REPARE: Regenerator Placement and Routing Establishment in Translucent Networks

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Abstract—Most research works in routing and design of optical networks assume that the optical medium can carry data signals without any bit error. However, physical impairments of the optical signal introduced by optical fibers and components, e.g., power loss, noise, and dispersions, impose fundamental constraints in WDM networks, and must be taken into consideration in the routing and design problems of WDM networks. Only through 3R (optical-electrical-optical) regeneration (reamplification, reshaping, retiming) with OEO conversion can a lightpath be recovered from those impairments. Because 3R regenerators are costly devices and the OEO conversion can affect the efficiency of optical networks we need to use the regenerators efficiently and effectively. In this paper, we study the problem of placing the minimum number of regenerators to accommodate all requests with the consideration of physical impairments. We first propose a novel ILP formulation for an optimal solution and a benchmark for this problem. We then provide an effective heuristic for large-sized WDM networks. Simulation results show that our schemes have good performance in terms of network design and running time.

Keywords: WDM networks, physical impairments, OEO module, regenerator, ILP formulation, route provisioning.

I. INTRODUCTION

Fiber optics have replaced copper as the primary transmission medium. Wavelength Division Multiplexing (WDM) networks effectively increase single-link bandwidth from 10Mbps to over 160Gbps, and have been considered as a promising candidate for the next-generation backbone network. All optical circuits, each on a separate wavelength called lightpaths [3], represent the first major method for optical communication. There have been many previous works on routing and wavelength assignment (RWA) and transparent optical network design problems [6], [9]. Most previous works have investigated the problems under the assumption that the optical medium is an ideal one which can carry data signals without any bit error. Under this assumption, the effects of transmission impairments on the quality of a connection are not considered. However, in reality, a wavelength-routed network faces several technical difficulties in overcoming the physical impairments introduced by optical fibers and optical components such as erbium-doped fiber amplifiers (EDFA) and optical cross connects (OXC's). Physical impairments, e.g., power loss, noises, and dispersions, impose fundamental constraints on the quality of signals in WDM optical networks [11]. Therefore, at the destination node, the received signal quality may be so poor that the bit-error rate (BER) could be too high to be acceptable, thereby making the lightpath unusable [1].

Huang et al. [5] proposed a hierarchical RWA model, as well as impairment-aware RWA algorithms. In that work, physical layer models, such as admission control, evaluate optical signal-to-noise ratio (OSNR) and polarization mode dispersion (PMD) effect on the candidate lightpath, and decide whether or not to set up the lightpath on the network layer.

With current technology, only OEO conversion can solve the transmission impairments problem [5], [13], [14]. A practical regeneration network model was proposed in [8]. However, the opaque optical network, in which OEO conversion is used for every wavelength at every node, is too expensive and inefficient. Therefore, the concept of translucent network was proposed in [7]. In a translucent WDM mesh network, a small number of OEO modules are sparsely placed. Route provisioning with sparse OEO consumption in translucent WDM mesh networks has also been studied recently. In [10], considering one signal constraint, the maximum distance that a lightpath may transmit without regeneration, the authors studied the placement of regenerators on a given number of nodes in order to get the minimum blocking probability for a given traffic matrix. In [12], with another signal constraint, the maximum number of links that a lightpath may transmit without regeneration, the authors also considered finding a given number of nodes to place regenerators while minimizing the blocking probability. Then, using the placed regenerators, they studied the issue of providing a path for the new-coming demand by using a minimum number of regenerators and then a minimum number of free wavelengths.

In [13], multiple optical impairments were considered. With regenerator placement already given, the authors considered survivable route provisioning for a given static traffic matrix, with the objective to minimize the number of regenerators and wavelengths consumed by all the connection requests.

In this paper, with the consideration of multiple optical signal constraints, we study a regenerator placement problem.
To our best knowledge, regenerator placement with multiple signal constraints has yet not been studied. We want to use the minimum number of regenerators for provisioning the given traffic matrix. In addition, by using the fewest regenerators possible, we intend to reduce the consumption of the free wavelengths.

The rest of the paper is organized as follows. In Section II, we introduce the transmission impairments in optical networks, the network model we use and the problem statement. In Section III, the translucent networks design problem is presented. We present an ILP formulation to give an optimal solution. This is followed by Section IV with a heuristic algorithm for the translucent networks design problem. Simulation results of our algorithms are presented in Section V. We conclude this paper in Section VI, summarizing our contributions.

