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Survivable Routing and Regenerator Placement in Optical Networks

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***Abstract*—The large capacity of WDM optical networks facilitates the transportation of impressive volumes of traffic, which make survivability schemes that can reroute traffic upon a failure in the network highly important. Besides survivability, the signal quality in optical networks, which degrades along its path due to physical impairments, needs consideration. In this paper, we consider the design problem of where to place regenerators in the network such that both the primary and backup lightpaths for a (predicted) traffic matrix obey the impairment constraints. We study the survivable routing and regenerator placement problem under dedicated and shared protection schemes, analyze the complexity of both problem variants, and subsequently propose efficient algorithms to solve or approximate them.**

***Index Terms*—Survivability, Regenerator Placement, Optical Impairments.**

I. Introduction

In wavelength division multiplexing (WDM) optical networks, the quality of a signal degrades due to physical impairments that accumulate along its path. This signal degradation may lead to an unacceptable bit-error rate (BER). Hence, the signal may need to be regenerated in order to regain its original quality. We define a *regeneration segment* of a lightpath (an optical point-to-point connection) to be a transparent (non-regenerated) segment (i.e., one or more links) between two consecutive regenerators (plus source and destination) of the lightpath. The impairment level on a regeneration segment is not allowed to exceed a given impairment threshold Δ. In practice, signals are regenerated per wavelength (and not per fiber), with optoelectronic regenerators and hence multiple regenerators may need to be installed at a node. A node that contains at least one regenerator is called a *regenerator node*. The main costs in deploying optoelectronic regenerators are equipment cost (CAPEX) and power consumption (OPEX), which are both directly proportional to the total number of regenerators in the network. Since regenerators are costly, it is desirable to minimize the number of regenerators in the network.

Lightpaths usually carry a large amount of data. Therefore, survivability, which is the ability to reconfigure and resume communication after link failure, is highly important in optical networks. The main approach to achieve fast survivability is through diverse routing, where link-disjoint *primary* and *backup* lightpaths are precomputed for each request. For a given request, the primary lightpath carries traffic during normal operation, while the backup lightpath takes over as soon as a failure is sensed on the primary lightpath. There exist two types of protection: *dedicated* and *shared* protection. In dedicated protection, the backup lightpaths do not share resources. In shared protection, backup lightpaths may share resources as long as their respective primary lightpaths do not share links.

In this paper, our main focus is on the survivable routing and regenerator placement problem where, given a (predicted) traffic matrix reflected in a set of requests, our objective is to allocate feasible link-disjoint primary and backup lightpaths for each request, while minimizing the total number of regenerators placed in the network. Each request is assumed to represent a single lightpath request (otherwise, each lightpath of a request is considered separately) and a lightpath has a capacity requirement of a single wavelength. We consider the problem of survivable routing and regenerator placement in the following two scenarios:

1) We first assume that enough fibers are already laid out to accommodate all the requests, and the main cost is associated with the regeneration capacity in the network. In this Routing and Regenerator Placement (RRP) scenario we can analyze the complexity of the regenerator placement problem independently from the routing and wavelength assignment (RWA) problem.
2) Subsequently we jointly solve the RWA and Regenerator Placement problems and call it the RWARP problem.

The RWA problem is NP-hard (cf. [5]) and usually solved via integer linear programming (ILP), which we will also use for scenario 2. This paper mainly focuses on scenario 1.

A. Regenerator Placement Context

Rai *et al.* [13] argued that most impairments can be modeled by (additive) link metrics. Consequently, in [11], we have considered impairment-aware path selection for multiple additive impairments. For a design problem, like placing regenerators, a more conservative approach suffices, where we consider a single impairment metric that represents the worst impairment among all the impairments on a link. Alternatively, the metric could reflect distance, which plays a key role in determining the quality of a signal, or a specific impairment metric like the Q-factor [1].

Even though a few technologies that allow for simultaneous regeneration of several wavelengths have been developed, optoelectronic devices, which offer per-wavelength regeneration, remain most practical and reliable [15]. In general, there are two approaches suggested in the literature with respect to regenerator placement: (1) designated regeneration sites and (2) selective, i.e. per-wavelength, regeneration [16]. In designated regeneration sites, regeneration can be performed only at a subset of nodes and the main objective is to minimize the total number of regenerator nodes. Moreover, it is assumed that a regenerator node has the capacity to provide regeneration for all lightpaths that need to be regenerated at that given node. Even though minimizing the total number of regenerator nodes has the advantage of reducing the number of active nodes, it is less flexible and may require more regenerators. This is even pronounced when add/drop equipment can be reused for regeneration. In selective regeneration, which is common practice (e.g., in combination with ROADMs [2]), the decision whether to regenerate a lightpath and where to perform regeneration is made on a per-wavelength basis and any node could be equipped with regenerators. The main objective in this scenario is to minimize the total number of regenerators. In this paper, we focus on selective regeneration, since it best reduces the cost of regeneration.

