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可生存 LR-PON 中基于连接可用性的成本有效规划方法

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摘　要:聚焦长距离无源光网络生存性机制研究,针对单共享风险链路组故障提出一种基于连接可用性的成本有效规划方法.首先,设计了一种基于故障概率的连接可用性模型,计算每个光网络单元的连接可用性.对于不满足连接可用性要求的每个工作光网络单元,为其分配备用光网络单元,其中每个备用光网络单元需要为工作光网络单元预留备用容量.然后,在不同光网络单元之间部署备用光纤,确保每对工作和备用光网络单元之间至少存在一条备用光路径.当一个工作光网络单元因为光纤链路故障而遭遇连接中断时,可将其业务通过备用光路径转移到备用光网络单元承载.通过仿真对所提方法在备用光纤部署成本方面的性能进行了分析.结果表明,该方法能实现比传统邻居保护方法更低的备用光纤部署成本,可解决备用容量分配和备用光纤部署的联合优化问题,在满足连接可用性要求的前提下,通过最小的备用光纤部署成本实现所有业务完全保护.

关键词:光纤网络;长距离无源光网络;生存性;保护;连接可用性;备用光纤;网络规划
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Cost-Efficient Approach Based on Connection Availability for Planning of Survivable Long-Reach Passive Optical Network

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Abstract: Focusing on the survivability of long-reach passive optical network against single shared-risk link group failure, a cost-efficient planning approach based on connection availability was proposed. First, a connection availability model based on failure probability was designed to estimate the connection availability of each optical network unit. Each primary optical network unit not satisfying the connection availability requirement would be allocated some backup optical network units, each of which needed to reserve the backup capacity for the primary optical network unit. Then, deployed the backup fibers among different optical network units to establish at least one backup-optical-path between each pair of primary and backup optical network units. Through the computational simulation, the performance of proposed approach in deployment cost of backup fibers was analyzed. Results show that the proposed

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approach can achieve much lower deployment cost than the previous neighbor protection approach. The proposed approach would solve the problem of the joint optimization of backup capacity allocation and backup fibers deployment. The objective was to fully protect all traffic demand in the network by the minimum deployment cost of backup fibers, while guaranteeing the connection availability requirement.

Key words: Fiber optics networks; Long-reach passive optical network; Survivability; Protection; Connection availability; Backup fiber; Network planning

OCIS Codes: 060.4256; 060.4257; 060.4261

0 Introduction

As a promising solution for Next-Generation Passive Optical Network (NG-PON), Long-Reach PON (LR-PON) has been proposed to extend the network reach up to 100 km with more Optical Network Units (ONUs) than current PON[1-3]. Generally, a typical architecture of LR-PON has a multi-stage tree topology with the Optical Line Terminal (OLT) as the root node and the ONUs as the leaf nodes. The fiber links at different stages are connected by the 1 : N splitters. The ONUs are responsible to collect and transmit the traffic from user-ends to OLT.

LR-PON is expected to carry a lot of high-rate traffic, thus huge data loss will be caused in the case of fiber failure. Therefore, survivability is one of the key issues in the planning of LR-PON. In LR-PON, each ONU connects to the OLT through multiple fiber links at different stages. Different ONUs may have the fiber links to OLT in a common physical resource such as conduits or cable. We refer to such common physical resource as Shared-Risk Link Group (SRLG)[4]. It is notable that, in the case of SRLG failure, multiple ONU may disconnect with the OLT simultaneously. However, the SRLG failure in LR-PON remains less touched in previous works.

Some approaches have been proposed and standardized for the protection of PON against fiber failure by duplicating fibers, e. g., ITU-T G. 983.1[5-7]. Once the failure of primary fiber, the interrupted traffic will be switched into the duplicated fiber. However, the duplication of fibers usually requires double splitting ratio, which may weaken the reach of optical signal. Furthermore, the primary fiber and duplicated fiber usually traverse into the common cable (i. e., common SRLG). They may fail simultaneously in the case of SRLG failure. Therefore, the standardized approaches may be not preferable for the protection of LR-PON, which requires longer fiber reach and stronger survivability.

Other approaches attempted to protect PON by deploying backup fibers between different ONUs[8-9]. When a primary ONU is disconnected with OLT due to fiber failure, the disconnected primary ONU can transfer its traffic into the neighboring backup ONUs through the backup fibers between them. However, most of these approaches remain the backup fibers underutilized, and thus require higher cost for the deployment of backup fibers. Furthermore, they ignore the backup capacity allocation, which plays an important role in the bandwidth guarantee for traffic recovery.

In this paper, we focus on the single SRLG failure and propose a Cost-efficient Planning based on Connection Availability (CPCA) to protect LR-PON by deploying backup fibers and allocating backup capacity.