II. PROBLEM FORMULATION

A. Transmission Impairment in Optical Networks

In this paper, we consider two major linear impairments: Polarization Mode Dispersion (PMD), and Amplifier Spontaneous Emission (ASE), which have been extensively discussed in many previous works [5], [8], [11], [13]. These two impairments are regarded as the key linear impairments that are practically applied to constrain optical transmissions [11].

1) Polarization Mode Dispersion: PMD management requires that the time-average differential time delay between two orthogonal states of polarizations, $\Delta \tau$, be less than a fraction $\alpha$ of the bit duration, $T=1/B$, where $B$ is the bit rate. A typical value for $\alpha$ is 0.1 [11]. Assume that a transparent segment consists of $M$ fiber spans, where the $k$th span has length $L(k)$ and PMD parameter $D_{PMD}(k)$. The constraint on the average differential delay can be expressed as:

$$B \sum_{k=1}^{M} D_{PMD}(k)^2 \cdot L(k) \leq \alpha. \quad (1)$$

Assume that the length of a fiber span is integral, and all fiber spans have the same PMD parameters, i.e., $D_{PMD}(k) = D_{PMD}$. an upper bound on the total length of the $M$-span segment, denoted by $L$ is $\alpha^2 / (B \cdot D_{PMD})^2$. Therefore, PMD gives the constraint on the length of a lightpath with acceptable BER:

$$L = \sum_{k=1}^{M} L(k) \leq \frac{\alpha^2}{B^2 D_{PMD}^2} \ = \ C_{PMD}. \quad (2)$$

2) Amplifier Spontaneous Emission: ASE is the dominant noise in optical networks, and degrades the signal to noise ratio. An acceptable optical SNR level ($SNR_{min}$) which depends on the bit rate and transmitter-receiver technology needs to be maintained at the receiver. The more EDFAs an optical signal traverses, the higher ASE noise power it suffers from. EDFAs are basically placed at nodes, at both input and output ports. We can obtain an upper bound on $M$, the maximum number of spans, using the OSNR constraint in [11]

$$\sum_{k=1}^{M} n_{sp}(k) (G(k) - 1) \leq \frac{P_L}{2hvB_o SNR_{min}}, \quad (3)$$

where $P_L$ is the average optical power launched at the transmitter, $G(k)$ and $n_{sp}(k)$ are the amplifier gain and excess noise factor, respectively, on the $k$th span, $h = 6.63 \times 10^{-34} J/Hz$ is the Planck’s constant, $v$ is the carrier frequency, and $B_o$ is the optical bandwidth.

Assume that the lightpath goes through $M$ optical spans, with each introducing the same noise power and that each optical amplifier has the same power gain $Gn$. Then

$$M \leq \left[ \frac{P_L}{2SNR_{min} n_{sp}hv (Gn - 1) B_o} \right] = C_{ASE}. \quad (4)$$

ASE can be understood as the constraint for the maximum number of links a lightpath may have.

B. Network Model

In this paper, we consider the translucent network model, shown in Fig. 1. A translucent network is a wavelength-routed mesh network with the capability of sparse OEO regeneration. Such a network consists of a number of wavelength-routing nodes with optional OEO modules and interconnected by optical fiber links. Each node has a fixed number of add and drop ports, through which the user data can access the network.

![Node model in a translucent network](13)

The wavelengths on an incoming fiber are de-multiplexed, switched by the wavelength routing switches (WRS) in a non-blocking way in the optical plane, and then multiplexed into the outgoing fiber. An access station exists in the node which can add or drop calls from or to the electronic branches. The node has inherent regeneration resources because it provides the basic regeneration resource of Tx/Rx pairs. 3R (regenerate, reshape and retiming) regenerators can be attached between a Tx-Rx pair to implement signal regeneration in the electronic plane. The combination of a transmitter, a receiver and an electronic 3R regenerator is called an OEO module [13]. Such a node model allows all-optical switching by WRS switching, as well as OEO regeneration by using an OEO module on the node. The path from the source node to the destination node is divided into several segments by OEO regenerations at intermediate nodes, which are named regeneration nodes. Each segment is defined as a regeneration segment [13].