B. Related Work

Saradhi and Subramaniam [14] have provided a broad overview of issues with respect to impairment-aware routing and thereby also devoted a small section to regenerator placement. Impairment-aware network planning and operation is discussed in [17] and a corresponding tool has been proposed by Azodolmolky *et al.* [1].

Most work on regenerator placement is for unprotected lightpaths and assumes designated regeneration sites, e.g., [4], [6], [7] and references therein. Chen *et al.* [4] have shown that the unprotected regenerator placement problem that minimizes the number of regenerator nodes is NP-hard, and have provided heuristic algorithms. Flammini *et al.* [6] have considered different variants (also NP-hard) of the same problem with the assumption that all links have the same cost.

Fewer papers consider regenerator placement in the context of selective regeneration. Kuipers *et al.* [11] and Mertzios *et al.* [12] consider selective regenerator placement in a given optical network, while Katrinis and Tzanakaki [10] combine regenerator placement with network design, where only the node locations are predetermined. Beshir *et al.* [3] minimize the amount of transceivers for survivable impairment-aware traffic grooming in WDM rings. However, none of these papers considers provisioning per-wavelength regenerators in general networks for accommodating backup routes (as proposed in this paper) that need to be established in case of a link failure.

C. Contributions and Organization of the Paper

In Sec. II and Sec. III, we study survivable routing and regenerator placement under dedicated and shared protection schemes, respectively. We prove that the problem is NP-hard in both variants. We subsequently establish an approximation algorithm for the dedicated protection scheme. In addition, we provide a heuristic algorithm that outperforms this approximation algorithm and is close to the optimal solution in typical scenarios. We also propose an efficient heuristic algorithm for the shared protection scheme and demonstrate its performance through simulations in Sec. IV. We conclude in Sec. V.

Fig. 1. Example how to construct an instance of the regeneration problem from an instance of the partition problem.

II. Dedicated Protection

We start with a formal definition of the problem considered in this section.

Dedicated Survivable Routing and Regenerator Placement (DSRRP) Problem: The physical optical network is modeled as an undirected graph $G(\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of N nodes and $\mathcal{L}$ is the set of L links. Associated with each fiber link $(u, v) \in \mathcal{L}$ is an impairment value $r(u, v)$. A set of requests is given, where request i is represented by a source-destination pair (s_i, d_i), $s_i, d_i \in \mathcal{N}$. Let Δ represent the impairment threshold. The problem is to place regenerators and to find for each request two link-disjoint paths that each satisfy the impairment threshold on their regeneration segments, such that the total number of regenerators needed by all the requests is minimized.

Since we are considering dedicated regeneration, the different requests do not share regenerators. Thus, each request can be considered individually as follows.

Single Request Survivable Routing and Regenerator Placement (SRSRRP) Problem: Given an undirected graph $G(\mathcal{N}, \mathcal{L})$, impairment values $r(u, v)$, a threshold Δ, and a request represented by (s, d), the problem is to find a pair of link-disjoint paths for the request, and to place regenerators along these paths, while minimizing the total number of regenerators needed for both paths.

There can be two variants of the problem: (i) *Dedicated-Dedicated*: there is no sharing of regenerators between the two link-disjoint paths and (ii) *Dedicated-Shared*: if the backup path is used only after failure of the primary path, regenerators on nodes that belong to both the primary and backup paths can be shared. We now show that the SRSRRP problem is NP-hard under both variants.

Theorem 1: Both *dedicated-dedicated* and *dedicated-shared* variants of the SRSRRP problem are NP-hard.

Our proof makes use of the NP-hard **partition problem** [8]: Given a set of weights $a_i \in A$, $a_i \geq 0$ for $i = 1, \ldots, n$, where $S = \sum_{i=1}^{n} a_i$. Is there a subset $I \subseteq A$ such that $\sum_{a_i \in I} a_i = \sum_{a_i \in A \setminus I} a_i = \frac{S}{2}$?

