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Minimizing Cost of Regeneration at Regeneration Sites–A New Approach for Dynamic Lightpath Establishment in Translucent Optical Networks

IRA NATH[1], VISHAL DEY[2], JOY HALDER[3], MONISH CHATTERJEE[4], (Member, IEEE), AND UMA BHATTACHARYA[3]
[1]Department of Computer Science and Engineering, JIS College of Engineering, Kalyani 741235, India
[2]Department of Computer Science and Engineering, The Ohio State University, Columbus, OH 43210, USA
[3]Department of Computer Science and Technology, Indian Institute of Engineering Science and Technology, Shibpur 711103, India
[4]Department of Computer Science and Engineering, Asansol Engineering College, Asansol 713305, India

Corresponding author: Monish Chatterjee (monish_chatterjee@yahoo.com)

ABSTRACT Lightpaths in translucent optical networks have to undergo regeneration at certain nodes designated as regeneration sites to maintain its quality of transmission. Regenerating an optical signal necessitates optical-electronic-optical conversion and is thus a costly affair due to use of regeneration resources. Thus minimizing the cost of regeneration in such networks is vital. Minimizing cost of regeneration leads to two different problems; 1) the problem of minimizing the total cost of regeneration for the connections served and 2) the problem of minimizing the cost of regeneration at regeneration sites while serving the connections. The previous works on lightpath establishment in such networks have mostly addressed the first problem. In this paper we study the second problem i.e. the problem of minimizing the cost of regeneration at regeneration sites during dynamic establishment of lightpaths. As the problem is NP-Complete, we propose an Integer Linear Program for small networks and then propose two heuristic routing approaches for large networks. Time complexity analysis shows that our heuristic algorithms run in polynomial time. Extensive simulation experiments reveal that our approaches are not only efficient to address the problem but can also provide better blocking performance when regeneration resources are scarcely deployed at regeneration sites.

INDEX TERMS Dynamic routing, minimizing regeneration, regeneration sites, translucent optical networks, wavelength assignment.

I. INTRODUCTION

In all-optical networks, also known as transparent networks, data communication takes place entirely in the optical domain without Optical-Electronic-Optical (O-E-O) conversion [1]. But Physical Layer Impairments (PLI) introduce factors such as optical noise, chromatic dispersion, nonlinear effects, polarization mode dispersion (PMD) and cross-talk [2], [3] due to which the Quality of Transmission (QoT) of an optical signal degrades as it propagates through a fiber. Optical signals usually have an *optical reach* a distance (ranging from 800 to 3000 km or from 500 to 2000 miles depending on the technology used), such that transmission beyond this distance causes its quality to degrade to an unacceptable level [4]. This degradation in QoT necessitates *re-amplification*, *re-shaping* and *re-timing* [2]. Thus optical signals that travel beyond the optical reach need to undergo regeneration at some node(s) in its path from source to destination in order to maintain the required QoT.

In *translucent* optical networks, only a subset of the nodes can have regeneration facility as regeneration is costly [5]. We shall henceforth refer to such nodes capable of regeneration as *regeneration sites*. In optical networks that employ Wavelength Division Multiplexing (WDM), a lightpath established between two end-nodes serve as optical communication link or channel for data communication. A lightpath must be assigned a wavelength in each fiber that it traverses in its path from source to destination. A lightpath established beyond the optical reach must undergo regeneration at the regeneration sites. We shall hereafter refer to lightpaths that undergo regeneration as *translucent lightpaths*. A translucent lightpath may consist of two or

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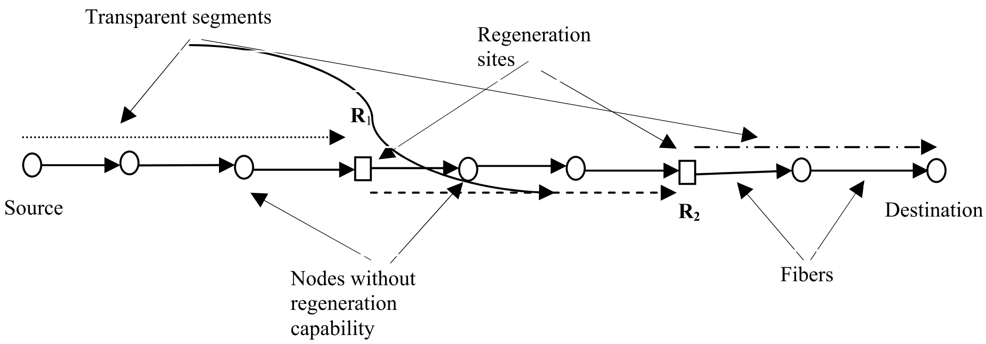

FIGURE 1. Translucent lightpath consisting of transparent segments routed through regeneration sites.

more transparent (all-optical) lightpaths. We shall hereafter refer to such transparent part of a translucent lightpath as *segment*. In a translucent lightpath exactly one segment is between the source and a regeneration site, exactly one segment is between a regeneration site and the destination and the rest, if any, are between two regeneration sites as shown in Fig. 1. The total length of fibers involving a segment should not surpass the optical reach.

