Energy-Efficient Protection Designs for Translucent Optical Networks Using Mixed Regenerator Placement

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Abstract: We investigate energy-efficient protection designs for translucent networks using mixed regenerator placement (MRP). For link-based *p*-cycle designs, we develop an ILP model and a heuristic. We also propose a path-based shared backup path protection design algorithm.

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1. Introduction

Translucent optical networks utilize sparse placements of optical-electronic-optical (O/E/O) 3R (reamplification, reshaping, and retiming) regenerators to improve the cost-effectiveness and energy-efficiency of wavelength-routed transport networks. Recent research works have suggested that the energy-efficiency of a translucent network could be further improved by mixed regenerator placement (MRP) that leveraged the low energy-cost of all optical 2R (reamplification and reshaping) regenerators [1, 2]. For each connection request, MRP arranges the placements of optical 1R/2R/3R regenerators for the minimum total energy-cost under the quality-of-transmission (QoT) constraint [1]. On the other hand, we usually need to protect working connections in transport networks with redundant resources to avoid huge data loss during node or link failures. Hence, protection needs additional energy for improving network survivability, which implies that there is a dilemma between energy-efficiency and survivability in network designs. The protection scheme for translucent networks using MRP still has not been explored so far.

In this paper, we investigate energy-efficient protection designs for translucent networks using MRP. We first consider link-based protection using pre-configured cycles (*p*-cycles). *p*-cycle utilizes ring arrangements to achieve efficient link protection in mesh network topologies [3]. We formulate and solve the energy-efficient *p*-cycle design for translucent networks using MRP with an integer linear programming (ILP) model. The ILP model optimizes the regeneration energy-cost of working and protection resources jointly. Then, in order to reduce the computation complexity of the *p*-cycle design, we propose a heuristic that minimizes the energy-cost of working and protection resources one after the other. In addition to the link-based *p*-cycle, we study a path-based protection scheme that employs shared backup path protection (SBPP) [4]. A heuristic to minimize the energy-cost of the SBPP design is proposed for translucent networks using MRP. With simulations using the NSFNET topology, we evaluate the energy-efficiency of the protection designs and investigate the tradeoff between energy-efficiency and network survivability.

2. Energy-Efficient Protection Designs for Translucent Networks using MRP

The problem of energy-efficient protection design for translucent networks using MRP can be defined as follows: Given network topology $G(V,E)$ and a traffic matrix Λ, perform routing and wavelength assignment (RWA) and MRP for both working and protection resources such that: 1) all requests can be served with working connections that satisfy the QoT requirement, 2) 100% restorability can be achieved for a single-link failure in the network, and 3) the total energy-cost of optical 2R and 3R regenerators in the network is minimized.

Fig. 1 illustrates the link-based *p*-cycle protection scheme. For instance, when the working channel that is on link $1-2$ fails, the protection channel on the *p*-cycle $1-3-7-2-1$ restores it. Our joint ILP solves the working and protection resource allocations simultaneously. To reduce computation complexity, we perform certain pre-calculations: **1)** for each source-destination pair (s-d, $s,d \in V$) in the topology, we calculate K shortest path candidates, denoted as $\{R^k_{s,d}, k = 1...K\}$, **2)** we find all cycles in the topology, denoted as $\{C_i, i = 1...N\}$, where N is total number of cycles, **3)** For each cycle C_i, we calculate a regenerator placement, *i.e.*, MRP, which has the minimum total energy-cost under the QoT constraint [1]. In this work, we evaluate the QoT of a lightpath with its end-to-end bit-error-rate (BER), and make sure that this BER is $< BER_t$, where BER_t is a preset threshold. Notice that in order to guarantee that the MRP of a C_i can satisfy any of its protection scenarios, we need to make sure that the end-to-end BER of the longest path in C_i is $< BER_t$ with certain margin. The margin is reserved for the additional transmission that is out of C_i. We assume that both 2R and 3R regenerators have wavelength conversion capability, and hence we only consider wavelength continuity constraint for the segments between two 2R/3R regenerators. The joint ILP model is,

Notations: 1) $G(V,E)$: network topology with node set V and link set E, **2)** W: number of wavelengths on a link, **3)** Λ: traffic matrix consists of the demand $\lambda_{s,d}$ between each s-d pair, **4)** $\{C_i, i = 1...N\}$: all N cycles in G, **5)** $\chi_{i,e}$: cycle protection indicator, $\chi_{i,e} = 1$ if C_i can protect link $e, e \in E$, otherwise it is 0, **6)** ω_i: cycle wavelength resources, the

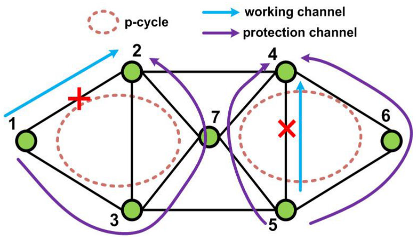

Fig. 1. An example of p-cycle.