Proof: Consider graph G in Fig. 1. For the weights associated with the labeled links $a_i \in A$, $0 < a_i < S$, for $i = 1, \ldots, n$, holds that $S = \sum_{i=1}^{n} a_i$. Links without labels have a cost of zero and $\Delta = S$. The objective is to find a pair of link-disjoint paths such that the total number of regenerators needed (shared or non-shared) for the two paths is minimized. There should definitively be regeneration at node t: one regenerator in case of regenerator sharing, and two if there is no sharing. The next step is to decide whether more regenerators are required at other nodes. Let the two selected paths be P^1_{s-t-d} and P^2_{s-t-d}. The only scenario where no more regenerators are required is when their two corresponding segments have a cost $r\left(P^1_{s-t}\right) = r\left(P^2_{s-t}\right) = S$. However, this involves equally partitioning the labeled links $a_i \in A$, $i = 1, \ldots, n$ between the two paths. ■

A min-sum link-disjoint paths algorithm that minimizes on the total weight of the two paths, such as Suurballe's algorithm [18], is an approximation algorithm. To prove this, we begin with two lemmas that relate to an unprotected path.

Lemma 1: The number of regenerators R required by any simple path P of length $r(P) > 0$ is bounded by

$$\left\lceil \frac{r(P)}{\Delta} \right\rceil - 1 \le R \le 2 \left\lceil \frac{r(P)}{\Delta} \right\rceil .$$

Fig. 2. For a given path P of length $r(P)$, a representation of any regenerator placement problem on a path.

Proof: The number of regenerators required by the given path is minimized if each regeneration segment covers as much length as possible. Hence, a best-case scenario for path P occurs when each regeneration segment, except possibly one, has a length exactly equal to Δ.

Without loss of generality, any placement of regenerators over a simple path P can be described as in Fig. 2, where there are $2k+1$ regeneration segments, and hence at most $2k$ regenerators needed. Furthermore, it is clear that for all i, $0 \le \varepsilon_i < \mu_i$; otherwise, the regenerator between the segments of length $\Delta - \varepsilon_i$ and μ_i could be omitted. Similarly, for all $i < k$, $\mu_i > \varepsilon_{i+1}$.

With $\beta = \min_i(\Delta - \varepsilon_i + \mu_i) > \Delta$ it follows that

$$k\beta + \delta \le \sum_{i=1}^{k} (\Delta - \varepsilon_i + \mu_i) + \delta = r(P),$$

or

$$k \le \frac{r(P) - \delta}{\beta} \le \frac{r(P)}{\Delta}.$$

For $\delta \ge 0$, the total number of regenerators, R, is at most $2k$. It follows that

$$R = 2k \le \frac{2r(P)}{\Delta} \le 2 \left\lceil \frac{r(P)}{\Delta} \right\rceil .$$

■

Lemma 2: If the optimal path between nodes s and d requires R^* regenerators, then the shortest (in terms of impairment) path from s to d requires at most $2(R^*+1)$ regenerators.

Proof: Let P be the shortest path from s to d, $r(P)$ be its length, and R be its required number of regenerators. Let P^* be the path that requires the optimal number of regenerators R^*. Hence, its length $r(P^*) \ge r(P)$.

Combining with Lemma 1,

$$R^* \ge \left\lceil \frac{r(P^*)}{\Delta} \right\rceil - 1 \ge \left\lceil \frac{r(P)}{\Delta} \right\rceil - 1.$$

By multiplying both sides by 2 and adding 2,

$$2R^* + 2 \ge 2 \left\lceil \frac{r(P)}{\Delta} \right\rceil .$$

According to Lemma 1, the number of regenerators required by the shortest path P is at most $2\left\lceil \frac{r(P)}{\Delta} \right\rceil$. ■

We are now ready to state our main result for the *dedicated-dedicated* case.

Theorem 2: Given an instance of the *dedicated-dedicated* SRSRRP problem, the min-sum (in terms of impairment) link-disjoint pair of paths between s and d require at most $2(R^*+3)$ regenerators, where R^* is the optimal solution for the given *dedicated-dedicated* SRSRRP instance.

Proof: Let P^*_1 and P^*_2 be the pair of link-disjoint paths that give the optimal solution, and require R^*_1 and R^*_2 regenerators, respectively. Thus, $R^*_1 + R^*_2 = R^*$. Similarly, let P_1 and P_2 be the shortest pair of link-disjoint paths, and R_1 and R_2 be their respective required number of regenerators.

Since $r(P^*_1) + r(P^*_2) \ge r(P_1) + r(P_2)$,

$$\left\lceil \frac{r(P^*_1) + r(P^*_2)}{\Delta} \right\rceil \ge \left\lceil \frac{r(P_1) + r(P_2)}{\Delta} \right\rceil .$$

Using the property of the ceiling function, $\lceil a \rceil + \lceil b \rceil \ge \lceil a + b \rceil \ge \lceil a \rceil + \lceil b \rceil - 1$, we obtain

$$\left\lceil \frac{r(P^*_1)}{\Delta} \right\rceil + \left\lceil \frac{r(P^*_2)}{\Delta} \right\rceil \ge \left\lceil \frac{r(P_1)}{\Delta} \right\rceil + \left\lceil \frac{r(P_2)}{\Delta} \right\rceil - 1.$$

