p-Cycle Design Without Candidate Cycle Enumeration in Mixed-Line-Rate Optical Networks

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***Abstract*—This paper develops and evaluates a new protection solution for pre-configured-cycle (p-cycle) design in Mixed-Line-Rate (MLR) optical networks. Conventional p-cycle approaches require enumerating candidate cycles in advance and screening p-cycles using heuristic algorithms. Our method generates p-cycles directly in one-step using an Integer Linear Programming (ILP) model. Cost-effective transponders and distance-adaptive line rates are provisioned for every p-cycle to minimize joint cost of transponders and spare capacity. The design problem is solved together with spectral clustering based graph partitioning, which permits to compute the optimal solution in independent sub-graphs concurrently. The results show that our protection method is cost-efficient for p-cycle design with mixed line rates and scalable for large optical networks.**

***Index Terms*—Network survivability; p-Cycle; Mixed line rates; Optical Networks; Graph partitioning.**

I. Introduction

Nowadays, for satisfying the heterogeneous traffic demand, cost-effective optical backbone network tends to support mixed line rates, $e.g.$, 10/40/100 $Gbps$ [1] [2]. In such Mixed-Line-Rate (MLR) optical networks, a failure in a network element ($e.g.$, a fiber cut) can cause huge data loss [3]. Therefore, survivability in MLR optical networks is a critical issue. Three major factors need to be considered in survivable MLR optical networks. First, transponders operating at different line rates are subject to different bandwidth-cost efficiency. For instance, a transponder operating at 100 $Gbps$ is about 3.75 times more costly than that operating at 10 $Gbps$ [4], thus the former transponder has a better bandwidth-cost efficiency. Secondly, line rate selection relies on the distances of protection paths due to physical impairments. The maximum transmission reaches of 10, 40, and 100 $Gbps$ are 1750, 1800 and 900 km, respectively, under the assumption that the network dispersion is minimized for 10 $Gbps$ [1]. Thirdly, wavelength continuity should be guaranteed. More specifically, a protection path should use the same wavelength along all the links. Therefore, there is an optimal combination among transponder cost, line rate and wavelength usage in MLR optical network protection.

Among substantial protection schemes in optical networks, Pre-configured-Cycle (p-cycle) strategy is very attractive for its high capacity efficiency and fast protection switching [5]. The dashed line a-b-c-d-e-a in Fig. 1 is an example of p-cycle. For the on-cycle link ($e.g.$, a-b), one protection path

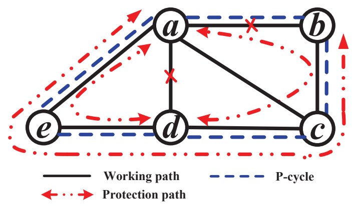


Fig. 1. The concept of a p-cycle.

($e.g.$, a-e-d-c-b) is provided. For the straddling link ($e.g.$, a-d), there exists two protection paths ($e.g.$, a-e-d and a-b-c-d). This distinguishing feature enables p-cycle to yield high capacity efficiency. In addition, since the spare capacity of protection path is fully configured in advance, only the two end nodes of failed link do real switching actions when a failure happens, which makes p-cycle own the ring-like switching speed.

Conventional p-cycle design approaches are implemented in two steps. The first step is to enumerate all distinct cycles. Then an Integer Linear Programming (ILP) model is designed to screen p-cycles from them in the second step. However, the number of candidate cycles in a network increases exponentially with the network size, which makes the cycle enumerating model intractable in large networks. Even though some methods are proposed to pre-select high potential candidate cycles, the "optimal solution" obtained in these methods is just the optimal one under partial promising p-cycles rather than the real optimal solution.

In this paper, we focus on p-cycle design protection without candidate cycle enumeration in MLR optical networks. Cost-effective transponders and distance-adaptive line rates are provisioned for the p-cycles. Our objective is to minimize the joint cost of transponders and spare capacity. Spectral clustering based graph partitioning is used to divide the network into small independent sub-graphs, which enables to compute optimal solution in these sub-graphs in parallel.

