathcal{M}$. Then, the for-loop of *Lines* 2-33 optimizes the DCI expansion with $N_{\max}$ trials to get the best-known scheme $\mathbb{R}^*$. In each iteration, we first allocate a temporary set $\tilde{V}_e$ to store all the deployed SNs and initialize it as V_e, and restore the capacities of new DCs to their original values (*Line* 3). Then, we try to satisfy the capacity of each new DC $v \in V_{cn}$ with the SNs in $\tilde{V}_e$, and update B_v as the unserved capacity (*Lines* 4-7). If the DC's capacity cannot be fully satisfied with all the SNs in

$\tilde{V}_e$, we invoke *Algorithm* 2 to deploy new SNs for the DC and update $\tilde{V}_e$ accordingly (*Lines* 8-10). The details of *Algorithm* 2 will be discussed later. *Lines* 3-11 finish the tasks of deploying new SNs and leasing fibers to set up new DC-SN connections.

Algorithm 2: Finding Locations to Deploy New SNs

Input: Current regional DCI $G(V,E)$, new DC $v \in V_{cn}$, current SN set $\tilde{V}_e$, and Λ and $\mathcal{H}$.
Output: Set of new SNs deployed for DC v.

1 $\tilde{V}_v = \emptyset$;
2 find all the unused huts in V_{un} that can connect to DC v within hop-count of $\mathcal{H}$, and put them in V_v;
3 **for** *each SN* $u \in \tilde{V}_e$ **do**
4   find all the unused huts in V_{un} that can connect to SN u within hop-count of $\mathcal{H}$, and put them in V_u;
5     $V_{v,u} = V_v \cap V_u$, $i = 1$, $N = |V_{v,u}|$;
6   **while** $(i \leq N)$ *AND* $(V_{v,u} \neq \emptyset)$ **do**
7   randomly select a hut $u' \in V_{v,u}$ to deploy an SN;
8   try to satisfy DC capacity B_v by connecting DC v to SN u';
9   **if** *the DC-SN connection of* v-u' *can be set up under constraints of* Λ *and* $\mathcal{H}$ **then**
10   update B_v as remaining capacity of DC V;
11   insert SN u' in $\tilde{V}_v$ and remove u' from $V_{v,u}$;
12   **else**
13   revert the SN deployment on u';
14   **end**
15   **if** $B_v > 0$ **then**
16             $i = i + 1$;
17   **else**
18   **break** ;
19   **end**
20   **end**
21   **if** $B_v = 0$ **then**
22   **break**;
23   **end**
24 **end**
25 **return** $\tilde{V}_v$;

Starting from *Line* 12, the iteration tries to accomplish the task of setting up SN-SN connections with an AG-based approach. *Lines* 12-19 generate a connection matrix $\mathbf{J}$ for this purpose, whose size is $|\tilde{V}_e| \times |\tilde{V}_e|$. Specifically, we first set the value of each element in $\mathbf{J}$, and then for each SN $u \in \tilde{V}_e$, if another SN $v \in \tilde{V}_e$ can be connected to u with a fiber path that satisfies the hop-count constraint of $\mathcal{H}$, we set the element $\mathbf{J}(u,v)$ as 1. Next, the AG $G_a(V_a, E_a)$ is built based on $\mathbf{J}$ (*Lines* 20-26), where we have $V_a = \tilde{V}_e$, connect two nodes $u, v \in V_a$ with a link if $\mathbf{J}(u,v) = 1$, and set the link's weight as the smaller total throughput between those of SNs u and v. Hence, the SN-SN connections can be set up by finding the minimum weight spanning tree in the AG G_a and leasing fibers accordingly (*Lines* 27-28). Finally, the iteration obtains a DCI expansion scheme $\mathbb{R}$ and its CAPEX $\mathcal{Q}_e$, and updates the best-known scheme if needed (*Lines* 29-32).