Multiplying both sides by 2 and adding 2, we get:

$$2\left(\left\lceil \frac{r(P^*_1)}{\Delta} \right\rceil - 1\right) + 2\left(\left\lceil \frac{r(P^*_2)}{\Delta} \right\rceil - 1\right) + 6 \ge$$
$$2\left\lceil \frac{r(P_1)}{\Delta} \right\rceil + 2\left\lceil \frac{r(P_2)}{\Delta} \right\rceil .$$

Combining with Lemma 1 yields

$$2(R^*_1 + R^*_2 + 3) = 2(R^* + 3) \ge R_1 + R_2.$$

■

Similarly, we obtain the following result for the *dedicated-shared* case.

Theorem 3: Given an instance of the *dedicated-shared* SRSRRP problem, the min-sum link-disjoint paths between s and d require at most $4R^*+6$ regenerators, where R^* is the optimal solution for the *dedicated-shared* SRSRRP instance.

Proof: The best case for the *dedicated-shared* SRSRRP problem occurs when all regenerators of one of the paths are shared by the other path. Using the same notation as in the proof of Theorem 2, we have that P_1^* requires at least $\left\lceil \frac{r(P_1^*)}{\Delta} \right\rceil - 1$ regenerators and P_2^* requires at least $\left\lceil \frac{r(P_2^*)}{\Delta} \right\rceil - 1$ regenerators. W.l.o.g., assume that $r(P_2^*) \geq r(P_1^*)$. Hence, the two link-disjoint paths require at least $\left\lceil \frac{r(P_2^*)}{\Delta} \right\rceil - 1$ regenerators; otherwise P_2^* is not feasible. Analogous to the proof of Theorem 2, it follows that $4R^* + 6 \geq R_1 + R_2$. ■

The above results can be strengthened in the case where all links have equal cost. Several papers (e.g., [12], [6]) take hopcount as the impairment metric and argue that a limit on the maximum hopcount between regenerators provides a valid placement strategy in practice. In such a case, each link has a cost of 1, corresponding to one hop. We begin with the following lemma.

Lemma 3: If all links in the network have equal cost, then the number of regenerators required by any path P with length $r(P)$ exactly matches the lower bound $\left\lceil \frac{r(P)}{\Delta} \right\rceil - 1$.

Proof: Let the cost of each link be r. We assume that $\Delta = \delta r$ is a multiple of r, with $\delta \in \mathbb{N} \backslash \{0\}$. Otherwise, since all links have the same cost r, if a given segment satisfies the threshold Δ, it also satisfies $r \left\lfloor \frac{\Delta}{r} \right\rfloor$. Therefore, Δ can be replaced by $r \left\lfloor \frac{\Delta}{r} \right\rfloor$. Thus, exactly $\left\lceil \frac{h(P)}{\delta} \right\rceil - 1 = \left\lceil \frac{r(P)}{\Delta} \right\rceil - 1$ regenerators are required, where $h(P)$ is the hopcount of path P and the -1 reflects that no regeneration is needed at the destination. ■

We then obtain the following improved approximation bound for the *dedicated-dedicated* case.

Theorem 4: For a given instance of the *dedicated-dedicated* SRSRRP problem, if all links in the network have equal cost, the min-sum link-disjoint paths between s and d require at most $R^* + 1$ regenerators, where R^* is the optimal solution for the given *dedicated-dedicated* SRSRRP instance.

Proof: From the proof of Theorem 2, we have

$$\left\lceil \frac{r(P_1^*)}{\Delta} \right\rceil + \left\lceil \frac{r(P_2^*)}{\Delta} \right\rceil \geq \left\lceil \frac{r(P_1)}{\Delta} \right\rceil + \left\lceil \frac{r(P_2)}{\Delta} \right\rceil - 1.$$

Subtracting 1 on both sides,

$$\left(\left\lceil \frac{r(P_1^*)}{\Delta} \right\rceil - 1 \right) + \left(\left\lceil \frac{r(P_2^*)}{\Delta} \right\rceil - 1 \right) + 1 \geq \left(\left\lceil \frac{r(P_1)}{\Delta} \right\rceil - 1 \right) + \left(\left\lceil \frac{r(P_2)}{\Delta} \right\rceil - 1 \right).$$

Combining this with Lemma 3 yields

$$R_1^* + R_2^* + 1 = R^* + 1 \geq R_1 + R_2.$$

■

Similarly, we obtain the following improved result for the *dedicated-shared* case.