1 Integer Linear Programming Problem Formulation

1.1 Notation

Given:

- N_{O}: number of ONUs in the network.
- N_{S}: number of SRLGs in the network.
- i, j, k, p, q: index of ONU, $i, j, k, p, q \in \{1, 2, \cdots, N_{\mathrm{O}}\}$.
- o_i: the ONU indexed by i.
- d_i: traffic demand of o_i.
- m: index of SRLG, $m \in \{1, 2, \cdots, N_{\mathrm{S}}\}$.
- g_m: the SRLG indexed by m.
- f_m: the event representing the failure of g_m.
- S_i: set of SRLGs of o_i, that is, the set of SRLGs traversed by the optical path from o_i to OLT.
- C: ONU capacity.
- u: index of residual capacity, $u \in \{1, 2, \cdots, C-d_i\}$.
- r_j^u: the uth residual capacity of o_j.
- θ_i^m: binary number taking 1 if $g_m \in S_i$, and 0 otherwise.
- A_i^{P}: availability of the primary connection of o_i.
- E_i: the event representing there is no any failure of fiber links on the optical path from o_i to OLT.
- $A_{\mathrm{R}}^{\mathrm{P}}$: availability requirement of primary connection.
- $A_{\mathrm{R}}^{\mathrm{B}}$: availability requirement of backup connection.
- σ_i: binary number taking 1 if $A_i^{\mathrm{P}} \geqslant A_{\mathrm{R}}^{\mathrm{P}}$, and 0 otherwise.
- $P(x)$: occurrence probability of any event x.

- $l_{p,q}$: deployment cost of backup fibers between o_p and o_q.
- I: a constant integer that is larger enough.

Variables:

- $\varepsilon_{i,j}$: binary variable, taking 1 if o_j is a backup ONU for o_i, and 0 otherwise.
- A_i^{B}: availability of the backup connection of o_i.
- $\delta_{p,q}$: binary variable taking 1 if a backup fiber is deployed between o_p and o_q, and 0 otherwise.
- $w_{i,j}^{p,q}$: binary variable taking 1 if a backup-optical-path from o_i to o_j traverses the edge between o_p and o_q, and 0 otherwise.
- $\lambda_i^{j,u}$: binary variable taking 1 if r_j^u is allocated to o_i as the backup capacity, and 0 otherwise.
- $\lambda_{i,k}$: binary variable, taking 1 if o_i and o_k share at least one unit of backup capacity, and 0 otherwise.
- $\lambda_{i,k}^{j,u}$: binary variable, taking 1 if o_i and o_k share r_j^u as their common backup capacity, and 0 otherwise.
- O_i^{B}: set of backup ONUs of o_i, where $O_i^{\mathrm{B}}=\{o_j \mid \varepsilon_{i,j}=1, \forall j\neq i\}$.
- S_i^{B}: set of SRLGs of the ONUs in O_i^{B}.
- O_i^{P}: set of the primary ONUs sharing at least one backup capacity with o_i, $O_i^{\mathrm{P}}=\{o_k \mid \lambda_{i,k}=1, \forall k\neq i\}$.
- S_i^{P}: set of SRLGs of the ONUs in O_i^{P}.
- μ_i^m: binary variable, taking 1 if g_m is not in the SRLG set of any ONU in $\{O_i^{\mathrm{B}} \cup O_i^{\mathrm{P}}\}$, and 0 otherwise.

1.2 Connection availability model

According to CPCA, each ONU in the network may be allocated multiple backup ONUs. As shown in Fig. 1, for any primary ONU o_i, the primary connection of o_i is defined as the optical path from o_i to OLT, and the backup connection of o_i is defined as the optical paths from all of its backup ONUs o_j, o_p and o_q to OLT.

It is assumed that each fiber link in the network traverses into only one SRLG and different SRLGs fail independently[4]. The primary connection of o_i is available only if there is no any failure of fiber link on the optical path from o_i to OLT. Thus, we can represent the primary connection availability of o_i as follows

$$A_i^{\mathrm{P}}=P(E_i)=1-P\Big(\bigcup_{m:g_m\in S_i} f_m\Big)=1-\sum_{m=1}^{N_{\mathrm{S}}}\theta_i^m \cdot P(f_m)\ \forall i \tag{1}$$

In CPCA, we allocate the backup capacity for each primary ONU o_i not satisfying the availability requirement of primary connection, i. e., $A_i^{\mathrm{P}}<A_{\mathrm{R}}^{\mathrm{P}}$. To reduce the consumption of backup capacity, we allow different primary ONUs to share the common unit of backup capacity. When the primary connection of o_i is unavailable, o_i first transfers its traffic into the backup ONUs along the backup-optical-paths between them, and then uses the backup capacity to transmit its traffic to OLT through the backup connection. In this case, the backup connection is available only if 1) there is no any failure of fiber links on the optical paths from the backup ONUs of o_i to OLT; and 2) there is no any failure of fiber links on the optical paths from the ONUs sharing at least one backup capacity with o_i to OLT, such that o_i can recover its traffic without any resource contention. Therefore, we can represent the backup connection availability of o_i as follows:

