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Content Connectivity Based Polyhedron Protection Against Multiple Link Failures in Optical Data Center Networks

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Abstract. To further improve the resource efficiency of the p-polyhedron protection scheme against multi-link failures in optical data center networks (ODCNs), the content connectivity is considered when constructing the p-polyhedron structure. In this paper, the content connectivity-based polyhedron protection (CCPP) scheme is proposed. An ILP model and a heuristic algorithm are developed to realize the CCPP scheme. Numerical results show that the proposed CCPP scheme has a lower network redundancy. Moreover, the network redundancy of the CCPP scheme is positively correlated with the degree of content connectivity.

Keywords. Optical network, network survivability, p-polyhedron protection, content connectivity

1. Introduction

Survivability has always been an important research focus for optical networks. At present, the existing survivability techniques can be divided into two categories, i.e., the protection scheme and the restoration scheme. The restoration scheme such as link-based restoration, path-based restoration, makes best effort to establish recovery channels for interrupted working flows using the remaining available network resources after disasters. For the protection scheme, backup resources are usually reserved to achieve the uninterrupted service transmission. The backup spectrum resources are usually organized into a specific protection structure. To evaluate the resource efficiency of each protection structure, network redundancy which is defined as the ratio of the working resource consumption to the backup resource consumption is proposed [1]. In [2], we have proven that the *k-regular* and *k-edge* connected structure is the optimal protection structure against multi-link failures. Based on the *k-regular* and *k-edge* connected structure, the p-polyhedron protection scheme which has low resource redundancy is proposed [3, 4]. In optical data center networks (ODCNs), the required data or services can be replicated and maintained in multiple geographically distributed data centers. Based on this, the content connectivity which represents the reachability of the required content from each user is defined for ODCNs.

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Moreover, the degree of content connectivity can be improved by increasing the number of copies of content [5-7]. Besides, the artificial intelligence technology has been applied into optical networks. In [8], the authors reviewed the graph-based deep learning models in various problems from different types of communication networks. In [9], a deep reinforcement learning (DRL) model based on graph neural networks was proposed to solve the sub-problem of multicast session selection. In [10], a hierarchical deep reinforcement learning (DRL) model based on graph neural network (GNN) was proposed to orchestrate the allocations of IT resources in datacenters (DCs) and spectrum resources on fiber links dynamically. In ODCNs, the content connectivity can be integrated with the p-polyhedron protection scheme. With the help of content connectivity, the resource efficiency of the p-polyhedron protection scheme can be further improved. This paper proposes the content connectivity based polyhedron protection (CCPP) scheme to minimize the network redundancy of ODCNs. An ILP model and a heuristic algorithm are developed to realize the CCPP scheme under static and dynamic circumstances respectively. Numerical results show that the proposed CCPP scheme has a lower network redundancy. Moreover, the network redundancy of the CCPP scheme is positively correlated with the degree of content connectivity.

2. The CCPP Scheme

Figure 1(a) shows an ODCN which is composed of four data centers, four optical nodes. Contents C_1, C_2 and C_3 are replicated and maintained in multiple datacenters. For each content, an aggregated topology is built. In this aggregated topology, data centers which store the same content are aggregated together into a content node. Then, the *k-edge* connected structure is extracted from this aggregated topology. The obtained CCPP structures are presented in Fig.1 (b).

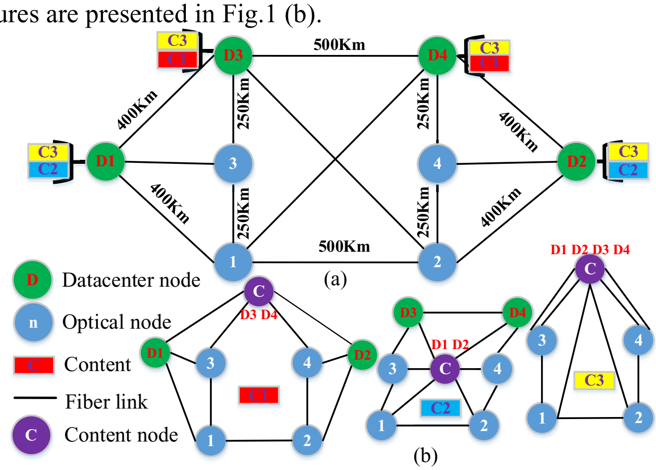

Figure 1. (a) The ODCN. (b) All built CCPPs.