Theorem 5: For a given instance of the *dedicated-shared* SRSRRP problem, if all links in the network have equal cost, the min-sum link-disjoint pair of paths between s and d require at most $2R^* + 1$ regenerators, where R^* is the optimal solution for the given *dedicated-shared* SRSRRP instance.

A. Heuristic Algorithm

While the algorithmic scheme based on Suurballe's algorithm provides proven (worst-case) performance guarantees, performance in typical scenarios could be improved. To that end, we present the following heuristic, termed DEdicated Survivable Regenerators Algorithm ($DESRA$), for solving the SRSRRP problem. Later, in Sec. IV, we will show through simulations that $DESRA$ performs better than Suurballe's algorithm (and, when operated in tandem, the same proven worst-case guarantees can be established).

Algorithm 1 $DESRA(G, s, d, \Delta)$

1) Make a graph $G^{'}(\mathcal{N}, \mathcal{L}^{'})$, where $\mathcal{L}^{'} = \{(u, v) \mid r(P_{u-v}^*) \leq \Delta\}$ and P_{u-v}^* is the shortest path between u and v. Assign a cost of 1 to each link in $G^{'}$.
2) Find the shortest path $P_{s-d}^{'}$ from s to d in $G^{'}$.
3) Substitute all the links (u, v) of $P_{s-d}^{'}$ with the corresponding subpaths P_{u-v}^* in G to obtain P_{s-d}.
4) Remove all loops of P_{s-d} in G to obtain path $P_{s-d;1}$.
5) Redirect all links in $P_{s-d;1}$ from d to s to obtain $G^{''}(\mathcal{N}, \mathcal{L}^{''})$ and assign a cost of 0 to these links.
6) On graph $G^{''}$ repeat steps $1-4$ to obtain path $P_{s-d;2}$.
7) Remove links that are both in $P_{s-d;1}$ and $P_{s-d;2}$ to obtain two link-disjoint paths.
8) Place regenerators (shared or not shared depending on what is needed) for each path.

In Step 1 of algorithm $DESRA$, graph $G^{'}$ is constructed by connecting all directly reachable nodes (i.e., within Δ). The links in graph $G^{'}$ represent subpaths in graph G. Once the shortest path is obtained in Step 2, the path is transformed to its equivalent path P_{s-d} in graph G. Since this path is made of a concatenation of path segments, it may not be a *simple* path in G. Loops are removed in Step 4 and the links along the loopless path $P_{s-d;1}$ are redirected from d to s to obtain graph $G^{''}$ in Step 5. In Step 6, the same procedures are repeated in graph $G^{''}$ to find the second loopless path $P_{s-d;2}$. The directed links in $G^{''}$ may result in cases where $P_{u \to v}^* \neq P_{v \to u}^*$, in which case the graph obtained from $G^{''}$ may contain two directed links between nodes u and v, one in either direction. Once the second path $P_{s-d;2}$ is computed, the interlacing links between $P_{s-d;1}$ and $P_{s-d;2}$ are removed to obtain the solution. Finally, the regenerators are placed on these paths. For the shared variant, the regenerators for the primary lightpath are placed first, followed by those of the backup lightpath, while reusing the regenerators of the primary path at the shared nodes, if any.

The complexity of algorithm $DESRA$ is dominated by constructing graphs $G^{'}$ and $G^{''}$ (e.g., using Dijkstra's algorithm N times). Thus, the total complexity of algorithm $DESRA$ is $O(N^2 \log N + NL)$.

III. Shared Protection

Shared Survivable Routing and Regenerator Placement (SSRRP) Problem: Given the input to DSRPP, the SSRRP problem is, for each request, to find a pair of link-disjoint paths that satisfy the impairment threshold on their regeneration segments. The objective is to place a minimum number of regenerators needed by all requests such that backup lightpaths can share regenerators as long as their primary lightpaths do not share links.

Unlike the dedicated case, sharing regenerators between backup paths prevents sharing between primary and backup paths. The problem **SSRRP** is NP-hard, since it contains the **SRSRRP** problem (shown to be NP-hard in Sec. II) when only one source-destination pair exists. Hence, we provide a heuristic algorithm.

A. Heuristic Algorithm

Our algorithm is named ShAred Survivable Regenerators Algorithm ($SASRA$). We employ an active-path-first approach where the primary path is computed first and then its links are dropped before the backup path is computed, because it is easier to determine the sharing of resources among backup paths when the primary paths are already in place.

