Energy-efficient Protection with Directed p-Cycles for Asymmetric Traffic in Elastic Optical Networks

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***Abstract*—This paper studies energy-efficient protection for asymmetric traffic in Elastic Optical Networks (EONs). Directed pre-configured Cycles (p-Cycles) are designed to protect directional traffic with flexible spectrum allocation and adaptive modulation formats. A Mixed Integer Linear Programming (MILP) model is formulated to minimize total energy consumption while generating directed p-cycles without candidate cycle enumeration. To enable the scalability, the MILP model is decomposed into a Promising Energy-efficient p-Cycle Selection (PECS) algorithm and a simplified Integer Linear Programming (ILP) model. Simulation results show that the proposed energy-efficient directed p-cycles achieve significant energy savings for asymmetric traffic protection compared with energy-efficient undirected p-cycles (up to 47.9%) and non-energy-efficient directed p-cycles (up to 35.7%).**

***Index terms*—** Energy Savings, Pre-configured Cycle (p-Cycle), Asymmetric Traffic, Elastic Optical Networks (EONs)

I. Introduction

Network survivability for Elastic Optical Networks (EONs) is an important issue since single fiber can carry a large amount of traffic in EONs [1]. Nowadays, there are some new trends in survivable EONs. New network services, $i.e.$, Content Delivery Networks (CDNs), Virtual Private Networks (VPN) and data centers, introduce asymmetric traffic pattern [2]. Specifically, the value of this traffic differs in the two directions between a pair of network nodes. It has been demonstrated that asymmetric traffic provisioning scenario saves up to 50% spectrum usage and up to 30% Capital Expenditure (CAPEX) cost compared with conventional symmetric traffic provisioning scenario [2]. Meanwhile, energy consumption in telecommunication networks keeps an average annual growth rate of 10% since 2007 [3]. These trends bring new challenges in EONs to protect asymmetric traffic energy-efficiently.

p-Cycle protection technique has drawn a lot of attention due to the benefits that it owns fast switching speed and provides protection capacity for both on-cycle links and straddling links [4]. Most of p-cycle designs for EONs in the literature only focus on reducing spectrum usage by efficiently selecting flexible spectrum slots and modulation formats. *Spectrum continuity* is satisfied to ensure the same Frequency Slots (FSs) on each link in one p-cycle while *spectrum contiguousness* ensures that the FSs assigned to p-cycles should be spectrally neighboring. However, in addition to the efficient spectrum allocation, it is also of great importance to reduce energy consumption in optical devices of Bandwidth Variable Transponders (BVTs), Bandwidth Variable Cross-Connects (BV-OXCs) and Optical Amplifiers (OAs) [5].

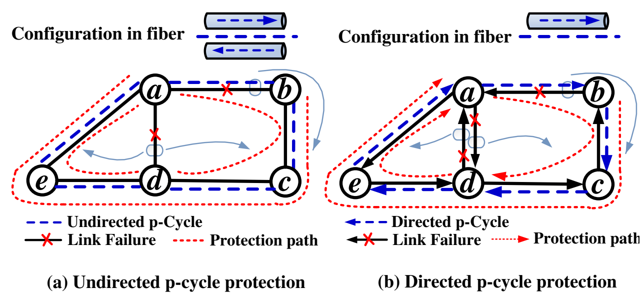


Figure 1. Two kinds of p-cycle protection scenarios.

Two kinds of p-cycle scenarios have been studied in the literature, as shown in Fig. 1. In common undirected p-cycles, the protection capacity is configured in the two directions in the on-cycle links. It means that once the undirected p-cycle is determined, the same spectrum slots and the same modulation formats are used in the two unidirectional fiber. However, directed p-cycle scenario only configures protection capacity in unidirectional direction in the directed on-cycle links. For asymmetric traffic protection, directed p-cycle can distinguish directional links and provide different protection capacity while undirected p-cycle provides the same protection capacity according to the maximum traffic amount of the two directed links. Thus, less protection capacity is required in directed p-cycle design.