C. Problem Statement

With the consideration of both ASE and PMD constraints, we study the REGenerator Placement And Routing Establishment (REPARe) problem in translucent networks. Given the following information:

1) The network topology is given, represented as a graph $G(V, E, \Omega)$, where $V$ is the set of vertices, $E$ is the set of links, and $\Omega$ is the set of wavelengths per fiber.
2) The traffic matrix of the network is also given.
3) The configuration of the optical devices is given, which includes:
   - The number of wavelengths on each fiber
   - The number of Transmitter/Receiver pairs per node
   - The ASE and PMD costs of each link

The objective of REPARE is to find a minimum number of nodes, with each having $X$ OEO modules placed, along with a routing scheme such that all the requests can be accommodated with satisfying both ASE and PMD constraints.

As in [12], $X$ is the total number of wavelengths on all incoming links at a node. We also want to reduce the consumption of free wavelengths using the fewest number of regeneration nodes. As in [8], [10], a wavelength graph is used to handle the lightpath routing and wavelength assignment. In the rest of the paper, we use $\text{graph}$ to represent wavelength graph, and use $\text{OEO}$ module and regenerator interchangeably.

III. OPTIMAL SOLUTION FOR REPARE

Because the basic static lightpath establishment (SLE) problem (even without regeneration consideration) has already been proven to be $NP$-hard in [2], we conjecture that REPARE is also $NP$-hard since it also needs to provide lightpaths for the traffic matrix. In this section, we propose a novel ILP formulation for an optimal solution to the REPARE problem.

It is worth noting that the REPARE problem is different from the problem studied in [13], which also considers multiple signal constraints. In that work, the regenerator placement, and consequently all regeneration segments, are known in advance. In our work, we do not have any regenerator placed, and need to place $\text{OEO}$ modules to set up the regeneration segments. One of our contributions is to present a novel graph transformation to simplify our ILP formulation for the REPARE problem.

A. Graph Transformation

To formulate an ILP directly for REPARE is very difficult because it is impossible to enforce signal quality constraints without knowing regeneration segments. To tackle the hardness of the problem, we first use a novel graph transformation to transfer REPARE to an equivalent problem.

**Definition 3.1 (neighbor pair):** For any two nodes $u$ and $v$ in a network, if there exists a path from $u$ to $v$ which can satisfy the signal quality constraints, then we say that $u$ and $v$ is a neighbor pair, and node $v$ is node $u$’s neighbor node.

Given an original graph $G$, we construct an auxiliary graph $G'$ in following way:
   - copy all nodes in $G$ into $G'$;
   - add an edge between two nodes in each neighbor pair.

**Definition 3.2 (component set):** For each pair of neighbor nodes in $G$, an edge connecting them is inserted in $G'$, which means that they can communicate with each other without signal regeneration in $G$. We use $E_{\text{aux}}$ to denote the set of these new edges in $G'$. Each edge $(u, v)$ in $E_{\text{aux}}$ actually represents a set of edges in $G$ (a path connecting node $u$ and $v$). Such a set of edges is called the component set of edge $(u, v)$.

If two nodes in $G$ are not a neighbor pair, then regeneration is necessary for connecting them in $G$.

Now we provide a problem equivalent to REPARE: For connection between two nodes which are not a neighbor pair, we need to find a path in $G'$, and place regenerators on each intermediate node on the path. Such a path corresponds to a feasible solution in $G$ within signal quality constraints. The objective is to minimize the total number of intermediate nodes in $G'$, which actually are regeneration nodes in $G$.

We use an example in Fig. 2(a) for illustration. In the original graph $G$, the label is the (ASE, PMD) cost on each edge. Assume $C_{\text{ASE}} = 2$ and $C_{\text{PMD}} = 2$. Fig. 2(b) gives the auxiliary graph $G'$ of $G$. Any two adjacent nodes in $G$ is a neighbor pair in $G'$. In addition, node 1 is node 3’s neighbor node because there is path $(3, 2, 1)$ connecting them without violating signal constraints. There are no other neighbor pairs.

Now suppose there is a connection request from 3 to 4. For this connection, since we try to minimize the number of intermediate nodes, we find a shortest path in $G'$, say $(3, 1, 4)$, which corresponds to the path $(3, 2, 1, 4)$ in the original graph $G$. Regenerators are placed on node 1, instead of 1 and 2.

