# Dynamic Lightpath Allocation in Translucent WDM Optical Networks†

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***Abstract*—The *optical reach* (the distance an optical signal can travel before the signal quality degrades to a level that necessitates regeneration) ranges from 500 to 2000 miles. To establish a lightpath of length greater than the optical reach, it is necessary to *regenerate* optical signals. In a *translucent optical network*, there are regeneration points, where the signal undergoes Optical-Electronic-Optical (O-E-O) conversion. In this paper we have proposed routing algorithms for translucent networks in a dynamic lightpath allocation environment in which requests for communication arrive continuously. In response to each request for communication, the objective is to establish, if possible, a path, from the source to the destination of the request for communication, so that a lightpath may be established, using the path that requires the fewest stages of regeneration. In practical transparent networks, a lightpath must satisfy the *wavelength continuity* constraint. However, in a translucent network, this constraint can be relaxed at the regeneration points. We have proposed an Integer Linear Program, to give the optimum results for small networks, as well as an efficient heuristic for this problem that works for larger networks. We have evaluated the heuristic through extensive simulations to establish that the heuristic produces close-to-optimal solutions in a fraction of the time needed for the optimal solutions. Our extensive evaluations demonstrate the relative impact of a set of network resources, such as (i) the number of regenerators, (ii) the optical reach of the regenerators and (iii) the number of wavelengths, on the network performance, measured in terms of the call blocking probability. To the best of our knowledge this is the first study that undertakes such an evaluation for translucent networks.**

## I. Introduction

Communication in *all-optical* or *transparent networks* is carried out purely in the optical domain without any Optical-Electronic-Optical (O-E-O) conversion. However, factors such as optical noise, chromatic dispersion, nonlinear effects, polarization mode dispersion (PMD) and cross-talk cause the optical signal quality to degrade as it propagates through a fiber [1]–[4]. The distance $r$ an optical signal can propagate before its quality degrades to a level that necessitates regeneration, is called the *optical reach*, which typically ranges from 500 to 2000 miles [2]. To establish any communication path greater than $r$, it is necessary to *reamplify, reshape* and *retime* the optical signal (often called *3R regeneration*) [3]. In *translucent networks*, since 3R regeneration is expensive, only a subset of the nodes are capable of performing the 3R regeneration. Henceforth we will call the lightpath from a source to a destination that involves one or more regenerators as a *translucent* lightpath. A translucent lightpath consists of two or more transparent (i.e., all-optical) lightpaths where one transparent lightpath is from the source of the communication to a regenerator, one from a regenerator to the destination for the communication and the remaining transparent lightpath(s), if any, is (are) from one regenerator to another. The total length of the fibers in each transparent lightpath must not exceed the optical reach, $r$. Two problems in translucent network design have received attention recently. The Regenerator Placement Problem (RPP) [1]–[9] is to find i) the minimum number of regenerators and ii) their locations, so that a communication path can be established between every pair of source-destination nodes in the network. In the Routing with Regenerators Problem (RRP), the locations of the regenerators are known and the objective is to compute a path between a source-destination node pair using as few regenerators as possible [10], [11]. In this paper we study the RRP problem.

We will call each transparent component of a translucent lightpath as a *segment*. It is important to carry out regeneration as sparingly as possible, since regeneration results in both increased delays and Bit Error Rates (BER) as a result of O-E-O conversion [10]. An important objective in dynamic translucent lightpath allocation in translucent networks is, therefore, to compute a source-destination path that requires a minimum number of regenerators. Since O-E-O conversion takes place at regenerators, wavelength conversion is available for free at the regenerators. We assume that all-optical wavelength converters are not available, so that the wavelength continuity constraint [12] must be satisfied for each segment. An example of a long haul network with distances between the nodes in miles is shown in Figure 1. If the optical reach is $r = 2000$ miles, an optical signal from node $A$ cannot reach node $H$ without regeneration. For communication between $A$ and $H$, if there is a regenerator at $D$, a translucent lightpath ($P = A \to B \to C \to D \to F \to G \to B \to C \to H$) with two segments ($S_1 = A \to B \to C \to D$) and ($S_2 = D \to F \to G \to B \to C \to H$) can be established.