Algorithm 2 explains how to select huts to deploy new SNs for satisfying the capacity B_v of a new DC v and setting up the corresponding DC-SN connections, and it can be used to deploy both EPS-based and OCS-based SNs. *Lines* 1-2 are for the initialization, where the set $\tilde{V}_v$ that is used to store new SNs is initialized as empty and we put all the feasible huts that can be used to deploy new SNs for DC v in V_v. Then, the for-loop of *Lines* 3-24 check each deployed SN $u \in \tilde{V}_e$ to deploy a new SN near it for DC v. *Line* 4-5 are for the initialization of an iteration, where we put all the feasible huts that can support valid DC-SN/SN-SN connections to DC v and SN u, respectively, in set $V_{v,u}$. Next, the while-loop of *Lines* 6-20 uses $|V_{v,u}|$ attempts at most to deploy SN(s) to satisfy B_v. Here, each attempt selects a hut in $V_{v,u}$ randomly to deploy an SN on it (*Line* 7), and if the SN is verified as feasible, we commit its deployment and the related DC-SN connections, put it in $\tilde{V}_v$, and update the corresponding variables (*Lines* 8-11). Finally, after the capacity of DC v has been fully satisfied with the newly-deployed SNs, we return set $\tilde{V}_v$ in *Line* 25.

Algorithm 3: Heuristic for OCS-based DCI Expansion

Input: Physical topology $G(V,E)$, locations of DCs V_{ce}/V_{cn} and existing SNs V_e, and Λ and $\mathcal{H}$.
Output: DCI expansion scheme $\mathbb{R}^*$ and its CAPEX $\mathcal{Q}_e^*$.

1 $\mathcal{Q}_e^* = \mathcal{M}$;
2 **for** *each* $i \in [1, N_{\max}]$ **do**
3     $\tilde{V}_e = \emptyset$, restore $\{B_v, \forall v \in V_{cn}\}$ to original values;
4     $B_v = B_v + |V_{cn}| - 1$;
5   *Lines* 4-11 in *Algorithm* 1 for deploying new OCS-based SNs and setting up DC-SN connections;
6   *Lines* 12-26 in *Algorithm* 1 for building AG $G_a(V_a, E_a)$ based on the set of new SNs $\tilde{V}_e$;
7   compute the minimum weight spanning tree $\mathcal{T}$ in G_a;
8   determine additional fibers for each connection between two OCS-based SNs;
9   set up SN-SN connections according to $\mathcal{T}$;
10   *Lines* 29-32 in *Algorithm* 1;
11 **end**

B. Algorithm Design for OCS-based DCI Expansion

Algorithm 3 explains the procedure for optimizing the OCS-based regional DCI expansion, which still leverages the iterative AG-based approach and thus is named as I-AG-OCS. *Line* 1 is still for the initialization, and the for-loop of *Lines* 2-11 still optimizes the DCI expansion with $N_{\max}$ iterations to get the best-known scheme $\mathbb{R}^*$. However, as the original regional DCI is based on EPS, we reset the set of OCS-based SNs $\tilde{V}_e$ as empty in *Line* 3, and add the required additional fibers to the capacity of each new DC according to *Theorem* 1 (*Line* 4), at the beginning of each iteration. Then, we reuse the *Lines* 4-11 and 12-26 in *Algorithm* 1 to deploy new OCS-based SNs and build an AG G_a based on them, respectively. *Line* 7 calculates the minimum weight spanning tree in G_a, *Line* 8 obtains the additional fibers for each connection between two OCS-based SNs, and *Line* 9 sets up all the SN-SN connections accordingly. Finally, we reuse the *Lines* 29-32 in *Algorithm* 1 to get the DCI expansion scheme $\mathbb{R}$ and its CAPEX $\mathcal{Q}_e$ for this iteration, and update the best-known scheme if necessary.

