Disaster Protection in Inter-DataCenter Networks leveraging Cooperative Storage

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***Abstract*—Natural disasters have challenged the survivability of Elastic Optical Inter-DataCenter Networks (EO-DCNs), and it is urgent to establish efficient disaster protection schemes. In this paper, we investigate the disaster-resilient service provisioning problem leveraging cooperative storage system (CSS) and multi-path routing. The studied problem involves data center (DC) assignment, content partition and placement, working/protection paths computation, as well as spectrum allocation. Our main objective is to jointly minimize the spectrum usage and maximal frequency slot index. Besides, we also expect to cut the content storage space. To this end, we first formulate the studied CSS-based protection problem as an integer linear program (ILP), and then propose a fast heuristic algorithm to improve the network scalability in large instances. Numerical simulations are conducted to compare the proposed schemes with the traditional protection strategy using entire content replication and single path routing. Simulation results demonstrate that the CSS-based protection scheme enables to cut up to 17.8% of the spectrum usage and half of the content storage space.**

***Index Terms*—Inter-DataCenter Networks, Elastic Optical Networks, Disaster resilience, Cooperative Storage System (CSS)**

I. Introduction

With the high spectrum efficiency and huge bandwidth capacity, Elastic Optical Inter-DataCenter Networks (EO-DCNs) have the ability to support big data storage and provide the platform for the deployment of diversified network services and applications [1]–[4]. However, as tens of natural disasters worldwide destroy power system and subsequently affect optical networks, EO-DCNs are facing the serious threats from large-scale disasters. A disaster zone (DZ) failure may affect several links and nodes on a large scale and for a relatively long time, but existing protection schemes for single link or node failure cannot deal with disaster failure [5].

To maintain the survivability of content delivery in EO-DCNs, anycast technique can be used to provide a backup path from a backup DC to provision the service against disaster failure [6] [7]. To store data reliably, the erasure codes provide a feasible method of building a cooperative storage system (CSS) for EO-DCN [8], in which a content can be encoded and divided into numerous different fragments, and they are then stored spatially in multiple DCs. Through maximum distance separable (MDS) coding, the receiving of several distinct coded segments permits to decode the original content, which are the same total size as the original data. Therefore, when a content is required, multiple DCs are assigned as the primary DCs and a multi-path connection from the source node to each of these primary DCs is established to serve the request. Besides, a backup DC is also assured to protect any one of the primary DCs. Meanwhile, the multiple working paths and a backup path from end to content are generated as DZ-disjoint to protect the services against single DZ failure. Furthermore, the DC assignment together with content partition and placement also needs to be explored.

Motivated by the fact that current disaster protection is based on the mirrored storage, we aim to design a novel disaster protection scheme in EO-DCNs leveraging CSS and multi-path routing. We focus on the cooperative dedicated end-to-content backup path protection (C-DEBPP) against disaster failure. The contributions of this paper are summarized as follows. We first formulate the joint problem as an integer linear program (ILP) to jointly minimize the spectrum usage and maximal index of occupied frequency slots (FSs) for the network, and the storage space is also reduced owing to content partition in CSS. To improve the scalability in large instances, we then propose a heuristic algorithm to solve the path generation and spectrum allocation based on the coloring algorithm. Simulation results demonstrate the significant performance improvement of the proposed method compared with the traditional one. To the best of our knowledge, it is the first time that the CSS and multi-path routing are employed for disaster protection in EO-DCNs.

II. Related Work

Several works about disaster protection in optical networks have been published. The RECODIS project was formed to

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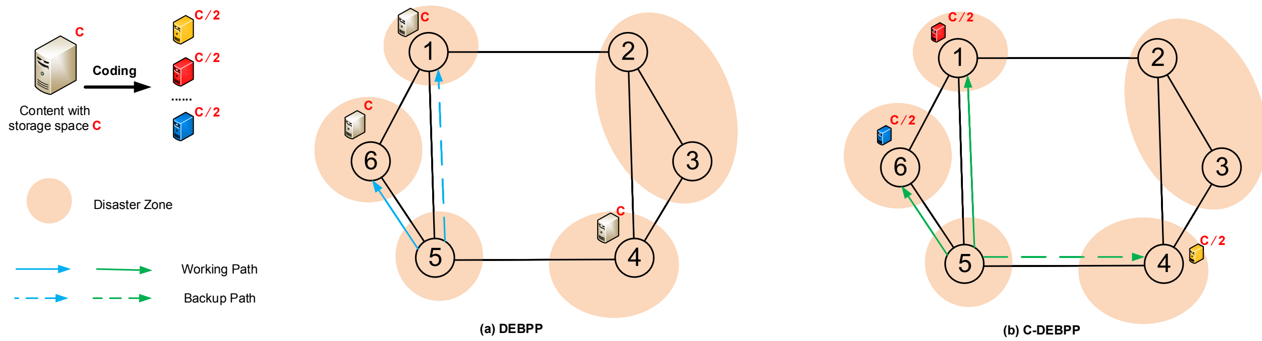