**Property 1:** *If a translucent lightpath involves two segments, $S_a$ and $S_b$ that have one or more common fiber (s), the same wavelength cannot be used for both segments $S_a$*

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*and $S_b$ [13].*

For instance, in Figure 1, the segments $S_1$ and $S_2$ of the translucent lightpath $P$ have the common fiber $B \rightarrow C$. If channel $c_1$ is available on all the fibers in the network, when processing a request for communication from $A$ to $H$, channel $c_1$ cannot be used for both segments $S_1$ and $S_2$.

Fig. 1. Long haul optical network with distances between the nodes in miles

To the best of our knowledge, this property has not been taken into account in translucent network design [1]–[11]. In other words, existing algorithms for routing in translucent networks may give an invalid route and wavelength if segments have common fiber(s). An important contribution of this paper is to show how this restriction may be taken into account when solving the RRP problem. In this paper, we have studied the problem of dynamic lightpath allocation to establish a lightpath from some node $S$ to some other node $D$ in the presence of other lightpaths (translucent or transparent), set up earlier in response to previous requests for communication. We have used Property 1 to

- propose an Integer Linear Program (ILP) which gives an optimal path for a translucent lightpath using a minimum number of regenerators[1].
- propose an efficient heuristic to compute the path with a minimum number of regenerators.
- establish, through extensive simulations with dynamic call arrivals, the effectiveness of the heuristic by measuring call blocking probability.
- demonstrate, through extensive simulations, the relative impact of a set of network resources, such as (i) the number of regenerators, (ii) the optical reach of the regenerators and (iii) the number of wavelengths, on the network performance, measured in terms of the call blocking probability.

The rest of the paper is organized as follows. Section II is a review of related work in this area. Section III proposes an ILP and a heuristic to solve the problem of establishing translucent lightpaths. Section IV describes the simulation results and section V concludes the paper.

## II. Related Work

Recently the Minimum Regenerators Path problem has received some attention [1], [10], [11]. In [14], the authors have proposed two dynamic routing algorithms based on the MPLS hierarchy that considers regeneration resources available at each regenerator and the link states. The proposed algorithms try to minimize the total number of regeneration hops and the total Bit Error Rate (BER) on the computed route. In [11], the authors provide an intra-domain routing algorithm considering a number of optical-layer constraints in a dynamic call arrival setting. However, it may be difficult to obtain BER, optical dispersion and other physical impairment factors in real-time. Recent research [1] indicates that the optical reach, $r$, can be used a rough approximation for all these factors. Simmons [2] suggests some techniques for finding the minimum regeneration route between a node pair, based on enumerating a large number of paths between the source and the destination. However, these techniques may not always ensure the existence of a solution. In addition, the existing routing techniques do not take into account the property mentioned above about segments that share fibers. As a result, the source to destination path computed by the existing techniques may not be a simple path (that is, edges may be repeated). Such a path cannot be used in case the overlapping segments have same channel number available for path establishment. There are a number of routing algorithms (e. g., [15]) that consider capacity constraints, physical impairments and the wavelength continuity constraint in minimizing the cost of the desired route. But, most of them use static computation in which the routes are computed before the requests arrive. The work in [11] is the closest to our work. However, since the authors in [11] consider different set of parameters than our problem, our solution techniques cannot be compared with their work.

## III. Formulations for Determining Dynamic Translucent Lightpaths

In the heuristic described in Section III-C, we will use the term *path intersection graph* to denote a graph $G_P = (V_P, E_P)$, where each vertex in $V_P$ represents a path through the optical network that may be used to set up a transparent lightpath. If $p$ and $q$ are two vertices in $V_P$, there will be an edge, in $E_P$, between $p$ and $q$, iff the paths through the optical network, corresponding to $p$ and $q$, share one or more edge(s).

