Optimal Regenerator Placement for Path Protection in Impairment-Aware WDM Networks

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***Abstract*—This paper addresses the regenerator placement problem (RPP) when designing resilient, impairment aware WDM optical networks. For the RPP, we have proposed two solutions; an optimal solution for small networks (less than 10 nodes) and a near-optimal heuristic solution for practical-sized networks. The optimal solution uses an Integer Linear Program which can be implemented by any solver for mathematical programming. The heuristic makes use of an approach, proposed in a recent paper, that requires a formulation involving an exponential number of constraints. It was shown in that paper that this formulation can be solved very efficiently using a branch-and-cut algorithm and that the approach may be used to design resilient networks which guarantees restoration. In this paper we have shown that this branch-and-cut approach may be used as a part of a highly efficient heuristic which gave optimal results in an overwhelming number of cases that we tested.**

I. Introduction

The quality of transmission (QoT) of an optical signal propagating through a wavelength division multiplexed (WDM) network degrades, due to physical layer impairments, such as *optical noise*, *chromatic and polarization mode dispersion*, *four wave mixing*, *cross-phase modulation* and *cross-talk* [1], [2]. When the quality of an optical signal becomes unacceptable, it is necessary to carry out *3R regeneration* (*reamplify*, *reshape* and *retime*) on the optical signal [1], [2]. *Optical reach* [2] (also called *transparent reach* [1], [12] is the maximum distance an optical signal can travel before 3R-regeneration is needed. Optical reach is a popular metric [2] to determine when 3R regeneration is needed and usually ranges from 2000 to 4000 km [2]. In a *translucent network* [1], [2], at least one optical signal is regenerated at one or more regeneration points (typically a selected subset of the nodes of the network have the capacity to carry out 3R-regeneration [1]), so that the signal may be communicated over long distances. In this paper, we will call a node which has the capacity to carry out 3R regeneration as a *regenerator node*.

These regenerators can be viewed as dividing a lightpath into *segments*. A segment starts from either a source of a lightpath or from a node where it undergoes regeneration and it ends at either the destination of the lightpath or at another node where it undergoes regeneration. We will designate a path from a source node to a destination node as a *viable path*, if the length of each of the segments, constituting the path, does not exceed the optical reach. The route used by a translucent lightpath must be a viable path to ensure that the quality of transmission always remains acceptable.

The type of requests for communication in a WDM network are broadly classified as *static* or *dynamic* [12], [5]. If the requests are dynamic lightpath demands (DLD), a lightpath is set up (if possible) when the requests is received and is taken down when the data communication is over. In a recent book [2], it was stated that though transport optical networks today are typically quasi-static, with connections often remaining established for months or years, the next step in this evolution is dynamic networking, where connections can be rapidly established and torn down without the involvement of operations personnel.

In a network that handles DLD, regenerators are placed at selected nodes during the design phase. This is called the *Regenerator Placement Problem* (RPP) [2], [7] and is defined as follows. Given a network topology, a minimum number of nodes to be regenerator nodes have to be selected, so that each node can communicate with any other node in the network, using either a transparent lightpath or a translucent lightpath. This standard definition of RPP assumes that the network never develops faults. In this paper we will slightly modify the definition to handle single link failures in the network. The

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RPP problem is known to be NP-complete [7] and heuristics are typically used to solve this problem[7], [8] for relatively larger networks.

Path protection is a well-known technique for handling faults in WDM networks [9]. For each request for communication, say from a source node, S to a destination node, D, provisions are made for setting up two possible lightpaths[1], both from S to D. The paths for these two lightpaths are enforced to be edge-disjoint to ensure that both the lightpaths do not fail at the same time for any single link failure.

In this paper, we consider RPP that guarantees communication using path protection, assuming the single link failure model[9]. Given an impairment-aware network, we want to find the minimum number of regenerator-capable nodes such that, for every request for communication from a source node S to a destination node D, it is always possible to find a primary path which is edge-disjoint with respect to a backup path from S to D with regenerators available, when needed [23]. We have proposed two approaches for RPP using path protection as follows:

- The first approach is an Integer Linear Programming (ILP) formulation that gives an optimal regenerator placement. This works only for small networks (10 or fewer nodes in our system), due to the large number of binary variables required for larger networks.
- The second approach uses a heuristic that may be used for practical-sized networks. Our experiments reveal that, in most cases, the heuristic does give the optimal solution.