Previously, we studied p-cycle design without candidate cycle enumeration in Mixed Line Rates (MLR) networks [6]. In this paper, we further address the spectrum allocation for p-cycles in EONs, and design energy-efficient directed p-cycles for asymmetric traffic protection against single link failure. A Mixed Integer Linear Programming (MILP) model, named EDPC, is formulated to minimize energy consumption while taking into account directed cycle generation, spectrum allocation and modulation format adaptation. To enable the scalability, we decompose EDPC into a Promising Energy-efficient p-Cycle Selection (PECS) algorithm and a simplified Integer Linear Programming (ILP) model, named De-EDPC.

We evaluate the energy savings in De-EDPC in comparison with undirected p-cycles.

The rest of this paper is organized as follows. Related work is reviewed in next section. Sec. III presents the design principle. The formulation in EDPC is developed in Sec. IV and the decomposed approach is given in Sec. V. We analyze the simulation results in Sec. VI and conclude the paper in Sec. VII.

II. Related Work

The asymmetric traffic protection in EONs was first addressed in [7], in which the authors investigated symmetric and asymmetric models for lightpath provisioning with Dedicated Path Protection (DPP). They concluded that asymmetric traffic protection earned significant BVT savings up to 25%. The similar conclusion was obtained in [2] that asymmetric traffic provisioning can bring significant resource savings compared with symmetric traffic provisioning (up to 50% spectrum usage savings and up to 30% Capital Expenditure (CAPEX) cost savings). However, the benefit of directed p-cycles for asymmetric traffic protection was only investigated by Jaumard et al. in Wavelength Division Multiplexing (WDM) networks [8]. They observed that using directed p-cycles for asymmetric traffic protection consumed less resource than undirected p-cycles, and the resource reduction became bigger with the increase of traffic asymmetry (45% for pure asymmetric traffic).

Energy-aware protection schemes for EONs was studied in [5] [9]. In [5], the authors discussed three energy-aware protection schemes, referred to 1+1 Dedicated Protection (DP), 1:1 DP and Shared Protection (SP). They evaluated the cost efficiency and energy efficiency improvement in comparison with fixed WDM networks. A hybrid path protection approach with energy efficient consideration was studied in [9]. However, these path protection schemes may suffer long restoration time when a failure happens. p-Cycle protection with energy consumption consideration was still unexplored for EONs even though efficient spectrum allocation has been taken into account in p-cycle design in EONs. The authors in [10] studied dynamic p-cycle protection with spectrum planning, and further investigated Failure-Independent Path protection (FIPP) p-cycles in [1].

However, conventional p-cycle designs for EONs mainly focused on improving spectrum efficiency, and moreover, directed p-cycle design was only explored in WDM networks. Thus, new energy-efficient directed p-cycles are urgent to be explored to meet the new trends in EONs.

III. Design Principle

In this section, we explain the design principle and key considerations of energy-efficient directed p-cycles for EONs.

An EON can be modeled as a layered digraph $G(V, E)$, which has the OXCs set V and the directional links set E. Between two adjacent optical OXCs v and u, there are two unidirectional links $v \rightarrow u$ and $u \rightarrow v$. The traffic volume l_{vu} and l_{uv} in the two links differs due to the asymmetric traffic between source nodes and destination nodes. We introduce a parameter called $TASY$ to describe traffic asymmetry in the network, given by Eq. (1) [8]. $TASY = 0\%$ and $TASY = 100\%$ represent symmetric traffic and pure asymmetric traffic, respectively.

$$TASY = \overline{TASYsd} \tag{1}$$

$$TASYsd = \frac{max\{l_{sd}, l_{ds}\}}{min\{l_{sd}, l_{ds}\}} \tag{2}$$

We develop energy-efficient directed p-cycles for asymmetric traffic protection in EONs. The main considerations are summarized as follows:

- ***Energy consumption***: Three kinds of optical devices are considered to consume energy. ***BVTs*** enable the selection of FSs usage and modulation formats in the starting and ending nodes. ***BV-OXCs*** are capable of switching channels of any bandwidth (multiple of $12.5\,GHz$), which are configured in each node. Erbium Doped Fiber Amplifier (EDFAs) are considered as ***OAs*** with span distance $80\,km$ between two neighboring EDFAs. The energy consumption of BVTs, BV-OXCs and EDFAs are referred to [5]. Our goal is to minimize the total energy consumption of BVTs, BV-OXCs and EDFAs.