$$A_i^{\mathrm{B}}=P\Big(\Big(\bigcap_{j:o_j\in O_i^{\mathrm{B}}} E_j\Big)\cap\Big(\bigcap_{k:o_k\in O_i^{\mathrm{P}}} E_k\Big)\Big|\bar{E}_i\Big)=\frac{P\Big(\bigcup_{m:g_m\in\Omega_i} f_m\Big)}{P(\bar{E}_i)}=\frac{\sum_{m=1}^{N_{\mathrm{S}}}\theta_i^m\cdot\mu_i^m\cdot P(f_m)}{P(\bar{E}_i)}\ \forall i \tag{2}$$

where $\Omega_i=S_i-\{S_i^{\mathrm{B}}\cup S_i^{\mathrm{P}}\}$. The allocation of backup capacity for o_i should ensure its backup connection availability to satisfy the requirement, i. e., $A_i^{\mathrm{B}}\geqslant A_{\mathrm{R}}^{\mathrm{B}}$.

1.3 Overview of CPCA

The proposed approach CPCA can be illustrated in Fig. 1. For any primary ONU o_i not satisfying the availability requirement of primary connection, we allocate it some backup ONUs. Each of the backup ONUs needs to reserve the residual capacity for o_i as the backup capacity under the availability requirement of backup connection. Then, deploy the backup fibers to establish at least one backup-optical-path between o_i and each of its backup ONUs. Here, the backup-optical-path refers to a path composed of multiple backup fibers. For example, the primary ONU o_i has a backup-optical-path of three hops to its backup ONU o_q and each hop traverses over a backup fiber. When the single SRLG failure occurs, the disconnected o_i can transfer its traffic into not only the neighboring backup ONU o_j but also the remote backup ONUs o_p and o_q along the backup-optical-paths between them. Thereafter, the backup ONUs o_j, o_p and o_q will transmit the traffic from o_i to OLT by using the backup capacity reserved for o_i. Thus, the traffic demand of

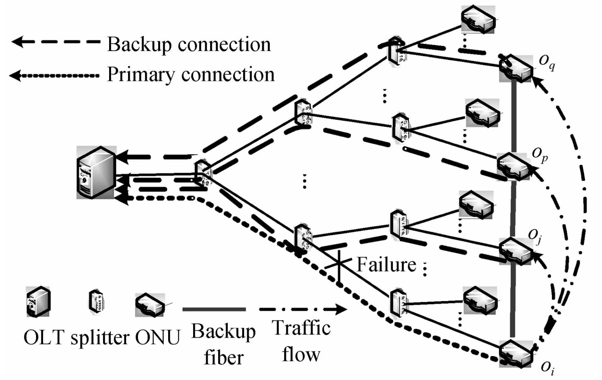
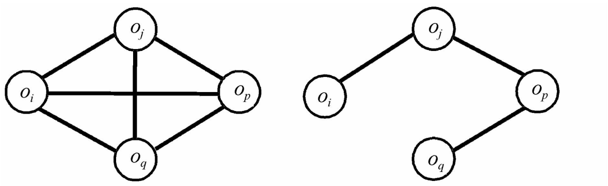


Fig. 1 Illustration of CPCA

o_i that can be protected by o_j, o_p and o_q is dependent on their backup capacity reserved for o_i. Particularly, o_i will be fully protected if its traffic demand is less than or equal to the total backup capacity provided by o_j, o_p and o_q.

Compared to the previous works in Ref. [8-9], which allows the disconnected primary ONUs to transfer their traffic into only the neighboring backup ONU, the proposed CPCA approach can utilize the backup fibers more efficiently, thus requires lower deployment cost of backup fibers. As shown in Fig. 2, assuming each ONU needs three backup ONUs (Here, we do not consider the availability requirement and backup capacity allocation for simplicity of illustration), six backup fibers need to be deployed according to the previous works[8-9] in Fig. 2 (a). However, the proposed CPCA approach in Fig. 2(b) needs only three backup fibers due to higher utilization of backup fibers.



(a) Only neighboring backup ONUs are used (b) Both neighboring backup ONUs and remote backup ONUs are used

Fig. 2 Comparison of backup fibers deployment between previous works in Ref. [8-9] and CPCA

1.4 Integer linear programming model

In CPCA, we consider the joint optimization of allocating backup capacity and deploying backup fibers. Our objective is to minimize the deployment cost of backup fibers under the constraints of constraint of connection availability requirement, constraint of full protection, and constraint of backup-optical-path length.