According to the work [3], it may be difficult to obtain chromatic dispersion and other PLI factors in real time and so optical reach can be considered as an approximation of almost all PLI factors. The two most important problems in translucent optical WDM networks that have attracted research attention are the *Regenerator Placement*(RP) problem [2]–[11] and the *Routing with Regenerators*(RR) problem [12]–[15]. In the RP problem, given a physical topology $G = (V,E)$, the length of fibers for each $e \in E$ and the optical reach, the problem is to find the minimum number of regeneration sites and their locations so that every pair of nodes i.e. source(S) and destination(D) can establish either a transparent lightpath (not exceeding optical reach) or a translucent lightpath. In the RR problem, given a physical topology $G = (V,E)$, the length of fibers for each $e \in E$, the optical reach and the location of the regeneration sites, the problem is to find a lightpath route for every (S, D) pair such that the lightpath will undergo least number of regenerations.

The authors [15] made an important observation that solutions to the RR problem [12], [13] and [14] may lead to computation of translucent lightpath routes having unavoidable cycles. This is a possibility, as for certain (S, D) pairs no lightpath route may exist without the ones containing a cycle because route computation occurs in the presence of fixed regeneration site locations. Route of a translucent lightpath can thus have overlapping segments and in such a case, the same wavelength cannot be used for assignment in the two segments that overlap. Thus it is important to identify translucent lightpath routes with overlapping segments. The manner in which wavelength assignment is carried out while addressing the RR problem thus becomes extremely important. This is because segments in a route that overlap (traverses common fiber(s)) have to be assigned distinct wavelengths. We will call this problem of identifying routes with overlapping segments and then assigning appropriate wavelengths to such segments the *Overlapping Segments Sub-Problem* (OSSP). Individual segments in route need not contain overlapping fibers. In this paper, our approaches for dynamic lightpath establishment consider OSSP.

Many earlier papers [6], [11], [15] and [29] have assumed that the optical reach of lightpaths due to the PLI factors is known for the given physical topology. So in this paper we address the problem of routing for dynamic lightpath establishment in translucent optical networks with the assumption that the optical reach is known for the physical topology used. It is important to perform regeneration of an optical signal as sparingly as possible since regeneration can introduce both delay and Bit Error Rates (BER) because of O-E-O conversion [14]. Also since regeneration of an optical signal requires O-E-O conversion, the process is costly and so for any solution to the RR problem the objective is primarily to reduce this cost i.e. minimize the total cost of regeneration (or the total number of regenerations) that takes place in the network for serving the requested connections between all (S, D) pairs. But providing service to connections in a way performed in the works [12]–[15] can result in increasing cost of regeneration at regeneration sites arbitrarily. This is because the objective in these works is to route connections through minimum stages of regeneration (MSR).

The sole objective of minimizing the regeneration stages to address the RR problem can cause regeneration resources to decrease appreciably at some regeneration sites, while at others resources can remain underutilized. This unbounded increase of regeneration cost at regeneration sites is a critical issue because regeneration resources being expensive are sparsely deployed at these sites. For regenerating an optical signal, at least a transmitter and a receiver are required at a site [4]. Thus non-uniform utilization of regeneration resources at regeneration sites can have serious consequences such as increasing the blocking probability of future connections. Thus the objective of any solution to the RR problem should not be just to route the requested connections through minimum stages of regeneration (MSR), but also to route connections in a way so that the number of regenerations that takes place at regeneration sites (or cost of regeneration at regeneration sites) is minimized.

The problem of minimizing cost of regeneration at regeneration sites (MCR–at–RS) becomes even more important in a dynamic scenario, where connections to be served are not known in advance but arrive continuously. In this paper, we first address the problem of dynamic lightpath establishment (DLE) focusing entirely on MCR–at–RS. We next address the problem of DLE by routing connections through MSR and in a way that addresses MCR–at–RS to the extent possible. To the best of our knowledge, this work is the first to address DLE in translucent optical networks to minimize the stages of regeneration of each connection subjected to MCR–at–RS taking into account OSSP.