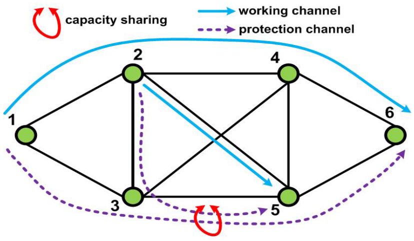

Fig. 2. An example of SBPP.

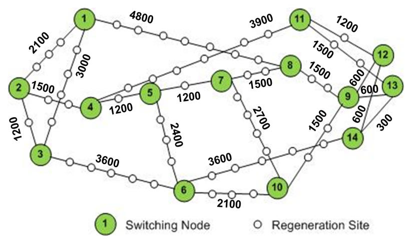

Fig. 3. NSFNET topology.

number of wavelength channels assigned to C_i, **7)** P_{2R}, P_{3R}: average energy-cost per 2R or 3R regenerator, **8)** $f_{u,i}^{C,j}$: cycle MRP flag, $f_{u,i}^{C,j} = 1$ if a j-R regenerator is placed at node u in cycle C_i, otherwise it is 0, **9)** $l_{s,d,r}$: r-th connection request from s to d, **10)** $\{R_{s,d}^k, k = 1...K\}$: K path candidates for a s-d pair, **11)** $f_{u,s,d,k}^{R,j}$: path MRP flag, $f_{u,s,d,k}^{R,j} = 1$ if a j-R regenerator is placed at node u in the k-th path candidate $R_{s,d}^k$ from s to d, otherwise it is 0, **12)** $\psi_{r,s,d,k}$: path selection indicator, $\psi_{r,s,d,k} = 1$ if the r-th connection from s to d takes the k-th path candidate, otherwise it is 0, **13)** $q_{i,e}^C$: cycle link-flag, $q_{i,e}^C = 1$ if C_i routes over link e, otherwise it is 0, **14)** $q_{s,d,e,r}^R$: working path link-flag, $q_{s,d,e,r}^R = 1$ if the r-th connection from s to d routes over link e, otherwise it is 0.

Objective:

$$\min \quad P = P_{2R}\Big(\sum_i \omega_i \sum_{u \in C_i} f_{u,i}^{C,2} + \sum_{s,d}\sum_r\sum_k \psi_{r,s,d,k} \sum_{u \in R_{s,d}^k} f_{u,s,d,k}^{R,2}\Big) + P_{3R}\Big(\sum_i \omega_i \sum_{u \in C_i} f_{u,i}^{C,3} + \sum_{s,d}\sum_r\sum_k \psi_{r,s,d,k} \sum_{u \in R_{s,d}^k} f_{u,s,d,k}^{R,3}\Big) \quad (1)$$

where the first part is the total energy-cost of the 2R regenerators for working and protection resources, and the second part is the total energy-cost of the 3R regenerators.

Constraints:

$$\sum_i \omega_i \cdot q_{i,e}^C + \sum_{s,d}\sum_r q_{s,d,e,r}^R \le W, \quad \forall e \in E \quad (2) \qquad \omega_i \ge 0, \forall i \quad (3)$$

$$\sum_k \psi_{r,s,d,k} = 1, \forall r \quad (4) \qquad \sum_r\sum_k \psi_{r,s,d,k} \ge \lambda_{s,d}, \forall r \quad (5) \qquad \sum_j f_{u,i}^{C,j} = 1, \forall u, i \quad (6)$$

$$\sum_j f_{u,s,d,k}^{R,j} = 1, \forall u, s, d, k \quad (7) \qquad \sum_i \omega_i \cdot \chi_{i,e} \ge \sum_{s,d}\sum_r q_{s,d,e,r}^R, \forall e \in E \quad (8)$$

Eqn. (2) is the capacity constraint. Eqns. (4) and (5) ensure all working connections are served and the total request capacities in the traffic matrix are satisfied. Eqns. (6) and (7) represent that for each wavelength channel of a cycle or a working path, only one regenerator should be placed at each intermediate node. Eqn. (8) ensures all working capacities are protected. After obtaining the working paths, the cycles and the associated MRP by solving the joint ILP, we assign wavelengths with a first-fit scheme under the wavelength continuity constraint. ILP can provide optimal solutions for energy-efficient p-cycle designs. However, it also requires numerous computation time, especially when the network has a large size and/or there are a lot of requests to serve. We propose a heuristic as follows,

Step 1: Serve working connections using the shortest path routing and maximum transparent segment wavelength assignment algorithm in [1], and allocate regenerators along the path.

Step 2: Find all cycles in the topology and allocate regenerators for each cycle.

Step 3: For each cycle, calculate its protection efficiency (PE), which is the ratio of the working capacity that it can protect in the current network to the capacity it occupies.

