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# Survivable routing and spectrum allocation algorithm based on *p*-cycle protection in elastic optical networks

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ABSTRACT

With the number of large capacity applications in core network increasing, the bandwidth requirement of optical connections in conventional Wavelength Division Multiplexing (WDM) networks keeps enhancing, so that the Orthogonal Frequency Division Multiplexing (OFDM) technology is adopted to provide higher spectrum efficiency and flexibility in the future elastic optical networks. Meanwhile, survivability in the conventional WDM optical networks has been widely studied as an important issue to ensure the service continuity. However, survivability in OFDM-based elastic optical networks is more challenging than that in conventional WDM optical networks because each fiber usually carries even more connections. Therefore, it is necessary to study the new lightpath protection algorithm in elastic optical networks. Since *p*-cycle protection scheme has short restoration time and simple protection switching procedure, in this paper, we study the static Survivable *p*-Cycle Routing and Spectrum Allocation (SC-RSA) problem with providing an Integer Linear Programming (ILP) formulation. Since RSA is a NP-hard problem, we propose a new heuristic algorithm called Elastic *p*-Cycle Protection (ECP) to tolerate the single-fiber link failure. For each demand, ECP scheme can compute highly-efficient *p*-cycles to provide protection for all of the on-cycle links and the straddling links. We also consider the load balancing and choose the proper working path for each demand. Simulation results show that the proposed ECP scheme achieves better performances than traditional single-line-rate survivable schemes.



## 1. Introduction

In recent years, Internet applications such as Internet Protocol Television (IPTV), video on demand and cloud computing applications are of various types and impose diverse bandwidth requirements [1–3]. As a result, the conventional Wavelength Division Multiplexing (WDM) network is challenged when carrying such traffic and applications due to its inflexible grid and coarse bandwidth granularity. For example, a sufficiently wide wavelength may be spectrally efficient for some super-wavelength traffic demands. However, this optical channel is over-provisioned for the sub-wavelength traffic demands. This mismatch in demand requirements and wavelength bandwidth results in a significant waste of optical spectrum and inefficient capacity utilization. To eliminate the above shortcomings, the Elastic Optical Network (EON) based on Orthogonal Frequency Division Multiplexing (OFDM) technology has been proposed as new network architecture [4–7]. Compared to traditional WDM networks, EON is able to provide arbitrary contiguous spectrum slots due to its flexible allocation of spectrum and sliced utilization of capacity.

As the EON continues being mature, a wavelength channel has the transmission rate of over 100 gigabits per second, while it is foreseen that optical networks will be required to support Tb/s class transmission in the near future [8,9]. Enormous data loss may be experienced in the event of network failures, such as node, link, or channel faults. Therefore, survivability has been a critical issue in the design of the next generation optical networks with very high transmission rate. Some works have extensively studied the survivability in conventional WDM optical networks [10–16] for the past decade. In general, survivability is one of the basic requirements of a network, both in traditional WDM networks and EON.

Survivability is more sophisticated in EON than that in WDM networks since a link failure will affect a larger number of connections. Thus, it is more critical to ensure that every destination node can receive the traffic from the source node via the protection path in case of failure [17–19]. In the literatures [20–23], several

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protection schemes have been proposed to provide partial or 100% protection against the single link failure which is a dominate failure scenario in current optical networks. In [20], the authors proposed a bandwidth squeezed restoration scheme. It enables spectrally efficient and highly survivable network recovery for best-effort traffic as well as bandwidth guaranteed traffic. In [21], a spectrum-shared backup path protection scheme is proposed which can allow two working lightpaths to share backup spectrum in their common links as long as their corresponding working lightpaths do not share any common link. In [22], the authors presented a survivable multi-path provisioning scheme that provides flexible protection levels in OFDM-based flexible optical networks, and then an Integer Liner Programming (ILP) formulation and an efficient heuristic algorithm are given to solve the survivable routing problem. In [23], the impact of the hourly network traffic variation is considered and then a protection scheme is proposed to allow for a reduction in power consumption while maintaining a high level of availability. These protection algorithms mentioned above are all based on the path-shared protection mechanism, in which each connection request will be first assigned a working path, and then the working path will be assigned a link-disjoint backup path. However, previous works [12] have pointed out that path-shared protection may lead to long restoration time and complicated protection switching procedure.

In order to solve this problem, previous works have proposed pre-configured protection cycles ($p$-cycles) [24]. The $p$-cycle method offers ring-like fast restoration because $p$-cycles are pre-cross-connected. Meanwhile, the $p$-cycle method offers mesh-like high efficiency. Therefore, $p$-cycles gather the desired characteristics of mesh-based and ring-based protection methods, and so far, $p$-cycles have been extensively studied for WDM network traffic protection [25–27]. Some works also considered extending the $p$-cycle concept to other optical network protection. Based on the mixed-line rate optical networks, the authors in [28] developed and evaluated a new solution for $p$-cycle design. By rearranging the $p$-cycles, the scheme can help reduce the needs for transponders and protection capacity. Simulation results showed increased protection efficiency over fixed line rate networks and indicated promising avenues for future extensions. As these evolutions unfold, there is a critical need to extend the $p$-cycle protection to the emerging EON as well.