The rest of this paper is organized as follows. Related work is reviewed in next section. Then, we present p-cycle protection in MLR optical networks in Section III. The ILP model for p-cycle and graph partitioning method are developed in Section IV. Section V gives the results. Finally, we conclude the paper in Section VI.

II. Related Work

Since p-cycle was introduced in 1998 [5], a lot of ILP models and algorithms based on p-cycle protection have been studied in optical networks. In [6] [7], the authors explore link-based p-cycles to protect individual link in wavelength division multiplexing (WDM) optical networks. Meanwhile, p-cycle begins to be extended for path protection and node protection [8] [9]. However, all the p-cycle approaches above use the conventional method to enumerate candidate cycles in advance, then to screen the final p-cycles from these candidate cycles using an ILP model. As the enumeration of all candidate cycles is an NP-hard problem, which is impossible to solve in large networks. Consequently, some heuristic algorithms are explored to enumerate partial candidate cycles with high merit rather than all cycles. In addition, a single-step method using column generation (CG) technique is proposed in [10], in which the generation of cycles is dynamic and embedded within the optimization process. However, real optimal solution can not be obtained using these methods, because only partial promising cycles are used as candidate cycles.

A p-cycle design ILP model is studied by Schupke et al. in 2004 [11], and to the best of our knowledge, this is the first p-cycle design without candidate cycle enumeration. However, a master node and several target nodes are introduced in their model, which makes the model quite complex, and they have to use a four-step heuristic to find a suboptimal solution. In [12], Bin Wu et al. propose ILP formulations for non-simple p-cycle and p-trail design in WDM mesh networks without candidate cycle/trail enumeration. Nevertheless, their models are limited by the network size and traffic load. Later, they propose three ILP formulations for p-cycle design without cycle enumeration in [13], which are based on recursion, flow conservation and cycle exclusion, respectively. The cycle exclusion-based p-cycle design shows the best performance due to less computing time. However, these p-cycle designs are developed in Single-Line-Rate (SLR) optical networks, which are no longer valid in the future optical networks with coexistence of multiple line rates. Even though a p-cycle design in MLR optical networks is proposed in [3], it still needs cycle enumeration. Moreover, they ignore maximum transmission reach of protection path at different line rates, which is not realistic.

III. Protection with p-Cycles in MIXED LINE RATE Optical Networks

Compared with traditional p-cycle protection in SLR optical networks, the model is more complex in MLR optical networks, because the line rate, distance and protection capacity of p-cycles should be considered simultaneously. The MLR optical network is modeled as a digraph $G(V, E)$. The set of optical nodes is denoted by V and the set of links is given by E. A set of line rates, denoted by R, *e.g.*, $R = \{10, 40, 100\ Gbps\}$, is assumed to be supported over all protection paths. We define h_r as the maximum transmission reach of a lightpath without regeneration, *i.e.*, $h_{10} = 1750$, $h_{40} = 1800$, $h_{100} = 900\ km$. t_r is defined as the normalized

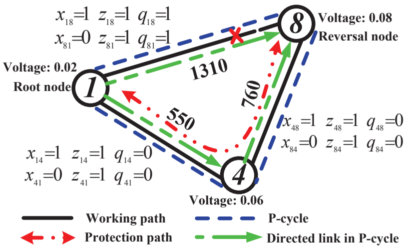


Fig. 2. The values of $x^i_{vu}, z^i_{vu}, q^i_{vu}$ in a p-cycle. The value around the edge shows the distance between two nodes.

cost of a transponder at line rate r and we assume that $\{t_{10} = 1,\ t_{40} = 2.5,\ t_{100} = 3.75\}$ [1]. Besides, c_{uv} indicates the cost of adding one unit of spare capacity (*e.g.*, wavelength cost) to the link (u, v). For simplicity, we use hop-count as the cost metric in this study, then $c_{uv} = 1$ for each link $(u, v) \in E$.