Fig. 1. Solution acquired by DEBPP and C-DEBPP with 6-node topology and 5 DZs.

achieve disaster resilience, and the members of its Working Group 1 gave a survey which summarized different disaster-resilient strategies of wavelength division multiplexing (WDM) optical networks [5]. The concept of disaster in the networks is described as a group of nodes and links, in which the disaster failure would destroy the corresponding nodes and links [9]. A stochastic model named earthquake risk and backbone optical network model was provided in [10], which estimated the impact of earthquake disasters on a backbone optical network.

While keeping the disaster resilience for optical network, there are several works proposed to optimize the spectrum usage. The algorithms both considering routing and spectrum assignment (RSA) problems for elastic optical networks were proposed in [11]. In [12], DC placement and content management were explored for EO-DCNs to minimize risk, which is defined as the expected loss of content. Content placement and independent end-to-content paths calculation were explored for the disaster-resilient k-node (edge) content connected EO-DCNs [13]. Cloud service and content delivery service in EO-DCNs against disaster failure were investigated in [1].

As for network storage system, the CSS has shown a better performance in storage efficiency. Literature [8] first gave the network codes design for CSS. With MDS codes, the required data is able to be recovered by offering several encoded fragments, which are the same size in all as the original data. The disaster protection scheme for EO-DCNs is only studied based on the traditional storage system, in which each redundancy of the content in EO-DCNs is a replica of the original data. The cost on the backup bandwidth is 100% for the traditional dedicated path protection, and the storage space is linearly increasing along with the backup DC growing in number [1]. There has not been related studies on disaster protection leveraging CSS for EO-DCNs, which has a potential for less spectrum usage and storage space. Therefore, it is essential to explore CSS based disaster protection strategy in EO-DCNs.

III. Problem Statement

A digraph $G(V, A, D)$ is used in this paper to model the network, where V denotes the set of nodes, A represents the set of symmetric directed links, and D is the set of DCs. Z is the set of disaster zones, of which each contains all the nodes and links that affected by the disaster zone. For any request $r(s_r, z_r, k_r, c_r, \phi_r)$, s_r is the source node, z_r is the disaster zone in which the source node is located, k_r is the number that the working paths are to be generated, c_r is the required content ID, and ϕ_r is the required bandwidth. Note that the request is blocked if a DZ (except z_r) fails more than one routing paths simultaneously, including working path and backup path. To avoid such situation, we force the paths of request can not be failed by the same DZ (except z_r). Furthermore, the range of k_r can be determined by the *Algorithm* 1 *line 1-11*. The main considerations of each subproblem can be summarized as follows.

1) **Content partition:** In this work, a cooperative strategy is proposed to optimize content partition against signal DZ failure. With MDS code, we assume a content with l size is divided into m fragments of equal size $\frac{l}{m}$. Then, they are jointly encoded into $\tilde{k}(\tilde{k} > m)$ fragments, each of $\frac{l}{m}$ size and placed at most $K(\tilde{k} > K > m)$ different DCs. Any m different fragments would successfully recover the original data. For the request r, each DC should store at least $\lceil \frac{m}{k_r} \rceil$ fragments, and bandwidth for each path is reduced as $\lceil \frac{\phi_r}{k_r} \rceil$ from ϕ_r. Therefore, the storage space for CSS in each DC is reduced as $\frac{l}{k_{r,c}^{min}}$, where $k_{r,c}^{min}$ is the minimum of k_r among the requests that require the content c.