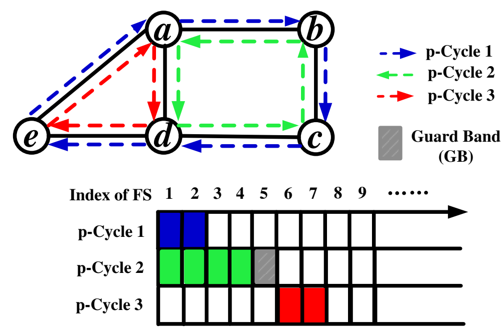


Figure 2. Spectrum allocation for directed p-cycle design in EONs.

- ***FSs allocation***: FSs allocation addresses both *spectrum continuity* and *spectrum contiguousness*. An example with three p-cycles is shown in Fig. 2. In each p-cycle, the same FSs are used on every on-cycle link. p-Cycles 1 and 2 can share some FSs with index 1 and 2 as they do not have the common link. However, for p-cycles 2 and 3 that have the common link, Guard Band (GB) with index 5 need to be reserved between the occupied FSs.
- ***Adaptive modulation formats***: BVTs utilize diverse modulation formats, $e.g.$, BPSK, QPSK, 8-QAM and 16-QAM. We assume each directed p-cycle uses the same modulation along all the on-cycle links. Moreover, we also consider the maximum transmission reaches of these modulation formats, which are referred to [1].

IV. EDPC Formulation

In this section, we formulate an MILP model for EDPC without candidate cycle enumeration, which ensures 100% protection for asymmetric traffic against single link failure.

Note that EDPC is guaranteed to reach the optimal solution due to the absence of candidate cycle enumeration. Notations in EDPC are defined in Tab. I. For the sake of readability, we use $\forall i$, $\forall v$, $\forall u$, $\forall m$, and $\forall e$ to denote $\forall i \in I$, $\forall v \in V$, $\forall u \in N_v$, $\forall m \in M$, and $\forall e \in E$, respectively. The directed link $v \rightarrow u$ also can be denotes by e.

Table I

Network Sets and Parameters	
I	The p-cycle set with maximum number $\|I\|$ allowed in EDPC, I_i indicates i-th p-cycle in I.
$G(V,E)$	Network topology with node set V and link set E.
N_v	The set of adjacent nodes of a node v.
M	The available modulation level set, $e.g.$, BPSK, QPSK, 8-QAM, 16-QAM.
d_{vu}	The length between node v and node u, L_{max} indicates the biggest length in network $G(V,E)$.
b_m	The available bandwidth provided by one slot at modulation level m, which is 12.5, 25, 37.5 and 50 $Gbps$ for BPSK, QPSK, 8-QAM and 16-QAM, respectively.
e_m^{BVT}	Energy consumption of the BVT at modulation m [5].
e_v^{OXC}	Energy consumption of the BV-OXC at node v [5].
e_e^{EDFA}	Energy consumption of all the EDFAs on link e [5].
h_m	Maximum transmission reach at modulation level m, which is 9600, 4800, 2400 and 1200 km for BPSK, QPSK, 8-QAM and 16-QAM, respectively. h_{max}=9600 km, and h_{min}=1200 km.
N_G	The number of FSs for guard band, regarded as 1.
B	The available FSs on each fiber link, regarded as 320.
l_{vu}	Traffic load on unidirectional link $v \rightarrow u$ after routing.
β	A pre-defined fractional constant, $\frac{1}{\|V\|} \geq \beta > 0$.
Variables	
$x_{vu}^i \in \{0,1\}$	Equals 1 if link $v \rightarrow u$ is used by I_i, and 0 otherwise.
$y_v^i \in \{0,1\}$	Equals 1 if node v is crossed by I_i, and 0 otherwise.
$f_v^i \in \{0,1\}$	Virtual $voltage$ value of node v in I_i.
$o_v^i \in \{0,1\}$	Equals 1 if node v is root node in I_i, and 0 otherwise.
$b_m^i \in \{0,1\}$	Equals 1 if I_i operates at modulation level m, and 0 otherwise.
$q_{vu}^i \in \{0,1\}$	Equals 1 if link $v \rightarrow u$ desires to be protected by I_i, and 0 otherwise.
$c_{ij} \in \{0,1\}$	Equals 1 if I_i and I_j share the common directed link, and 0 otherwise.
$s_i \in [0,B]$	The starting index of FSs in I_i.
$o_{ij} \in \{0,1\}$	Equals 1 if the starting index of FSs in I_i is smaller than that in I_j, and 0 otherwise.
$n_i \in [0,32]$	The number of occupied FSs of I_i. The maximum FSs is 32 due to the limited capacity in BVT.
$t_b \in [0,B]$	The maximum index of occupied FSs in all the p-cycles.
$\pi_{vu}^{im} \in [0,32]$	The number of FSs provided by I_i to protect link $v \rightarrow u$ at modulation level m.
$n_{vu}^i \in [0,32]$	The number of occupied FSs of I_i on link $v \rightarrow u$.