Algorithm 2 $SASRA(G, \Delta)$

For each request i,
1) In G, find the shortest paths $\{P^*_{u-v}\}$ between all nodes $u, v \in \mathcal{N}$, for which $r(P^*_{u-v}) \leq \Delta$.
2) Create a graph $G^{'}(\mathcal{N}, \mathcal{L}^{'})$, where $\mathcal{L}^{'} = \{(u,v) \mid r(P^*_{u-v}) \leq \Delta\}$ and assign a cost of 1 to each link. Find the shortest path $P^{'}_{s_i-d_i}$ from s_i to d_i in $G^{'}$.
3) Substitute the links of $P^{'}_{s_i-d_i}$ with the corresponding subpaths P^*_{u-v} in G to obtain $P_{s_i-d_i}$.
4) Remove all loops of $P_{s_i-d_i}$ in G to obtain path $P_{s_i-d_i;1}$. Place the necessary regenerators for $P_{s_i-d_i;1}$.
5) Remove all links in $P_{s_i-d_i;1}$ to obtain $G^{''}(\mathcal{N}, \mathcal{L}^{''})$.
6) For each primary path that does not share a link with $P_{s_i-d_i;1}$, set the cost of each link incident to the regenerator nodes of its backup path to zero.
7) Repeat Steps $1-4$ to obtain $P_{s_i-d_i;2}$. Place the necessary regenerators for $P_{s_i-d_i;2}$.

For each request, a graph G', containing links between all reachable nodes in graph G is obtained in Steps 1 and 2 of $SASRA$. The shortest path between the source and destination nodes of the request in G' is transformed to its equivalent path in graph G in Step 3. Then, its loops are removed and the necessary regenerators are placed in Step 4. The links of this path ($P_{s_i-d_i;1}$) are removed in Step 5 and the cost of links incident to shareable regenerator nodes are set to zero in Step 6 to encourage the re-use of regenerators in those nodes, before similarly computing the second path in Step 7. Per request, $SASRA$ has the same complexity as $DESRA$, namely $O(N^2 \log N + NL)$.

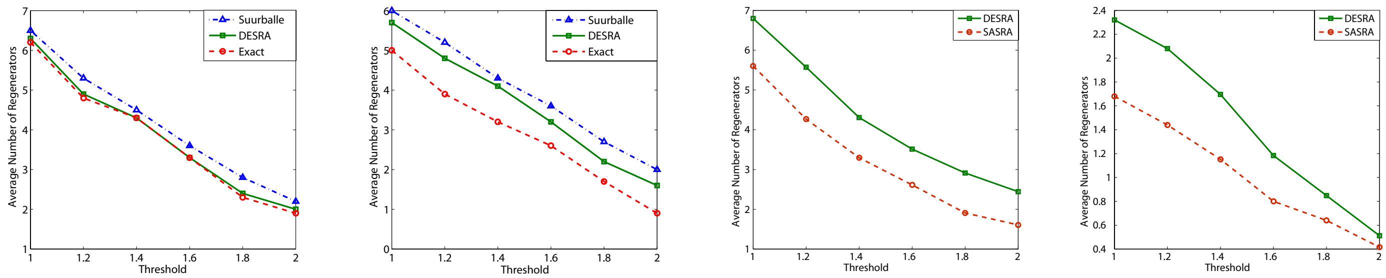
IV. Simulation Results

In this section, we evaluate the performance of our proposed heuristics, namely $DESRA$ and $SASRA$. We first provide simulation results that show the average number of regenerators needed *per request* on a typical carrier backbone network. As can be seen in [7], [10], [11], [13], often (a variation on) the NSFNET, ARPANET, or USANET is chosen as a typical network. We choose the larger of the three, namely the USANET network of 28 nodes and 45 links [9]. In our simulations, we use scaled impairment values, which are randomly and uniformly generated in the range $(0, 1]$, impairment threshold values Δ in the range $[1, 2]$, and randomly selected source and destination nodes. The simulation results represent an average of 10 iterations, each for a traffic matrix consisting of 100 requests. Fig. 3(a) shows a comparison of Suurballe's algorithm, $DESRA$ and an exact solution (obtained via an ILP formulation given in the Appendix) for the *dedicated-dedicated* problem variant, while Fig. 3(b) shows the same for the *dedicated-shared* problem variant. These results show that $DESRA$ always outperforms Suurballe's algorithm (which on its turn performs better than the worst-case bounds derived in Sec. II) and performs close to the exact solution, especially for the *dedicated-dedicated* variant.

The USANET network provides a benchmark, but confines the study to one network. Therefore, we have extended our simulations to 1000 networks (using the same settings as for USANET, except that we use 1 instead of 10 iterations) in the classes of lattices (two-dimensional square grids) and Erdős-Rényi random networks. Since it is too time-consuming to iterate the ILP 1000 times, we compare the performance of $SASRA$ to $DESRA$ in Fig. 3(c) and (d). As one might expect, sharing of regenerators among backup lightpaths decreases the number of regenerators needed. Within the considered threshold range, this improvement remains fairly constant for lattice networks, while it diminishes with increasing threshold in random networks, where the average hopcount of a path is smaller than that of lattice networks, thereby decreasing the need for regenerators (and also sharing) at higher thresholds.