2) **DC assignment and content placement:** Based on the DC probable locations and the prior information, DC assignment and content placement are jointly optimized. Then, maximal DC number and minimal storage space per content are also given. In order to ensure content survivability, at least $(k_{r,c}^{max} + 1)$ DZ-disjoint DCs should be assigned as the storage DC, where $k_{r,c}^{max}$ is the maximum of k_r among the requests that require the content c. Note that the fragments stored at each DC are different from each other in the proposed scheme.

3) **Working paths and backup path generation:** We focus on the disaster failure caused by single DZ, in which situation the working paths and backup paths should be generated as DZ-disjoint (except z_r). Along the paths, the flow conversation should be followed. The dedicated backup path generation method based on CSS is considered, *i.e.*, C-DEBPP. For C-DEBPP, backup paths are generated with dedicated spare

TABLE I
SYSTEM PERFORMANCE IN DEBPP AND C-DEBPP.

Schemes	FSs usage	Maximal occupied FS index	Storage space
DEBPP	16	8	2C
C-DEBPP	12	4	3C/2

capacity.

4) **Spectrum allocation:** For each path, the spectrum is allocated under the following principles. a)*Spectrum continuity:* Without spectrum conservation in this work, each link is assigned with the same FSs along the path. b)*Spectrum contiguity:* The FSs to be assigned for the request should be continuous for each path. c)*Spectrum conflict:* The spectrum allocation for each backup path is dedicated in C-DEBPP, in which each FS of each link cannot be assigned for multiple requests.

To show the advantage of the disaster protection scheme leveraging CSS, we give a simple example in Fig. 1. We consider a 6-node network with 3 DCs (nodes 1, 4, and 6), 1 content and 5 DZs. The request is assumed that the source node is node 5, and it requires 8 FSs bandwidth.

In the path protection with mirrored storage system, *i.e*, dedicated end-to-content backup path protection (DEBPP) [1], the request is provisioned with working path 5-6 and backup path 5-1, and each link needs 8 FSs, as shown in Fig 1 (a). For C-DEBPP, node 5 is able to receive from two working DCs simultaneously, *i.e.* $k_r = 2$. Thus, the request is provisioned with two working paths and one backup path, which are generated as DZ-disjoint. Each working and backup path benefits from the cooperative method to lower its transmission load, which only needs half of the required bandwidth in this instance. Supposing the storage space for the content 1 is C, then C-DEBPP allows each DC only costs $C/2$ in this case. The spectrum usage, maximal occupied FS index and storage space are then summarized in Table I.

IV. JOINT ILP FORMULATION

In this section, we formulate joint ILP model for C-DEBPP. The notations are presented in Table II. For the sake of readability, we use $\forall w$, $\forall b$, $\forall v$, $\forall z_r^w$, $\forall a$, $\forall d$, $\forall c$, $\forall z$, and $\forall r$ to denote $\forall w \in W_r$, $\forall b \in B$, $\forall v \in V$, $\forall z_r^w \in Z_r^w$, $\forall a \in A$, $\forall d \in D$, $\forall c \in C$, $\forall z \in Z$, and $\forall r \in R$ respectively. We also use $\forall w'$, $\forall r'$, and $\forall r \neq r'$ to denote $\forall w' \in W_r$, $\forall r' \in R$, and $\forall r, r' \in R, r \neq r'$ respectively, if it is not indicated specifically.

A. C-DEBPP ILP model

The studied disaster protection problem can be formulated by the following ILP, namely **C-DEBPP ILP**

$$\min \quad \theta_1 \cdot \Big(\sum_{w \in W_r} \sum_{a \in A} \sum_{r \in R} p_{ra}^w \cdot \lceil \frac{\phi_r}{k_r} \rceil + \sum_{a \in A} T_a\Big) + \theta_2 \cdot \Delta \quad (1)$$

s.t. Constraints (2)-(34).

In the objective function, the first term calculates the total spectrum usage on all the links of all the paths, and the second term denotes the maximal occupied FSs index. Their values affect the overall spectrum utilization. θ_1 and θ_2 are two adjustable weights. The constraints for C-DEBPP ILP can be divided into four parts, **DC assignment and content placement constraints** (2)-(6), **flow-conservation constraints** (7), **disaster-zone-disjoint path constraints** (8)-(12) and **spectrum allocation constraints** (13)-(34).

