

Tabu Search Optimization in Translucent Network Regenerator Allocation

Zhaoyi Pan, Benoît Châtelain,
David V. Plant
Electrical & Computer Engineering
McGill University
Montreal, Canada

François Gagnon,
Christine Tremblay
Département de génie électrique
École de technologie supérieure
Montreal, Canada

Éric Bernier
Advanced Research, CTO Office
Nortel
Ottawa, Canada

Abstract— This paper introduces the Tabu Search optimization algorithm to solve the regenerator allocation problem in translucent networks. The problem consists of finding the minimum number of regenerator nodes which primarily affects the cost of the translucent network. The problem is first solved with an ILP formulation to find the optimal solution without taking into consideration its time performance. The optical reach limit due to the dispersion compensation module and full (static) traffic demand with a 1+1 protection scheme are considered in the network model. The proposed algorithm is then compared with two other heuristics: the maximum infeasibility reduction (MIR) algorithm and the maximum regeneration demand (MRD) algorithm. Numerical results show that the Tabu Search procedure either outperforms or equals the performance of the reference algorithms, while having a lower implementation complexity and comparable convergence speed.

Keywords—*Tabu search; translucent network; regenerator; optical reach limit; full traffic demand; 1+1 protection scheme.*

I. INTRODUCTION

Translucent networks were first introduced by Ramamurthy and al. in 1999 [1]. By taking into account the limited transmission reach of optical signals, translucent network design deals with finding optimal locations for electronic regeneration sites so as to minimize cost. Another design goal is to maximize the protection and facilitate restoration [2]. The optimization algorithm presented in this paper is motivated by the above two constraints to minimize the cost of robust transparent networks. The algorithm calculates the minimum number of 3R (reamplification, reshaping and retiming) regenerators inside translucent networks by using a modern heuristic: tabu search (TS).

Finding optical paths by allocating the minimum number of 3R regenerators is a NP-complete k-center problem [2]; therefore, efficient heuristics should be used to solve this optimization problem. Heuristics perform a local search to find a solution which might be a local optimum since unvisited regions in the search domain may contain a better solution. Meta-heuristics are optimization techniques that can find a local optimum solution and escape from it to visit the rest of the search domain. TS is an iterative meta-heuristics method which is guided by an implemented memory. This memory, which records a number of visited solutions, sets a tabu

(forbidden) list of solutions in order to escape the local optimum and to discover new regions of the search domain. Moreover, TS demonstrates great performance in many research fields including the field of network design [3]. The TS method proposed in this paper has only one short-term recency memory and counters as an objective function that finds the best neighboring solution. Also, the TS algorithm uses few parameters and little memory to deal with large network optimization problems. For example, the two algorithms in [4] select regenerator nodes for each possible lightpath; however, the proposed TS algorithm predetermines a set of regenerator nodes for a network and verifies if it satisfies all of the constraints iteratively. By doing so, a current solution which consists of a set of regenerator nodes can be changed directly in every iteration instead of pre-selecting regenerator nodes over all possible lightpaths in order to make a change in the current solution.

Furthermore, the TS algorithm is compared with an integer linear program (ILP) and two previously published algorithms, mentioned above: maximum infeasibility reduction (MIR) algorithm and regeneration demand (MRD) algorithm. The rest of this paper is organized in the following way. In section II, a literature review on translucent networks and the tabu search is performed. In section III the network model is introduced. In section IV, an ILP and the TS optimization function are presented respectively. In section V, the numerical analysis is presented.

II. LITERATURE REVIEW

In dense wavelength division multiplexing (DWDM) translucent networks, photonic transparent cross-connects (OXC) are used at nodes to perform wavelength routing. Retiming, reshaping and re-amplifying (3R) regenerators are also needed to ensure the network performance and the quality of optical signals propagating beyond an optical limit distance [2]. Therefore, a translucent node consists of an OXC fitted with a bank of electronic 3R regenerators. Since 3R regenerators are usually the most expensive resources in a DWDM network, the design objective is to minimize the number of 3R nodes.

In translucent network design, both the transparent islands strategy and the sparse placement strategy are studied. In [5]

and [6], it is shown that the sparse placement strategy generally leads to a solution with fewer regenerator nodes than the transparent islands approach.