### A. Notation used in the formulations

- $\boldsymbol{r}$ : the optical reach.
- $\boldsymbol{n}$ : the total number of nodes in the network.
- $\boldsymbol{s}$ : a constant denoting the maximum possible number of segments in a translucent lightpath.
- $\boldsymbol{d_{ij}}$ : a constant denoting the distance of the edge $i \rightarrow j$.
- $\boldsymbol{\delta_i}$ : a constant for node $i, 1 \leq i \leq n$, defined as follows: $$\delta_i = \begin{cases} 1 & \text{if the } i^{\text{th}} \text{ node is a 3R regenerator,} \\ 0 & \text{otherwise.} \end{cases}$$
- $\boldsymbol{E}$ : the set of all pairs $(i, j)$ of nodes such that $i \rightarrow j$ is an edge in the physical topology.
- $\boldsymbol{n_{ch}}$ : the number of channels available on a fiber.
- $\boldsymbol{w_{ij}^p}$ : A constant defined as follows $$w_{ij}^p = \begin{cases} 1 & \text{if an existing lightpath uses channel } p \\ & \text{on edge } i \rightarrow j, \\ 0 & \text{otherwise.} \end{cases}$$

[1]The rationale for using regenerators as sparingly as possible has been mentioned earlier.

$\boldsymbol{W_p^k}$ : A binary variable denoting whether channel $p$ is allocated to segment $k$ such that

$$W_p^k = \begin{cases} 1 & \text{if the } k^{\text{th}} \text{ segment of the new} \\ & \text{translucent lightpath uses channel } p, \\ 0 & \text{otherwise.} \end{cases}$$

$\boldsymbol{X_{ij}^k}$ : a binary variable for each edge $i \to j$ in the physical topology and for each segment $k$, such that

$$X_{ij}^k = \begin{cases} 1 & \text{if the } k^{\text{th}} \text{ segment of the new} \\ & \text{lightpath uses the edge } i \to j \\ 0 & \text{otherwise.} \end{cases}$$

$\boldsymbol{m}$ : the number of paths, for transparent lightpaths, that will be pre-computed between every node pairs.

$\boldsymbol{\mathcal{P}_{xy}}$ : the set of pre-computed paths from node $x$ to $y$.

$\boldsymbol{\mathcal{S}}$ : a set of states that need to be explored.

$\boldsymbol{\mathcal{N}}$ : a set of new states.

$\boldsymbol{\mathcal{C}}$ : a set of paths from the current node.

$\boldsymbol{\mathcal{R}}$ : the set of regenerator nodes in the optical network.

$\boldsymbol{x}$ : a node in the optical network.

$\boldsymbol{P}$ : the set of paths, each with a total length $\leq r$, that may be used to reach $x$ from source $S$.

$\boldsymbol{c_{ij}}$ : the set of channels still available on edge $i \to j$.

$\boldsymbol{\mathcal{W}_v}$ : the set of colors to color vertex $v$ of $G_P$.

$\boldsymbol{\mathcal{W}}$ : the set of the set of colors $\{\mathcal{W}_v : v \in V_P\}$.

$\boldsymbol{p}$ : A transparent path.

$\boldsymbol{v}$ : A vertex of a path intersection graph.

### B. An ILP formulation for the problem

The ILP formulation below determines the minimum number of regenerators to ensure that a translucent lightpath may be set up from any source to any destination. This formulation does not take into account existing lightpaths or the pattern of requests for connections in a dynamic lightpath allocation scenario. In our experiments we have shown that an increase in the number of regenerators in a translucent network decrease the blocking probability and the number determined by the ILP represent the minimum number of regenerators required in a translucent network. One important feature of the translucent lightpath is that there may be unavoidable cycles in the path used. For instance, in Figure 1, there is a cycle $C \to D \to F \to G \to B \to C$. The ILP below allows such cycles in a translucent lightpath by setting up segments which satisfy standard flow balance equations. Clearly, the path for a segment (over which a transparent lightpath may be defined) need not contain a cycle. Here it is necessary to specify an upper limit on the value of $s$, the number of segments in the path. This will be determined by the acceptable limits on the delay and the Bit Error Rates (BER) [10].