It is important to note that works on Physical Layer Impairment aware Routing and Wavelength Assignment (PLI-RWA) such as [19], [20] and [23] and those that addresses the RR problem such as [13] and [14] which considers various factors of physical layer impairments (PLIs) separately during establishment of lightpaths cannot be directly compared with our proposed approaches. This is because we assume that the optical reach for the physical topology due to the various factors of PLIs is known in a way similar to the works [5], [11], [15] and [29]. Moreover recent works on routing and wavelength assignment (RWA) for translucent optical networks such as [28] that proposes Integer Linear Program (ILP) formulation to minimize total cost of O-E-O conversion and [29] that presents RWA strategies to identify minimum number of regeneration sites cannot be compared with our work.

In translucent networks, wavelength conversion is possible at the regeneration sites due to O-E-O conversion. So though the entire translucent lightpath route is not constrained to follow wavelength continuity, the individual segments in the route must use a single wavelength. The RWA problem is known to be NP-Complete [32]. So the RR problem which can be solved only through RWA of lightpaths is also NP-Complete. Efficient heuristics are thus needed to provide solutions to the RR problem. The heuristics proposed in this paper are designed to provide efficient solution to the RR problem.

The rest of the paper is organized as follows. In sec.II we discuss the related works, in sec.III we mention the contributions of our work, in sec.IV we provide the Integer Linear Program formulation for addressing our objective, in sec.V we provide the heuristics and analyze time complexity, in sec.VI we include performance comparisons and finally in sec.VII we conclude with a summary of this work.

II. RELATED WORKS

Schemes for finding a route with fewest stages of regenerations between (S, D) pairs by enumerating a large number of routes between S and D is proposed in [12]. The work [13] proposes dynamic routing strategies for allocation, advertisement and discovery of regeneration resources to facilitate transmitter-receiver sharing between regeneration and access functions. An intra-domain routing algorithm [14], for dynamic allocation of regeneration resources is proposed considering many optical layer constraints such as chromatic dispersion, polarization mode dispersion, amplified spontaneous emission noise, cross talk etc to address routing in a single domain. The authors [15] observe that the works [13], [14] and [15] may lead to computation of infeasible translucent lightpath routes between certain (S, D) pairs if segments have overlapping fibers leading to OSSP. An ILP for solving the dynamic RR problem and an efficient heuristic for large networks is proposed in [15] that considers OSSP.

The authors [16] provide a comprehensive survey of various PLIs, their effects and a survey of various PLI-RWA algorithms. The work [17] provides a survey of PLI-RWA algorithms and the impact of wavelength conversion on these algorithms. An economic analysis of PLI-RWA problem to justify the concept of translucent optical networks is provided in [18]. In [19], the authors investigate the problems of RWA in transparent optical networks that can support unicast and multicast applications taking into consideration the PLIs. Given, a network topology, the number of available wavelengths and a traffic matrix, authors [20] focus on the offline PLI-RWA problem and propose an algorithm that selects the regeneration sites for a given set of connection requests solving the RP problem. The work [21] too proposes offline PLI-RWA iterative heuristics where RP is carried out based on RWA of connection requests to minimize lightpath blocking and regeneration equipment cost. BER performance estimation is performed by authors [22] in connection with PLI-RWA to investigate the role of regeneration and wavelength conversion in optical networks.

The problem of RWA of connections within a single domain and inter-domain connections so that the QoT of each connection is satisfied and blocking probability is minimized is considered [23]. In [24] the authors propose a heuristic for identifying regeneration sites and the number of electronic regenerating resources to be installed in, based on island-of-transparency approach that minimizes both capital expenditures and operational expenditures. The authors [25] propose an ILP formulation for identifying the optimal number of regeneration sites. The work [26] addresses the problem of static impairment-aware multicast RWA for transparent WDM metro area networks considering a number of PLIs. The problem of preventive assignment of regenerators is addressed in [27] by proposing an algorithm that reduces the blocking probability caused by lowering of QoT of existing optical signals when a new optical circuit is established in the network.

Recently the work [28] addresses the RWA problem in translucent networks by proposing two ILP formulations; the first minimizes the total cost of O-E-O conversions and the second to minimize the network load by minimizing the highest assigned wavelength. In a recent work, the authors [29] presented a heuristic RWA algorithm to identify minimum number of the regeneration sites. In [30], the problem of allocating regenerators in flexible-grid optical networks is studied.