1) **DC assignment and content placement constraints**: Assuming that a content of size l is divided into m parts with equal size, and they are jointly decoded into $\tilde{k}(\tilde{k} \geq m)$ fragments via MDS code, and every m fragments would recover the original data [8]. Each assigned DC should store at least $\lceil \frac{m}{k_{r,c}^{min}} \rceil (k_{r,c}^{min} \leq m)$ fragments to guarantee the content provisioning, where $k_{r,c}^{min}$ is the minimum of k_r among the source nodes requesting the corresponding content c_r. Thus, the coding length for the content is at least $(k_{r,c}^{min} \cdot l \cdot \sum_{d \in D} R_d^{c_r})$, where $\sum_{d \in D} R_d^{c_r}$ represents the number of DCs that store the content c_r.

Constraints (2)-(6) ensure k_r primary DCs and one backup DC are assigned for each request. Constraints (4)-(5) give the lower and upper bounds on the number of content storage DCs. Constraint (6) assures that these DCs are different from each other so that the DZ-disjoint paths can be generated.

$$\sum_{d \in D} \Lambda_{rd}^w = 1, \qquad \forall r, \forall w \quad (2)$$

$$\sum_{d \in D} \Lambda_{rd}^B = 1, \qquad \forall r \quad (3)$$

$$1 + k_r \leq \sum_{d \in D} R_d^{c_r}, \qquad \forall r \quad (4)$$

$$\sum_{d \in D} R_d^c \leq \tilde{k}, \qquad \forall c \quad (5)$$

$$\Lambda_{rd}^B + \sum_{w \in W_r} \Lambda_{rd}^w \leq R_d^{c_r}, \qquad \forall r, \forall d \quad (6)$$

2) **Flow-conservation constraints**: Constraint (7) uses flow conservation to generate all the paths. For each node, the outgoing flow and incoming flow of each request should be equal in each path, unless for source node, which has only outgoing flow, or a DC, which has only incoming flow.

$$\sum_{a \in \Psi_v^+} p_{ra} - \sum_{a \in \Psi_v^-} p_{ra} = \begin{cases} 1, & v = s_r \\ -\Lambda_{rv}, & v \in D, \\ 0, & \text{otherwise} \end{cases} \qquad \forall r \quad (7)$$

3) **Disaster-zone-disjoint path constraints**: Constraints (8)-(11) determine whether the working paths and backup paths are affected by each DZ. Constraint (12) ensures that the working and backup paths of the same request are generated as DZ-disjoint (except z_r).

$$\alpha_{rz}^w \leq \sum_{a \in z} p_{ra}^w, \qquad \forall r, \forall z, \forall w \quad (8)$$

$$\alpha_{rz}^w \geq p_{ra}^w, \qquad \forall r, \forall z, \forall a \in z, \forall w \quad (9)$$

$$\alpha_{rz}^B \leq \sum_{a \in z} p_{ra}^B, \qquad \forall r, \forall z \quad (10)$$

$$\alpha_{rz}^B \geq p_{ra}^B, \qquad \forall r, \forall z, \forall a \in z \quad (11)$$