As is stated in [3], TS has been implemented successfully in many combinatorial problems, such as the vehicle routing problem, the traveling salesman problem, the quadratic assignment problem and the multidimensional knapsack problem. More specifically related to network design, the TS method proposed in [7] efficiently solves the problem of routing and wavelength assignment (RWA) in transparent networks. However, that particular TS method applies in transparent networks with scheduled lightpath demands rather than translucent networks with the static full demand which is presented in this paper. Coincidentally, the k -shortest path is computed in the pre-search section of the TS algorithms in both papers. Thus, this paper proposes the TS algorithm to solve, for the first time, the regenerator allocation problem in translucent networks.

III. NETWORK MODEL

The use of dispersion compensation modules is considered in this study [8]. More specifically, physical impairments, such as chromatic dispersion, polarization mode dispersion, amplified spontaneous emission (ASE), and propagation losses are converted to one single constraint: optimal reach limit.

The network model in this paper uses a full traffic demand with a 1+1 link-disjoint protection scheme for all connections, similar to [9]. The general idea is to satisfy a worst-case scenario network model in order to have a robust network design. Since all possible connections are taken into account, the obtained solution is valid for busiest traffic scenarios with no network defect.

Fig. 1 gives a detailed view of the node model used in this paper. A node can either be transparent (without 3R regenerator) or translucent (with 3R regenerator), but every node has an OXC switcher. The type of amplifiers and DEMUXs vary with the number of wavelengths that are coming in and out of the node. In this modeling, the cost of a network depends primarily on the number of translucent nodes,

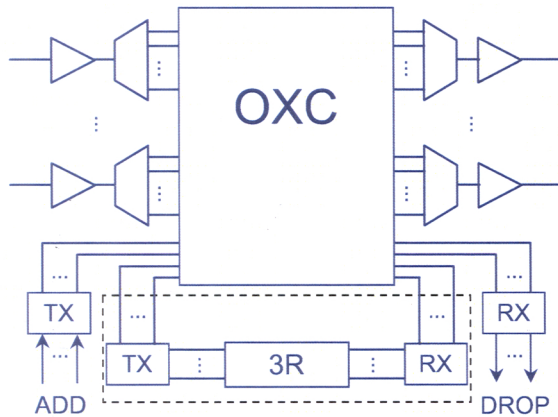


Figure 1. Node Model: the optional dashed box determines whether a node is an 3R regenerator node or not.

since adding 3R regenerators is more expensive than adding wavelengths. Consequently, the proposed TS method only attempts to find the routes of each connection and the minimal number of 3R regenerator nodes; the wavelength assignment is assumed to be performed separately.

IV. OPTIMIZATION FUNCTIONS

The output of the ILP and TS optimization functions is the minimum number of 3R regenerator nodes, and the primary and protection paths assignment. The ILP can be used to find optimal solutions for small networks and can also be used to approximate performance bounds for the TS procedure.

A. ILP formulation

To describe the ILP model, a notation similar to that of [10] is used:

$G = (V, E)$: A directed graph with the set of network nodes V and the set of optical links E .

i, j : Originating and terminating nodes of a lightpath.

Values given:

R : The optical reach distance.

K : A large number, $K > R$

N : The number of nodes in the network.

Q : The number of connections. Since a full demand matrix is considered, there are $N^2 - N$ connections.

P : The network physical topology matrix. If $P_{ij} = 1$, there exists a physical link between i and j . P is of size N by N .

D : The distances matrix. The distance in kilometers between nodes i and j is given by D_{ij} . D is of size N by N .

S : The set of source nodes. S^q is the source node of the q^{th} connection ($q = 1, 2, \dots, Q$).

T : The set of destination nodes. T^q is the destination node of the q^{th} connection.

L_i^+ : The set of "outgoing" links of node i , that consists of the set of unidirectional links having the node i as one extreme and leaving the node.

L_i^- : The set of "incoming" links of node i , that consists of the set of unidirectional links having the node i as one extreme and pointing towards the node.

Variables:

a_{ij}^q : A binary variable indicating when it equals to 1, that for the q^{th} connection, the link between nodes i and j is on the primary path. Similarly, \bar{a}_{ij}^q equals to 1 if the link between nodes i and j is on the protection path.

b_{ij}^q : A binary variable indicating when it equals to 1, that for the primary path of the q^{th} connection, a regeneration channel at nodes i is used for the signal propagation toward node j . Similarly, \bar{b}_{ij}^q indicates when it equals to 1 that for the protection path, a regeneration channel at node i is used for the signal propagation toward node j .

c_{ij}^q : The accumulated distance at node i in the direction of node j , for the primary path of connection q .