Our goal is to find optimal p-cycles and configure spare capacity while minimizing the joint cost of transponders and spare capacity. The following optical layer constraints will be taken into account in our ILP model:

- *Maximum Transmission Reach Constraint*: A p-cycle can operate at line rate r if its protection path is no longer than the maximum transmission reach h_r.
- *Full Protection Constraint*: The protection capacity provided by all the p-cycles should be sufficient to protect the traffic load in the whole network. In this study, we focus on single link failure protection.
- *Uniform Line Rate Constraint*: Only one line rate $r \in R$ can be selected for a p-cycle, and all the protection paths provided by this p-cycle should operate at the same line rate.

IV. ILP Formulations for p-Cycle Design

A. ILP Model for p-Cycle Design

We summarize the notations in Table I. For the sake of readability, we use $\forall i$, $\forall v$, $\forall u$, $\forall r$, and $\forall a$ to denote $\forall i \in [\![I]\!]$, $\forall v \in V$, $\forall u \in N_v$, $\forall r \in R$, and $\forall a \in E$, respectively. The objective of our ILP model is to minimize the joint cost of transponders and spare capacity while ensuring 100% single link failure protection, which is as follows,

$$\min \quad \beta \cdot C_T + \theta \cdot C_L \tag{1}$$

$$C_T = \sum_{i \in [\![I]\!]} \sum_{r \in R} \sum_{v \in V} t_r \cdot y_v^{ir}$$

$$C_L = \sum_{i \in [\![I]\!]} \sum_{a \in E} c_a \cdot x_a^i$$

where C_T is total transponder cost, and C_L is total spare capacity. β and θ are adjustable parameters for weighting of these two metrics. In this study, we regard both of them as 1.

The p-cycle is generated based on the value called *voltage*, which is first introduced to generate the p-cycle in SLR optical networks in [12] and we apply this method into MLR optical networks. Our p-cycle design model is subject to constraints (2)-(16). Constraint (2) ensures that at most one unidirectional

TABLE I
MAIN NOTATIONS

Network Sets and Parameters	
$G(V,E)$	The graph modeling of the optical network.
a	The link corresponds to (u,v) $(Gbps)$.
I	The number of cycles needed in the model, which can be estimated by equation (22).
i	The index of a p-cycle, $i.e.$, $i \in [\![I]\!]$.
$r \in R$	The set of available line rates, $i.e.$, $R = \{10\ Gbps, 40\ Gbps, 100\ Gbps\}$.
h_r	The maximum transmission reach for each line rate r: $h_{10} = 1750\ km$, $h_{40} = 1800\ km$, $h_{100} = 900\ km$.
h_{max}	The maximum transmission reach for three line rates 10, 40, 100 $(Gbps)$, $h_{max} = 1800\ km$.
h_{min}	The minimum transmission reach for three line rates 10, 40, 100 $(Gbps)$, $h_{min} = 900\ km$.
N_v	The set of adjacent nodes of v.
d_{uv}	The distance between node u and node v (km).
c_{uv}	The cost of adding one unit of spare capacity to link (u,v).
l_{uv}	The traffic load on link (u,v) $(Gbps)$.
L_{max}	The maximum distance between two nodes (km) in the network.
t_r	The cost of a transponder operating at line rate r.
α	A pre-defined fractional constant, $\frac{1}{\lvert V \rvert} \geq \alpha > 0$.
ILP Variables	
$x^i_{uv} \in \{0,1\}$	Equals 1 if link (u,v) is used by i-th p-cycle CS_i, otherwise 0.
$y^i_v \in \{0,1\}$	Equals 1 if node v is crossed by i-th p-cycle CS_i, otherwise 0.
$y^{ir}_v \in \{0,1\}$	Equals 1 if node v needs a transponder at line rate r in i-th p-cycle CS_i, otherwise 0.
$z^i_{uv} \in \{0,1\}$	Equals 1 if link (u,v) is promising to be protected by i-th p-cycle CS_i, otherwise 0.
$q^i_{uv} \in \{0,1\}$	Equals 1 if i-th p-cycle CS_i has the ability to protect link (u,v), otherwise 0.
$q^{ir}_{uv} \in \{0,1\}$	Equals 1 if i-th p-cycle CS_i has the ability to protect link (u,v) at line rate r, otherwise 0.
$o^i_v \in \{0,1\}$	Equals 1 if node v is the root of the i-th p-cycle CS_i, otherwise 0.
$f^i_v \in [0,1]$	Virtual voltage value of node v in the i-th p-cycle CS_i.
$b^i_r \in \{0,1\}$	Equals 1 if i-th p-cycle CS_i operates at line rate r, otherwise 0.
$p^{ir}_{uv} \in \{0,1,2\}$	Equals 1 if link (u,v) is an on-cycle link of i-th p-cycle CS_i at line rate r, equals 2 if link (u,v) is straddling span of CS_i at line rate r, otherwise 0.