In reality, each ONU need to be equipped with splitter and optical switch to support the functions of message broadcast and protection switch in CPCA, respectively. These components will cause the extra cost for network deployment. However, this part of extra cost is usually not considered because it is negligible compared to the huge deployment cost of backup fibers, including the expenditure for not only the fiber material itself but also the construction such as digging and paving. It is notable that the deployment cost of backup fibers is mainly determined by the fibers deployment distance. Thus, we can translate the objective of minimum deployment cost of backup fibers into minimizing the deployment distance as follows:

$$\min \sum_{p=1}^{N_O-1} \sum_{q=p+1}^{N_O} l_{p,q} \cdot \delta_{p,q} \tag{3}$$

1) Constraint of connection availability requirement: According to the statements in Subsection 1.2, we can represent the constraint of availability requirement as follows

$$A_i^B \geqslant A_R^B \cdot (1-\sigma_i) \qquad \forall i \tag{4}$$

where A_i^B is computed in Eq. (2) and μ_i^m should be subject to the following linear constraints

$$\mu_i^m \geqslant 1-\Big(\sum_{k=1,k\neq i}^{N_O} \lambda_{i,k} \cdot \theta_k^m + \sum_{j=1,j\neq i}^{N_O} \varepsilon_{i,j} \cdot \theta_j^m\Big) \qquad \forall i,m \tag{5}$$

$$\mu_i^m \leqslant 1-\Big(\sum_{k=1,k\neq i}^{N_O} \lambda_{i,k} \cdot \theta_k^m + \sum_{j=1,j\neq i}^{N_O} \varepsilon_{i,j} \cdot \theta_j^m\Big)/I \qquad \forall i,m \tag{6}$$

Considering the physical meaning of $\lambda_{i,k}$ in Eqs. (5) and (6), we further impose the following linear constraints

$$\lambda_{i,k} \geqslant \sum_{j=1,j\neq i,k}^{N_O} \sum_{u=1}^{C-d_j} \lambda_{i,k}^{j,u}/I \qquad \forall i,k \tag{7}$$

$$\lambda_{i,k} \leqslant \sum_{j=1,j\neq i,k}^{N_O} \sum_{u=1}^{C-d_j} \lambda_{i,k}^{j,u} \qquad \forall i,k \tag{8}$$

$$\lambda_{i,k}^{j,u} \leqslant \lambda_i^{j,u} \qquad \forall i,j,k,u \tag{9}$$

$$\lambda_{i,k}^{j,u} \leqslant \lambda_k^{j,u} \qquad \forall i,j,k,u \tag{10}$$

$$\lambda_{i,k}^{j,u} \geqslant (\lambda_i^{j,u}+\lambda_k^{j,u})-1 \qquad \forall i,j,k,u \tag{11}$$

2) Constraint of full protection: For any ONU o_i ($\sigma_i=0$), the number of backup capacity allocated to o_i should be equal to the traffic demand of o_i such that o_i is fully protected. Thus, we can represent the constraint of full protection as follows

$$\sum_{j=1,j\neq i}^{N_O} \sum_{u=1}^{C-d_j} \lambda_i^{j,u} = d_i \cdot (1-\sigma_i) \qquad \forall i \tag{12}$$

3) Constraint of backup-optical-path length: To limit the recovery time and optical signal loss, we introduce the constraint of backup-optical-path length into CPCA. It is ensured that each pair of primary and backup ONUs should have the length of backup-optical-path less than or equal to H hops. Thus, we can formulate the constraint of backup-optical-path length as follows

$$\sum_{q=1}^{N_O} w_{i,j}^{p,q} - \sum_{q=1}^{N_O} w_{i,j}^{q,p} = \begin{cases} \varepsilon_{i,j}, & \text{if } p=i \\ -\varepsilon_{i,j}, & \text{if } p=j \\ 0, & \text{otherwise} \end{cases} \qquad \forall i,j,p \tag{13}$$

$$\varepsilon_{i,j} \geqslant \sum_{u=1}^{C-d_j} \lambda_i^{j,u}/I \qquad \forall i,j \tag{14}$$

$$\varepsilon_{i,j} \leqslant \sum_{u=1}^{C-d_j} \lambda_i^{j,u} \qquad \forall i,j \tag{15}$$

$$\delta_{p,q} \geqslant \sum_{i=1}^{N_O} \sum_{j=1,j\neq i}^{N_O} w_{i,j}^{p,q}/I \qquad \forall p,q \tag{16}$$

$$\delta_{p,q} \leqslant \sum_{i=1}^{N_O} \sum_{j=1,j\neq i}^{N_O} w_{i,j}^{p,q} \qquad \forall p,q \tag{17}$$

$$\sum_{p=1}^{N_O} \sum_{q=1,q\neq p}^{N_O} w_{i,j}^{p,q} \leqslant H \cdot \varepsilon_{i,j} \qquad \forall i,j \tag{18}$$

The constraints in Eq. (13) ensure the flow conservation from any primary ONU to each of its backup ONUs such that the backup-optical-path between them satisfies the routing continuity. The constraints in Eqs. (14) and (15) specify that o_j is a backup ONU for o_i if o_i uses at least one of the residual capacity of o_j as the backup capacity. The constraints in Eqs. (16) and (17) specify that a backup fiber need to be deployed between o_p and o_q if at least one backup-optical-path traverses the edge between o_p and o_q. Finally, the constraint in Eq. (18) ensures that, if o_j is a backup ONU for o_i, there should be at least one backup-optical-path between them whose length is less than or equal to H hops.