II. Formulations for Solving the RPP with Path Protection

We view the RPP with path protection as a network flow programming problem [3] as follows. Here each commodity is characterized by its source (S) and its destination (D). To simplify the work, we first eliminate all source-destination pairs (S, D), such that there exists two edge disjoint paths from S to D, each with a length less than the optical reach. For such commodities, we do not need any regenerator and hence they need not be considered when solving RPP with path protection. For each of the remaining commodities, the problem is to find a pair of valid edge-disjoint paths as defined above, so that it is possible to ship one unit of each commodity from its sources to its destination using either the primary path or the backup path.

[1]often called the primary lightpath and the backup lightpath.

A. An Integer Linear Program to solve the RPP

Notation

G : a connected graph that represents the network.
N : a set of nodes in the network.
E : a set of physical edges in the network, each representing a fiber.
(i, j) : an edge in the network (so that $(i, j) \in E$), that represents a fiber from node i to node j.
K : a set of commodities, each specified by a source and a destination.
$x^k_{ij}(y^k_{ij})$: a binary variable, for all $k \in K$, and all edge $(i, j) \in E$ where

$$x^k_{ij}(y^k_{ij}) = \begin{cases} 1, & \text{if } (i,j) \text{ is in the primary (backup) path,} \\ 0, & \text{otherwise.} \end{cases}$$

r_j : a binary variable, where

$$r_j = \begin{cases} 1, & \text{if node } j \ (j \in N) \text{ is identified to be a regenerator-capable node,} \\ 0, & \text{otherwise.} \end{cases}$$

d_{max} : the optical reach for the network.
d_{ij} : the distance from node i to node j.
$v^k_i(w^k_i)$: a continuous non-negative variable, $k \in K$, $i \in N$, denoting the distance of node i from the last regenerator before node i, in the primary (backup) path. If there is no regenerator before node i, in the primary (backup) path, $v^k_i(w^k_i)$ denotes the distance of node i from the source.
$S(k)(D(k))$: the source (destination) node of commodity k.

Objective Function:

Our objective is to identify a minimum number of regenerator-capable nodes, such that, for each commodity, $k \in K$, there are two valid edge-disjoint paths. The objective function is as follows:

$$minimize \sum_{j:j \in N} r_j$$

subject to:

(a) Flow balance equations for the primary and the backup path must be satisfied.

$$\sum_{j:(i,j)\in E} x^k_{ij} - \sum_{j:(j,i)\in E} x^k_{ji} = \begin{cases} 1 & \text{if } i = S(k), \\ -1 & \text{if } i = D(k), \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

$$\sum_{j:(i,j)\in E} y^k_{ij} - \sum_{j:(j,i)\in E} y^k_{ji} = \begin{cases} 1 & \text{if } i = S(k), \\ -1 & \text{if } i = D(k), \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

(b) For each commodity, the primary path and the backup path must be edge-disjoint.

$$x^k_{ij} + y^k_{ij} \leq 1 \quad \forall k \in K, \forall (i,j) \in E. \tag{3}$$

(c) Both the primary path and the backup path must obey the optical reach requirement. To ensure this we use distance labels v_i^k and w_i^k as follows:

$$v_i^k + d_{ij} \,.\, x_{ij}^k - d_{max}(1 - x_{ij}^k + r_j) \leq v_j^k \quad (4)$$

$$v_i^k + d_{ij} \,.\, x_{ij}^k \leq d_{max} \quad \forall k \in K,\, \forall (i,j) \in E \quad (5)$$

$$v_i^k \leq d_{max}(1 - r_i)\, \forall k \in K, \forall i \in N, i \neq D(k). \quad (6)$$

$$v_i^k = 0 \quad \forall k \in K,\, \forall i \in N, i = S(k). \quad (7)$$

$$w_i^k + d_{ij} \,.\, y_{ij}^k - d_{max}(1 - y_{ij}^k + r_j) \leq w_j^k \quad (8)$$

$$w_i^k + d_{ij} \,.\, y_{ij}^k \leq d_{max} \quad \forall k \in K,\, \forall (i,j) \in E. \quad (9)$$

$$w_i^k \leq d_{max}(1 - r_i) \quad \forall k \in K,\, \forall i \in N, i \neq D(k). \quad (10)$$

$$w_i^k = 0 \quad \forall k \in K,\, \forall i \in N, i = S(k). \quad (11)$$

Constraints (4) and (8) are to be repeated for all $k \in K$ and for all $(i,j) \in E$, $j \neq D(k)$.