Objective:

$$\min \quad E_{BVTs} + E_{OXCs} + E_{EDFAs} + t_b \tag{3}$$

$$E_{BVTs} = \sum_{i \in I} \sum_{m \in M} \sum_{e \in E} 2 \cdot e_m^{BVT} \cdot \pi_e^{im} \tag{4}$$

$$E_{OXCs} = \sum_{i \in I} \sum_{v \in V} \sum_{u \in N_v} \frac{n_{vu}^i}{B} \cdot e_v^{OXC} \tag{5}$$

$$E_{EDFAs} = \sum_{i \in I} \sum_{e \in E} \frac{n_e^i}{B} \cdot e_e^{EDFA} \tag{6}$$

The objective is to minimize total energy consumption of BVTs, BV-OXCs and EDFAs. E_{BVTs} is introduced at the starting and ending nodes of the protection path depending on the number of occupied FSs and modulation format. E_{OXCs} and E_{EDFAs} are calculated related to the number of occupied FSs on each link. We also minimize the maximum index of occupied FSs to ensure the *spectrum contiguousness*. Note that this does not affect the optimization of minimizing the total energy consumption, as the value of the maximum index of occupied FSs can not be comparable to that of the total energy consumption.

Constraints:

EDPC includes the following categories of constraints; **directed cycle generation** (7)-(11), **FSs allocation** (12)-(16), **modulation adaptation** (17)-(18) and **protection capacity** (19)-(23).

1) **Directed cycle generation***:* Constraints (7)-(9) ensure only one directed link between two nodes can be used in a p-cycle, and if node v must have one incoming link and one outgoing link if it is crossed by the p-cycle. Constraints (10) and (11) assign virtual $voltage$ in each node to guarantee single cycle generation for each p-cycle. These constraints generate single cycle with either clockwise or counterclockwise.

$$x_{vu}^i + x_{uv}^i \leq 1, \qquad \forall i, \forall v, \forall u \tag{7}$$

$$\sum_{u \in N_v} x_{uv}^i - \sum_{u \in N_v} x_{vu}^i = 0, \qquad \forall i, \forall v \tag{8}$$

$$y_v^i = \sum_{u \in N_v} x_{vu}^i, \qquad \forall i, \forall v \tag{9}$$

$$f_u^i - f_v^i + o_u^i \geq (1+\beta) \cdot x_{vu}^i - 1, \qquad \forall i, \forall v, \forall u \tag{10}$$

$$\sum_{v \in V} o_v^i \leq 1, \qquad \forall i \tag{11}$$

2) **FSs allocation***:* Constraints (12)-(14) allocate the order of FSs for each p-cycle. They avoids spectrum conflict by adding GB and also ensure that two p-cycles can share the same FSs if they do not have any common link. Constraint (15) implies the maximum index of FSs, which is minimized in Eq. (3) to ensure $spectrum\ contiguousness$. Constraint (16) indicates the $spectrum\ continuity$ in the on-cycle links in one p-cycle.

$$x_e^i + x_e^j - 1 \leq c_{ij}, \qquad \forall i, j, i \neq j, \forall e \tag{12}$$

$$o_{ij} + o_{ji} = 1, \qquad \forall i, j, i \neq j \tag{13}$$

$$s_i + n_i + N_G - s_j \leq B \cdot (2 - o_{ij} - c_{ij}), \qquad \forall i, j, i \neq j \tag{14}$$

$$s_i + n_i \leq t_b, \qquad \forall i \tag{15}$$

$$n_e^i = x_e^i \cdot n_i, \qquad \forall i, \forall e \tag{16}$$

3) **Modulation adaptation***:* Constraint (17) guarantees modulation format adaptation with maximum transmission reach consideration. Constraint (18) ensures that only one modulation format can be assigned for one p-cycle.