TABLE II
NOTATIONS AND VARIABLES

Network Sets and Parameters	
$G(V, A, D)$	Network with node set V, link set A and DC set D.
C	Set of content.
K	Number of assigned DC for the content placement.
R	Set of requests $r(s_r, z_r, k_r, c_r, \phi_r)$, where s_r, z_r, k_r, c_r and ϕ_r are source node, disaster zone that source node is placed, the number of working paths to be generated, content, and the required FSs.
D_r	Set of the content-placed DCs for request r. $\|D_r\|$ is the number of the content-placed DCs for request r.
$k_{r,c}^{max}/k_{r,c}^{min}$	Maximum/Minimum of k_r among the requests that require the content c.
$z \in Z$	DZ/DZs set. $Z \subset G$ contains the sets of links and nodes.
W_r	Set of working paths for the request r.
S	Set of FSs on each link. $\|S\|$ denotes the number of available FSs.
$\mu_{r,d}$	Generated path from d to s_r.
Ψ_v^+/Ψ_v^-	Set of outgoing/incoming links for node $v \in V$.
Variables in ILP model and heuristic	
$p_{ra} \in \{0,1\}$	Whether link a is used by any path of request r.
$p_{ra}^w \in \{0,1\}$	Whether link a is used by the working path w of request r.
$p_{ra}^B \in \{0,1\}$	Whether link a is used by the backup path of request r.
$\Lambda_{rd} \in \{0,1\}$	Whether DC d is assigned for request r.
$\Lambda_{rd}^w \in \{0,1\}$	Whether DC d is used as the working DC and the end node of working path w for request r.
$\Lambda_{rd}^B \in \{0,1\}$	Whether DC d is used as the backup DC and the end node of backup path b for request r.
$\alpha_{rz}^w \in \{0,1\}$	Whether working path w of r goes through DZ z.
$\alpha_{rz}^B \in \{0,1\}$	Whether backup path b of r goes thorough DZ z.
$R_d^c \in \{0,1\}$	Whether content c is placed at DC d.
$g_r^w \in [0, \|S\|-1]$	Integer variable denoting the assigned starting FS index of working path w for request r.
$g_r^B \in [0, \|S\|-1]$	Integer variable denoting the assigned starting FS index of backup path for request r.
$\beta_r^{ww'} \in \{0,1\}$	Whether g_r^w is smaller than $g_r^{w'}$ for request r.
$\beta_r^{wB} \in \{0,1\}$	Whether g_r^w is smaller than g_r^B for request r.
$\beta_{rr'}^{ww'} \in \{0,1\}$	Whether g_r^w of request r is smaller than $g_{r'}^{w'}$ of request r'.
$\beta_{rr'}^B \in \{0,1\}$	Whether g_r^B of request r is smaller than $g_{r'}^B$ of request r'.
$\beta_{rr'}^{wB} \in \{0,1\}$	Whether g_r^w of request r is smaller than $g_{r'}^B$ of request r'.
$\gamma_r^{ww'} \in \{0,1\}$	Whether the working paths w and w' of request r have any common link.
$\gamma_{rr'}^{ww'} \in \{0,1\}$	Whether two working paths, w of r and w' of r', have any common link.
$\gamma_{rr'}^B \in \{0,1\}$	Whether two backup paths of r and r' have any common link.
$\gamma_{rr'}^{wB} \in \{0,1\}$	Whether the working path w of r and backup path of r' have any common link.
$T_a \in [0, \|S\|]$	Total spare capacity (FS) that need to be served for link a.
$\Delta \in [0, \|S\|]$	Maximal index of occupied FSs.

$$\alpha_{rz}^B + \sum_{w \in W_r} \alpha_{rz}^w \leq 1, \quad \forall r, \forall z \in \{x | x \in Z, x \notin z_r\} \tag{12}$$

4) **Spectrum allocation constraints**: Constraints (13)-(20) indicate whether any two paths have any common link. Constraints (21)-(25) compare the starting index of FSs between any two paths. Constraints (26) and (27) imply the maximum index of occupied FSs.

$$p_{ra}^w + p_{ra}^{w'} - 1 \leq \gamma_r^{ww'}, \quad \forall r : k_r \geq 2, \forall a, \forall w, w', w > w' \tag{13}$$

$$\gamma_r^{ww'} = \gamma_r^{w'w}, \quad \forall r : k_r \geq 2, \forall w, w', w > w' \tag{14}$$

$$p_{ra}^w + p_{ra}^B - 1 \leq \gamma_r^{wB}, \quad \forall r, \forall a, \forall w \tag{15}$$

$$p_{ra}^w + p_{r'a}^{w'} - 1 \leq \gamma_{rr'}^w, \quad \forall r > r', \forall a, \forall w \in W_r, w' \in W_{r'} \tag{16}$$

$$\gamma_{rr'}^{ww'} = \gamma_{r'r}^{w'w}, \quad \forall r > r', \forall w \in W_r, w' \in W_{r'} \tag{17}$$

$$p_{ra}^B + p_{r'a}^B - 1 \leq \gamma_{rr'}^B, \quad \forall r, r', r > r', \forall a \tag{18}$$

$$\gamma_{rr'}^B = \gamma_{r'r}^B, \quad \forall r > r' \tag{19}$$

$$p_{ra}^w + p_{r'a}^B - 1 \leq \gamma_{rr'}^{wB}, \quad \forall r, r', r \neq r', \forall a, \forall w \tag{20}$$

$$\beta_r^{ww'} + \beta_r^{w'w} = 1, \quad \forall r : k_r \geq 2, \forall w, w', w > w' \tag{21}$$