III. ILLUSTRATION OF THE NEED TO CONSERVE RESOURCES AND OUR CONTRIBUTIONS

A transmitter (T) at the source (S) and a receiver (R) at the destination (D) is necessary to establish a transparent lightpath between S and D. A (T, R) pair is also a minimum requirement at a regeneration site for regeneration of a translucent lightpath [4]. We illustrate that regeneration resources can be sparsely available at regeneration sites with a simple example. Let us assume that node A is the source whereas node B is the destination of m and n transparent lightpaths respectively established due to the arrival of ($m+n$) requests for connection. The m lightpaths that start at A and the n lightpaths that terminate at B consumes m number of Ts and n number of Rs at A and B respectively. Let us assume that nodes A and B are also regeneration sites in a translucent optical network which were initially deployed with x number of transceivers or (T, R) pairs. Then the number of Ts and Rs that are now available at A are $x- m$ and x respectively whereas at B the number of Ts and Rs is now x and $x - n$ respectively. It may be noted that though both A and B were initially deployed with x number of (T, R) pairs, only $x - m$ and $x - n$ of them are now available at A and B respectively to regenerate translucent lightpaths that may need regeneration at these sites in future. Thus regeneration resources are always sparsely available at regeneration sites. So efficient routing schemes are needed for the connections that require establishment of translucent lightpaths so that (T, R) pairs are conserved at the regeneration sites to reduce blocking probability for future translucent lightpaths.

Thus it is important to minimize the cost of regeneration (or the number of regenerations that occurs) at regeneration sites to conserve the scarce resources. This conservation further becomes extremely important in a dynamic scenario where connections to be served are not known in advance but arrive one at a time continuously. The sole objective of routing dynamic connections through fewest stages of regeneration in the works [12]–[15] can definitely minimize the total number of regenerations for the requested connections but cannot guarantee conservation of resources at regeneration sites. To address this issue we propose two heuristic routing schemes. To the best of our knowledge this is the first work to address the problem of MCR–at–RS. Furthermore this work is also the first to minimize the stages of regeneration that a connection has to pass through subjected to MCR–at–RS in a dynamic scenario. We contribute by

1) proposing an Integer Linear Program (ILP), which determines a path for communication between source and destination to address the problem of MCR–at–RS during dynamic lightpath allocation considering OSSP,
2) proposing two heuristic routing schemes to address the said issue in a dynamic scenario for large networks taking into consideration OSSP and
3) extensively studying the effect of the following on the connection blocking probability; a) number of segments in a translucent lightpath route with fixed number of regeneration resources b) number of regeneration resources with a given number of allowable segments in translucent lightpath routes and c) other network resources such as number of wavelengths in links.

IV. FORMULATION FOR ROUTING TO ESTABLISH DYNAMIC LIGHTPATHS

In this section we present an ILP formulation for dynamic establishment of lightpaths in translucent optical networks. Our ILP formulation addresses the problem of MCR–at–RS taking into account OSSP in a scenario where requests for connection arrive one at a time continuously and are not known in advance. We assume that the optical reach of lightpaths due to physical layer impairments is known for the given physical topology. This assumption has been made in a number of earlier works [5], [11], [15] and [29]. We specify the number of allowable segments in a translucent lightpath route because optical signals should be regenerated sparingly to prevent introduction of delay and Bit Error Rates (BER) [14]. It may be noted that paths of individual segments (representing transparent lightpaths) in a translucent lightpath route will not contain a cycle but a translucent lightpath route can have unavoidable cycles leading to OSSP.

A. NOTATIONS USED IN THE FORMULATION

V: the set of nodes of the physical topology.

E: the set of edges of the physical topology.

S: source of new connection.

D: destination of new connection.

R: the set of nodes capable of regeneration (regeneration sites).

K: the number of allowable segments in a translucent lightpath route.

SP: the set of all node pairs (i, j) such that i and j will be the first node and last node respectively of a segment that can become part of the translucent lightpath route between S and D, where $i = S$ or $i \in R$ and $j = D$ or $j \in R$ and $i \neq j$.

n^i: an integer value indicating the weight of node $i \in R$. Each node $i \in R$ is assigned a positive value. If the node i is used frequently its weight is low otherwise its weight is high.

$P_{(i,j)}$: the set of paths for pair $(i, j) \in SP$ that are within the optical reach.

$W_{(i,j,k)}$: the set of wavelengths available in k^{th} path of $P_{(i,j)}$.

$L^{(i,j)}_{(k,e)}$: a binary parameter defined as follows.

$$L^{(i,j)}_{(k,e)} = 1 \text{ if } k^{th} \text{ path of } P_{(i,j)} \text{ traverses link } e \in E,$$
$$= 0 \text{ otherwise.}$$

$\alpha^{(i,j)}$: a binary variable defined as follows.

$$\alpha^{(i,j)} = 1 \text{ if pair } (i, j) \text{ is selected for the lightpath route,}$$
$$= 0 \text{ otherwise.}$$

z^i: a binary variable defined as follows.
$z^i = 1$ if $i \in R$ and is used by new connection,
$= 0$ otherwise.
$\beta_k^{(i,j)}$: a binary variable defined as follows.
$\beta_k^{(i,j)} = 1$ if the k^{th} path of $P_{(i,j)}$ is selected,
$= 0$ otherwise.
$w_{(k,l)}^{(i,j)}$: a binary variable defined as follows.
$w_{(k,l)}^{(i,j)} = 1$ if l^{th} wavelength of k^{th} path of $P_{(i,j)}$ is used,
$= 0$ otherwise.