The idea behind the graph transformation is that we transfer the hard part of the REPARE problem, how to decide and choose different regeneration segments, into the equivalent problem of how to route for connections. For example, if node 3 chooses neighbor node 1, and path $(3, 1, 4)$ in $G'$, we actually decide to place regenerators on 1, and use two regeneration segments in $G$, $(3, 2, 1)$ and $(1, 4)$. If we choose node 2 and path $(3, 2, 1, 4)$ in $G'$, then regenerators are placed on both 1 and 2. Now in $G$ three regeneration segments, $(3, 2), (2, 1), (1, 4)$, are used. By minimizing the usage of intermediate nodes in $G'$, we can minimize the usage of regeneration segments and the placed regenerators in $G$.

B. ILP Formulation

In this section, we present the ILP formulation to provide connections for the traffic matrix with the minimum number of intermediate nodes in $G'$.

1) **Notation**
   - $\text{role}(u)$: 1 if regenerators are placed on $u$, 0 otherwise.
   - $\Omega$: The set of wavelengths.
   - $K$: The set of connection requests in the traffic matrix.
   - $\text{src}(k)$: The source node of the $k^{th}$ request.
   - $\text{tgt}(k)$: The destination node of the $k^{th}$ request.
   - $f_{u,v,\omega}^{k}$: If the wavelength link $(u, v, \omega)$ is used for the $k^{th}$ request, the value is 1. Otherwise, the value is 0.
   - $\text{out}(u)$: The outgoing adjacent node set of node $u$.

Now we present the ILP formulation for an optimal solution to the REPARE problem.
• $in(u)$: The incoming adjacent node set of node $u$.
• $com(u, v)$: The component set of edge $(u, v)$ in $E_{aux}$.

2). Objective

$$\min \sum_{u \in V} role(u)$$

(5)

3). Constraints

$$\sum_{k \in \Omega} f_{s,v,\omega}^k - \sum_{k \in \Omega} f_{v,s,\omega}^k = 1; \forall k \in K, s = src(k)$$

(6)

$$\sum_{k \in \Omega} f_{v,t,\omega}^k - \sum_{k \in \Omega} f_{t,v,\omega}^k = 1; \forall k \in K, t = tgt(k)$$

(7)

$$\sum_{k \in \Omega} f_{u,v,\omega}^k = \sum_{k \in \Omega} f_{v,u,\omega}^k$$

(8)

$$\forall k \in K, \forall \omega \in \Omega, \forall u \in V(\neq src(k) \text{ or } tgt(k))$$

$$\sum_{k \in \Omega} f_{u,v,\omega}^k \leq 1,$$

$$\forall k \in K, \forall \omega \in \Omega, (u, v) \in E,$$

(9)

$$\sum_{k \in \Omega} f_{u,v,\omega}^k + \sum_{k \in \Omega} f_{m,n,\omega}^k \leq 1;$$

$$\forall (u, v) \in E_{aux}, (m, n) \in com(u, v), \forall \omega \in \Omega$$

(10)

$$\forall k \in K, \forall \omega \in \Omega, \forall u \in V(\neq src(k) \text{ or } tgt(k))$$

$$\forall k \in K, \forall \omega \in \Omega, \forall u \in V$$

(11)

The objective is to minimize the total number of nodes on which regenerators are placed. Constraints (6), (7), and (8) are the flow conservation constraints for all connection requests. Constraint (8) also guarantees the wavelength continuity for each lightpath. With constraints (9) and (10), it is ensured that no two lightpaths can share the same wavelength. In constraint (11), for a node $u$, which is used as intermediate node for some connection, it will be a regenerator node.

It is worth noting that our ILP formulation can attain savings on the free wavelength consumption. If we use $W$ as the total number of wavelengths on each fiber, and $K$ as the total number of connection requests, from constraint (11), we can have

$$W \cdot K \cdot role(u) \geq \sum_{k \in K} \sum_{\omega \in \Omega} \sum_{u \in V} f_{u,v,\omega}^k$$

(12)

then we have

$$W \cdot K \cdot \sum_{u \in V} role(u) = \sum_{u \in V} (W \cdot K \cdot role(u))$$

(13)

$$\geq \sum_{u \in V} \sum_{k \in K} \sum_{\omega \in \Omega} f_{u,v,\omega}^k$$

(14)

$$= \sum_{k \in K} \sum_{\omega \in \Omega} \sum_{u \in V} f_{u,v,\omega}^k$$

(15)

Note that (15) is the total number of free wavelengths used for all requests. Therefore, our ILP minimizes the lefthand side of (13), and it also reduces the consumption of free wavelengths. This ILP formulation is a very simple and practical one.