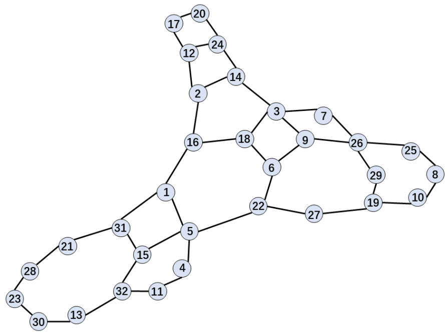


Fig. 4. Physical topology used in small-scale simulations.

C. Complexity Analysis

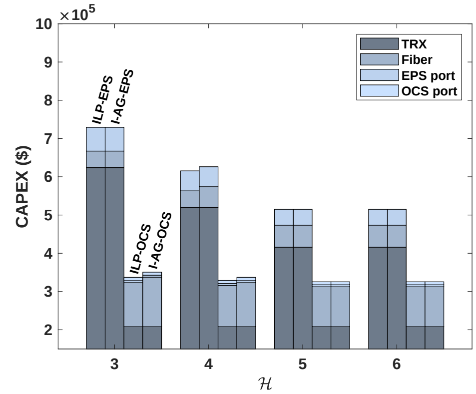
The time complexity of *Algorithm* 2 is $O(|V_{un}|^2)$. The time complexity of *Algorithm* 1 can be analyzed as follows. The complexity of the for-loop of *Lines* 4-11 is $O(|V_{cn}| \cdot (|V_{un}| + |V_{un}|^2))$, the for-loop of *Lines* 13-19 can run $O(|V_{un}|^2)$ times at most, and the complexity of the for-loop of *Lines* 21-26 is $O(|V_{un}|^2)$. *Line* 27 finds the minimum weight spanning tree in the AG and its time complexity is $O(|V_{un}|^2 \cdot \log(|V_{un}|))$. Hence, the time complexity of *Algorithm* 1 is $O(N_{\max} \cdot (|V_{cn}| \cdot (|V_{un}| + |V_{un}|^2) + |V_{un}|^2 + |V_{un}|^2 + |V_{un}|^2 \cdot \log(|V_{un}|)))$. The difference between *Algorithms* 1 and 3 is the calculation of additional fibers for each connection between two OCS-based SNs. The time complexity of *Line* 8 is $O(|V_{un}|^2)$, thus the time complexity of *Algorithm* 3 is $O(N_{\max} \cdot (|V_{cn}| \cdot (|V_{un}| + |V_{un}|^2) + |V_{un}|^2 + |V_{un}|^2 + |V_{un}|^2 \cdot \log(|V_{un}|) + |V_{un}|^2))$.

VI. Performance Evaluations

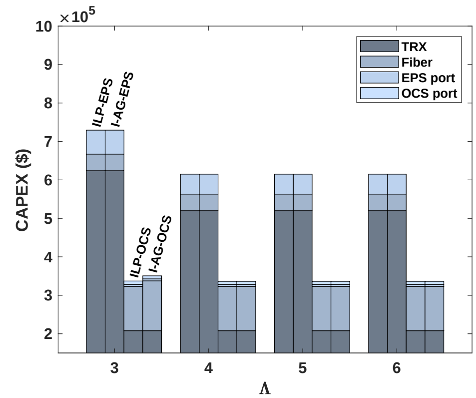
In this section, we conduct numerical simulations to compare the EPS-based and OCS-based regional DCI expansion.