B. ILP FORMULATION

Our formulation determines the lightpath route of a new connection in a way that if the route exceeds the optical reach then it is regenerated at regeneration sites that has been used the least. In the proposed formulation the lesser used regeneration sites have a larger weight (integer value) compared to sites that are used frequently.

Objective: Maximize $\Sigma_i z^i * n^i$

Subjected to the following constraints (1-6).

Constraints:

1. The flow conservation constraints that ensure flow conservation over the segments.

$$\Sigma_{j:(i,j)\in SP}\alpha^{(i,j)} - \Sigma_{j:(j,i)\in SP}\alpha^{(j,i)} = 1, \text{ if } i = S.$$
$$\Sigma_{j:(i,j)\in SP}\alpha^{(i,j)} - \Sigma_{j:(j,i)\in SP}\alpha^{(j,i)} = -1, \text{ if } i = D.$$
$$\Sigma_{j:(i,j)\in SP}\alpha^{(i,j)} - \Sigma_{j:(j,i)\in SP}\alpha^{(j,i)} = 0, \text{ otherwise}.$$

2. The number of segments in a lightpath route should not exceed the allowable number K.

$$\Sigma_{(i,j)\in SP}\alpha^{(i,j)} \leq K.$$

3. A lightpath is always regenerated at $i \in R$ if pair $(i, j) \in SP$ with $i \neq S$ is selected to form the lightpath route.

$$z^i = \Sigma_{j\in R\cup\{D\}}\alpha^{(i,j)}, \forall i \in R, i \neq S.$$

4. Only one path is selected for a pair $(i, j) \in SP$ that is chosen to form the lightpath route.

$$\Sigma_{k\in\{1\ldots|P(i,j)|\}}\beta_k^{(i,j)} = \alpha^{(i,j)}, \forall(i, j).$$

5. Only one wavelength is used for a path selected for pair $(i, j) \in SP$.

$$\Sigma_{l\in\{1\ldots|W(i,j,k)|\}}w_{(k,l)}^{(i,j)} = \beta_k^{(i,j)}, \forall(i, j), \forall k.$$

6. If paths of two segments share a common link then they cannot use a common wavelength.

$$w_{(k1,l)}^{(i1,j1)} + w_{(k2,l)}^{(i2,j2)} \leq 2 - L_{(k1,e)}^{(i1,j1)} * L_{(k2,e)}^{(i2,j2)},$$
$$\forall(i1, j1) \in SP, \forall(i2, j2) \in SP, \forall k1, \forall k2, \forall l, \forall e.$$

V. HEURISTICS FOR DYNAMIC LIGHTPATH ESTABLISHMENT

We provide the proposed heuristic RWA algorithms H-$RWA1$ and H-$RWA2$. We first discuss about the common data structures and schemes used in both the heuristics.

A. DATA STRUCTURES AND SCHEMES USED IN THE HEURISTICS

The set $P_{ab} = \{p_1, p_2, \ldots, p_k\}$ represents the set of $k$paths between two nodes $a, b \in V$ such that $\forall p_i \in P_{ab}$, $1 \leq i \leq k$, the length of $p_i \leq d$ (the optical reach). It may be noted that there can be fewer than k paths in P_{ab}, if all k paths does not exist in the physical topology $G = (V, E)$. P_{set} represents the set of all such path sets P_{ab}, $|P_{set}| = n(n-1)$ where $|V| = n$. We assume that every fiber link has W number of wavelengths. The set W_{ij} represents the set of all wavelengths currently available in link $i \rightarrow j$. W_{set} represents the set of all such wavelength sets W_{ij}, $|W_{set}| = |E|$.

The set $R \subset V$ represents the set of regeneration sites in the network whose locations are known. A variable c_i is associated with every regeneration site $i \in R$, which represents the cost of regeneration (the number of regenerations) at i so far. The variable c_i is initially 0, but is incremented for every connection that gets regenerated at i. The value of c_i at any instant represents the number of (T, R) pairs that have been consumed at i for regeneration. A hash-map *regCost* $= \{< c_e, e >, < c_f, f >, \ldots, < c_m, m >\}$ of size $|R|$, maps regeneration sites to their corresponding cost values. Each member of *regCost* is of the form $< c_i, i >$ where c_i is the cost of regeneration at regeneration site i so far. The *cost* matrix is an $n \times n$ matrix such that $cost[i][j]$, gives the value l_{ij}, the length of the fiber link $i \rightarrow j$ in the physical topology. Note that $cost[i][j] = \infty$ (infinite) if link $i \rightarrow j$ is absent i.e. if node i and node j are not physically connected.