$$\frac{\sum_{e \in E} d_e \cdot x_e^i - q_e^i \cdot d_e}{h_m} \leq \frac{h_{max}}{h_{min}} \cdot (1 - b_m^i) + \frac{L_{max}}{h_m} \cdot (1 - q_e^i) + b_m^i, \qquad \forall i, \forall m, \forall e \tag{17}$$

$$\sum_{m\in M} b_m^i \le 1, \qquad \forall i \qquad (18)$$

4) **Protection capacity***:* Constraints (19) and (20) indicate the desire of link $v \rightarrow u$ to be protected by I_i. Note that both on-cycle links and straddling links are guaranteed to be protected if they desire to be protected. Constraints (21) determines the number of FSs that provided by I_i at modulation level m to protect link e. Constraint (22) ensures the maximum capacity 400 *Gbps* in a BVT [5]. Constraint (23) ensures 100% protection against single link failure.

$$q_{vu}^i \le \frac{1}{2}(y_v^i + y_u^i), \qquad \forall i, \forall v, \forall u \qquad (19)$$

$$q_e^i \le 1 - x_e^i, \qquad \forall i, \forall e \qquad (20)$$

$$\pi_e^{im} \le q_e^i \cdot b_m^i \cdot n_i, \qquad \forall i, \forall m, \forall e \qquad (21)$$

$$\pi_e^{im} \cdot s_m \le 400, \qquad \forall i, \forall m, \forall e \qquad (22)$$

$$\sum_{i\in I}\sum_{m\in M} \pi_e^{im} \cdot s_m \ge l_e, \qquad \forall e \qquad (23)$$

In order to ensure linearity, constraints (16) and (21) are rewritten as constraints (24) and (25), respectively.

$$\Longrightarrow \begin{cases} n_e^i \le n_i, & \forall i, \forall e \\ n_e^i \le x_e^i \cdot 32, & \forall i, \forall e \\ n_e^i \ge n_i - (1 - x_e^i) \cdot 32, & \forall i, \forall e \end{cases} \qquad (24)$$

$$\Longrightarrow \begin{cases} \pi_e^{im} \le n_i, & \forall i, \forall m, \forall e \\ \pi_e^{im} \le q_e^i \cdot 32, & \forall i, \forall m, \forall e \\ \pi_e^{im} \le b_m^i \cdot 32, & \forall i, \forall m, \forall e \end{cases} \qquad (25)$$

Note that the predetermined parameter $|I|$ should be sufficiently large to ensure the optimal solution, but a larger $|I|$ will slow down execution time due to the increase in variables and constraints. Here, we estimate the $|I|$ according to Eq. (26). As the maximum protection capacity is 400 *Gbps* in a p-cycle, the we choose the possible number of p-cycles to protect each link depending on the traffic volume, and then divide it by 3 as there exists at least 3 links in one p-cycle. A small positive integer δ is added in case that $|I|$ is not large enough.

$$|I| = \delta + \frac{1}{3}\sum_{(v,u)\in E} \lceil \frac{l_{vu}}{400} \rceil \qquad (26)$$

V. Decomposed approach

Although EDPC can reach the optimal solution by avoiding candidate cycle enumeration, the high computational complexity results in the scalability problem. Then, we decompose it into a Promising Energy-efficient p-Cycles Selection (PECS) algorithm and a simplified ILP model, called De-EDPC.

A. PECS algorithm

PECS algorithm forms a set $[\![I]\!]$ with energy-efficient candidate cycles for De-EDPC. The main idea of PECS is that we select p-cycles with different circumferences, so that the selected p-cycles can be assigned diverse modulation formats in De-EDPC in an energy-efficient way.