A. Simulation Setup

Our simulations consider both small-scale and large-scale problems. The small-scale simulations use the topology in Fig. 4, which is adapted from a realistic metro fiber plant [27] and consists of 32 facility huts and 42 fiber ducts. As for the large-scale simulations, we generate a random topology, containing 50 facility huts and 118 fiber ducts, and the degree of each hut is set within $[2, 3]$. In each simulation, we assume that the existing EPS-based regional DCI contains $[5, 20]$ DCs, while the number of new DCs will not exceed this number, according to the scenario of practical regional DCI expansions [11]. In line with the practical values used in [11, 28, 29], we set $\mathcal{W} = 40$ (*i.e.*, each fiber accommodates 40 wavelength channels), and set the unit costs (per year) as $C_f = 3,600$, $C_t = 1,300$, $C_e = 130$ and $C_o = 150$, all in US dollars. Note that, the unit cost of OCS ports actually depends on the scale of an OCS switch, but according to the analysis in [29], the unit cost will not change dramatically if the port-counts of OCS switches do not vary largely, which is actually the case in regional DCI expansions. Hence, setting the unit cost of OCS ports as a fixed value is still a reasonably good approximation. Meanwhile, since by definition, a regional DCI consists of a collection of DCs (typically 5-20) within tens of kilometers of each other [11], the longest distance between two DCs in it will generally not be long enough to affect the modulation format used by a TRX. Hence, we assume that all the TRXs are of the same type, *i.e.*, their unit costs are the same.



(a) Different length constraint $\mathcal{H}$



(b) Different availability constraint Λ

Fig. 5. CAPEX in small-scale simulations (cost of OCS port is $C_o = 150$).

The simulations consider 4 algorithms, which are the ILP-EPS and ILP-OCS for EPS-based and OCS-based expansions, respectively, and the two corresponding heuristics (*i.e.*, I-AG-EPS and I-AG-OCS based on *Algorithms* 1 and 3, respectively). We set $K = 10$ for the K-shortest path routing used in the algorithms, and use $N_{\max} = 300$ for I-AG-EPS and I-AG-OCS. All the simulations run on a computer with 40 Intel Xeon Silver 4210 CPUs at 2.20 GHz and 64 GB of memory, and the software environment is MATLAB 2022b with Gurobi 10.0.3 [30]. To ensure statistical accuracy, we obtain each data point by averaging the results from 10 independent runs.

B. Small-Scale Simulations

We first conduct small-scale simulations with the topology in Fig. 4, to check the performance gaps between the ILPs and their corresponding heuristics. Each simulation sets $\mathcal{H} = \Lambda = 3$, first randomly selects three huts to place the existing DCs with capacities of $\{1, 1, 2\}$, respectively, connects them with an EPS-based SN, and then randomly selects other huts to deploy the new DCs. The number of new DCs will not exceed 3 and their capacities can be selected from $\{1, 2\}$ fibers.

Table I shows the simulation results, when we set $\Lambda = 3$ and change $\mathcal{H} \in [3, 6]$. The optimization objectives (*i.e.*, the total

TABLE I
RESULTS OF SMALL-SCALE SIMULATIONS WITH DIFFERENT LENGTH CONSTRAINT $\mathcal{H}$ (COST OF AN OCS PORT IS $C_o = 150$).

$\mathcal{H}$	ILP-EPS			ILP-OCS			I-AG-EPS			I-AG-OCS		
	Obj.	Ω_e	*Time (s)*	*Obj.*	Ω_o	*Time (s)*	*Obj.*	Ω_e	*Time (s)*	*Obj.*	Ω_o	*Time (s)*
3	729,600	12	158,285	337,100	32	720,516	729,600	12	8.7346	350,600	36	10.4627
4	615,200	12	215,682	329,000	30	751,130	626,000	15	9.2766	337,100	32	12.3652
5	515,200	16	288,752	325,400	29	834,297	515,200	16	9.5984	325,400	29	12.4915
6	515,200	16	328,045	325,400	29	1,026,105	515,200	16	9.6723	325,400	29	13.0983

TABLE II
RESULTS OF SMALL-SCALE SIMULATIONS WITH DIFFERENT AVAILABILITY CONSTRAINT Λ (COST OF AN OCS PORT IS $C_o = 150$).