In both heuristics we employ best-first search [33] to find the route of a new connection requested between source S and destination D that satisfies the required objective. The search space SP consists of pairs (a, P), where $a \in V$ and P is the set of *transparent* paths determined by the search such that node $a$can be reached from S using the paths in P. For *wavelength assignment* to *segments* in a lightpath route, we use the well-known *First-Fit* (FF) policy [13] for simplicity. The heuristics identify overlapping segments in a translucent lightpath route to address OSSP. If two segments in a route overlap due to common fiber(s) then they are assigned distinct wavelengths. Addressing OSSP becomes possible as wavelength conversion is available at the regeneration sites. We next provide the heuristic $RWA1$.

B. HEURISTIC ALGORITHM H-RWA1

The heuristic H-$RWA1$ attempts to find a route for the requested connection (S,D) in a way that will reduce cost of regeneration at regeneration sites to the extent possible. The details of the heuristic are shown in Fig. 2.

Input: The inputs to algorithm are 1) S, the source of the requested connection 2) D, the destination of the requested connection 3) d, the distance representing optical reach 4) s, the number of allowable segments 5) R, the set of regeneration sites 6) P_{set}, the set of path sets 7) W_{set}, the set of wavelength sets 8) the matrix *cost* and 9) the hash-map *regCost*.

Output: The output is the pair (P, *regCost*), where P is the set of transparent paths determined by the heuristic using

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Heuristic H-RWA1 ($S$, $D$, $d$, $s$, $R$, $P_{set}$, $W_{set}$, $cost$, $regCost$)
begin
1   $SP \leftarrow (S, \phi)$;
2   $P_{temp} \leftarrow \phi$;
3   repeat
4       $((a, P), SP) \leftarrow findBest(SP, s, regCost)$;
5       if ($a = null$) then
6           return ($\phi$, $regCost$);
7       if ($a = D$) then
8           $OS_{set} \leftarrow findOverlaps(P)$;
9           $P \leftarrow assignWav(OS_{set}, P, W_{set})$;
10          if ($P \neq \phi$) then
11              $regCost \leftarrow updateCost(P, regCost)$;
12              return ($P$, $regCost$);
13          else
14              return ($\phi$,$\phi$);
15          end if
16      else
17          $P_{aD} \leftarrow findPathSet(P_{set}, a, D)$;
18          if ($cost[a][D] \leq d$) then
19              $P_{temp} \leftarrow P_{temp} \cup P_{aD}$;
20          else
21              for each $i \in R$ do
22              begin
23                  $P_{ai} \leftarrow findPathSet(P_{set}, a, i)$;
24                  $P_{temp} \leftarrow P_{temp} \cup P_{ai}$;
25              end for
26              $P_{temp} \leftarrow P_{temp} \cup P_{aD}$;
27          end if
28      end if
29      for each $p \in P_{temp}$ do
30      begin
31          $x \leftarrow findLastNode(p)$;
32          $P' \leftarrow P \cup p$;
33          $SP \leftarrow SP \cup \{(x, P')\}$;
34      end for
35  forever
end heuristic
```

FIGURE 2. Heuristic algorithm ***H-RWA*1**.

which it will be possible to reach D from S and *regCost* is the updated hash-map after serving the new connection.

Method: The algorithm works as follows. Initially the search space *SP* contains the pair (S, ϕ). The procedure *findBest*() is used to obtain the best pair (a, P) presently available in *SP*, such that the paths in P will lead to establishment of a lightpath from source S to D not exceeding the specified number of segments s subjected to reducing the cost of regeneration at the regeneration sites (line 4). If $a = null$ which indicates that no pair (a, P) exists in *SP* with $|P| \leq s$, the connection is considered to be blocked and the pair (ϕ, *regCost*) is returned (line 6). If $a \neq null$ then there can be two possibilities, either Dcan be reached using the paths in P or D cannot be reached.