Algorithm 1: PECS Algorithm

Input : $G(V, A)$, h_m, $\forall m \in M$, $m =$ 0,1,2,3.
Output: Selected candidate cycle set $[\![I]\!]$

1 **for** $m \in M$ **do**
2   **if** $m < 3$ **then**
3   enumerate the complete cycle set $[\![\hat{I}]\!]$ whose circumference in the range $(h_{m+1}, h_m]$ using the approach in [4];
4   **else**
5   enumerate the complete cycle set $[\![\hat{I}]\!]$ whose circumferences in the range (0, h_3] using the approach in [4];
6   solve the PCS model with the complete cycle set $[\![\hat{I}]\!]$;
7   store the selected cycles obtained from PCS model in $[\![I]\!]$;
8 **output** $[\![I]\!]$

Algorithm 1 shows the PECS procedure. Considering the different maximum transmission reaches of modulation format set M, *Lines* 2-5 explain how to enumerate complete cycle set $[\![\hat{I}]\!]$ with different circumferences. *Line* 6 performs PCS model to select just enough cycles from $[\![\hat{I}]\!]$, which will be explained next. Specifically, the cycles obtained in PCS model are able to protect the links that can be originally protected by the enumerated cycles. We store the selected cycles in $[\![I]\!]$. Thus, we obtain the candidate cycles with different circumferences to provide energy-efficient protection.

Here, a simple p-Cycle Selection (PCS) ILP model is formulated to select just enough p-cycles instead of enumerating a large number of p-cycles in the complete candidate cycle set $[\![\hat{I}]\!]$. The parameters and variables are shown in Tab. II. Its objective is to minimize the total number of links in all the p-cycles. Constraint (28) ensures the selected p-cycles should be able to protect all the links that can be initially protected by p-cycles in the complete candidate cycle set $[\![\hat{I}]\!]$.

Table II

Network Sets and Parameters in PCS	
$[\![\hat{I}]\!]$	Complete candidate cycle set with cycle enumeration.
$x_e^i \in \{0,1\}$	Equals 1 if cycle $\hat{I}_i$ crosses link e, and 0 otherwise.
$z_e^i \in \{0,1\}$	Equals 1 if cycle $\hat{I}_i$ can protect link e, and 0 otherwise.
Variables in PCS	
$w_i \in \{0,1\}$	Equals 1 if cycle $\hat{I}_i$ is selected, and 0 otherwise.

$$min \qquad \sum_{i\in[\![\hat{I}]\!]}\sum_{e\in E} w_i \cdot x_e^i \qquad (27)$$

$$\sum_{i\in[\![\hat{I}]\!]} w_i \cdot z_e^i \ge z_e^i, \qquad \forall e \qquad (28)$$

For the PECS algorithm, we only use it once to obtain the candidate cycle set $[\![I]\!]$ in the network initialization. Thus, it will not cause intolerable computational complexity afterwards.

Table III

QUALITY OF SOLUTION AND EXECUTION TIME IN EDPC AND DE-EDPC.

Six-node network						NSFNET network					
Traffic*	EDPC(6)†		De-EDPC(6)†		Gap	Traffic*	EDPC(15)†		De-EDPC(20)†		Gap
	Results	Execution Time	Results	Execution Time			Results	Execution Time	Results	Execution Time	
$1X$	4516.69	3146.89 s	4712.23	0.18 s	4.15%	$1X$	10257.7	21270.66 s	10299.9	0.39 s	0.41%
$2X$	6352.91	2818.22 s	7018.97	0.52 s	9.49%	$2X$	11079.6	26547.16 s	11997.4	0.57 s	7.65%
$3X$	8175.31	4598.2 s	9437.9	0.38 s	13.38%	$3X$	12116.3	26645.57 s	15550.8	0.46 s	22.0%
$4X$	11268.8	8129.9 s	12437.1	0.38 s	9.39%	$4X$	13254.8	21327.01 s	17495.6	0.44 s	24.2%
$5X$	13111.5	11606.2 s	15079.3	0.38 s	13.04%	$5X$	15512	24661.38 s	20373.3	0.49 s	23.86%

* The basic traffic is 320 $Gbps$ and 100 $Gbps$ in 6-node network and NSFNET network, respectively.

†In six-node network, the number of $|I|$ obtained by Eq. (26) for EDPC is 6, and the number of $[\![I]\!]$ obtained by PECS algorithm for De-EDPC is also 6. In NSFNET network, the two value is 15 and 20, respectively.