$$RR_c = \frac{BLN_c * m}{(m+1)*|E| - m*BLN_c} \tag{1}$$

$$RR\_CCPP = \frac{\sum_{c \in C} RR_c * B_c}{\sum_{c \in C} B_c} \tag{2}$$

It can be seen that the number of on-body links (BLN) on the conventional polyhedron structure equals the total number of fiber links in this ODCN. The number of on-body links on each CCPP is not greater than that of the conventional polyhedron structure. For the CCPP, the proportional relation among the assigned working resources on on-body links, the assigned backup resources on on-body links, and the assigned working resources on stride links is 1:*m*: *m*+1, where *m* is the number of resisted failures. The network redundancy of the CCPP can be calculated by Eq. (1), where BLN_c is the number of used links on this CCPP and $|E|$ is the total number of fiber links. The consumed backup resources on each CCPP are determined by the bandwidth requirements of the corresponding content. The weighted mean of resource redundancies of all CCPPs can be obtained by Eq. (2), where B_c is the required bandwidth of content *c*. For the conventional protection structure, the lower bound of network redundancy is *m*/(*d*-*m*), where *d* is the average node degree [11].

3. The ILP Formula and Heuristic Algorithm

In the developed ILP formula, the CCPP scheme does not need to fully satisfy the *k-regular* and *k-edge* connected constraint. The objective function is minimizing the total number of links used to achieve content reachability. The number of on-body links on each CCPP structure and the total number of on-body links on all CCPP structure are considered simultaneously.

Notations and Variables:

K: The number of independent paths, $k \in [1, K]$.

V: The set of optical nodes, $v \in V$.

D: The set of datacenter nodes, $d \in D$.

E: The set of links, $<i, j> \in E$.

C: The set of contents, $c \in C$.

T^d : Initial content storage condition on datacenter *d*, $t_c^d \in T^d$.

Δ : A large integer constant.

$Y_{s,c}^{k,\ \langle i,j\rangle}$: Equals 1 if the k^{th} path uses link $<i, j>$ to reach content c for node s.

$Z_s^{d,c}$: Equals 1 if node *s* reach content c on datacenter *d*.

$U_c^{\langle i,j\rangle}$: Equals 1 if link $<i, j>$ is used on the CCPP for *c*.

$G^{\langle i,j\rangle}$: Equals 1 if link $<i, j>$ is used on one CCPP.

Optimization Objective

$$Minimize(\sum_{c\in C}\sum_{<i,j>\in E} U_c^{<i,j>} + |C| * \sum_{<i,j>\in E} G^{\langle i,j\rangle}) \tag{3}$$

Constraints:

$$\sum_{j:<i,j>\in E} Y_{s,c}^{k',\langle i,j\rangle} - \sum_{j:<j,i>\in E} Y_{s,c}^{k',\langle j,i\rangle} = \begin{cases} 1 & i=s, i\notin D \\ 1-Z_s^{i,c} & i=s, i\in D \\ -Z_s^{i,c} & i\neq s, i\in D \\ 0 & else \end{cases} \tag{4}$$

$$\forall k' \in [1, K'], s, i \in V, c \in C$$

$$\sum_{k\in K} Y_{s,c}^{k,\langle i,j\rangle} \le 1 \quad \forall <i,j>\in E, s\in V, c\in C \tag{5}$$

$$Z_s^{d,c} \le t_c^d \quad \forall d \in D, c \in C, s \in V \tag{6}$$

$$\sum_{s \in S} \sum_{k \in K} Y_{s,c}^{k,\langle i,j \rangle} \ge U_c^{<i,j>} \quad \forall <i,j> \in E, c \in C \tag{7}$$

$$\sum_{s \in S} \sum_{k \in K} Y_{s,c}^{k,\langle i,j \rangle} / \Delta \le U_c^{<i,j>} \quad \forall <i,j> \in E, c \in C \tag{8}$$

$$\sum_{c \in C} U_c^{\langle i,j \rangle} / \Delta \le G^{\langle i,j \rangle} \le \sum_{c \in C} U_c^{\langle i,j \rangle} \quad \forall <i,j> \in E \tag{9}$$

Constraints (4-6) ensure that there are k link-disjoint paths used to achieve content reachability. Constraints (7-9) ensure that all links used to achieve content reachability must exist on the CCPP structure. The CCPP construction algorithm is developed to quickly get the CCPP structure based on the current content distribution. It aggregates the data center nodes stored content c as content node v_c and search the *k-edge connected* structure with the least on-body links in the aggregated topology.

The CCPP Construction Algorithm

INPUT: content c

OUTPUT: used links E_c on CCPP for c .