link between two nodes can be used in a p-cycle. Constraint (3) denotes each node has either two adjacent links or zero adjacent link in a p-cycle. Constraint (4) ensures that there is only one root node in a p-cycle. Constraint (5) indicates that a node v has two outgoing links if it is root node, otherwise it has at most one outgoing link. Constraint (6) ensures that when node v is not the root node, the voltage of node v should be bigger than that of node u if the link (u,v) is used in a p-cycle, as shown in Fig. 2. The absolute value of $voltage$ is not important, we just care about the value difference between two adjacent nodes. Constraint (7) makes sure that if both the starting and ending nodes of an link (u,v) are on a p-cycle, then the link (u,v) is promising to be protected by this p-cycle. Constraint (8) indicates even if a link is promising to be protected by a p-cycle, the p-cycle can not manage to protect it due to the distance limit of protection path. Constraints (9) and

$$x^i_{vu} + x^i_{uv} \leq 1, \qquad \forall i, \forall v, \forall u \tag{2}$$

$$\sum_{u \in N_v} (x^i_{vu} + x^i_{uv}) = 2y^i_v, \qquad \forall i, \forall v \tag{3}$$

$$\sum_{v \in V} o^i_v \leq 1, \qquad \forall i \tag{4}$$

$$\sum_{u \in N_v} x^i_{vu} \leq 1 + o^i_v, \qquad \forall i, \forall v \tag{5}$$

$$f^i_u - f^i_v \geq (1+\alpha)x^i_{vu} - 1, \qquad \forall i, \forall v, \forall u \tag{6}$$

$$z^i_{vu} \leq \frac{1}{2}(y^i_v + y^i_u), \qquad \forall i, \forall v, \forall u \tag{7}$$

$$q^i_a \leq z^i_a, \qquad \forall i, \forall a \tag{8}$$

$$p^{ir}_a \leq 2 \cdot q^i_a, \qquad \forall i, \forall r, \forall a \tag{9}$$

$$2z^i_{vu} - x^i_{vu} - x^i_{uv} \geq p^{ir}_{vu}, \qquad \forall i, \forall r, \forall v, \forall u \tag{10}$$

$$q^{ir}_a = q^i_a \cdot b^i_r, \qquad \forall i, \forall r, \forall a \tag{11}$$

$$y^{ir}_v \geq q^{ir}_{vu}, \qquad \forall i, \forall r, \forall v, \forall u \tag{12}$$

$$\frac{\sum_{a \in E} d_a \cdot x^i_a - (q^i_{vu} + q^i_{uv}) \cdot d_{vu}}{h_r} \leq \frac{h_{max}}{h_{min}} \cdot (1 - b^i_r) + b^i_r + \frac{L_{max}}{h_{min}} \cdot [1 - (q^i_{vu} + q^i_{uv})] \qquad \forall i, \forall r, \forall v, \forall u \tag{13}$$

$$\sum_{r \in R} b^i_r \leq 1, \qquad \forall i \tag{14}$$

$$2 \cdot b^i_r \geq p^{ir}_a, \qquad \forall i, \forall r, \forall a \tag{15}$$

$$\sum_{i \in [\![I]\!]} \sum_{r \in R} p^{ir}_a \cdot r \geq l_a, \qquad \forall a \tag{16}$$

(10) determine the protection capacity of a p-cycle. It means that if one p-cycle is able to protect on-cycle link (u,v), then one unit protection capacity will be provided, while if link (u,v) is straddling link, then the p-cycle will provide two units protection capacity. Constraints (11) indicates that link a can be protected by a p-cycle at line rate r. In order to ensure linearity feature of proposed ILP model, constraint (11) is rewritten to constraints (17) and (18).