V. Conclusions

We have studied the survivable regenerator placement problem, where the objective is to minimize the total number of regenerators placed in an optical network such that feasible primary and backup lightpaths can be assigned to the requests of a given traffic matrix. We have considered two protection schemes: dedicated and shared protection. These schemes have been studied in two scenarios, namely 1) routing and regenerator placement, and 2) routing, wavelength assignment, and regenerator placement. For the latter an ILP has been formulated, while for the first we have shown that the problem is NP-hard in both schemes. For the case of dedicated protection, we established a constant-factor approximation based on Suurballe's algorithm. Furthermore, we provided a heuristic algorithm that, based on simulations, was shown to outperform the approximation scheme and was close to optimal in typical scenarios. For the case of shared protection, we have provided a heuristic algorithm, and demonstrated its good performance through simulations.



(a) Dedicated-dedicated (b) Dedicated-shared (c) Lattice network (d) Random network

Fig. 3. Comparison of the average number of regenerators needed *per request* for the (a) *dedicated-dedicated* variant in USANET, (b) *dedicated-shared* variant in USANET, (c) in Lattice networks of 49 nodes, and (d) in random networks of 50 nodes and link density $p = 0.2$.

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APPENDIX

We provide an exact integer linear programming (ILP) formulation using network flow equations to solve the RWARP problem (see Sec. I). Since this is a design problem, all the requests should be accommodated. Hence, we assume that there are enough wavelengths to optimally and feasibly route all the lightpaths; otherwise the problem is infeasible. The same ILP formulation can be used for solving the SRSRRP problem of Sec. II by setting $F = 1$ and $W = 1$.

Indices:

- $i = 1, \ldots, F$ — ID of requests.
- $\lambda = 1, \ldots, W$ — ID of wavelengths.
- $\mathcal{L}^-(u)/\mathcal{L}^+(u)$ — Incoming/outgoing links of node u.

Variables (binary):

- $x_{i,l,u,\lambda}$ — is 1 if the primary lightpath of request i uses wavelength λ on link l, and node u is its last regenerator node (or the source node) before encountering link l; 0 otherwise.
- $y_{i,l,u,\lambda}$ — is 1 if the backup lightpath of request i uses wavelength λ on link l, and node u is its last regenerator node (or the source node) before encountering link l; 0 otherwise.
- $\tau_{i,u,v,\lambda}$ — is 1 if the primary lightpath of request i uses a regenerator at node u directly followed by a regenerator at node v on wavelength λ; 0 otherwise. Node u can also be the source node.
- $\psi_{i,u,v,\lambda}$ — is 1 if the backup lightpath of request i uses a regenerator at node u directly followed by a regenerator at node v on wavelength λ; 0 otherwise. Node u can also be the source node.
- $\alpha_{i,u}$ — (Only for the shared variant) is 1 if a regenerator (shared or not) is needed at node u for request i; 0 otherwise.

Objective:

Minimize the total number of regenerators needed by the primary and backup lightpaths.

For the *dedicated-dedicated* variant:

$$Minimize: \sum_{i} \sum_{\lambda} \sum_{u \in \mathcal{N}} \sum_{v \in \mathcal{N}} (\tau_{i,u,v,\lambda} + \psi_{i.u,v,\lambda}) \quad (1)$$

For the *dedicated-shared* variant:

$$Minimize: \sum_{i} \sum_{u \in \mathcal{N}} \alpha_{u,i} \quad (2)$$

Constraints:

Flow Conservation constraints:

At the source node of each request there are exactly two flows leaving the source node: one for the primary and another for the backup lightpaths.

$$\sum_{\lambda} \sum_{l \in \mathcal{L}^+(s_i)} (x_{i,l,s_i,\lambda} + y_{i,l,s_i,\lambda}) = 2 \quad \forall i \quad (3)$$

For each request, at its intermediate nodes:

If a given node v is not the source or the destination node, then the flow related to the primary/backup lightpath that enters v has to leave it after being regenerated ($\tau_{i,u,v,\lambda} = 1$ for the primary and $\psi_{i,u,v,\lambda} = 1$ for the backup lightpath) or not ($\tau_{i,u,v,\lambda} = 0$ for the primary and $\psi_{i,u,v,\lambda} = 0$ for the backup lightpath).