B. Justification of the ILP

Constraints (1) to (3): these are straight-forward.

Constraints (4) to (7): These constraints define the distance of any node from the start of the segment that contains the node and are used to ensure that no segment of a primary lightpath exceeds the optical reach. these constraints work as follows:

1) In constraint (4), $(1 - x_{ij}^k + r_j)$ has a value 0, 1 or 2. If $(1 - x_{ij}^k + r_j)$ is 1 or 2, constraint (4) is clearly satisfied, since constraint (5) guarantees that $v_i^k + d_{ij} \cdot x_{ij}^k \leq d_{max}$, so that the LHS is negative. The value of $(1 - x_{ij}^k + r_j)$ can be 0 only if $x_{ij}^k = 1$ and $r_j = 0$. In that case, constraint (4) becomes $v_i^k + d_{ij} \leq v_j^k$. In other words, if node j is not used for regeneration and is not the destination node, $D(k)$, constraint (4) computes the value of v_j^k, where i is the node proceeding j, in the primary path from $S(k)$ to $D(k)$.
2) Constraint (5) ensures that the length of a segment never exceeds d_{max}.
3) Constraint (6) ensures that, if node i is used for regeneration (i. e., $r_i = 1$), v_i^k = 0, so that the length of the segment starting node i is 0.
4) Constraint (7) ensures that, if node i is the source node, $S(k)$), v_i^k = 0, so that the length of the segment starting at the source node is 0.

Constraints (8) to (11): these are similar to constraints (4) to (7) and are applicable to the backup path.

C. Heuristic solution for RPP with path protection

In [6] a novel ILP was proposed to *optimally* solve the RPP for translucent networks using dynamic lightpath allocation. The formulation involves an exponential number of constraints, known only implicitly. To solve this problem the well known *Branch-and-Cut* method [4] was used. The branch-and-cut is a branch-and-bound method [4] with cuts (valid inequalities for the integer program) generated as the branch-and-bound algorithm proceeds. The method starts with finding an optimal solution to some linear relaxation of the integer program. If this optimal solution, call it x^*, is not a feasible solution of the integer program being solved, a "separation" problem is solved to identify, if possible, a cut which is violated by x^*. If such a valid inequality is found, it is added to the relaxation problem and the problem is resolved. Branching, as in usual branch-and-bound procedure, takes place if such a cut is not identified by the "separation" routine. This approach works very efficiently, so that optimal solutions for relatively large networks can be obtained.

In [10] was extended to *optimally* solve the RPP for survivable translucent networks where the restoration technique is used. Experiments reported in [10] reveal that only a relatively small number of the constraints are usually needed, so that the basis size is, in general, quite small and the LP relaxations can be solved very quickly. We have used this algorithm as a key component for our heuristic, SOL-H.

Lemma 1: Any regenerator placement that satisfies the requirements for RPP with path protection is a placement which guarantees that restoration is possible in the event of single-link failures.

Proof: A RPP for path protection guarantees that, for every source-destination pair (S, D), there is a valid primary path and a valid backup path that are edge disjoint. Let $S \rightarrow a_1 \rightarrow a_2 \ldots \rightarrow a_m \rightarrow D$ ($S \rightarrow b_1 \rightarrow b_2 \ldots \rightarrow b_p \rightarrow D$) be the primary (backup) path when RPP with path protection was solved for the commodity (S, D). If this is a valid scheme for restoration, then for every single link failure in the primary path, a path from S to D must exist that does not involve the failed edge. This is guaranteed, since the backup path $S \rightarrow b_1 \rightarrow b_2 \ldots \rightarrow b_p \rightarrow D$ is edge-disjoint with respect to the primary path and can be used for failure in *any* link in the primary path. ∎

Clearly, any regenerator placement, which guarantees that restoration is possible in the event of single-link failures, does not necessarily give a regenerator placement that satisfies the requirements for RPP with path protection.

Lemma 2: If an optimum regenerator placement, which guarantees that restoration is possible in the event of single-link failures, gives a regenerator placement that satisfies the requirements for RPP with path protection, then the placement is also optimal for RPP with path protection.