Based on the Integer Linear Programming (ILP) model in Eqs. (3) ~ (18), we can obtain the optimal solution for the joint optimization problem of allocating backup capacity and deploying backup fibers in CPCA.

2 Heuristic Approach

Considering the time-consuming nature of ILP, we also propose the heuristic Maximized Cost-Efficiency (MCE) algorithm for the application of CPCA in large-scale network.

For simplicity of presentation, the notations are introduced as follows:

- w: index of backup fiber.
- $h_w^{i,j}$: length of the backup-optical-path from o_i to o_j when deploying the wth backup fiber.
- $\gamma_w^{i,j}$: binary variable taking 1 if the backup-optical- path from o_i to o_j does not satisfy the length constraint (i. e. ,$h_w^{i,j} > H$), and 0 otherwise.
- $\rho_{w,p,q}^{i,j}$: binary variable taking 1 if o_j becomes one of possible backup ONUs for o_i by deploying the wth backup fiber between o_p and o_q, and 0 otherwise.
- $B_{w,p,q}^{i}$: set of possible backup ONUs for o_i if the wth backup fiber is deployed between o_p and o_q.
- $P_{w,p,q}^{j}$: set of possible primary ONUs for o_j if the wth backup fiber is deployed between o_p and o_q.
- $O_{j,u}$: set of the ONUs using r_j^u as the backup capacity.
- $P_{w,p,q}^{j,u}$: set of ONUs in $P_{w,p,q}^{j}$ that can share r_j^u with the ONUs in $O_{j,u}$ as their common backup capacity.
- $\lambda_{i,w,p,q}^{j,u}$: binary variable, taking 1 if r_j^u is allocated to o_i as the backup capacity when deploying the wth backup fiber between o_p and o_q, and 0 otherwise.
- $D_{w,p,q}^{i}$: number of traffic demand of o_i that is protected by deploying the wth backup fiber between o_p and o_q.
- D_i: total number of protected traffic demand of o_i.
- $E_w^{p,q}$: cost-efficiency of the wth backup fiber deployed between o_p and o_q.

In the MCE algorithm, we will deploy the backup fibers one-by-one in a greedy manner until all traffic demand in the network is fully protected. Particularly, when deploying the wth backup fiber, the allocation of backup capacity is implemented, which determines the number of protected traffic demand over the whole network. The deployment of the wth backup fiber is expected to bring about more protected traffic demand, while the length of the wth backup fiber is minimized.

For example, there exist four ONUs o_i, o_j, o_p and o_q, where $A_i^P < A_R^P$ and $h_w^{i,j} > H$. When we deploy the wth backup fiber between o_p and o_q, we can find two backup-optical-paths newly established from o_i to o_j with the length $h_w^{i,p}+1+h_w^{q,j}$ and $h_w^{i,q}+1+h_w^{p,j}$, respectively. If either of these two backup-optical-paths has the length less than or equal to H hops, i. e. , $h_w^{i,p}+1+h_w^{q,j} \leqslant H$ or $h_w^{i,q}+1+h_w^{p,j} \leqslant H$, the ONU o_j will become one of possible backup ONUs for o_i. Thus, we can represent the binary variables $\rho_{w,p,q}^{i,j}$ as follows

$$\rho_{w,p,q}^{i,j} = \begin{cases} 1, & \text{if } h_w^{i,p}+1+h_w^{q,j} \leqslant H \\ \text{or } h_w^{i,q}+1+h_w^{p,j} \leqslant H & \forall w,p,q,i,j \\ 0, & \text{otherwise} \end{cases} \tag{19}$$

It is clear that, when the wth backup fiber is deployed between o_p and o_q, ONU o_j will become one of the possible backup ONUs for o_i only if $\gamma_w^{i,j} \cdot \rho_{w,p,q}^{i,j} = 1$. Accordingly, we can determine the set of possible backup ONUs for o_i as follows

$$B_{w,p,q}^{i} = \{o_j \mid \gamma_w^{i,j} \cdot \rho_{w,p,q}^{i,j} = 1, \forall j \neq i\} \quad \forall w,p,q,i \tag{20}$$

In turn, for any ONU $o_j \in B_{w,p,q}^{i}$, we can determine the set of possible primary ONUs for o_j as follows:

$$P_{w,p,q}^{j} = \{o_i \mid o_j \in B_{w,p,q}^{i}, \forall i \neq j\} \quad \forall w,p,q,j \tag{21}$$