$$\sum_{l \in \mathcal{L}^-(v)} x_{i,l,u,\lambda} - \sum_{l \in \mathcal{L}^+(v)} x_{i,l,u,\lambda} = \tau_{i,u,v,\lambda} \text{ and} \quad (4)$$
$$\sum_{l \in \mathcal{L}^-(v)} y_{i,l,u,\lambda} - \sum_{l \in \mathcal{L}^+(v)} y_{i,l,u,\lambda} = \psi_{i,u,v,\lambda}$$
$$\forall i; \forall v \in \mathcal{N} \backslash \{s_i, d_i\}; \forall u \in \mathcal{N} \backslash \{v\}; \forall \lambda$$

If a lightpath is regenerated at node v, the last regenerator node in the new segment should be node v.

$$\sum_{l \in \mathcal{L}^+(v)} x_{i,l,v,\lambda} - \sum_{u \in \mathcal{N} \backslash \{v\}} \tau_{i,u,v,\lambda} = 0 \quad \text{and} \quad (5)$$
$$\sum_{l \in \mathcal{L}^+(v)} y_{i,l,v,\lambda} - \sum_{u \in \mathcal{N} \backslash \{v\}} \psi_{i,u,v,\lambda} = 0$$
$$\forall i; \forall v \in \mathcal{N} \backslash \{s_i, d_i\}; \forall \lambda$$

Disjointedness constraints:

The primary and backup lightpaths of a given request should be link disjoint.

$$\sum_{\lambda}\sum_{u\in\mathcal{N}}(x_{i,l,u,\lambda}+y_{i,l,u,\lambda})\leq 1 \qquad \forall i;\forall l\in\mathcal{L} \tag{6}$$

Wavelength constraints:

A wavelength on a given link can only be used by a single lightpath.

$$\sum_{i}\sum_{u\in\mathcal{N}}(x_{i,l,u,\lambda}+y_{i,l,u,\lambda})\leq 1 \qquad \forall l\in\mathcal{L};\forall\lambda \tag{7}$$

Simple path constraints:

Lightpaths should not contain loops. At the source node of each request, there should not be a flow of the request associated with any of its incoming links.

$$\sum_{\lambda}\sum_{l\in\mathcal{L}^-(s_i)}\sum_{u\in\mathcal{N}}(x_{i,l,u,\lambda}+y_{i,l,u,\lambda})=0 \qquad \forall i \tag{8}$$

In addition, any flow of a request that exits its source node, other than the one originating at the source node, should explicitly be set to 0.

$$\sum_{\lambda}\sum_{l\in\mathcal{L}^+(s_i)}\sum_{u\in\mathcal{N}\setminus\{s_i\}}(x_{i,l,u,\lambda}+y_{i,l,u,\lambda})=0 \quad \forall i \tag{9}$$

Similarly, for any intermediate node, there can at most be one flow of the primary or backup lightpath entering the node.

$$\begin{aligned}&\sum_{\lambda}\sum_{l\in\mathcal{L}^-(v)}\sum_{u\in\mathcal{N}}x_{i,l,u,\lambda}\leq 1 \text{ and} \\ &\sum_{\lambda}\sum_{l\in\mathcal{L}^-(v)}\sum_{u\in\mathcal{N}}y_{i,l,u,\lambda}\leq 1 \qquad \forall v\in\mathcal{N}\setminus\{s_i\};\forall i\end{aligned} \tag{10}$$

Impairment constraints:

The physical impairment of any transparent segment should be less than the threshold.

$$\begin{aligned}&\sum_{\lambda}\sum_{l\in\mathcal{L}}r(l)\cdot x_{i,l,u,\lambda}\leq\Delta \text{ and} \\ &\sum_{\lambda}\sum_{l\in\mathcal{L}}r(l)\cdot y_{i,l,u,\lambda}\leq\Delta \qquad \forall u\in\mathcal{N};\forall i\end{aligned} \tag{11}$$

Only for the *dedicated-shared* variant:

$$\sum_{\lambda}\sum_{u\in\mathcal{N}}(\tau_{u,v,\lambda,i}+\psi_{u,v,\lambda,i})\leq 2\cdot\alpha_{v,i} \qquad \forall v\in\mathcal{N};\forall i \tag{12}$$

The aforementioned equations are for directed networks. For undirected networks, we first replace each link with two directed links in either direction. Let for each directed $l=(u,v)\in\mathcal{L}$, its corresponding oppositely directed link be $l^{'}=(v,u)\in\mathcal{L}$. Then, replace Eq. 6 with the following equation.

$$\sum_{\lambda}\sum_{u\in\mathcal{N}}(x_{i,l,u,\lambda}+y_{i,l,u,\lambda}+x_{i,l',u,\lambda}+y_{i,l',u,\lambda})\leq 1 \ \forall i;\forall l\in\mathcal{L} \tag{13}$$

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