$$\beta_r^{wB} + \beta_r^{Bw} = 1, \quad \forall r, \forall w \tag{22}$$

$$\beta_{rr'}^{ww'} + \beta_{r'r}^{w'w} = 1, \quad \forall r > r', \forall w \in W_r, w' \in W_{r'} \tag{23}$$

$$\beta_{rr'}^{wB} + \beta_{r'r}^{Bw} = 1, \quad \forall r \neq r', \forall w \tag{24}$$

$$\beta_{rr'}^B + \beta_{r'r}^B = 1, \quad \forall r > r' \tag{25}$$

$$g_r^w + \lceil \frac{\phi_r}{k_r} \rceil \leq \Delta, \quad \forall r, \forall w \tag{26}$$

$$g_r^B + \lceil \frac{\phi_r}{k_r} \rceil \leq \Delta, \quad \forall r \tag{27}$$

$$g_r^w + \lceil \frac{\phi_r}{k_r} \rceil - g_r^{w'} \leq \Delta \cdot (2 - \gamma_r^{ww'} - \beta_r^{ww'}), \quad \forall r : k_r \geq 2, \forall w, w', w \neq w' \tag{28}$$

$$g_r^w + \lceil \frac{\phi_r}{k_r} \rceil - g_{r'}^{w'} \leq \Delta \cdot (2 - \gamma_{rr'}^{ww'} - \beta_{rr'}^{ww'}), \quad \forall r, r', r \neq r', \forall w \in W_r, \forall w' \in W_{r'} \tag{29}$$

$$g_r^w + \lceil \frac{\phi_r}{k_r} \rceil - g_r^B \leq \Delta \cdot (2 - \gamma_r^{wB} - \beta_r^{wB}), \quad \forall r, \forall w \tag{30}$$

$$g_r^B + \lceil \frac{\phi_r}{k_r} \rceil - g_r^w \leq \Delta \cdot (2 - \gamma_r^{wB} - \beta_r^{Bw}), \quad \forall r, \forall w \tag{31}$$

$$g_r^w + \lceil \frac{\phi_r}{k_r} \rceil - g_{r'}^B \leq \Delta \cdot (2 - \gamma_{rr'}^{wB} - \beta_{rr'}^{wB}), \quad \forall r \neq r', \forall w \tag{32}$$

$$g_r^B + \lceil \frac{\phi_r}{k_r} \rceil - g_{r'}^{w'} \leq \Delta \cdot (2 - \gamma_{r'r}^{w'B} - \beta_{rr'}^{Bw'}), \quad \forall r \neq r', \forall w' \in W_{r'} \tag{33}$$

$$g_r^B + \lceil \frac{\phi_r}{k_r} \rceil - g_{r'}^B \leq \Delta \cdot (2 - \gamma_{rr'}^B - \beta_{rr'}^B), \quad \forall r \neq r' \tag{34}$$

$$T_a \geq \sum_{r \in R} p_{ra}^B \cdot \lceil \frac{\phi_r}{k_r} \rceil, \quad \forall a \tag{35}$$

The spectrum conflict occurs if any two paths have any common link. Then based on the Starting Slot Assignment

(SSA) principle, which assigns the starting FSs to the demand, constraints (28) and (29) avoid spectrum conflict among all the working paths. The $spectrum\ contiguity$ is ensured by setting a contiguous range of FSs ϕ_r for each request and $\lceil \frac{\phi_r}{k_r} \rceil$ for each working path. Constraints (30) and (31) avoid spectrum conflict between working path and backup path for same request. Similarly, constraints (32) and (33) avoid spectrum conflict between any two working path and backup path for different requests. Constraint (34) restricts that any backup paths cannot share FS on each link. At last, constraint (35) calculates the total number of FSs served for backup paths.

V. Heuristic

To improve the scalability in the scenarios with large requests, we propose the heuristic algorithm to solve the path generation and spectrum allocation. *Algorithm* 1 shows the heuristic solution for C-DEBPP (HSCDP), which runs after the DC assignment and content placement in ILP, *i.e.*, ILP constraints (2)-(6). *Lines 1-3* generate k-shortest path and calculate the cost for each path, and then select the path with minimum cost as the first working path for request r, and corresponding DC d as the first primary DC. Similarly to the objective function in ILP, the cost for path is the weighted sum of FS usage and maximal occupied FS index, and the weights are set the same as the ILP objective function (1), *i.e.*, θ_1 and θ_2. *Lines 4-13* generate the maximal DZ-disjoint paths based on minimal objective for each path, and update k_r if necessary. *Lines 14-18* generate conflict graph to assigns the FSs [14]. Then *Line 19* calculates the total cost.