Objective function:

$$\text{minimize} \sum_{k=1}^{s} \sum_{(i,j)\in E} \delta_i \cdot X_{ij}^k \tag{1}$$

subject to:

1) Satisfy the flow balance equations.

$$\sum_{j:(S,j)\in E} X_{Sj}^1 = 1; \qquad \sum_{k=1}^{s} \sum_{j:(j,S)\in E} X_{jS}^k = 0 \tag{2}$$

$$\sum_{k=1}^{s} \sum_{j:(j,D)\in E} X_{jD}^k = 1; \qquad \sum_{k=1}^{s} \sum_{j:(D,j)\in E} X_{Dj}^k = 0 \tag{3}$$

$$\sum_{j:(i,j)\in E} X_{ij}^k - \sum_{j:(j,i)\in E} X_{ji}^k = 0 : \; \delta_i = 0, \quad \forall k, 1 \leq k \leq s, \quad \forall i, 1 \leq i \leq n \tag{4}$$

$$\sum_{j:(i,j)\in E} X_{ij}^{k+1} - \sum_{j:(j,i)\in E} X_{ji}^k = 0 : \; \delta_i = 1, \quad \forall k, 1 \leq k \leq s, \quad \forall i, 1 \leq i \leq n \tag{5}$$

2) The length of a segment cannot exceed the reach $r$.

$$\sum_{j:(i,j)\in E} X_{ij}^k \cdot d_{ij} \leq r, \qquad \forall k, 1 \leq k \leq s \tag{6}$$

3) Each segment of the translucent lightpath must have exactly one channel number assigned to it.

$$\sum_{p=1}^{n_{ch}} W_p^k = 1, \qquad \forall k, 1 \leq k \leq s \tag{7}$$

4) The channel number assigned to a segment must be unused on each fiber used in the lightpath.

$$w_{ij}^p \cdot X_{ij}^k + W_p^k \leq 1, \qquad \forall (i,j) \in E, \forall k, 1 \leq k \leq s \tag{8}$$

5) If two segments share a fiber, they must be assigned distinct channel numbers.

$$X_{ij}^{k1} + X_{ij}^{k2} + W_p^{k1} + W_p^{k2} \leq 3, \; \forall (i,j) \in E, \quad \forall k1, k2, 1 \leq k1, k2 \leq s, \quad \forall p, 1 \leq p \leq n_{ch} \tag{9}$$

### C. A heuristic for the problem

The objective of the heuristic outlined below is to establish, if possible, a translucent lightpath, using a minimum number of regenerators. The heuristic is not for use for designing a network with a minimum number of regenerators but for use once the network has been deployed with regenerators in place. This heuristic has used a simple scheme of considering a fixed number of routes when establishing a transparent lightpath [12], [15] and has not considered how to avoid using critical resources such as the last regenerator in a regenerating node. Our primary objective was to show how to handle the problem of overlapping segments discussed in Section I. This heuristic is based on the "central agent" approach [12] where an end-node of the network is designated as the site where the heuristic will be executed. A request for a communication from $S$ to $D$ has to be communicated from $S$ to the site where the heuristic will be executed and, if the heuristic succeeds in establishing a route for the translucent lightpath, messages have to be communicated to the routers and the 3R regenerators in the path, followed by a time lag sufficient to set up the routers and the 3R regenerators before communication can start. Another approach which could be used is to have a distributed heuristic which uses local information to determine, if possible, the path for a translucent lightpath. The performance of the heuristic below is based on global information and therefore gives a lower bound on the performance which is useful for calibrating any distributed heuristic based on a similar approach. The site where the heuristic is executed has access to a database containing

1) the set $\mathcal{P}_{xy}$ of $m$ (or fewer, if all $m$ paths cannot be found) paths, for all node pairs $(x, y)$ where the total length of each path $\leq r$.
2) the set of channels, $c_{pq}$, currently available on each fiber $p \rightarrow q$ in the network.
3) the distance $d_{ij}$ between all pairs of end-nodes.
4) a list of all nodes capable of 3R regeneration.

Each path in $\mathcal{P}_{xy}$ is a potential candidate for setting up a transparent lightpath from $x$ to $y$. Given a path of length $\leq r$, say $u \rightarrow v \rightarrow \cdots \rightarrow y \rightarrow z$, the values of $c_{uv}, \cdots, c_{yz}$ allow us to determine the set of channel numbers that may be used to set up a new transparent lightpath from $u$ to $z$.