$G_c(V_c, D_c, E_c) == G(V, D, E)$

build the datacenter nodes set B_c , $v_c \to V_c$

for $b \in B_c$ **do**

  for $<b,i>$, $<i,b> \in E_c$ **do**

    $<v_c, b> \to E_c, <b, v_c> \to E_c$;

  end for

end for

G_c=G_c / B_c

for $<i,j> \in E_c$ **do**

  if ($G_c / <i,j>$ *is k-edge-connected*) **do**

    E_c=$E_c / \{<i,j>\}$;

  end if

end for

G_c=$G_c \bigcup B_c$;

for $<i, v_c> \in E_c$ **do**

  for $b \in B_c$ **do**

    if ($<i,b> \notin E_c$ **&&** $<i,b> \in E$) **do**

      $<i,b>, <b,i> \to E_c$;

      E_c=$E_c / \{<i,v_c>, <v_c,i>\}$;

    break

    end if

  end for

end for

4. Performance evaluation

Simulations are conducted in COST239.We assume each fiber link has 200 spectrum and 6 optical nodes are randomly selected as data centers. The initial number of copies of content ranges from 2 to 6 and each content are randomly distributed in data centers. The bandwidth requirement of each content is uniformly distributed between 1 and 10 slots. The degree of content connectivity is represented by *cc* and its value range can be determined by the ODCN topology (*cc*>=4 and *cc*<=5). The number of BLNs used by the CCPP under different content is different, so we calculate the average of BLNs on CCPPs to compare the performance with the conventional p-polyhedron protection (CPP) scheme and P-*cycle*. As shown in Fig. 2(a), the CCPP structure requires fewer on-body links against multi-link failures. Figure 2(b) shows that the network redundancy of the CCPP structure is less than that of the conventional polyhedron structure. Moreover, increasing the degree of content connectivity can further reduce the network redundancy of the CCPP structure.

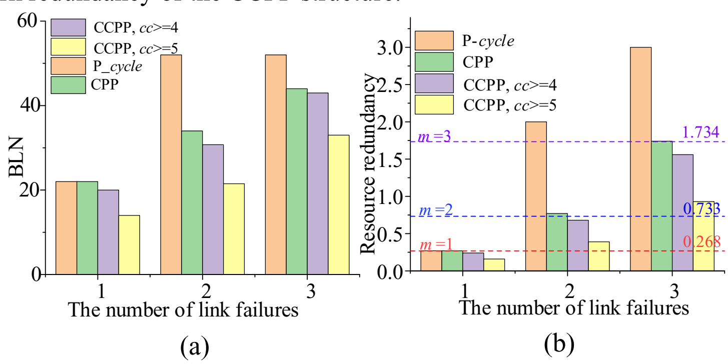

Figure 2. (a) BLN on each protection structure. (b) Resource redundancy of different protection structure.

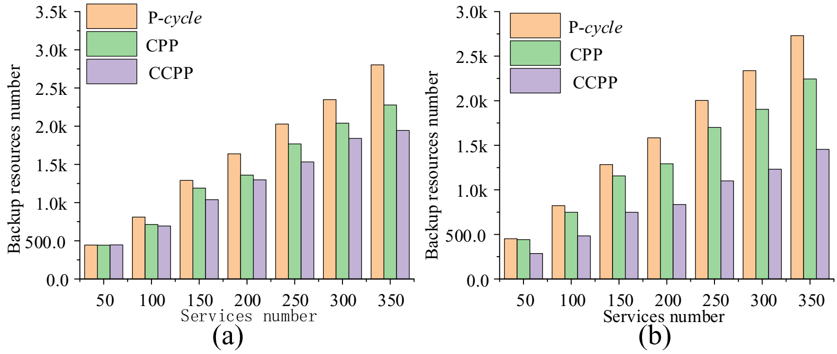

Figure 3. (a) Backup resources number under *cc*=4 and *m*=2. (b) Backup resources number under *cc*=5 and *m*=2.

Two kinds of content distributions with *cc*=4 and *cc*=5 are used to conduct the service simulation. The consumed backup resources are shown in Fig. 3 (a)-(b). Results show that increasing content connectivity has a small impact on the network redundancy of the conventional polyhedron structure. The slight change is mainly caused by the change of the service working path under different content distribution. However, it can greatly reduce the consumed backup resources on the CCPP structure. Under the two content distributions, CCPP can use the less backup resources to protect the same number of working resources against double link failures than P-cycle and LCPP, and this advantage of CCPP emerges as services number increases.

5. Conclusion

This paper introduces the content connectivity into the construction of the polyhedron protection structure, and numerical results show this structure can effectively reduce the resource redundancy against multiple link failures.

Acknowledgements
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