C. Implementation

One important issue for our ILP formulation is the graph transformation process. In detail, how to decide if two nodes in $G$ are neighbor pair or not. To tackle this issue, we present a novel scheme, listed in Algorithm 1 to implement graph transformation in this section.

Let us use Fig. 3 to illustrate our algorithm. Given $C_{ASE} = 3$, $C_{PMD} = 2$, $(ASE, PMD)$ cost as marked on each edge. Assume we need to check if nodes 1 and 2 are neighbor nodes. Given $pmd = 2$, we split each node into 3 copies, each of which represents the node with a specific $PMD$ cost. For example, we split node 1 into nodes $1^0$, $1^1$, and $1^2$, which stand for node 1 with $PMD$ cost 0, 1, and 2, respectively.

From node $1^0$, an edge to node $2^2$ is added in $E_{pmd}$. This edge represents that from node 1, with $PMD$ being 0, through edge $(1, 2)$ in $G$, we can reach node 2 with $PMD$ cost 2. In addition, the cost of this edge is 3, which is the $ASE$ cost of edge $(1, 2)$ in $G$. By using $(1, 2)$, the $ASE$ cost will be increased by a value of 3 from node 1 to node 2.

Algorithm 1 Checking Neighbor Nodes($G, s, t$)

1: Construct an auxiliary directed graph $G_{pmd}$ with node set $V_{pmd} = V \times \{0, 1, \ldots, pmd\}$;
2: for (each edge $(u, v)$ in $E$) do
3: Insert an edge $e$ from $(u, C_u)$ to $(v, C_v)$ such that $C_v = C_u + PMD(u, v)$ into $E_{pmd}$;
4: assign cost $\text{ASE}(u, v)$ on edge $e$;
5: end for
6: for ($C = 0$ to $C_{PMD}-1$) do
7: Insert zero cost edges from $(t, C)$ to $(t, C_{PMD})$ into $E_{pmd}$;
8: end for
9: Compute a shortest path from $(s, 0)$ to $(t, C_{PMD})$ in $G_{pmd}$;
10: if there is a path $p$ from $(s, 0)$ to $(t, C_{PMD})$ then
11: $t$ and $s$ is a pair of neighbor nodes;
12: end if

Note that from node $1^1$ or $1^2$, there is no edge to the copies of node 2 because any edge will violate the $PMD$ constraint. Such operations will be repeated for all edges in $G$ (Lines 2-5). From node $1^0$, we can find 2 paths to $2^2$ for the request $(1, 2)$, $(1^0, 2^2)$, marked by blue thick solid edge, and $(1^0, 3^1, 2^2)$, marked by dashed red links. We choose the latter path because it has the minimum $ASE$ cost (Lines 9-12).

Note that if nodes $u$ and $v$ are neighbor nodes, our algorithm guarantees to find a feasible path which has the minimum $ASE$ cost. Using Algorithm 1, we can construct neighborhood of each node in $G$, construct the auxiliary graph $G'$, and implement our ILP formulation.
IV. AN EFFECTIVE HEURISTIC

The proposed ILP formulation is simple and able to provide an optimal solution. However, ILP may not be suitable for large networks. Therefore, we propose an effective heuristic (listed in Algorithm 2) for the REPARE problem in this section.

In Lines 1-6, all the neighbor pairs, found by Algorithm 1, will be accommodated without signal regeneration. If all connections are provisioned, then the algorithm finishes. Otherwise, in Line 11-15, we find a candidate path with minimum PMD cost for each unaccommodated request. Then, we calculate the minimum number of regenerations needed for this path by calling Algorithm 3.

Algorithm 3 starts with the source of a candidate path, computes the ASE and PMD costs for each node along the path. Regenerators are placed when necessary.