The heuristic uses A*, a well-known best-first search [16]. In the heuristic, each state in the state-space for the problem consists of the triple ($x$, $P$, $G_P$) where $x$ is a node in the network, $P$ is the set of transparent paths used by the search to reach node $x$ starting from node $S$ and $G_P$ is the path intersection graph corresponding to $P$. Here the cost of a translucent lightpath is the number of regenerators needed in the path used by the lightpath. Given a state ($x$, $P$, $G_P$), the cost to reach node $x$ from node $S$ is $|P| - 1$. The heuristic estimate of the cost to reach $D$ from $x$ is $\lceil d_{xD}/r \rceil$. This is clearly an admissible heuristic [16].

A state ($x$, $P$, $G_P$) is valid if it may be used to set up a translucent lightpath from $S$ to $x$. Let a vertex $v \in G_P$ correspond to the path $p = u \rightarrow v \rightarrow \cdots \rightarrow y \rightarrow z$. The set of channel numbers that may be used to set up a transparent lightpath from $u$ to $z$, using path $p$, may be viewed as the set of colors $\mathcal{W}_v$ to color vertex $v$ of the path intersection graph $G_P = (V_P, E_P)$. If two nodes $u, v \in V_P$ are adjacent in $G_P$, it means that the paths corresponding to $u$ and $v$ share one or more fiber (s). In this situation, to satisfy the property given in Section I, transparent lightpaths using the paths through the optical network, corresponding to $u$ and $v$, cannot be assigned the same channel number. We have used a list coloring algorithm [17], with $\mathcal{W}_v$ as the list of colors for vertex $v$ to color graph $G_P$. If the coloring algorithm succeeds, every path in $P$ may be used to set up a transparent lightpath, using the channel number obtained using the coloring algorithm, and the state ($x$, $P$, $G_P$) is valid. Only essential points of the heuristic are included in Algorithm 1.

In Algorithm 2, we have described the function $createNewStates(\mathcal{C}, P, G_P)$. The remaining functions in Algorithms 1 and 2 are informally described below.

$removeBest(\mathcal{S})$: This function takes a set of states $\mathcal{S}$ and returns the state $X = (x, P, G_P), X \in \mathcal{S}$ with the lowest estimated value of the number of regenerators needed to reach node $D$ from node $S$. The function removes the state $X$ from $\mathcal{S}$ as well.

**Algorithm 1** *Dynamic lightpath allocation from $S$ to $D$*

$\mathcal{S} \leftarrow (S, \{\}, (\{\}, \{\}))$
**while** $\mathcal{S} \neq \{\}$ **do**
  $(x, P, G_P) \leftarrow removeBest(\mathcal{S})$
  **if** $x = D$ **then**
    return ($P$, $G_P$)
  **else**
    **if** $d_{xD} \leq r$ **then**
      $\mathcal{C} \leftarrow \mathcal{P}_{xD} \bigcup pathsToRegenerators(x)$
    **else**
      $\mathcal{C} \leftarrow pathsToRegenerators(x)$
    **end if**
    $\mathcal{N} \leftarrow createNewStates(\mathcal{C}, P, G_P)$
    $\mathcal{S} \leftarrow \mathcal{S} \bigcup \mathcal{N}$
  **end if**
**end while**

**Algorithm 2** $createNewStates(\mathcal{C}, P, G_P)$

$\mathcal{N} \leftarrow \{\}$
**for** *each path* $p \in \mathcal{C}$ **do**
  $G_P^{new} \leftarrow augmentGraphByPath(p, G_P)$
  $P^{new} \leftarrow P \bigcup \{p\}$
  **for** *each node* $v \in V_P^{new}$ **do**
    $\mathcal{W}_v \leftarrow assignListColors(v)$
  **end for**
  **if** $listColor(G_P^{new}, \mathcal{W})$ **then**
    $\mathcal{N} \leftarrow \mathcal{N} \bigcup (lastNode(p), P^{new}, G_P^{new})$
  **end if**
**end for**
return $\mathcal{N}$

$pathsToRegenerators(x)$: This function takes a node $x$ of the network and returns the set of pre-computed paths from $x$ to all regenerators that are within the optical reach of $x$.