Λ	ILP-EPS			ILP-OCS			I-AG-EPS			I-AG-OCS		
	Obj.	Ω_e	*Time (s)*	*Obj.*	Ω_o	*Time (s)*	*Obj.*	Ω_e	*Time (s)*	*Obj.*	Ω_o	*Time (s)*
3	729,600	12	158,285	337,100	32	720,516	729,600	12	8.7346	350,600	36	10.4627
4	615,200	12	179,171	336,200	32	925,506	615,200	12	9.3708	336,200	32	11.5737
5	615,200	12	268,733	336,200	32	1,026,436	615,200	12	9.4525	336,200	32	12.5485
6	615,200	12	337,138	336,200	32	1,033,928	615,200	12	9.7241	336,200	32	12.2552

TABLE III
RESULTS OF SMALL-SCALE SIMULATIONS WITH DIFFERENT LENGTH CONSTRAINT $\mathcal{H}$ (COST OF AN OCS PORT IS $C_o = 200$).

$\mathcal{H}$	ILP-EPS			ILP-OCS			I-AG-EPS			I-AG-OCS		
	Obj.	Ω_e	*Time (s)*	*Obj.*	Ω_o	*Time (s)*	*Obj.*	Ω_e	*Time (s)*	*Obj.*	Ω_o	*Time (s)*
3	729,600	12	158,285	340,000	32	732,467	729,600	12	8.7346	353,200	36	9.2195
4	615,200	12	215,682	331,600	30	781,080	626,000	15	9.2766	340,000	32	11.0519
5	515,200	16	288,752	328,000	29	926,534	515,200	16	9.5984	328,000	29	11.1573
6	515,200	16	328,045	328,000	29	1,024,180	515,200	16	9.6723	328,000	29	12.4865

TABLE IV
RESULTS OF SMALL-SCALE SIMULATIONS WITH DIFFERENT AVAILABILITY CONSTRAINT Λ (COST OF AN OCS PORT IS $C_o = 200$).

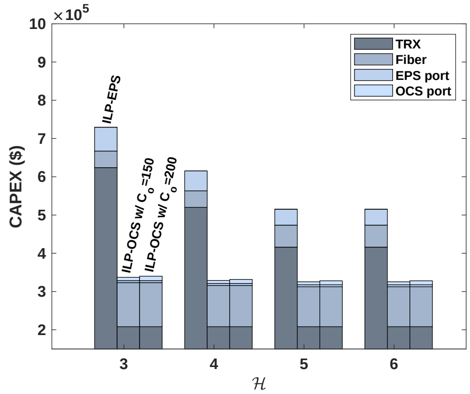
Λ	ILP-EPS			ILP-OCS			I-AG-EPS			I-AG-OCS		
	Obj.	Ω_e	*Time (s)*	*Obj.*	Ω_o	*Time (s)*	*Obj.*	Ω_e	*Time (s)*	*Obj.*	Ω_o	*Time (s)*
3	729,600	12	158,285	340,000	32	732,467	729,600	12	8.7346	353,200	36	9.2195
4	615,200	12	179,171	338,800	32	890,940	615,200	12	9.3708	338,800	32	10.6878
5	615,200	12	268,733	338,800	32	1,013,240	615,200	12	9.4525	338,800	32	11.2134
6	615,200	12	337,138	338,800	32	1,017,910	615,200	12	9.7241	338,800	32	12.1297

CAPEX) from ILP-EPS and I-AG-EPS both decrease with $\mathcal{H}$. This is because a larger $\mathcal{H}$ relaxes the length constraint for DC-SN and SN-SN connections, and thus certain new EPS-based SNs are avoided. The analysis can be verified by the fact that the number of newly-leased fibers Ω_e generally increases with $\mathcal{H}$, but this actually does not make the total CAPEX increase with $\mathcal{H}$, indicating that the major contributors to the CAPEX of EPS-based expansion are the costs of new TRXs and EPS ports, which can be effectively reduced by increasing $\mathcal{H}$. Moreover, we observe that the objectives from ILP-EPS and I-AG-EPS converge when we have $\mathcal{H} \geq 5$. This is because the network size of a regional DCI is limited [11], and the number of huts that a DC-SN or SN-SN connection can go across is also upper-bounded. Then, when $\mathcal{H}$ approaches to its upper-bound, it will no longer have a noticeable impact on the result of DCI expansion. The results in Table I also indicate that ILP-EPS and I-AG-EPS provide similar objectives while the running time of I-AG-EPS is 5 magnitudes shorter than that of ILP-EPS, confirming the effectiveness of I-AG-EPS on optimizing EPS-based DCI expansion.