Next, we consider how to allocate the residual capacity of o_j to its possible primary ONUs in $P_{w,p,q}^{j}$. For the purpose of higher utilization of backup capacity, we will allocate the residual capacity already occupied as the backup capacity prior to that unoccupied. For any one unit of residual capacity r_j^u, we first compute the set of ONUs $P_{w,p,q}^{j,u} \in P_{w,p,q}^{j}$, where each ONU in $P_{w,p,q}^{j,u}$ can share r_j^u with the ONUs in $O_{j,u}$ as their common backup capacity. It should be ensured that any ONU $o_i \in P_{w,p,q}^{j,u}$ and the ONUs in $O_{j,u}$ can satisfy the availability requirement of backup connection if r_j^u is allocated to o_i as the backup capacity. Thus, we can compute $P_{w,p,q}^{j,u}$ as follows

$$P_{w,p,q}^{j,u} = \{o_i \mid \widetilde{A}_i^{\mathrm{B}} \geqslant A_{\mathrm{R}}^{\mathrm{B}}, \widetilde{A}_{k,i}^{\mathrm{B}} \geqslant A_{\mathrm{R}}^{\mathrm{B}}, \forall k: o_k \in O_{j,u}, \forall o_i \in P_{w,p,q}^{j}\} \quad \forall w,p,q,j,u \tag{22}$$

where $\widetilde{A}_i^{\mathrm{B}}$ and $\widetilde{A}_{k,i}^{\mathrm{B}}$ denote the backup connection availability of o_i and o_k, respectively, if r_j^u is allocated to o_i as the backup capacity. It is worth noting that, if r_j^u is allocated to o_i as the backup capacity, we need to combine $O_{j,u}$ into O_i^{P}, o_j into O_i^{B} and o_i into O_k^{P} ($\forall k: o_k \in O_{j,u}$), respectively. Thus, according to Eq. (2), we can compute $\widetilde{A}_i^{\mathrm{B}}$ by replacing O_i^{P} with $\{O_i^{\mathrm{P}} \cup O_{j,u}\}$ and O_i^{B} with $\{O_i^{\mathrm{B}} \cup o_j\}$. Similarly, we can compute $\widetilde{A}_{k,i}^{\mathrm{B}}$ by replacing O_k^{P} with $\{O_k^{\mathrm{P}} \cup o_i\}$.

We denote $R_w^{p,q} = \{r_j^u \mid \forall j: o_j \in B_{w,p,q}^{i}, \forall u, \forall i\}$ as the set of residual capacity to be allocated. It is expected that any residual capacity $r_j^u \in R_w^{p,q}$ with larger $|P_{w,p,q}^{j,u}|$ may be shared by more primary ONUs as their common backup capacity. For higher utilization of backup capacity, we should allocate the residual capacity $r_j^u \in R_w^{p,q}$ one-by-one in the descending order of $|P_{w,p,q}^{j,u}|$.

According to Eq. (2), if we allocate r_j^u to any ONU o_i as the backup capacity, all of o_i and the ONUs in $O_{j,u}$ will have the decreased availability of backup connection. Thus, we should ensure that the allocation of r_j^u can minimize the maximum decrement of backup connection availability, such that r_j^u can be shared by more primary ONUs with the satisfied availability requirement of backup connection. Motivated by this, we allocate r_j^u to the primary ONU $o_{\hat{i}}$ according to the following strategy:

$$o_{\hat{i}} = \min_{o_i \in P_{w,p,q}^{j,u}} \{\max\{(A_i^{\mathrm{B}} - \widetilde{A}_i^{\mathrm{B}}), (A_k^{\mathrm{B}} - \widetilde{A}_{k,i}^{\mathrm{B}}), \forall k: o_k \in O_{j,u}\}\} \tag{23}$$

After the allocation of r_j^u to $o_{\hat{i}}$, we need to combine $O_{j,u}$ into $O_{\hat{i}}^{\mathrm{P}}$, o_j into $O_{\hat{i}}^{\mathrm{B}}$, $o_{\hat{i}}$ into $O_{j,u}$ and $o_{\hat{i}}$ into O_k^{P} ($\forall k: o_k \in O_{j,u}$), respectively. We also need to update $\lambda_{\hat{i},w,p,q}^{j,u}$ by setting 1, $D_{w,p,q}^{\hat{i}}$ by adding 1, and $P_{w,p,q}^{j,u}$ by excluding $o_{\hat{i}}$, respectively. The iterative allocation of r_j^u will not terminate until $P_{w,p,q}^{j,u} = \phi$. Thereafter, update $R_w^{p,q}$ by excluding r_j^u. In such a way, we will iteratively allocate the residual capacity in $R_w^{p,q}$ one-by-one until there is no longer any residual capacity used for backup capacity, i. e., $R_w^{p,q} = \phi$.