Algorithm 2 TND(G)

1: for (each connection request (s, t)) do
2: Finding_Neighbor_Nodes(G, s, t);
3: if (the destination node t is in s neighborhood) then
4: Provision connection for this request;
5: end if
6: end for
7: if (All requests have been satisfied) then
8: done = 1;
9: else
10: done = 0;
11: for (each unaccommodated requests C) do
12: Provide a candidate connection by finding a path with minimum PMD cost;
13: R = φ;
14: dmd[C] = OEO_demand(C, R);
15: end for
16: end if
17: while (!done) do
18: for (each node u in the candidate connections) do
19: for (each connection C) do
20: pd[C, u] = OEO_demand(C, R ∪ {u});
21: bonus[C] = dmd[C] - pd[C, u];
22: end for
23: benefit[u] = \sum_{C} (bonus[C]);
24: end for
25: Choose node m with the maximum benefit[m];
26: R = R ∪ {m};
27: for (each connection C) do
28: dmd[C] = pd[C, m];
29: end for
30: if (each connection C has dmd[C] == 0) then
31: done = 1;
32: end if
33: end while

From Line 17 to Line 33 in Algorithm 2, for each node u used for candidate paths, if node u is not a generation node, we ask a question "if we use u for regeneration, can we save regenerator usage for all connections?". In Line 20, we calculate the number of necessary regenerators with regenerator set R ∪ {u}. Then, in Line 21, compared to previous OEO demands, we can see how many regenerators we can save, which is the bonus for using node u. We choose the node with the maximum bonus to be the next regeneration node, and update the regenerator usage for all connections. If no connection needs more regeneration after placing regenerators on m, the algorithm stops.

Let us use Fig. 4 for the illustration of Algorithms 2 and 3.

Algorithm 3 OEO_demand(C, R)

1: n = source(C); demand = 0;
2: ASE_N(n) = PMD_N(n) = 0;
3: while (n ≠ target(C)) do
4: m is the next hop on connection C;
5: if (m ∈ R) then
6: ASE_N(m) = ASE(n, m);
7: PMD_N(m) = PMD(n, m);
8: else
9: ASE_N(m) = ASE_N(n) + ASE(n, m);
10: PMD_N(m) = PMD_N(n) + PMD(n, m);
11: if (ASE_N(m) > C_ASE) OR (PMD_N(m) > C_PMD) then
12: regenerator is necessary on node n;
13: demand = demand + 1;
14: ASE_N(m) = ASE(n, m);
15: PMD_N(m) = PMD(n, m);
16: end if
17: end if
18: n = m;
19: end while
20: return demand;

(ASE, PMD) costs are marked on each edge. Now suppose C_ASE=C_PMD=2, and we have 3 connection requests: (1,4), (3, 5), (3, 6). We first use path (1,4) for the first request because it does not need regeneration, and use the minimum ASE cost. Then, we find two candidate paths (3,2,1,5) and (3,2,4,6), for other 2 requests, respectively. Using Algorithm 3, we find that two regeneration are needed, one for each request. To find the regeneration nodes (Lines 17-33), we first check node 3, if it is used for regeneration, two regenerations are still needed for each request. Therefore, the bonus of placing regenerators on node 3 would be 0. Similarly, no bonus for using node 5 or 6. If we use node 1 as regeneration node, request (3,5) is satisfied without any more regeneration. But we still need one more regeneration on path (3, 2, 4, 6) for request (3, 6). Thus, the bonus for using node 1 is 1. Similarly, we can analyze the case for using node 4. Next, if we use node 2 for regeneration, both requests can be satisfied without using any more regeneration. Therefore, the bonus of using node 2 is 2. We choose node 2 as a regeneration node because it brings the maximum bonus. Now all requests are accommodated, and the algorithms stops with regenerator placement on node 2.
V. NUMERICAL EVALUATION

In this section, we present some numerical results to show the performances of our solutions. We use a well-known Internet topology to study the algorithms. Pacific Bell network (15 nodes and 21 links), shown in Fig. 5, is used as the test network. Each link is labeled by its length in kilometers.

![The 15-node/21-link Pacific Bell network.](image)

Fig. 5. The 15-node/21-link Pacific Bell network.