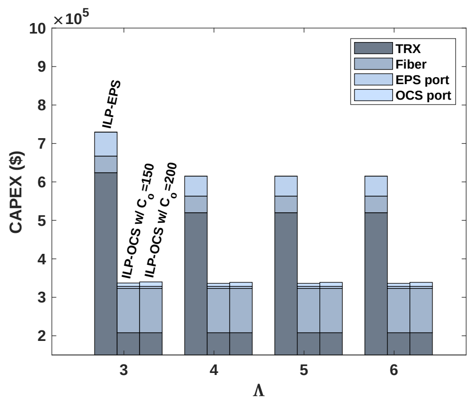
Similarly, the objectives from ILP-OCS and I-AG-OCS in Table I also decrease with $\mathcal{H}$. By comparing ILP-OCS with ILP-EPS, we can see that OCS-based expansion generally needs to lease more fibers due to the requirements of additional fibers, but its CAPEX can be significantly less than that of EPS-based expansion. This is attributed to the savings on new TRXs and EPS ports achieved by OCS-based expansion. The results in Table I also verifies that I-AG-OCS can approximate ILP-OCS well. It can be seen that the running time of I-AG-OCS is longer than that of I-AG-EPS. This is because I-AG-EPS preferentially considers to connect new DCs to existing EPS-based SNs, while I-AG-OCS has to first place new OCS-based SNs and then connect new DCs to them.

Table II explores the impact of Λ by fixing $\mathcal{H} = 3$ and changing $\Lambda \in [3, 6]$. The CAPEX of EPS-based and OCS-based expansions also decrease with Λ, and OCS-based expansion is still more cost-efficient than EPS-based expansion.

We plot the contributions of the costs from TRXs, fiber leasing, EPS ports, and OCS ports to CAPEX in Fig. 5. Specifically, Fig. 5(a) plot the results when we set $\Lambda = 3$ and change $\mathcal{H} \in [3, 6]$, while Fig. 5(b) is for the cases where we have $\mathcal{H} = 3$ and $\Lambda \in [3, 6]$. We can see that for different



(a) Different length constraint $\mathcal{H}$



(b) Different availability constraint Λ

Fig. 6. Comparisons of CAPEX in small-scale simulations.

combinations of $\mathcal{H}$ and Λ, the contribution of the cost of each type of network components is similar. As for the EPS-based expansion, the major contributor to CAPEX is the total cost of TRXs, while the total costs of fiber leasing and EPS ports are comparable. The CAPEX of each OCS-based expansion is much lower than that of its EPS-based counterpart, attributing to the fact that the total cost of TRXs is significantly reduced and becomes even lower than that of fiber leasing. Meanwhile, for the OCS-based expansion, the total costs of EPS ports and OCS ports are much lower than those of fiber leasing and TRXs, making their contributions to CAPEX almost ignorable.

Finally, to further analyze the impact of the unit cost difference between EPS and OCS ports, we keep $C_e = 130$ but increase C_o from 150 to 200 and redo the simulations. The results in Tables III and IV show similar trends as those in Tables I and II. Fig. 6 compares the cost distributions provided by ILP-EPS, ILP-OCS with $C_o = 150$, and ILP-OCS with $C_o = 200$, and we can see that increasing C_o does not change the overall trend in OCS-based expansion, *i.e.*, the total cost of OCS ports is much lower than those of fiber leasing and TRXs and its contribution to CAPEX is almost ignorable.