Step 4: Select the cycle that has the largest PE and implement it, and subtract the capacity that this cycle can protect from the current working capacity.

Step 5: Repeat Steps 2 and 3 until all working capacities are protected.

Fig. 2 illustrates an example of the SBPP scheme. The backup paths of the working channel over 1−2−4−6 and 2−5 share the same wavelength channel on link 3−5, since their working paths are disjoint. We propose an SBPP design algorithm as follows,

Step 1: For each request, find K shortest paths and calculate MRP for each path. Select two paths that have the smallest combined energy-cost.

Step 2: Perform wavelength assignment for the working path using the maximum transparent segment algorithm [1],

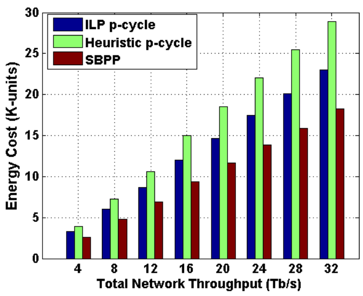

Fig. 4. Energy-cost results.

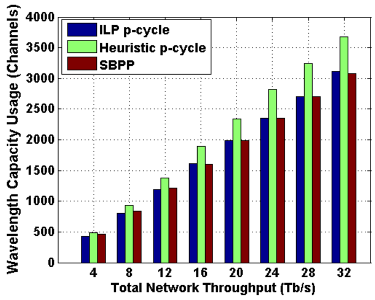

Fig. 5. Wavelength capacity usage.

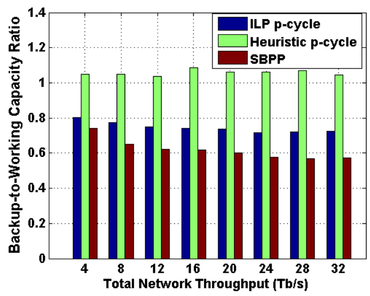

Fig. 6. Backup-to-working capacity ratio.

and insert additional 2R regenerators if necessary.

Step 3: For each link in the backup path, check whether a wavelength channel can be shared. In SBPP, the protection paths of multiple connections can share the same link resources if their working paths are disjoint. Perform first-fit wavelength assignment on the backup path's links that have not shared so far.

Step 4: Repeat Steps 1 to 3 until all pending requests are served.

3. Simulation Results

We perform simulations with the NSFNET topology shown in Fig. 3. We define two types of nodes in the topology, 1) switching nodes (labeled with numbers) where the connections can start and end, and 2) by-pass regeneration sites where the connections can only pass through. The distance between two adjacent regeneration sites is 600 km. Since a connection can only choose its *s*-*d* pair from the switching nodes, we obtain 259 cycles from this topology with the algorithm developed in [5]. We assume the average energy-costs of 2R and 3R regenerators are 2 and 15 units, respectively, based on the results in [6]. The data-rate of each wavelength channel is 40 Gb/s and each link can accommodate 160 channels. Our simulations generate connection requests by choosing the *s*-*d* pair randomly, and each request consumes a wavelength channel. We assume that $BER_t = 10^{-4}$. Fig. 4 compares the total energy-costs of the designs from the three algorithms for different volumes of requests. It can be seen that the SBPP scheme provides the highest energy-efficiency. This is due to the reason that SBPP is a path-based protection scheme, which is intrinsically more resource-efficient than the link-based *p*-cycle schemes [4]. In average, heuristic *p*-cycle consumes 24% extra energy than the ILP *p*-cycle. Fig. 5 shows the wavelength capacity usages of the designs from the algorithms. As connections can only origin from and end at switching nodes, we count the wavelength capacity usage as the number of wavelength channels over a primary link, *i.e.*, a link between two adjacent switching nodes. We observe that the wavelength capacity usage of the ILP *p*-cycle is very close to that of SBPP, while on average, the heuristic *p*-cycle requires 17.5% more wavelength capacity than the ILP. Fig. 6 illustrates the simulation results on backup-to-working capacity ratios. We define the backup-to-working capacity ratio (BWCR) as the ratio of the wavelength usage of the backup to that of the working connections. In this work, all three algorithms can achieve 100% restoration when there is a single failure. However, when multiple failures happen, the network's survivability is proportional to BWCR. Statistically, if a unit working capacity is protected by more backup capacity, the network is more survivable. We observe that the designs from the heuristic *p*-cycle have the largest BWCRs, while the SBPP provides the smallest BWCRs. Therefore, there is a clear tradeoff between the energy-efficiency of protection design and the network survivability.

4. Conclusion

We investigated both *p*-cycle and SBPP schemes for energy-efficient protection designs in translucent networks using MRP. Simulation results indicated that SBPP gained the highest energy-efficiency. For the *p*-cycle scheme, the heuristic required 17.5% extra wavelength usage and 24% extra energy-cost, when compared to the results of the ILP.

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