\bar{c}_{ij}^q corresponds to the accumulated distance at node i in the direction of node j for the protection path.

X : A binary vector of N elements representing the presence (1) or the absence (0) of regenerators at each node.

In the example given by Fig. 2, the optical path of connection #1 is represented. The source node is node 1 and the destination node is 6. The optical path is [1 2 3 6], making a_{12}^1, a_{23}^1 and a_{36}^1 equal to 1. Since link 1-2 is of length 10, the accumulated distance c_{23}^1 is equal to 10. With $b_{36}^1 = 1$, node 3 is a regenerator node. Since there is a regeneration channel at node 3, $X(3) = 1$.

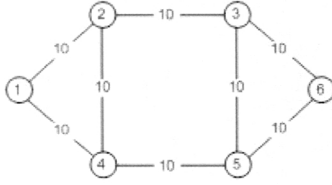


Figure 2. 6 nodes optical network.

The design guidelines for the routing and regenerator nodes allocation of translucent network with 1+1 protection can be summarized as follow:

- Minimize the number of regenerator nodes:

$$\text{Minimize } \sum_{n=1}^N X_n. \quad (1)$$

- A single link coming out of the source node is selected:

$$\sum_{j \in L_i^+} a_{ij}^q = 1, \quad \sum_{j \in L_i^+} \bar{a}_{ij}^q = 1 \quad \forall q, i = S^q. \quad (2)$$

- A single link coming in the destination node is selected:

$$\sum_{i \in L_j^-} a_{ij}^q = 1, \quad \sum_{i \in L_j^-} \bar{a}_{ij}^q = 1 \quad \forall q, j = T^q. \quad (3)$$

- Outgoing links from the destination node must not be selected:

$$a_{ij}^q = 0, \quad \bar{a}_{ij}^q = 0 \quad \forall q, i = T^q, \forall j \in L_i^+. \quad (4)$$

- At intermediate nodes, if one incoming link is selected, an outgoing link must also be selected:

$$\sum_{j \in L_i^+} a_{ij}^q = \sum_{j \in L_i^-} a_{ji}^q, \quad \sum_{j \in L_i^+} \bar{a}_{ij}^q = \sum_{j \in L_i^-} \bar{a}_{ji}^q \quad \forall q, \forall i \notin S^q \cup D. \quad (5)$$

- At intermediate nodes, an incoming link (i, j) and outgoing link (j, i) can not be selected simultaneously:

$$a_{ij}^q + a_{ji}^q \leq 1, \quad \bar{a}_{ij}^q + \bar{a}_{ji}^q \leq 1 \quad \forall q, \forall i \notin S^q \cup T^q, \forall j \in L_i^+. \quad (6)$$

- Accumulated distance from the source nodes does not depend on previous accumulated distances:

$$c_{ij}^q = 0, \quad \bar{c}_{ij}^q = 0 \quad \forall q, i = S^q, \forall j \in L_i^+. \quad (7)$$

- All incoming accumulated distance to the source nodes are equal to zero:

$$c_{ji}^q = 0, \quad \bar{c}_{ji}^q = 0 \quad \forall q, i = S^q, \forall j \in L_i^-. \quad (8)$$

- At intermediate nodes, if there is a regeneration channel at node i , the accumulated distance from node i to j corresponds to the link distance D_{ij} :

$$c_{ik}^q \geq \sum_{i \in L_i^-} D_{il} a_{il}^q + K(a_{ik} - 1), \quad \bar{c}_{ik}^q \geq \sum_{i \in L_i^-} D_{il} \bar{a}_{il}^q + K(\bar{a}_{ik} - 1)$$

$$c_{ik}^q \leq \sum_{i \in L_i^-} D_{il} a_{il}^q + K(1 - b_{il}), \quad \bar{c}_{ik}^q \leq \sum_{i \in L_i^-} D_{il} \bar{a}_{il}^q + K(1 - \bar{b}_{il}) \quad (9)$$

$$\forall q, \forall l \notin S^q \cup T^q, \forall k \in L_i^+,$$

where K is a constant that exceeds the value of R .