$$q^{ir}_a \leq \frac{1}{2}(q^i_a + b^i_r), \forall i, \forall r, \forall a \tag{17}$$

$$q^{ir}_a \geq q^i_a + b^i_r - 1, \forall i, \forall r, \forall a \tag{18}$$

Constraint (12) indicates that a transponder at line rate r should be placed in node v of one p-cycle if at least one link incident to v is protected by this p-cycle. Constraint (13) permits to find the suitable line rate for every p-cycle, which is presented in section IV-B. Constraint (14) ensures that only one line rate can be selected for a p-cycle. Constraints (15) and (16) ensure 100% single link failure protection.

In the proposed ILP model, there are $|I| \times (9|E| + 6|V| + 3)$ dominant variables and $|I| \times (25|E| + 2|V| + 2) + |E|$ constraints (*we assign |R|=3 as we have three line rates*). Note that, even though a relaxation voltage is used in the model, we still call it an ILP for simplicity.

B. Distance-adaptive Line Rate Selection

In order to consider transmission reach limit of protection path in terms of line rates, three variables are used in the ILP formulations to generate effective p-cycles, $i.e.$, x^i_{vu}, z^i_{vu}, q^i_{vu}. The links 1→4, 1→8 and 4→8 in Fig. 2 are used to generate the p-cycle, thus the variables x_{14}, x_{18} and x_{48} are assigned value 1. Since the nodes 1, 4 and 8 are on the p-cycle, any link comprising from these nodes are promising to be protected by this p-cycles. Then z_{14}, z_{41}, z_{18}, z_{81}, z_{48} and z_{84} equal 1. Finally, the value of q^i_{vu} depends on whether the p-cycle has the ability to protect $link(v, u)$. The $links(1, 8)$ and $(8, 1)$ can be protected by the path along nodes $(1, 4, 8)$, because the sum distance of protection path is less than 1800 km. However, $links(1, 4)$, $(4, 1)$, $(8, 4)$ and $(4, 8)$ can not be protected by this p-cycle, because the sum distance of their protection paths is longer than 1800 km. Therefore, q_{18} and q_{81} equal 1, while q_{14}, q_{41}, q_{48} and q_{84} equal 0.

Since all the protection paths in a p-cycle should operate at the same line rate, it is necessary to check all the protection path in a p-cycle to determine a suitable line rate. When q^i_{vu} or q^i_{uv} equals 1, a protection path is configured between node v and node u if and only if the total distance of protection path is no longer than h_{max} (1800 km), we can get

$$\sum_{a\in A} d_a \cdot x^i_a - d_{vu} \le h_{max} \tag{19}$$

Then we can get the following equation to determine line rate,

$$\frac{\sum_{a\in A} d_a \cdot x^i_a - d_{vu}}{h_r} \le \frac{h_{max}}{h_{min}} \cdot (1 - b^i_r) + b^i_r \tag{20}$$

While for the other links ($q^i_{vu} = 0$ and $q^i_{uv} = 0$), we just need to ensure that the line rate previously selected still works. As the longest distance of a p-cycle can be $(h_{max} + L_{max})$, then

$$\sum_{a\in A} d_a \cdot x^i_a \le h_{max} + L_{max}$$

$$\frac{\sum_{a\in A} d_a \cdot x^i_a}{h_r} \le \frac{h_{max} + L_{max}}{h_{min}}$$

The equation above is able to ensure the line rate selected by equation (20), which is described clearly as follows,

$$\frac{\sum_{a\in A} d_a \cdot x^i_a}{h_r} \le \frac{h_{max}}{h_{min}} \cdot (1 - b^i_r) + b^i_r + \frac{L_{max}}{h_{min}} \tag{21}$$

C. Spectral Clustering based Graph Partitioning Method

Our ILP model permits to compute the real optimal solution for p-cycle design. In addition, spectral clustering based graph partitioning is used to decrease the computing time for p-cycle design model, which is conducted in two stages.