The system parameters are set to typical values as in [11]:
- \( \alpha \) has value 0.1, and \( D_{PM} \) is 0.5ps/\( \sqrt{\text{km}} \);
- The data rate on each wavelength channel \( B \) is 10 Gb/s;
- \( P_L = 4 \text{dBm}, \text{SNR}_{\text{min}} = 25 \text{dB}, n_{sp} = 2.5 \), \( G = 25 \text{dB} \) with \( h = \text{B}_0 = 58 \text{dBm} \);
- Maximum number of spans, \( C_{ASE} \) is 3.
- Maximum transparent segment length, \( C_{PMD} \) is 400 km.

In simulations, the number of wavelengths \( (W) \) on each fiber is set to 32. We implemented our heuristic of this paper (denoted by TND in the figures), and compared it with the optimal solution given by ILP (denoted by ILP in the figures). Different size of traffic matrixes are randomly generated. Each request in a matrix is generated with random source node and destination node. Our numerical results are presented in Fig. 6 and Fig. 7, where each figure shows the average of 10 runs. It’s worth noting that we have also tested both algorithms on some randomly generated network topologies. The results are similar. Therefore we only present the results for Pacific Bell Network here due to the page limit.

![The number of placed regeneration nodes.](image)

Fig. 6. The number of placed regeneration nodes.

First, we compare the number the regeneration nodes computed by the ILP formulation and our heuristic. We used CPLEX [4] to solve the ILP formulation, and performed our simulations on a machine with an Intel Pentium 1.70GHz CPU, and 512MB memory. The results are shown in Fig. 6. The \( x \)-axis \( K \) represents the traffic matrix size (the number of connection requests), while \( y \)-axis \( R \) gives the number of regeneration nodes placed.

We notice that when the number of connections is more than 70, the ILP formulation cannot provide solution due to the memory limitation. On the other hand, our heuristic delivers good performances compared to the optimal solution. For example, when the traffic matrix size is 60, the optimal solution needs 4 regeneration nodes on average. TND needs only 6 regeneration nodes on average. Another observation is that when the traffic matrix is large, the number of regeneration nodes placed by our heuristic is around 7, which means, by using only at most 50% of all nodes as regeneration nodes, all requests can be satisfied.

![The running times of our approaches.](image)

Fig. 7. The running times of our approaches.

The second comparison is the running time performance of our solutions. For ease of exposition, the metric for TND is \textit{millisecond}, while for ILP is \( 10^3 \text{-millisecond} \). Fig. 7 concedes this difference in scale. For request numbers 80, 90 and 100, the ILP running times are the times CPLEX returned when memory limitation is reached, which is less than the actual ILP running time. It is easy to see that TND is much faster in comparison to ILP. For 70 connection requests, ILP consumed average 300 seconds, while TND only spent 40 milliseconds with comparable results.

![How much can TND help connection provisioning?](image)

Fig. 8. How much can TND help connection provisioning?

Next we show the effect of our algorithm in terms of lower the blocking probability of connection requests. We studied the case by comparing TND with routing schemes in WDM networks without regenerators. First, we try to set up lightpaths [3] for the requests (denoted by \textit{Lightpath} in Fig. 8). For each connection request, we try to find a lightpath on a wavelength plane with \textit{shortest path length}. If the lightpath satisfies signal quality constraints, we keep it. Otherwise, we drop the connection request. Second, we use the algorithm in [15] (denoted by \textit{Light-Trail} in Fig. 8) to construct \textit{Light-Trails} for connections. Light-trails allows multiple connections to be transmitted on the same wavelength link. Therefore a light trail uses wavelengths more efficiently than a lightpath. Similarly, any light-trail without satisfied signal quality will be dropped. It can be seen from Fig. 8 that Light-Trail can accommodate
more connections than the Lightpath. To answer the question of how much can regenerators help connection provisioning?, we placed \( K \) regenerators for the requests using our algorithm. When \( K = 25\% \cdot |V| \), we stop placing more regenerators. As we expected, with TND, a small number of regenerators are effectively placed. The routing performance is obviously better than traditional lightpath and light trail schemes.

VI. CONCLUSIONS

In this paper, we considered a Translucent Networks Design problem with multiple signal quality constraints. We proposed a simple and well-formulated ILP solution for an optimal solution. Moreover, an efficient heuristic was proposed for large-sized networks. Simulation results showed that our ILP formulation is practical, and the heuristic algorithm is very fast and scalable with comparable results. Moreover, our heuristic can help to effectively lower the connection blocking probability.

REFERENCES