- At intermediate nodes, if there is no regeneration channel at node i , the accumulated distance from node i to j corresponds to the sum of the previous accumulated distances and to the link distance D_{ij} :

$$c_{ik}^q \geq \sum_{i \in L_i^-} c_{il} + D_{il} a_{il}^q - K b_{il} + K(a_{ik} - 1)$$

$$\bar{c}_{ik}^q \geq \sum_{i \in L_i^-} \bar{c}_{il} + D_{il} \bar{a}_{il}^q - K \bar{b}_{il} + K(\bar{a}_{ik} - 1) \quad (10)$$

$$c_{ik}^q \leq \sum_{i \in L_i^-} c_{il} + D_{il} a_{il}^q, \quad \bar{c}_{ik}^q \leq \sum_{i \in L_i^-} \bar{c}_{il} + D_{il} \bar{a}_{il}^q$$

$$\forall q, \forall l \notin S^q \cup T^q, \forall k \in L_i^+.$$

- At intermediate nodes, the accumulated distance at node i in direction of node j must be inferior to the optical reach distance R if the outgoing link ij is selected. Otherwise, the accumulated distance equals to 0:

$$c_{ij}^q \leq R a_{ij}^q, \quad \bar{c}_{ij}^q \leq R \bar{a}_{ij}^q \quad \forall q, \forall i \notin S^q \cup T^q, \forall j \in L_i^+. \quad (11)$$

- No regeneration needed at the source node:

$$b_{ij}^q = 0, \quad \bar{b}_{ij}^q = 0 \quad \forall q, i = S^q, \forall j \in L_i^+. \quad (12)$$

- No regeneration at the destination node:

$$b_{ij}^q = 0, \quad \bar{b}_{ij}^q = 0 \quad \forall q, j = T^q, \forall i \in L_j^-. \quad (13)$$

- A regeneration channel can only be activated if the link is chosen:

$$b_{ij}^q \leq a_{ij}^q, \quad \bar{b}_{ij}^q \leq \bar{a}_{ij}^q \quad \forall q, i = 1, 2, \dots, N, \forall j \in L_i^+. \quad (14)$$

- If a regeneration channel b_{ij}^q is used, then node i is an 3R node:

$$X_i - b_{ij}^q \geq 0, \quad X_i - \bar{b}_{ij}^q \geq 0 \quad \forall q, i = 1, 2, \dots, N, \forall j \in L_i^+. \quad (15)$$

- The primary and protection paths must be linked-disjoint:

$$a_{ij}^q + \bar{a}_{ij}^q \leq 1 \quad i = 1, 2, \dots, N, \forall j \in L_i^+ \\ a_{ij}^q + \bar{a}_{ji}^q \leq 1 \quad i = 1, 2, \dots, N, \forall j \in L_i^- \quad (16)$$

B. TS procedure

1) Algorithm Complexity Analysis

Basically, the algorithm goes through each node-to-node connection from the network traffic demand, and finds the k-shortest paths for both the primary path and link-disjoint protection path. Then the iterative TS algorithm starts with an initial solution which consists of an arbitrary binary vector

array that records transparent nodes as 0 and translucent nodes as 1. Also, there are two types of lightpaths: translucent (with 3R node) or transparent (full optical path). At each iteration, the current solution is passed to a verification function that checks if the current solution can satisfy a 1+1 protection lightpath pair out of all the possible pre-calculated k -shortest paths. If the current result is correct, then one 3R node is dropped from the current 3R nodes. If the current solution is incorrect, then one OEO node is added from the current transparent nodes. Each node that has been added or dropped is updated in the tabu list as tabu (unable to add or drop) for a few iterations, the number of which is preset by function parameters.

Once again, this is a NP-complete k -center problem [4] with N as the number of nodes in a network. The time complexity of the following three algorithms is compared: the MIR and the MRD from [5], and the TS algorithm in this paper. Only the search part but not the initialization part of the algorithms is considered for comparison purpose.

The MIR has a time complexity of $O(N^3)$, and the MRD has a time complexity of $O(N^2)$. In the TS algorithm, the time complexity is mainly based on the verification function which checks through every node-to-node connection giving a time complexity of $O(N^2)$. A translucent path requires $O(N)$ time complexity to check, and a transparent path requires $O(I)$ to check. If the verification function checks through the k -shortest paths of each node-to-node connection, then the worst-case overall time complexity of the TS algorithm would be $O(N^3)$. As shown in table 1, the TS algorithm time complexity sits between the MIR's and the MRD's.