At first, spectral clustering is used to partition graph [14]. A Laplacian matrix L is computed, subject to $L = D - W$, where D is an $n \times n$ diagonal matrix composed of the degree of each node in a graph $G(V, E)$, and W is the adjacency matrix of graph $G(V, E)$. Then we choose k eigenvectors corresponding to the smallest k eigenvalues of L, and put them into new matrix H as column vectors. The graph partitioning result

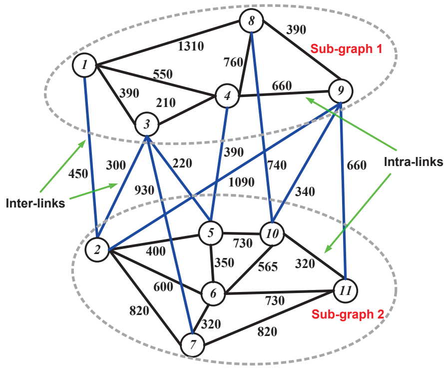


Fig. 3. 11-node European COST239 Network and 2 sub-graphs scenario

is computed by k-means algorithm to minimize the number of inter-links connecting different sub-graphs. For instance in Fig. 3 [1], European COST239 network is partitioned into two sub-graphs using this method.

The second stage is to solve the previous ILP model in Section IV.A. In every sub-graph, p-cycles are generated from intra-links, inter-links to other sub-graphs, and the links connecting the nodes of inter-links in other sub-graphs, but it is important to notice that the computed p-cycles just protect intra-links in this sub-graph and some inter-links to other sub-graphs. The method to determine which sub-graph protects inter-link is in such a manner that the final sum of working links in different sub-graph are as equal as possible.

D. Discussion

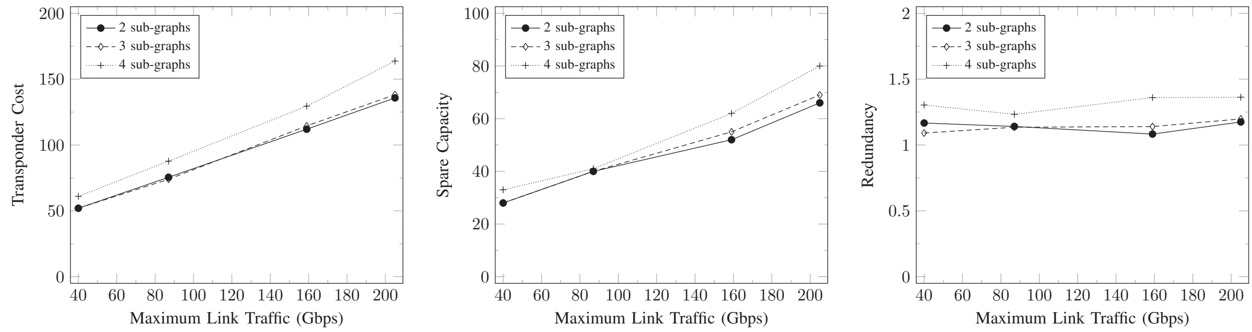
$$\begin{aligned}|I| = \delta + \frac{1}{3}\sum_{a\in E}\Bigg\{ &\lfloor\frac{l_a}{100}\rfloor + \lfloor\frac{l_a \bmod 100}{40}\rfloor \\ &+ \lfloor\frac{l_a - \lfloor\frac{l_a}{100}\rfloor\cdot 100 - \lfloor\frac{l_a \bmod 100}{40}\rfloor \cdot 40}{10}\rfloor\Bigg\}\end{aligned} \tag{22}$$

Equation (22) is used to estimate a large enough value $|I|$ in our model, since it is very sensitive to computing time. At first, we suppose that every link in the network is protected by several p-cycles, and the number of the p-cycles is determined by the traffic load and the transponder efficiency. After calculating the total number of p-cycles required for the whole network protection, the value of $|I|$ is obtained by dividing total required p-cycles by 3, because there exists at least 3 links in one p-cycle. In the equation, δ is a small positive integer and l_a is the traffic load on the link $a \in E$.