Proof: Let this claim be false. Let R_1 be a placement for graph (G, w) such that:

- R_1 is an optimum regenerator placement, which guarantees that restoration is possible in the event of single-link failures, but
- R_1 is not an optimal regenerator placement for RPP with path protection.

This means there exists a better placement R_2 (meaning that $|R_2| < |R_1|$) for RPP with path protection. By Lemma 1, R_2 is also a regenerator placement which guarantees that restoration is possible in the event of single-link failures. This means that placement R_1 for graph (G, w) is not an optimum regenerator placement, which guarantees that restoration is possible in the event of single-link failures (since $|R_2| < |R_1|$). This is a contradiction, hence the claim is true. ∎

We will now describe a heuristic for the RPP using path protection. In the heuristic, we have used the branch-and-cut approach for optimal RPP, satisfying the requirements for restoration, described in [10] to generate R_1, an initial placement of regenerators. As pointed out above, this initial placement does not necessarily give a regenerator placement for RPP with path protection. To check whether the requirements for RPP with path protection are fulfilled by R_1, we have taken all distinct-source pairs (S, D), and checked whether it is possible to establish two viable edge-disjoint paths from S to D using R_1. This is quite feasible, since RPP is done off-line, during the design phase. Due to lack of space, we have not described how we tested whether a pair of edge-disjoint paths exists for each source-destination pair. Details of an ILP to achieve this are available in [11].

Our experiments, reported in Section III, show that, in an overwhelming number of cases, R_1 does fulfill the requirements for RPP with path protection. Using Lemma 2, we see that, in all such cases, R_1 is an optimal placement of regenerators for path protection. In cases where an edge-disjoint pair of viable paths cannot be established for all distinct source-destination pairs (S, D), SOL-H augments R_1 with additional nodes, so that all distinct-source pairs (S, D) can be handled.

Notation used in SOL-H

R_1 : an initial placement of regenerators, satisfying the requirements of restoration.
R : a placement of regenerators that satisfies the requirements of RPP with path protection.
$placementForRestoration(G, w)$: a function that invokes the branch-and-cut algorithm in [10] to generate an initial placement of regenerators. The argument for the function is the weighted graph (G, w) representing the network, where $G = (N, E)$.
$\mathbb{B}$: a set of source-destination pairs (S, D), such that two edge-disjoint viable paths cannot be established from S to D using placement R_1.
$currentCommodity$: a source-destination pair (S, D) that is currently under consideration.
$\mathbb{S}$: a set of source-destination pairs (S, D) which have not been considered yet.
$allCommodities$: a set of all possible source-destination pairs (S, D) for graph $G = (N, E)$.
$removeNextCommodity(\mathbb{S})$: a function that deletes any one element from set $\mathbb{S}$ and returns the deleted element.
$commodityCannotBeHandled$: a function whose arguments are $G, w, R_1, currentCommodity$. The function returns true if it is not possible to establish two edge-disjoint viable paths from S to D. Otherwise it returns false.
$augmentRegeneratorSites$: a function whose arguments are G, w, R_1 and $\mathbb{B}$. The function computes a minimum augmentation of the regenerator placement R_1, such that the weighted graph (G, w), with this augmented set of regenerators, allows every source-destination pair in set $\mathbb{B}$ to establish two viable edge-disjoint paths from S to D.

D. Details of the heuristic SOL-H

The inputs for the heuristic consists of i) a connected graph (G, w) representing the network and ii) $allCommodities$ - a set of all node pairs, each representing a commodity to be considered. In Step 1, the function $placementForRestoration(G, w)$ calls the branch-and-cut algorithm, developed in [10] to return a set of regenerator-capable nodes, which is saved in the set R_1. In Step 6, we check, using function $commodityCannotBeHandled$, whether the current commodity, represented by source-destination pair, say (S, D), can be handled by the network using the regenerators in R_1. If the function returns true, an edge-disjoint pair of valid paths exist from S to D. We have implemented function $commodityCannotBeHandled$ using the RRP algorithm[2], which has been omitted due to lack of space. If the test in Step 6 fails, it means that we need one or more regenerators, at sites different from those in R_1, in order to handle the pair (S, D). Such (S, D) pairs are included in set $\mathbb{B}$ (Step 7). When Step 9 is over, set $\mathbb{B}$ contains

[2]The RRP algorithm has been described in [11].