$augmentGraphByPath(p, G_P)$: This function takes a path $p$ in the network from some node $x$ and the path intersection graph $G_P = (V_P, E_P)$ corresponding to the paths used to go from $S$ to $x$. The function returns a graph $G_P^{new}$ by adding, to $G_P$, a new vertex $v$ corresponding to path $p$ and requisite new edges between $v$ and the nodes in $V_P$.

$assignListColors(v)$: This function takes vertex $v$ of the path intersection graph $G_P = (V_P, E_P)$ (which corresponds to some path in the network with a total length $\leq r$) and returns the set of channel numbers that are not used on any of the edges in the path. This set is used to define $\mathcal{W}_v$ that can be used to color vertex $v$.

$listColor(G_P, \mathcal{W})$: This function takes a path intersection graph $G_P = (V_P, E_P)$ and, for each vertex $v \in V_P$, a set of colors $\mathcal{W}_v$. The function returns true if it can successfully use a list coloring algorithm to assign a color from $\mathcal{W}_v$ to vertex $v, \forall v \in V_P$.

$lastNode(p)$: This function takes a transparent path $p$ through the optical network and returns the last node in $p$.

## IV. Simulation Results and Analysis

We conducted two sets of experiments to study the efficacy of our heuristics on many realistic networks of varying sizes,

Fig. 2. Effect of varying the number of paths considered

Fig. 3. Blocking probability v/s traffic load for LATA 'X'

namely, ARPANET(20 nodes, 32 links), LATA 'X'(28, 47) and USANET(53,68) [18]. The link distances in these networks were uniformly randomly chosen between 1 and 1000 miles. In the first set of experiments, the design parameters considered were (i) *number of precomputed paths between regenerators* (ii) *varying traffic load* (iii) *number of regenerators in the network* and (iv) *optical reach distance*. We studied the effect of these design parameters on the *call blocking probability* for a dynamic call scenario. We assumed 10,000 calls to arrive dynamically in the system. Each call $i$ was a tuple $(s_i, t_i, a_i, d_i)$ where $s_i, t_i$ are the source and destination of the call respectively, $a_i$ is the arrival time and $d_i$ is the duration of the call. The call arrival process was assumed to follow the Poisson distribution and exponential holding time was assumed for the call durations. The traffic load in the network was defined to be the ratio of the call arrival rate to the service rate. The traffic load was varied by changing the arrival and the service rates. In all these experiments, nodes with regeneration capabilities were uniformly randomly selected.

Figure 2 shows the effect of the number of precomputed paths maintained by the heuristic on the call blocking probability. In this experiment, the number of wavelengths available on each link and traffic load were taken to be 8 and 50 erlangs respectively. For the different networks, it can be observed from the graph that maximum improvement in terms of call blocking probability can be achieved by maintaining 5 precomputed paths between every pair of regenerators. The improvement in call blocking probability is not significant beyond 5 precomputed paths. Correspondingly, in the subsequent experiments, we selected the number of precomputed paths to be 5. the results indicate the tradeoff between the time taken by the heuristic and the quality of the solution produced by the heuristic. For all the networks, the heuristic completed within $\approx$5 seconds when number of paths was $\leq$5 and took several ($\leq$2) minutes when more than 5 paths were computed between every pair of regenerators.

Figures 3 and 4 shows the effect of varying traffic load on the call blocking probability for different number of wavelengths per link in the LATA 'X' and ARPANET network respectively. Here the traffic load was varied until 50 erlangs in steps of 5 erlangs. The call blocking probabilities were measured for 4, 8, 12 and 16 wavelengths per link in the networks. The value of $r$ was set to be 1000 miles and $\approx 33\%$ of nodes were randomly selected as regenerators. It

Fig. 4. Blocking probability v/s traffic load for ARPANET

can be observed that at higher loads, increasing the number of wavelengths significantly reduces the call blocking probability. For instance, it can be observed that at load 50, the call blocking probability improves by 13-fold when number of wavelengths are increased from 4 to 16 in ARPANET.