If D can be reached i.e. if $a = D$ (line 7), then the paths in P can be used to establish a lightpath from $S$to D and so the procedure *findOverlaps*() is called to obtain OS_{set}, the set of paths in P that overlaps. The procedure *assignWav*() is then used to assign wavelengths to segments (paths in P) in a way that addresses OSSP as explained earlier in this section. If wavelength assignment is successful, *assignWav*() returns the wavelength assigned path set P. If wavelength assignment fails, the procedure returns ϕ. If wavelength assignment is successful i.e. $(P \neq \phi)$ (line 10) then procedure *updateCost*() is called to update the cost at the regeneration sites in the route from S to D that can be formed by the paths in P. The procedure *updateCost*() returns the updated hash-map *regCost*. The path set P and *regCost* are returned by the heuristic (line 12). If wavelength assignment fails, the heuristic returns (ϕ,ϕ) (line 14).

If D cannot be reached using the paths in P i.e. if $a \neq D$, then the algorithm calls procedure *findPathSet*() (line 17) to obtain P_{aD}, from P_{set}. The algorithm next proceeds to check whether $cost[a][D]$ i.e. l_{aD} is within the optical reach d or not. If $l_{aD} \leq d$, then the paths in P_{aD} are added to a temporary path set P_{temp} (line 19). If $l_{aD} > d$, then $\forall i \in R$, procedure *findPathSet*() is used to find P_{ai}, from P_{set}. The paths in sets P_{ai}, $\forall i \in R$ are then added to P_{temp}. Finally the paths in P_{aD} are added to P_{temp} (line 26). New pairs are then added to *SP* in the following manner. The procedure *findLastNode*() is used to find the last node x in a path p in P_{temp}. For each path $p \in P_{temp}$ a new pair (x, P') is added to *SP* (line 33) where $P' = P \cup p$ (line 32). The process repeats itself until the required pair (a, P) is obtained from *SP* such that $a = D$.

Procedure *updateCost*(): The inputs to the procedure are P and *regCost*. This procedure is used to update the cost associated with the regeneration sites in the lightpath route $\boldsymbol{R}_{SD}$ from S to D formed by the paths in P determined by the search. The procedure increments the values of c_i in every $< c_i, i >$ in *regCost* if $\boldsymbol{R}_{SD}$ undergoes regeneration at regeneration site i. For example, if P consists of three transparent paths $\{S \rightarrow q \rightarrow r \rightarrow t, t \rightarrow u \rightarrow v \rightarrow w, w \rightarrow x \rightarrow y \rightarrow z \rightarrow D\}$, then $\boldsymbol{R}_{SD}$ is the route $S \rightarrow q \rightarrow r \rightarrow t \rightarrow u \rightarrow v \rightarrow w \rightarrow x \rightarrow y \rightarrow z \rightarrow D$ formed by the concatenation of the transparent paths. The values of c_t in $< c_t, t >$ and c_w in $< c_w, w >$ in *regCost* are incremented to represent the updated cost of regeneration at regeneration sites t and w. The updated hash-map *regCost* is returned by the procedure.

Procedure *findBest*(): This procedure is used to obtain the best pair (a, P) presently available in *SP*, such that the paths in P will lead to establishment of a lightpath route from S to D with the allowable number of segments s in a way that the cost of regeneration at the regeneration sites will be reduced. The inputs to the procedure are *SP*, s and *regCost*. The details of *findBest*() is shown in Fig. 3. The procedure works as follows.

The procedure begins by checking whether *SP* contains a single pair (S, ϕ). If the pair (S, ϕ) is only present then it is removed from *SP* and the procedure returns (S, ϕ) and