Require: A connected graph (G, w) and $allCommodities$ - a set of all commodities that need to be considered.
Ensure: A set of regenerator-capable nodes R, that is a solution for RPP with path protection.

```
1: R_1 ← placementForRestoration(G, w)
2: 𝕊 ← allCommodities
3: 𝔹 ← ∅
4: while (𝕊 ≠ ∅) do
5:     currentCommodity ←
       removeNextCommodity(𝕊)
6:     if
       (commodityCannotBeHandled(G, w, R_1,
       currentCommodity)) then
7:         𝔹 ← 𝔹 ∪ {currentCommodity}
8:     end if
9: end while
10: if (𝔹 ≠ ∅) then
11:     R ←
        augmentRegeneratorSites(G, w, R_1, 𝔹)
12: else
13:     R ← R_1
14: end if
15: return R
```

Algorithm 1: Heuristic for RPP with path protection

all pairs (S, D) which cannot be handled by the regenerators in R_1. In Step 10, if set $\mathbb{B}$ is empty, it means that the regenerators in R_1 is adequate to handle all source-destination pairs and R, the final set of regenerators, will be the same as the initial set of regenerators R_1 (Step 13) and the heuristic terminates. In Step 10, if set $\mathbb{B}$ is not empty, function $augmentRegeneratorSites(G, w, R_1, \mathbb{B})$ augments set R_1 with additional sites for regenerators, so that the requirements for path protection is satisfied by all commodities in $\mathbb{B}$. Function $augmentRegeneratorSites$ returns this augmented set and the heuristic terminates. Function $augmentRegeneratorSites$ uses a modification of the formulation for RPP, described in Section II-E, to augment the set of regenerators. Details of this modification are given below. Our experiments described in Section III indicate that set $\mathbb{B}$ contains relatively few node pairs, which our modified ILP can easily handle within a reasonable time.

E. Modified ILP for SOL-H

The objective of the modified ILP for RPP with path protection is the same as that described in Section II, except that we supply the ILP with $R_1 \subset N$, an initial set of regenerator-capable nodes, that was identified in Step 1 of the heuristic SOL-H. The ILP has to identify an additional set of nodes R_2 which have to be equipped with regenerators so that, for each commodity, say the pair $(S, D) \in \mathbb{B}$, two valid edge-disjoint paths exist from S to D. To achieve this, we have to replace constraints (4) and (8) by constraints (12) and (13) given below.

$$v_i^k + d_{ij} \, . \, x_{ij}^k - d_{max}(1 - x_{ij}^k + r_j) \leq v_j^k \quad (12)$$

$$w_i^k + d_{ij} \, . \, y_{ij}^k - d_{max}(1 - y_{ij}^k + r_j) \leq w_j^k \quad (13)$$

Constraints (12) and (13) have to be repeated for all $k \in K$, and for all $(i, j) \in E, j \neq D(k), j \notin R_1$. We also have to add the following two constraints.

$$v_i^k = 0 \quad \forall k \in K, \, \forall i \in R_1 \quad (14)$$

$$w_i^k = 0 \quad \forall k \in K, \, \forall i \in R_1 \quad (15)$$

$$w_{S(k)}^k = 0 \quad \forall k \in K, \quad (16)$$

Constraint (12) is similar to Constraint (4), except that if node j is already identified to be a site for regenerators (i.e., if $j \in R_1$), we do not calculate the value of v_j^k from the value of v_i^k. In such a case, constraint (14) forces the value of v_j^k to be 0. The discussions for constraints (13) and (15) are similar.

III. Experimental Results

We ran the experiments on a virtual server, with 2GB of RAM and two 2.66 GHz processors using CPLEX [20].

To study the formulations described above and to get an idea of the execution times of the formulations for various network sizes, we carried out several experiments. The results of these experiments are given below.

A. Execution time to compute optimal solutions

For networks with 10 or fewer nodes, we executed the RPP algorithm described in Section II 10 times, using different networks. For networks with more than 10 nodes, the resources available on the environment we used were not sufficient for the formulation to converge within a reasonable time. Table I, below, shows the average execution times.

# of Nodes in network	# of networks	Average run-time (seconds)
5	10	0.1
6	10	0.3
7	10	5
8	10	215
9	10	2610
10	5	17238

TABLE I: Average run-time for optimal solutions

B. *Experiments using the Heuristic SOL-H*

We had the following two objectives for our experiments

- What is the largest network that the heuristic can handle?
- How good are the results obtained by the heuristic?