C. Large-Scale Simulations

Large-scale simulations are then performed to further compare OCS-based and EPS-based DCI expansions, and due to the time complexity of ILP-EPS and ILP-OCS, we only consider I-AG-EPS and I-AG-OCS this time.

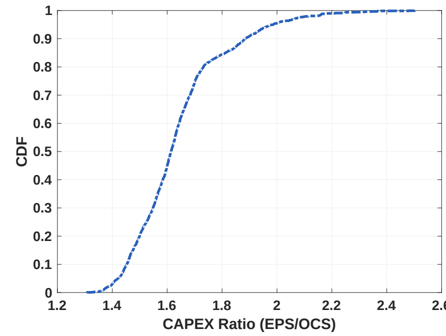


Fig. 7. CDF of CAPEX ratios of EPS-based expansion to OCS-based one.

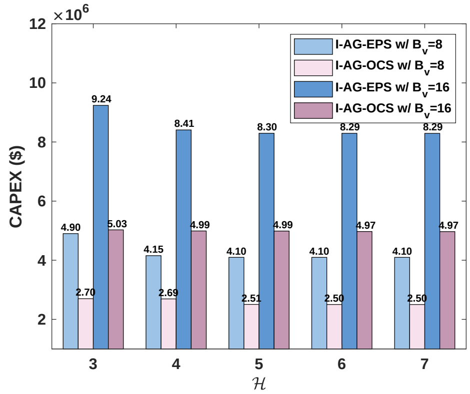
First, we would like to compare the CAPEX of OCS-based and EPS-based DCI expansions comprehensively by considering $3,000$ different scenarios. In each scenario, we set the number of existing DCs as 8 and the capacities of DCs (B_v) as $\{8, 16\}$ fibers, randomly select $\mathcal{H}$ and Λ from $\{3, 4, 5\}$ and $\{100, 150\}$, respectively, and choose the number of new DCs within $[1, 8]$. Fig. 7 plots the cumulative distribution function (CDF) of the CAPEX ratios of EPS-based expansion to OCS-based expansion, which indicates that OCS-based expansion is always more beneficial in terms of CAPEX.

Next, we conduct more simulations to further investigate the impacts of the factors such as the number of new DCs ($|V_{cn}|$), the capacity of new DCs (B_v), $\mathcal{H}$ and Λ. We first fix the number of existing DCs as 8, set $\mathcal{H} = 3$ and $\Lambda = 60$, and then change the number of new DCs and their capacities in each simulation. Specifically, the number of new DCs ($|V_{cn}|$) and the capacities of new DCs (B_v) are set according to four scenarios: 1) $|V_{cn}| = 4$ and $B_v = 8$, 2) $|V_{cn}| = 4$ and $B_v = 16$, 3) $|V_{cn}| = 8$ and $B_v = 8$, and 4) $|V_{cn}| = 8$ and $B_v = 16$. As for each scenario, we randomly generate 50 existing EPS-based DCIs and carry out simulations to average the results. The results on CAPEX are shown in Figs. 8 and 9.