2) The Detailed Procedure of the TS algorithm

1. Set a network topology and traffic demand;
2. Calculate the k -shortest paths (with 1+1 protection scheme);
3. Sort translucent and transparent paths with their indices;
4. Initialize initial regenerator nodes for a given network as a starting network configuration;
5. Check if the current network configuration is correct;
6. If it is correct, drop a regenerator node, update tabu list;
7. If it is not, add a regenerator node according to the tabu list, update tabu list;
8. Go back to step 5 until the maximum number of iterations is reached;
9. Generate graphs.

V. NUMERICAL RESULTS

The ILP formulation and the performance of the TS procedure are first validated on the 8 nodes and 9 nodes optical networks of Fig. 3 (a) and Fig. 3 (b). The ILP was implemented in CPLEX, a commercial LP solver while the TS algorithm was implemented in Matlab. With an optical reach of 2000 km, the ILP, finds an optimal solution of 4 regenerator nodes for the network of Fig. 2 (a) and 4 regenerator nodes for the network of Fig. 2 (b). Both solutions are found after 1 minute of

computation. While the TS algorithm achieves the same results in term of number of 3R nodes, it does so in less than 2 seconds.

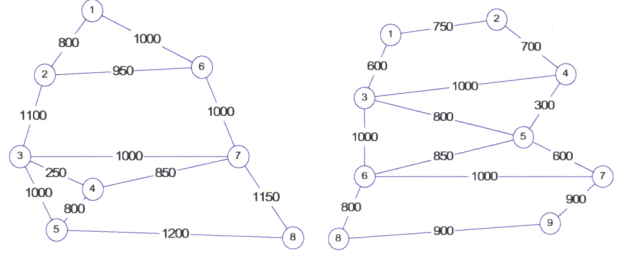


Figure 3. 10 nodes (a) and 11 nodes (b) optical networks.

For larger network such as the one represented in Fig. 4, the ILP model cannot be used. The TS algorithm is thus compared with two other heuristics: the MIR and MRD algorithms.

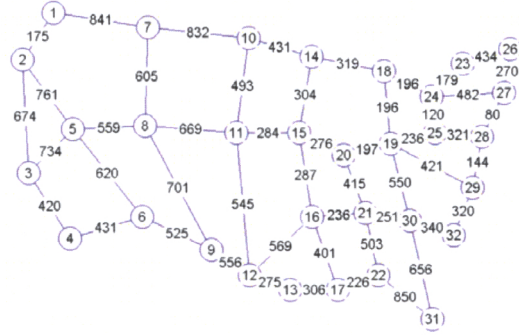


Figure 4. The US network topology with 32 nodes.

As seen in Table 1, the TS algorithm always finds a lower number of 3R nodes.

TABLE I. REGENERATION NODES AND COMPUTATION TIME OF THE MIR, MRD AND TS ALGORITHMS

	Reach	MIR	MRD	TS Algorithm
3R nodes ^a	1500	6	7	6
	2000	4	5	3
	2500	2	2	2
Time ^b	1500	3711	255	1448
	2000	3028	363	492
	2500	2319	412	868
Solutions ^c	1500	5, 7, 9, 11, 19, 21	5, 7, 9, 11, 14, 19, 21	5, 8, 9, 11, 16, 19
	2000	8, 9, 11, 21	8, 10, 12, 15, 16	8, 12, 15
	2500	11, 15	7, 15	11, 16

a. Number of 3R nodes in the network.

b. Time per one run in seconds.

c. Solution examples.

The convergence time in the TS algorithm does not necessary depend on the reach distance as the MIR and the MRD. In fact, it depends on the parameter k as in k -shortest

path algorithm. We could notice this behavior in the time section of the TS algorithm column in Table 1. Considering the high cost of 3R regeneration technology, the diminution of one or two 3R nodes has a major impact on the network cost. Table 1 also indicates that the convergence time of the proposed algorithm is faster than the MIR but slower than the MRD. This is explained by the fact that the algorithm was implemented in Matlab, an interpreted language. The optimization time could be further reduced by using a compilable language such as C++.

VI. CONCLUSION

A new tabu search algorithm was proposed to solve the regenerator allocation problem in translucent networks. The proposed algorithm outperforms previous attempts in minimizing the number of 3R nodes in an optical communication network. The added performance of the proposed algorithm is obtained without any increase in computational or time complexity.

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