We executed the algorithm on networks having 30, 40, 50 and 60 nodes. For many of the networks with more than 60 nodes, the branch-and-cut heuristic did not converge within a reasonable amount of time. For each size of the network, we generated 200 different network topologies. As discussed in Section II-C, if the heuristic does not execute Step 11, it means we have obtained an optimal solution. We have reported below the number of times the heuristic algorithm determined optimal solutions. In each of the remaining cases, we noted how many additional regenerators were added in Step 11. We show the results of our experiments in Table II below.

Network Size	# of topologies optimally solved (out of 200 instances)
30	199
40	198
50	197
60	197

TABLE II: Regenerator placement using heuristic SOL-H

We make the following interesting observations:

- In 97 - 99.5% of the networks, the heuristic SOL-H provides optimal solutions. This is a remarkable result and establishes that SOL-H is an extremely effective heuristic.
- In all cases, where the heuristic executed Step 11, only one additional regenerator-capable node was necessary to obtain a solution for RPP with path protection. This does not necessarily mean that the regenerator placement we obtained is sub-optimal. The results obtained by the branch-and-cut algorithm is merely a lower limit on the number of regenerator-capable nodes needed in the network. We cannot prove that the solution we obtained was optimal and can only conclude that, in all cases where the heuristic executed Step 11, our solutions were potentially sub-optimal. It is remarkable that, in all cases we tried where Step 11 had to be executed, the solution using SOL-H involved only one node more than the lower limit for the optimal solution.

IV. Conclusions and Future Work

We have shown that it is possible to design impairment-aware optical WDM networks that guarantee protection against single-link failures by optimal and near-optimal placement of regenerators. We developed an optimal solution for small networks and a near-optimal solution for practical-sized network that works for networks having 60 nodes or less. The approach outlined in this paper may be easily extended to include SRLG failures.

References

[1] G. Shen and R. S. Tucker, Translucent optical networks: the way forward, *IEEE Communications Magazine 2007, Vol. 45, no. 2, pp. 48–54*

[2] , J. M. Simmons, Optical Network Design and Planning, *Springer, 2014.*

[3] R. K. Ahuja, T. L. Magnanti and J. B. Orlin, Network Flows: Theory, Algorithms, and Applications, *Prentice Hall, 1993.*

[4] Wolsey, L. A., Integer Programming, *John Wiley and Sons,1998, May 2009.*

[5] M. Angelou, S. Azodolmolky and I. Tomkos, Dynamic Impairment-Aware Routing and Wavelength Assignment, in Cross-Layer Design in Optical Networks, *Springer, pp. 31 - 51, 2013.*

[6] Q. Rahman, S. Bandyopadhyay, Y. P. Aneja, Optimal Regenerator Placement in Translucent Optical Networks. *Optical Switching and Networking, Vol. 15, no. 1, pp. 134 147, January 2015.*

[7] A. Sen, S. Murthy and S. Bandyopadhyay, On Sparse Placement of Regenerator Nodes in Translucent Optical Network, *Global Telecomm. Conf., (IEEE/GLOBECOM), pp. 1 - 6, 2008.*

[8] G. B. Mertzios, M. Shalom, P. W. H. Wong and S. Zaks, Online Regenerator Placement, *LNCS, Principles of Distributed Systems, Vol. 7109, no. 1, pp. 4 - 17, 2011.*

[9] S. Bandyopadhyay, Dissemination of Information in Optical Networks: From Technology to Algorithms, *Springer, 2008.*

[10] Rahman, Q. Aneja, Y. ; Bandyopadhyay, S. ; Jaekel, A. Optimal regenerator placement in survivable translucent networks, *10th*

Inter. Conf. on the Design of Reliable Communication Networks (DRCN), pp. 1 - 7, 1-3 April, 2014.