It should be noted that we do not compare our p-cycle design model to conventional ILP models with candidate cycle enumeration [3] [6] or candidate cycle preslection [7] [10], due to the reasons as follows. First, we investigate p-cycle design in MLR optical networks, then the line rates are provisioned in a more flexible way to increase protection efficiency. However, the existing p-cycle design models are mainly developed in SLR optical networks, making the performance comparison rather meaningless. Second, the p-cycle ILP in MLR optical networks in [3] ignores the physical impairment in protection

TABLE II
RESULTS IN EUROPEAN COST239 NETWORK WITH GRAPH PARTITIONING

COST239	Maximum Link Traffic 40 Gbps			Maximum Link Traffic 87 Gbps			Maximum Link Traffic 159 Gbps			Maximum Link Traffic 205 Gbps		
	Total Cost	Gap	Time	Total Cost	Gap	Time	Total Cost	Gap	Time	Total Cost	Gap	Time
2 sub-graphs	80	<1%	3.4 s	115.5	<1%	633 s	164	<3%	10446.26 s	201.75	<5%	53960.63 s
3 sub-graphs	80	0%	2.53 s	114	<1%	10.64 s	169.5	<1%	4519.99 s	207.25	<3%	22654.23 s
4 sub-graphs	94	0%	1.02 s	128.75	0%	4.14 s	191.5	<1%	1062.46 s	243.75	0%	29.43 s



(a) Transponder Cost vs. Traffic Load (b) Spare Capacity vs. Traffic Load (c) Redundancy vs. Traffic Load

Fig. 4. Results with graph partitioning in European COST239 Network

paths, thus it does not consider the transmission reach limit in terms of line rates, which makes it difficult to compare our p-cycle method with theirs.

V. NUMERICAL RESULTS

We use CPLEX 12.06 to solve the proposed ILP model, which is conducted on an Intel Core PC equipped with a 3.5 $GHz\ CPU$ and 8 $GBytes\ RAM$. European COST239 network [1] (**11 nodes** and **26 links**) in Fig. 3 and US Backbone network [15] (**28 nodes** and **45 links**) are studied as test beds. For simplicity, we focus on undirected networks, and only consider the upper triangle of the symmetric traffic matrix. The link traffic load in the symmetric traffic matrix is obtained by routing all the traffic demands between source nodes and destination nodes using Dijkstra's shortest-path algorithm. The following metrics are evaluated in this study:

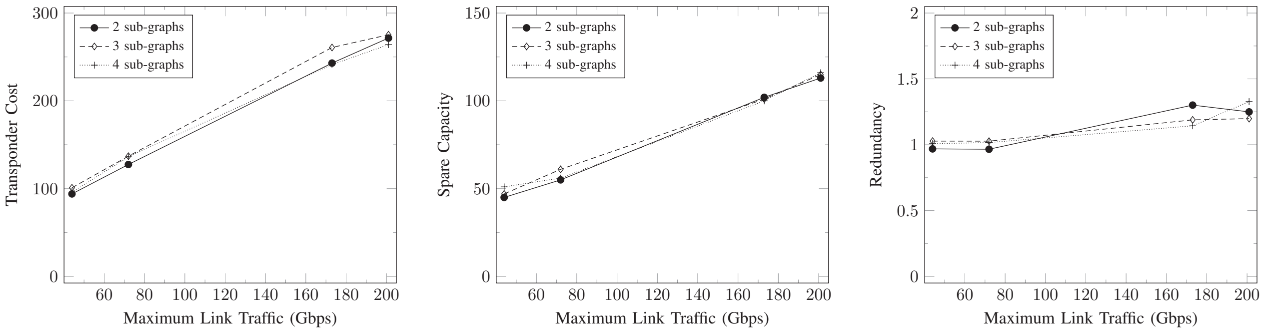
- *Total Cost*: The total cost contains transponder cost and spare capacity, and we treat them as equally important in this study, as shown in equation (1).
- *Redundancy*: It is defined as the ratio of spare capacity (number of links used by p-cycle) to the working capacity (number of links protected by p-cycle).