B. De-EDPC formulation

Table IV

New Network Sets and Parameters in De-EDPC	
$[\![I]\!]$	Candidate cycle set obtained by PECS algorithm.
$x_e^i \in \{0,1\}$	Equals 1 if cycle I_i crosses link e, and 0 otherwise.
$z_e^i \in \{0,1\}$	Equals 1 if cycle I_i can protect link e, and 0 otherwise.
$c_{ij} \in \{0,1\}$	Equals 1 if cycle I_i and I_j share at least one common link, and 0 otherwise.

De-EDPC is decomposed from EDPC in Sec. IV. The parameters in De-EDPC are shown in Tab. IV. Note that instead of using a specific cycle repeat variable, the candidate cycle set $[\![I]\!]$ is scaled by repeating the candidate cycles obtained by PECS algorithm according to the total traffic volume. Thus, the parameters x_e^i, z_e^i and c_{ij} can be determined before solving De-EDPC. De-EDPC uses $x_{vu}^i \cdot n_i$ instead of variable n_{vu}^i, and the objective function in Eqs. (5) and (6) are rewritten as follows,

$$E_{OXCs} = \sum_{i \in [\![I]\!]} \sum_{v \in V} \sum_{u \in N_v} \frac{x_{vu}^i \cdot n_i}{B} \cdot e_v^{OXC} \tag{29}$$

$$E_{EDFAs} = \sum_{i \in [\![I]\!]} \sum_{e \in E} \frac{n_e^i}{B} \cdot e_e^{EDFA} \tag{30}$$

The majority constraints in De-EDPC are the same as those in EDPC, including ***FSs allocation*** (13)-(15), ***Modulation adaptation*** (17)-(18), ***Protection capacity*** (21)-(23). Constraints (19) and (20) are replaced by constraint (31).

$$q_e^i \leq z_e^i, \qquad \forall i, \forall e \tag{31}$$

There are $|I| \cdot (|I| \cdot |E| + 26|E| + 2|V| + 2|I| + 3) + |E|$ constraints in EDPC while De-EDPC has $|[\![I]\!]| \cdot (21|E| + 2|[\![I]\!]| + 2) + |E|$ constraints (we assign $|M| = 4$).

VI. PERFORMANCE EVALUATIONS

We use CPLEX 12.06 to perform EDPC and De-EDPC. We first evaluate the solution in De-EDPC compared with that in EDPC, and then investigate the energy savings in De-EDPC for asymmetric traffic protection in comparison with undirected p-cycles. In the simulations, we generate asymmetric traffic with $TASY$ among [0%,100%], and set up the routing path with Dijkstra's shortest-path routing.

A. Quality of solution in De-EDPC

To verify the efficiency of decomposed approach with PECS algorithm and De-EDPC, we perform both EDPC and De-EDPC in six-node [1] and NSFNET networks [11] with small traffic demands. De-EDPC is solved on an Intel Core PC equipped with 8 GBytes memory while EDPC is solved by a server with 500 GBytes memory due to the high computation complexity. The traffic is generated with $TASY = 20\%$ and set up by Dijkstra's shorted-path routing.

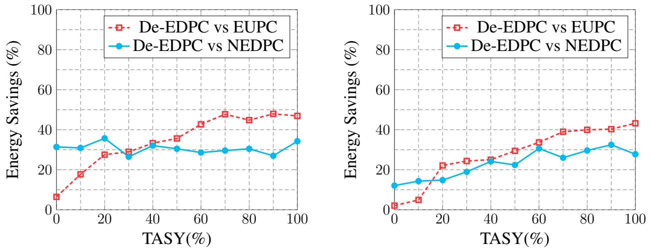
Table III shows the results. In both six-node and NSFNET networks, at low traffic, De-EDPC achieves comparable solutions within dramatically lower execution time compared with the solutions in EDPC. As traffic increases, the introduced optimality gap compared with EDPC becomes bigger. This is because De-EDPC has relatively smaller feasible region due to the fixed candidate cycles. However, it should be noted that the low execution time in De-EDPC is attractive as the traffic volume increases. We can obtain that the proposed PECS algorithm and De-EDPC offers a time-efficient way to solve the directed p-cycle design problem.