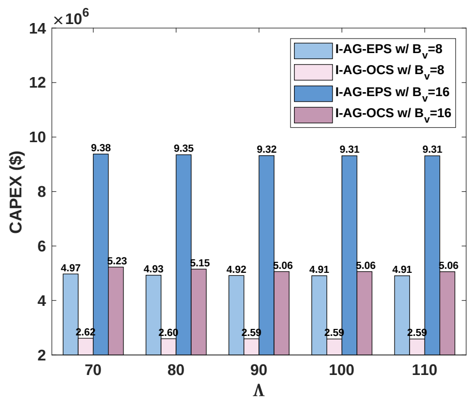
Fig. 8(a) compares the results on CAPEX from I-AG-EPS and I-AG-OCS when we fix $\Lambda = 60$ and $|V_{cn}| = 4$ and change $\mathcal{H} \in [3, 7]$. We observe that the CAPEX of EPS-based and OCS-based expansions both first decreases with $\mathcal{H}$ and then converges, showing similar trends as those in Table I. It can also be seen clearly that OCS-based expansion always saves CAPEX over the corresponding EPS-based one. Fig. 8(b) shows how the CAPEX from I-AG-EPS and I-AG-OCS changes with Λ when we fix $\mathcal{H} = 3$ and $|V_{cn}| = 4$. Similar to the results in Table I, the CAPEX first decreases with Λ and then converges. Moreover, we can see that the impact of Λ on CAPEX is not as significant as that of $\mathcal{H}$. To further analyze the impacts of $\mathcal{H}$ and Λ, we increase the problem scale to $|V_{cn}| = 8$ and redo the simulations. Figs. 9(a) and 9(b) show the results on CAPEX when we change $\mathcal{H}$ and Λ, respectively, and similar trends can be seen as those in Figs. 8(a) and 8(b).

VII. Conclusion

In this paper, we studied the problem of optimizing the expansion of an existing EPS-based regional DCI such that the network expansion's CAPEX can be minimized, and both EPS-based and OCS-based expansions were considered. We

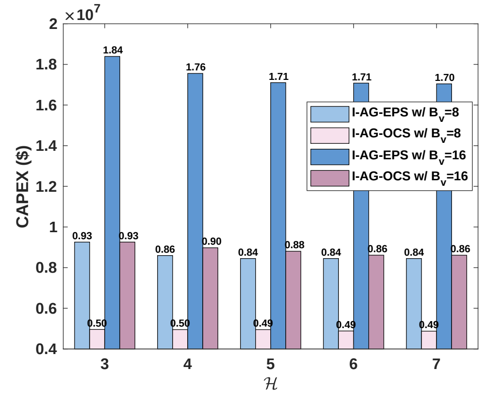


(a) Different length constraint $\mathcal{H}$

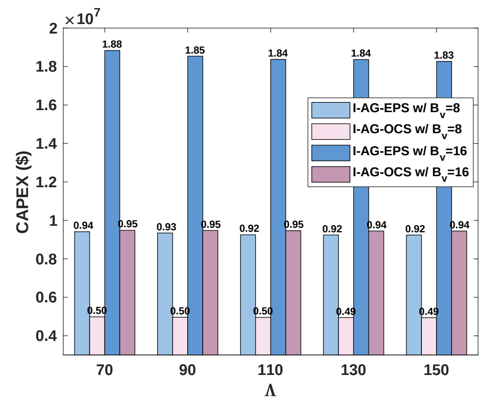


(b) Different availability constraint Λ

Fig. 8. CAPEX in large-scale simulations (number of new DCs is $|V_{cn}| = 4$).



(a) Different length constraint $\mathcal{H}$



(b) Different availability constraint Λ

Fig. 9. CAPEX in large-scale simulations (number of new DCs is $|V_{cn}| = 8$).

first formulated two ILP models to solve the problems of EPS-based and OCS-based expansions exactly. Then, we proposed two heuristics by leveraging an AG-based iterative approach, to find near-optimal solutions in polynomial time. Finally, extensive simulations were performed to use the proposed algorithms to compare EPS-based and OCS-based expansions. The results demonstrated the effectiveness of the ILPs for solving small-scale problems and verified that the heuristics can obtain near-optimal solutions. By evaluating the impacts of various factors on CAPEX, including the number of new DCs ($|V_{cn}|$), the capacity of new DCs (B_v), $\mathcal{H}$ and Λ, our simulations indicated that $\mathcal{H}$ and Λ have similar effects on the CAPEX of the two kinds of expansions, that is, the CAPEX of expansion initially decreases with $\mathcal{H}$ or Λ and then converges, and the impact of Λ on CAPEX is not as significant as that of $\mathcal{H}$. Moreover, the results proved that OCS-based expansion is always more beneficial in CAPEX than EPS-based one.

Acknowledgments

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