Algorithm 1: HSCDP

Input : $G(V, A, D)$, D_r, $\forall r \in R$, $\forall z \in Z$, S.
Output: $\mu_{r,d}$, T_a, R_d^c, k_r, $\forall d \in D$, $\forall a \in A$, $\forall c \in C$, $\forall r \in R$, Cost.

1 **for** $r \in R$ **do**
2 Generate $|D_r|$ shortest paths from $d \in D$ to s_r, and calculate the cost for the path as the weighted sum of spectrum usage and maximal occupied FS index;
3 Select the path with minimal cost as the working path $\mu_{r,d}^0$, and $R_d^{c_r} = 1$;
4 **for** $d \in D_r, R_d^{c_r} \neq 1$ **do**
5 **for** k ***from*** 1 ***to*** k_r **do**
6 Delete the DZ-joint (except z_r) links and nodes of the former generated path $\mu_{r,d}^{k-1}$;
7 Based on graph G^{k-1}, generate graph G^k;
8 Generate $|D_r - 1|$ shortest paths from $d^k \in D$ to s_r;
9 **if** *Path* $\mu_{r,d}^k$ *cannot be generated* **then**
10 Assign $\mu_{r,d}^{k-1}$ as the backup path;
11 Update $k_r = k - 1$; **Break**;
12 **else**
13 Select the path with minimal cost as the working path $\mu_{r,d}^k$, and $R_d^{c_r} = 1$;
14 **for** $r \in R$ **do**
15 **for** $d \in D_r, R_d^{c_r} = 1$ **do**
16 **for** k ***from*** 1 ***to*** k_r **do**
17 Generate conflict graph, and allocate FSs based on the conflict graph [14];
18 Record the path $\mu'_{r,d}$ with maximal occupied FS index T_a;
19 Calculate the total cost as the weighted sum of all the path spectrum usage and maximal occupied FS index for each link;

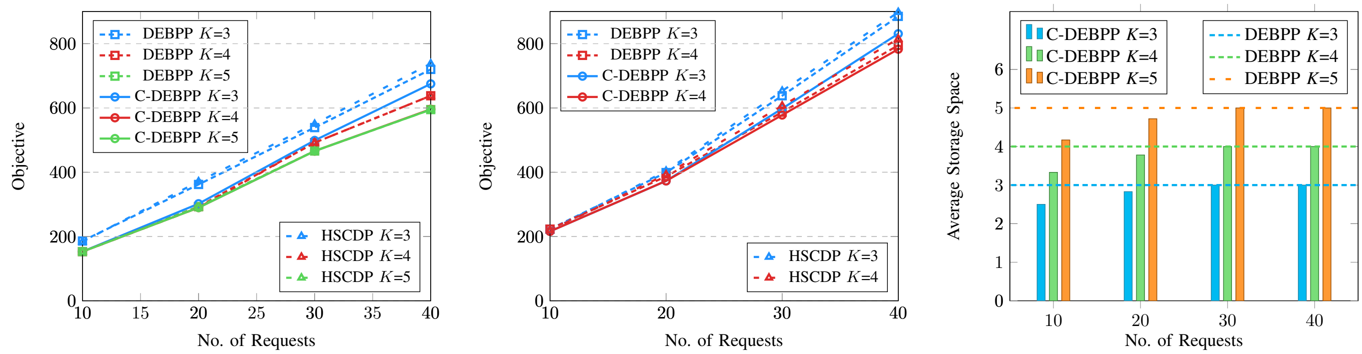
VI. Simulations and Performance Evaluations

We use CPLEX 12.06 to solve the proposed ILP models and heuristic on a PC with a 3.5 GHz CPU and a 8 GBytes RAM. The NSFNET [1] and COST239 [12] are used as test beds, and the simulation parameters for different situations are set as follows. In NSFNET: 1) 5 available DC locations at nodes 2, 5, 6, 7 and 11; 2) 4 available DC locations at nodes 2, 5, 9 and 11. In COST239: 1) 5 available DC locations at nodes 1, 2, 8, 10 and 11; 2) 4 available DC locations at nodes 1, 2, 8 and 11 [1] [12]. Then, to evaluate the disaster resilience performance of EO-DCN with cooperative system, we compare C-DEBPP with DEBPP. Note that DEBPP is formulated by ILP model. The requests are randomly generated with 10 contents, and each link is set with maximum 300 FSs to carry the traffic of big data. For simplicity, the number of maximal working path is set as 2, *i.e.*, $k_{r,c}^{max} = 2$; and the weights of the objective are set as the same value, *i.e.*, $\theta_1 = \theta_2 = 1$. To evaluate the performance of storage space, we assume the total size of the original content data is normalized. Thus, in traditional storage system, the storage space for each content equals the number of assigned DCs, *i.e.*, K.