[11] R. RAMLALL Optimal Regenerator Placement for Path Protection in Impairment-Aware WDM Networks, *M. Sc. Thesis, University of Windsor, Windsor, Ontario, N9B 3P4, Canada, July 2014.*

[12] AZODOLMOLKY, S., KLINKOWSKI, M., MARIN, E., CAREGLIO, D., SOL-PARETA, J., AND TOMKOS, I. 2009. A Survey on Physical Layer Impairments Aware Routing and Wavelength Assignment Algorithms in Optical Networks. *Elsevier Comput. Netw., vol. 53, no. 7, pp. 926 - 944, May 2009.*

[13] AZODOLMOLKY, *et. al.* 2010. A novel offline physical layer impairments aware RWA algorithm with dedicated path protection consideration. *Jour. of Light. Tech., 28, 20, 3029-3040.*

[14] AZODOLMOLKY, S., POINTURIER, Y., ANGELOU, M., SOLE PARETA, J., AND TOMKOS, I. 2009. An offline impairment aware RWA algorithm with dedicated path protection consideration. *Optical Fiber Comm. OFC 2009. Conference, 1-3.*

[15] BANDYOPADHYAY, S., RAHMAN, Q., BANERGEE, S., MURTHY, S., AND SEN, A. 2009. Dynamic Lightpath Allocation in Translucent WDM Optical Networks. *Communications, 2009, IEEE Inter. Conf. Comm., 1 - 6.*

[16] DOS SANTOS ROSA, S., DRUMMOND, A., AND DA FONSECA, N. 2010. Path protection WDM networks with impaired-transmission. *Photonic Network Communications, 19, 2 , 212-222.*

[17] GAGNAIRE, M. AND ZAHR, S. 2009. Impairment-aware routing and wavelength assignment in translucent networks: state of the art. *IEEE Commun. Mag., pp. 5561, May 2009.*

[18] GAO, C., CANKAYA, H., PATEL, A., JUE, J., WANG, X., ZHANG, Q., PALACHARLA, P., AND SEKIYA, M. 2011. Survivable impairment-aware traffic grooming and regenerator placement with dedicated connection level protection. *2011 IEEE International Conference, 1-5.*

[19] GUO, L., AND JI, Y. 2007. Shared protection schemes for multi-granularity optical networks. *Proc. SPIE 6784, Network Architectures, Management, and Applications V, 678410 November 19, 2007; doi:10.1117/12.745381*

[20] ILOG: CPLEX *http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer*

[21] KOKKINOS, P., MANOUSAKIS, K., AND VARVARIGOS, E. 2010. Path protection in WDM networks with quality of transmission limitations. *IEEE Inter. Conf., 2010, 1-5.*

[22] PATEL, A., GAO, C., JUE, J., WANG, X., ZHANG, Q., PALACHARLA, P., AND NAITO, T. 2010. Traffic grooming and regenerator placement in impairment-aware optical WDM networks. *Optical Network Design and Modeling (ONDM), 2010, 1-6.*

[23] PATEL, A., JUE, J., WANG, X., ZHANG, Q., PALACHARLA, P., AND NAITO, T. 2010. Survivable impairment-aware traffic grooming with dedicated path protection. *Optical Communication (ECOC), 2010 1-3.*

[24] SARADHI, C., AND SUBRAMANIAM, S. 2009. Physical layer impairment aware routing (PLIAR) in WDM optical networks: issues and challenges. *Communications Surveys and Tutorials, IEEE 11, 4, 109-130.*

[25] SHAO, X., CHENG, X., YEO, Y. K., ZHOU, L., WANG, Y., AND BAI, Y. 2010. Performance enhancement for impairment-aware SRLG failure protection in wavelength-routed optical networks. *Photonic Network Communications 20, 1, 1-9.*

[26] TOMKOS, I., *et. al.* 2008. Impairment aware networking and relevant resiliency issues in all-optical networks. *Optical Communication, 2008. ECOC 2008. 34th European Conference, 1-4.*

[27] YANG, X., AND RAMAMURTHY, B. Dynamic Routing in Translucent WDM Optical Networks: The intradomain case. *Journal of Lightwave Technology. 23, 3, 955 - 971, 2005*

[28] YANG, X., SHEN, L., AND RAMAMURTHY, B. Survivable lightpath provisioning in WDM mesh networks under shared path protection and signal quality constraints. *Jour. Light. Tech., 2005. 23, 4, 1556-1567.*

[29] ZHAI, Y., POINTURIER, Y., SUBRAMANIAN, S., AND BRANDT-PEARCE, M. 2007. Performance of dedicated path protection in transmission-impaired DWDM networks. *In: Proceedings of IEEE Inter. Conf. on Comm., 2342-2347.*