Thereafter, we can compute the cost-efficiency of the wth backup fiber deployed between any pair of ONUs o_p and o_q as follows

$$E_w^{p,q} = \frac{\sum_{i=1}^{N_{\mathrm{O}}} D_{w,p,q}^i}{l_{p,q}} \qquad \forall w, p, q \tag{24}$$

Because our objective is to fully protect all traffic demand with the minimum deployment cost of backup fibers, we should deploy the wth backup fiber between the ONUs $o_{\hat{p}}$ and $o_{\hat{q}}$ with the maximum $E_w^{\hat{p},\hat{q}}$. After the deployment of the wth backup fiber, we need to update $\delta_{\hat{p},\hat{q}}$ by setting 1, D_i by adding $D_{w,\hat{p},\hat{q}}^i$ and $\lambda_i^{j,u}$ by taking the value of $\lambda_{i,w,\hat{p},\hat{q}}^{j,u}$ $\forall i, j, u$.

According to the above procedure, we will deploy the backup fibers one-by-one until the traffic demand of each ONU is fully protected, i. e., $D_i = d_i$ $\forall i$. Due to the limited space, we do not show the pseudo-code procedure of the MCE algorithm. More details will be described in our future extended works.

3 Performance evaluation

3.1 Simulation Settings

In the simulation, we plan a LR-PON according to the *Pyramid* topology[9] with N_{O} ONUs randomly placed in a 80 km×80 km square area. The *Pyramid* topology uses the 1 : N splitter at each stage. Each 1 : N splitter in the intermediate stage connects $N-2$ ONUs and the remaining 2 branches connect to the next stage. At the last state, each splitter connects to N ONUs. Thus, the *Pyramid* topology with S stages has the total number of ONUs $N_{\mathrm{O}} = \sum_{i=1}^{S-2}(N-2)\times 2^{i-1} + N\times 2^{S-2}$. Here, we set $N=4$. Without of generality, it is assumed that the feeder fiber nearest OLT is duplicated and the duplicated fiber is SRLG failure disjoint with the primary fiber. Thus, they will not fail simultaneously in the scenario of single SRLG failure, that is, the feeder fiber nearest OLT is always available[10-13]. Assuming 10 SRLG in the network, each fiber link except the feeder fiber nearest OLT is randomly designated one SRLG. Each SRLG takes the failure probability randomly in $[0.1\times 10^{-4}, 0.5\times 10^{-4}]$. All ONUs equally have 20 units of capacity[14-16]. Each ONU is randomly assigned the traffic demand with the upper bound of 12. For simplicity, we set the same availability requirement for primary connection and backup connection, i. e., $A_{\mathrm{R}}^{\mathrm{P}} = A_{\mathrm{R}}^{\mathrm{B}} = A_{\mathrm{R}}$. The constraint of backup-optical- path length H is set to 3.

3.2 Results and analysis

The simulation results are presented in two parts. In the first part (see Figs. 3 and 4), we make the comparison among the ILP-based CPCA, Heuristic-based CPCA and Neighbor ONU Protection (NOP)[8-9] and investigate the impact of different traffic demand and number of LR-PON stages S on the Deployment Distance of Backup Fibers (DDBF). In the second part (see Figs. 5 and 6), we investigate the performance of CPCA in DDBF and Number of Consumed Backup Capacity (NCBC) with different availability requirement A_{R}. It is worth mentioning that, besides DDBF and NCBC, the traffic recovery efficiency and protection switch time are also key metrics to evaluate the performance of protection approach. However, this involves the design of physical architecture that is a complex issue and out of the scope of this paper.

In Fig. 3, we show the DDBF of three approaches with different ONU traffic demand. Here, $S=5$ and $A_{\mathrm{R}} = 0.99994$. With the increasing traffic demand, each ONU requires more backup capacity for full protection. In this case, more backup fibers need to be deployed to establish the backup-optical-path with the satisfied length constraint between each pair of primary and backup ONUs. Thus, we observe that all three approaches have the increasing DDBF. However, our CPCA approach outperforms NOP by much lower DDBF. Particularly, the performance gain reaches to 30.8% when ONU traffic demand takes in [9, 12].

This is because our CPCA approach can utilize the backup fibers more efficiently than NOP. Furthermore，we observe that Heuristic-based CPCA has the DDBF much near to that of ILP-based CPCA with the gap of lower than 5.3%. Furthermore，we experimentally observe that the solution time of Heuristic-based CPCA is measured in the level of seconds，while that of ILP-based CPCA is measured in the level of hours. This demonstrates that the near-optimality of the proposed heuristic approach is achieved by much less time consumption.