The simulations are conducted for different number of probable DC locations and number of DCs per content. As shown in Fig. 2 and Fig. 3, performances of the CSS based schemes are better than the traditional schemes, and the reduction of objective is up to 17.8%. This is because the proposed method allows the multiple DZ-disjoint working paths generation, and FSs allocated for backup path is reduced. We also observe that the more DC locations and larger K there are, the better improvement C-DEBPP tends to obtain. In Fig. 2 (c) and Fig. 3 (c), the proposed system also shows the superiority on storage space, the cut storage space is up to 50%. In addition, the scenario with small number of requests can be seen as the targeted content provisioning applications, in which the content is only supplied for part of the nodes in the network due to the concerns of copyright, cost, etc. Thus, the proposed system achieves lower storage space in this scenario. As request number increases in NSFNET, the even request distribution tends to traverse all network nodes, thus storage space would grow to serve the request whose $k_r = 1$. Therefore, the storage space of the CSS tend to have the same storage space as the conventional one in Fig. 2 (c). However, the node degree in COST239 is large, in which the minimal k_r is 2. Thus, C-DEBPP in such situation allows storage space to be reduced to 50%.

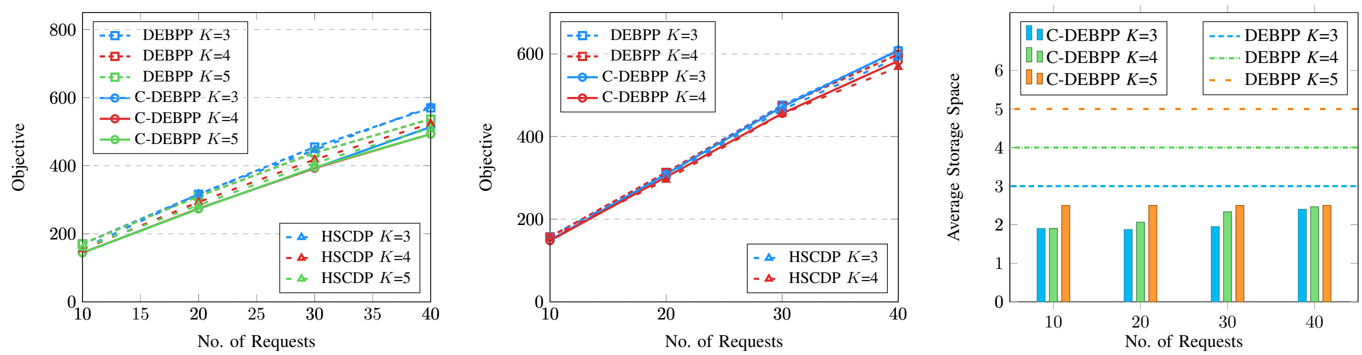
VII. Conclusion

In this paper, we have proposed a novel disaster protection scheme in EO-DCNs leveraging CSS. To jointly minimize the spectrum usage and maximal occupied FS index, an ILP model and a heuristic are developed to find the optimal protection



(a) Objective vs. K (5 probable DC locations) (b) Objective vs. K (4 probable DC locations) (c) Average Storage Space per Content

Fig. 2. System Performance for different No. of probable DC locations in NSFNET.



(a) Objective vs. K (5 probable DC locations) (b) Objective vs. K (4 probable DC locations) (c) Average Storage Space per Content

Fig. 3. System Performance for different No. of probable DC locations in COST239.

solution, which involves content partition and placement, routing, protection mechanisms, as well as spectrum allocation. Compared with existing method using entire content replication as redundancy strategy, our scheme significantly improves the protection efficiency in terms of objective combined by spectrum usage and maximal occupied FS index, and storage space.

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