Figure 5 shows the effect of the number of regenerator capable nodes in the ARPANET network on the call blocking probability for traffic load = 50 erlangs and optical reach distance = 1000 miles. An interesting observation that can be made from this plot is that the increasing the number of wavelengths per link in the network has a higher impact on the call blocking probability than increasing the number of regenerators in the network. For instance, doubling the number of regenerators from 6 to 12 marginally reduces the call blocking probability from 0.515 to 0.458, whereas doubling the number of wavelengths from 4 to 8 reduces the call blocking probability from 0.515 to 0.286 in ARPANET.

Figure 6 shows the effect of varying optical reach distances on the call blocking probability for the ARPANET network with traffic load = 50 erlangs and 6 regenerators. From the figures, it can be observed that increasing the optical reach

Fig. 5. Blocking probability v/s number of regenerator for ARPANET

Fig. 6. Blocking probability v/s optical reach distance for ARPANET

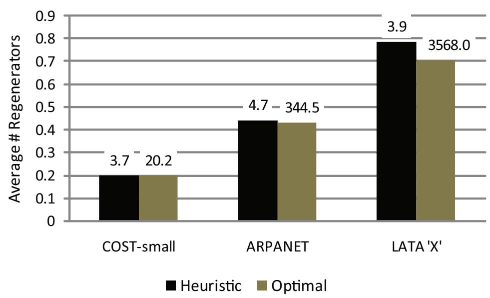


Fig. 7. Average number of regenerators computed by the heuristic and optimal solutions for different networks

has marginal benefit in terms of reducing the call blocking probability. It is to be noted that the tradeoffs between the different design parameters presented in this paper can be effectively used by a network designer to select the right set of additional resources to improve the network performance.

In the second set of experiments, the goal was to compare the number of regenerators on the path produced by the heuristic with that of the optimal solution found by solving the Integer Linear Program (ILP). In these experiments, a single common wavelength was assumed to be available on each link of the network. The heuristic was used to compute the end-to-end path for each node-pair in the network. The experiments were conducted on 3 different networks - COST-SMALL[2], ARPANET and LATA 'X'. The ILP was solved using CPLEX-10 optimizer. The results of these experiments are shown in Figure 7. The number on the bars indicates the total execution time in *seconds* taken by the heuristic and CPLEX to compute the end-to-end paths for all node pairs. The number of regenerators for only those node pairs are considered in the average computation for which the heuristics found a solution. It is evident from the results that the heuristics produce near-optimal solutions in a fraction of time needed to find the optimal solutions, even for medium-size networks. Also, for LATA 'X' network, the heuristic failed to find a path even when such a path existed (as shown in the optimal results) for a total 11 source-destination pairs out of 338 source-destination paths.

[2]COST-SMALL network consists of 11 nodes and 22 edges. USANET results are omitted since the ILP did not produce optimal solution even after a significant amount of time.

## V. Conclusions

Existing algorithms for dynamic lightpath allocation have not taken into account an important constraint when lightpath segments overlap. We have given an example where this can happen and shown that there may be cycles in the path from a source to a destination, where the cycle includes a regenerator. There are two repercussions of this - normal network flow techniques do not allow cycles and results using existing dynamic lightpath allocation may give invalid solutions. We have shown how to develop an ILP formulation by adapting single commodity network flow techniques where this constraint has been taken into account. We have also shown that an A* algorithm using an admissible heuristic can be developed to handle medium or large size networks. The constraint mentioned above can be handled satisfactorily in our A* algorithm using list coloring algorithms. It is possible that existing algorithms may adopt the same approach to take care of the constraint mentioned here. The simulation experiments conducted with several realistic network graphs demonstrate the low call blocking probability even in the presence of high traffic load in the network. In addition, the comparison with the optimal solution obtained by solving the Integer Linear Program showed that the heuristic performs well compared to the ILP and that the heuristic runs in a fraction of the time required to solve the ILP.

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