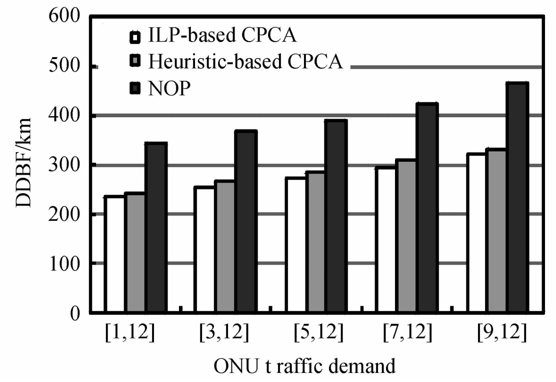


Fig. 3 DDBF with different ONU traffic demand

In Fig. 4，with the ONU traffic demand taking in [5，12] and $A_R = 0.999\ 94$，we show the DDBF of three approaches with different number of LR-PON stage S. Lager S indicates more ONUs in the network，thus more backup fibers are required. Therefore，we observe the increasing DDBF when S is larger. However，our CPCA always has lower DDBF than NOP and the advantage is more obvious when S is larger. For example，in the case of $S=3$，Heuristic-based CPCA reduces the DDBF of 21.5%，while in the case of $S=7$，Heuristic-based CPCA reduces the DDBF of 32.4%. This demonstrates that our CPCA approach is more cost-efficient in the planning of larger-scale LR-PON.

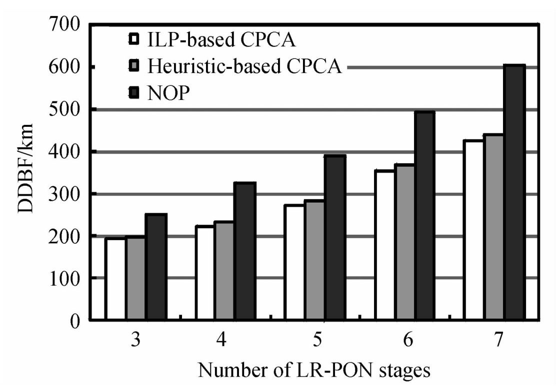


Fig. 4 DDBF with different number of LR-PON stages

In Fig. 5，with the ONU traffic demand taking in [5，12] and $S=5$，we show the NCBC of three approaches with different availability requirement A_R. When A_R is larger，more primary ONUs need to be protected due to the unsatisfied availability requirement. Furthermore，different ONUs are discouraged to share the common backup capacity，which results in lower utilization of backup capacity. Thus，we observe that all three approaches have higher NCBC in the case of larger A_R. However，the NCBC of our CPCA approach remains lower than that of NOP. This is because NOP allows the primary ONUs to use the backup capacity only from the neighboring backup ONUs. In our CPCA approach，each primary ONU can use the backup capacity from not only the neighboring backup ONUs but also the remote backup ONUs. Therefore，CPCA can improve the utilization of backup capacity，which contributes to lower NCBC.

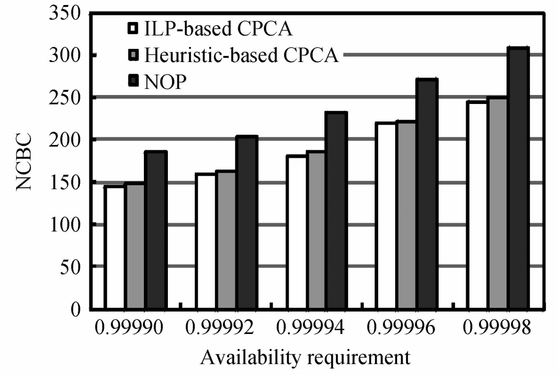


Fig. 5 NCBC with different availability requirement

In Fig. 6，we show the results of DDBF for three approaches under the same setting as Fig. 5. As addressed above，larger A_R results in more consumed backup capacity. Thus，more backup fibers are required to establish more backup-optical-paths for each primary ONU. The DDBF increases when A_R is larger. However，due to less consumed backup capacity，our CPCA approach always outperforms NOP with lower DDBF. Particularly，when $A_R = 0.999\ 98$，the ILP-based CPCA and Heuristic-based CPCA reduce the DDBF of 19.4% and 18.8% compared with NOP，respectively.

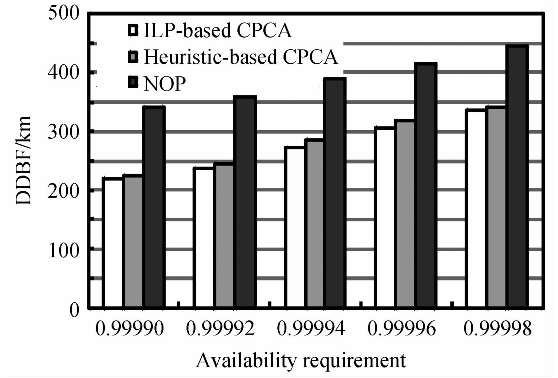


Fig. 6 DDBF with different availability requirement

4 Conclusion

In this paper，we have proposed a novel planning approach called CPCA for survivable LR-PON against single SRLG failure. In CPCA，a connection

availability model is proposed to estimate the availability of primary connection and backup connection for each ONU. Under the constraint of availability requirement, the objective of CPCA is to fully protect all traffic demand in the network with the minimum deployment cost of backup fibers. We deal with the joint optimization of allocating backup capacity and deploying backup fibers. Both ILP and heuristic approaches are proposed for CPCA. Simulation results show that CPCA can significantly reduce the deployment cost of backup fibers and the number of consumed backup capacity.

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