B. Energy savings in De-EDPC with diverse $TASY$

We further conduct simulations with De-EDPC to study the performance of asymmetric traffic protection with $TASY$ among [0%, 100%] in both NSFNET [1] and US Backbone networks [11]. To evaluate the energy savings in De-EDPC, the following benchmarks are used:

- EUPC: It develops undirected p-cycles to minimize energy consumption with the similar ILP model based on De-EDPC.
- NEDPC: It is modified from the optimal p-cycle design in [12], which is formulated to minimize the total FSs usage.

Figure 3 shows the energy consumption in De-EDPC, EUPC and NEDPC. The total traffic is around $4\,Tbps$ in



(a) Energy Saving in NSFNET (b) Energy Saving in US Backbone

Figure 3. Energy savings in De-EDPC compared with EUPC and NEDPC in NSFNET and US Backbone networks.

NSFNET and 8 $Tbps$ in US Backbone network. We can see that in both NSFNET and US Backbone networks, the energy savings in De-EDPC VS EUPC grows with the increase of $TASY$ from 0% to 100% ($i.e.$, from symmetric traffic to pure asymmetric traffic). Specifically, for the symmetric traffic with $TASY = 0\%$, the energy savings is 6.46% and 2.08% in NSFNET and US Backbone networks, respectively. For the pure asymmetric traffic with $TASY = 100\%$, the energy saving is even 46.91% in NSFNET network and 43.24% in US Backbone network. It is because directed p-cycles in De-EDPC are designed according to the directional traffic in each direction, while the undirected p-cycles in EUPC ignore traffic direction by assigning the same resources twice in the two directions on each link corresponding to the maximum unidirectional traffic. However, the trend of energy savings in De-EDPC VS NEDPC is not the same in the two networks due to typology differences. In NSFNET network, it maintains between 26% and 36%. In US Backbone network, it increases from 12% for $TASY = 0\%$ to 33% for $TASY = 100\%$.

Table V
TOTAL FSS USAGE IN DE-EDPC, EUPC AND NEDPC.

TASY	NSFNET			US Backbone		
	De-EDPC	EUPC	NEDPC	De-EDPC	EUPC	NEDPC
0%	1385	1546	969	1635	1748	1349
20%	1247	2036	867	1834	2220	1563
40%	1194	2088	860	1903	2306	1603
60%	1334	2246	1018	2805	2788	2251
80%	1391	2546	1062	3057	3138	2483
100%	2007	3216	1482	3292	3278	2548

We also investigate the total FSs usage in De-EDPC, EUPC and NEDPC to make a fair comparison. Table V shows the total FSs usage with partial $TASY$. As the $TASY$ increases, more FSs are required in De-EDPC, EUPC and NEDPC except a small declining trend for De-EDPC and NEDPC with $TASY$ from 0% to 40% in NSF network. This downward is due to random asymmetric traffic generation. It means that the $TASY$ has a big impact on the FSs allocation. It is also observed that NEDPC requires fewer FSs than De-EDPC and EUPC. This is because it is optimized to minimize spectrum usage. De-EDPC outperforms EUPC in terms of FSs usage because that EUPC allocates twice FSs for the undirected p-cycles without consciousness of the different traffic volume while De-EDPC effectively allocates the FSs according to the different traffic volume in each direction.

Simulation results demonstrate that directed p-cycles provide an energy-efficient way to protect asymmetric traffic in EONs. De-EDPC with directed p-cycles earns significant energy savings and FSs savings against EUPC with undirected p-cycles, especially for asymmetric traffic with high $TASY$. De-EDPC also earns energy savings compared with NEDPC, and the amount of energy savings depends on the topology.

VII. Conclusion

We have addressed the issue of energy-efficient directed p-cycle protection for asymmetric traffic in EONs. Simulation results demonstrate that directed p-cycle earn significant energy savings and FSs savings compared with undirected p-cycles. Moreover, the energy savings rise with the increase of traffic asymmetry. Meanwhile, energy-efficient directed p-cycles also achieve energy savings compared with directed p-cycles with spectrum optimization. This provides useful insights for exploring asymmetric traffic protection for EONs energy-efficiently.

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