In European COST239 network, the user demands are uniformly among $[0,10]$ $Gbps$, $[0,20]$ $Gbps$, $[0,30]$ $Gbps$ and $[0,40]$ $Gbps$, respectively. We get the near-optimal solution through graph partitioning, as shown in Table II. It is important to note that the near-optimal solution obtained in more sub-graphs scenario requires less computing time at the expense of cost, this is because the searching space in every sub-graph is reduced. Fig. 4 compares the results of transponder cost, spare capacity and redundancy in terms of different sub-graphs scenarios in COST239 network. It shows that 2 sub-graphs scenario achieves the best performance among all the three metrics, since it has a wider searching space to find near-optimal p-cycles. Even though there is relative larger transponder cost in Fig. 4(a) and redundancy in Fig. 4(c) when using the method in 4 sub-graphs scenario, the computing time is decreased remarkably. The spare capacity in Fig. 4(b) is dependent on the configuration links in p-cycles. Spare capacity in 4 sub-graphs scenario is larger than that in other sub-graphs scenarios with the increase of traffic load as it desires more links in every sub-graph. In addition, the redundancy of p-cycles is above 1.0 in Fig. 4(c), this is because some on-cycle links and straddling links can not be protected by p-cycles due to the maximum transmission reach limit.

To show the scalability of our method, we also present the results for a larger network, $i.e.$, US Backbone network [15]. Since the link in US Backbone network is too large to generate the p-cycle under transmission limit 1800 km, we divide the link distance by 2. Traffic demands are uniformly among $[0,1]$ $Gbps$, $[0,2]$ $Gbps$, $[0,5]$ $Gbps$ and $[0,6]$ $Gbps$, respectively. We get the near-optimal solution through graph partitioning, as shown in Table III. The difference of total cost in the three sub-graphs scenarios is less than 8%. Fig. 5 shows the results of transponder cost, spare capacity and redundancy in terms of different sub-graphs scenarios. It indicates that 3 sub-graphs scenario requires the largest transponder cost in Fig. 5(a) and spare capacity in Fig. 5(b), which is due to the special structure of US Backbone topology. The redundancy in Fig. 5(c) seems much close to each other among the

TABLE III
RESULTS IN US BACKBONE NETWORK WITH GRAPH PARTITIONING

US Backbone	Maximum Link Traffic 44 Gbps			Maximum Link Traffic 72 Gbps			Maximum Link Traffic 173 Gbps			Maximum Link Traffic 201 Gbps		
	Total Cost	Gap	Time	Total Cost	Gap	Time	Total Cost	Gap	Time	Total Cost	Gap	Time
2 sub-graphs	139	<1%	689.56 s	182.5	<2%	2451.26 s	345	<3%	6741.23 s	384.5	8%	57841.12 s
3 sub-graphs	148	0%	210.66 s	198	<1%	6361.27 s	351.75	<2%	13784.51 s	390.25	<5%	34561.23 s
4 sub-graphs	147	0%	3.36 s	192.25	0%	5.22 s	341.25	<1%	75.11 s	380	<2%	1374.66 s



(a) Transponder Cost vs. Traffic Load (b) Spare Capacity vs. Traffic Load (c) Redundancy vs. Traffic Load

Fig. 5. Results with graph partitioning in US Backbone Network

three sub-graphs scenarios, which is different from results in COST239 network. This similar characteristic also owes to special structure of US Backbone network, in which fewer cycles can be generated. It can be concluded that our p-cycle model works well in US Backbone network, as the p-cycle results are obtained quickly and optimally.

It is worth noting that graph partitioning is an efficient method to enable computing model in sub-graphs concurrently. Even though the total cost and cycle redundancy are a little bigger in a network with more sub-graphs, the computing time is saved effectively. Thus, our p-cycle method is an efficient solution for traffic protection in MLR optical networks.

VI. Conclusion

In this paper, we investigate the p-cycle design in MLR optical networks without candidate cycle enumeration. The proposed ILP model permits to find the real optimal solution in the consideration of cost-effective transponders and distance-adaptive line rates, and graph partitioning enables computing p-cycles in different sub-graphs concurrently. Results show that our method is cost-efficient for p-cycle design with mixed line rates and scalable for large optical networks.

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