In this paper, we study the static Survivable $p$-Cycle Routing and Spectrum Allocation (SC-RSA) problem in OFDM-based elastic optical networks. As an analogy to the Routing and Wavelength Assignment (RWA) problem in WDM optical networks, the SC-RSA problem is also proved NP-hard [29]. We present ILP formulation for the SC-RSA problem, which can provide protection for connection requests by optimally allocating the sub-carriers in the network. We then propose a heuristic algorithm called Elastic $p$-Cycle Protection (ECP) to tolerate the on-cycle link failure or the straddling link failure. Compared with previous protection algorithm, ECP can obtain better performances in resource utilization ratio and computation complexity.

The rest of this paper is organized as follows: Section 2 describes the network model and the ILP formulation in detail. Section 3 proposes the heuristic steps of ECP. Section 4 presents the simulation and analysis. Section 5 concludes this paper.

## 2. Problem statement

### 2.1. Network model

The network topology is defined as $G(N,L)$ for an optical mesh network, where $N$ is the set of nodes, and $L$ is the set of fiber links which is bidirectional and contains two unidirectional fibers with

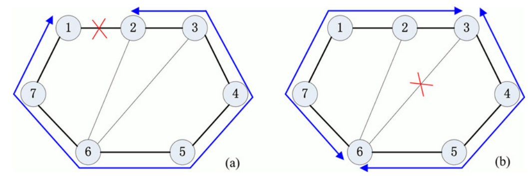


**Fig. 1.** Illustration of $p$-cycles protection.

contrary direction. In each link an ordered set $S = \{s_1, s_2, \ldots, s_k\}$ of frequency slots is given. We assume all links are assigned the same number of slots. Let $R$ denote the set of demands. The $i$th demand is denoted as $r_i(T_s, T_d, s_n)$, where $T_s$ is the source node, $T_d$ is the destination node, and $s_n$ is the number of slots needed by this demand. In order to achieve $p$-cycle protection, a set of disjoint $p$-cycles is generated based on the physical topology of the network. For the simplicity of calculation, we assume $a$ and $b$ are the starting node and the ending node of a $p$-cycle, respectively. In fact, there are no starting and ending nodes on a cycle. The shortest path algorithm, i.e., Dijkstra's algorithm, is applied to compute the route.

An example is given in Fig. 1; there exists a $p$-cycle 1–2–3–4–5–6–7. All the links in the network can be divided into two categories: on-cycle links denoted as $(u, v)$ and straddling links denoted as $(m, n)$. Any single failure of on-cycle link can be protected by the residual links along the $p$-cycle. For example, the failure of link (1, 2) can be protected by the backup path 1–7–6–5–4–3–2 as shown in Fig. 1(a). On the other hand, any single failure of straddling link can be protected by the residual links along either side. For example, the failure of straddling link (3, 6) can be protected by two backup paths 3–2–1–7–6 and 3–4–5–6.

### 2.2. ILP formulation

We initially present an optimal ILP formulation that minimizes the utilized spectrum. The following notations are introduced.

$J$: Maximum number of cycle sets in the solution.
$j$: $p$-Cycle index, where $j \in \{1, 2, \ldots, J\}$.
$y_s^j$: Binary variable, describing the usage of slot $s$. It is 1 if slot $s$ is allocated to $PC_j$, and 0 otherwise.
$x_{abs}^{uvj}$: Binary variable. It is 1 if span $(u, v)$ is an on-cycle span of $PC_j$ and it is allocated the slot $s$, and 0 otherwise.
$c_{mn}^j$: Binary variable. It is 1 if span $(m, n)$ can be protected by $PC_j$ and 0 otherwise.
$z_m^j$: Binary variable. It is 1 if node $m$ is on $PC_j$ and 0 otherwise.
$W_{ab}^j$: Total number of working slots allocated after the demands are accepted.

The ILP aims to minimize the number of slots required by the accepted demands in the network:

$$\text{minimize} \sum_j \sum_{s \in S} y_s^j \tag{1}$$

subject to the following constraints:

$$x_{abs}^{uvj} + x_{a'b's}^{uvj} \le y_s^j \qquad \forall (a,b) \ne (a',b'), \quad s \in S, \quad (u,v) \in E \tag{2}$$

$$x_{abs}^{uvj} - x_{abs}^{(u+1)(v+1)j} = 0 \qquad \forall (a,b) \in E, \quad s \in S, \quad \forall (u,v) \in E, \quad u+1 = v \tag{3}$$