```
Procedure findBest(SP, s, regCost)
begin
1   if SP contains the single pair (S, ϕ) then
2           SP ← SP – {(S, ϕ)};
3           return ((S, ϕ), SP);
4   end if
5   found ← false;
6   sort the <c_i, i> in regCost in non-decreasing
    order of c_i values;
7   for each (a, P)∈ SP with |P| ≤ s
8   begin
9       found ← true;
10      regList ← getRegList(P);
        // regList contains u, v, w,…and z, the
        //  regeneration sites involved in the
        // translucent lightpath route that can be
        // formed by the transparent segments in P
11      (<c_u, u>,<c_v, v>,…,<c_z, z>)←makeSeq(regCost,
                                                regList);
        // c_u, c_v,… and c_z are the cost of regenerations
        // at u, v, w,…and z respectively
12      (c_u, c_v,…, c_z) ← removReg((<c_u, u>, <c_v, v>,…,
                                        <c_z, z>));
13      add [(c_u, c_v,…, c_z), (a, P)] to seqMap;
14  end for
15  if (found = true) then
16      seqMap ← sortMap(seqMap);
17      get (a_1, P_1), the pair corresponding to the first
        member in seqMap;
18      SP ← SP – {(a_1, P_1)};
19      return ((a_1, P_1), SP);
20  else
21      return ((null, ϕ), SP);
22  end if
end procedure
```

FIGURE 3. Procedure ***findBest*****.**

SP (lines 1 – 4). If *SP* contains more than one pair then the procedure works as follows. The variable *found* is initialized to *false*. If at least a pair (a, P) is available with |P| $\leq s$, then *found* will be set to *true* else it remains *false*. First, the members $< c_i, i >$ in *regCost* are sorted in non-decreasing order of c_i values. Then $\forall(a, P) \in SP$ having $|P| \leq s$ the following operations take place. The procedure *getRegList*() (line 10) is used to obtain *regList*, the list of regeneration sites that are involved in the translucent path formed by the segments in P.

The procedure *makeSeq*() (line 11) is then used to obtain a sequence of the form ($< c_u, u >, < c_v, v >, \ldots, < c_z, z >$) of length ($s$ – 1) or less, by copying the members in the order in which they appear in the sorted *regCost* corresponding to regeneration sites $u, v, \ldots, z$ present in *regList*. The procedure *removReg*() (line 12) is used to delete regeneration site i from every member $< c_i, i >$ of the sequence. Thus the sequence ($< c_u, u >, < c_v, v >, \ldots, < c_z, z >$) gets modified to ($c_u$, $c_v, \ldots, c_z$). The member [($c_u, c_v, \ldots, c_z$), (a, P)] is then added to *seqMap*. The hash-map *seqMap* is defined to map each sequence to its corresponding pair (a, P). It is important to note that sequences will vary in length as its length depends on the number of transparent segments present in P of (a, P) from which it has been derived.

The procedure *sortMap*() (line 16) is then used to sort *seqMap*. In the sorted *seqMap*, for any two consecutive members [(x_1,$x_2, \ldots, x_k$), (a_x, P_x)] and [($y_1, y_2, \ldots, y_l$), (a_y, P_y)] the relation [(x_1,$x_2, \ldots, x_k$), (a_x, P_x)] < [($y_1, y_2, \ldots, y_l$), (a_y, P_y)] implies $x_k < y_l$ or ($x_k = y_l$ and $x_{k-1} < y_{l-1}$) or ($x_k = y_l$, $x_{k-1} = y_{l-1}$ and $x_{k-2} < y_{l-2}$) and so on. The pair (a_1, P_1) that corresponds to the first member in sorted *seqMap* is chosen as the best. The procedure *findBest*() also removes (a_1, P_1) from *SP*. The pair (a_1, P_1) and the updated *SP* are returned by the procedure. If none of the pairs (a, P) in *SP* has $|P| \leq s$ i.e. if *found* is false, then the request is considered to be blocked and the procedure returns (*null*, ϕ) and *SP*.

We do not include the details of the procedures *findPathSet*(), *findLastNode*(), *findOverlaps*(), *assignWav*(), *getRegList*(), *makeSeq*(), *removReg*() and *sortMap*() as they are simple to understand.

Lemma 1: The number of (a, P) pairs in search space *SP* will be O($sk|R|$).

Proof: The algorithm proceeds by adding (a, P) pairs into the search space *SP* from the current best (a, P) pair returned by *findBest*() at each iteration till the goal pair (a, P) with $a = D$ (line 7 of Fig. 2) is reached. There are no loops in the search space as only the best (a, P) pair is expanded and also removed from *SP*. The algorithm begins with a single pair (S, ϕ) in search space *SP*. Since k pre-computed paths are used for each node pair and the network has $|R|$ number of regeneration sites, (a, P) pairs are generated from the current best pair with a branching factor which can be at most $k + k|R| \approx k|R|$ (lines 21 – 26 of Fig. 2). Since the depth of the search space is limited by s (the number of allowable segments), the number of pairs at each level 0, 1, 2 …, s – 1 can be at most 0, ($k|R|$ - 1), ($k|R|$ - 1),…, ($k|R|$ - 1) respectively (the best pair at each iteration is removed from *SP*). Let us assume the worst-case i.e. the goal pair (a, P) is reached at depth s. The total number of pairs (a, P) in *SP* is then ($k|R|$ - 1) + ($k|R|$ - 1) + …upto (s – 1) times = ($k|R|$ - 1)(s – 1) $\approx sk|R|$, proving that the number of (a, P) pairs in search space to be O($sk|R|$).

Lemma 2: For a given physical topology $G = (V, E)$ with each fiber link having W wavelengths, *H-RWA*1 can take at the most O($s^3k|R|\log sk|R| + s|R||V|^2 + W|E|$) time to complete.

Proof: The performance of *H-RWA*1 depends largely on the performance of *findBest*() which is called at the most s+ 1 times (s is the number of allowable segments and also the depth of the search space). The time to sort *RegCost* is O($|R|\log|R|$) since we employ heap sort [34]. The time taken by *getRegList*() to generate *regList* that contains the regeneration sites traversed by the translucent lightpath route formed by the transparent segments in P is O(s). The time taken by *makeSeq*() to generate the sequence of $<c_i, i>$ values from *RegCost* is O($|R|$). The time taken by *removReg*() is O(s). The time taken by *sortMap*() to sort *seqMap* is O($s^2k|R|\log sk|R|$). This is because a sequence is generated for each pair (a, P) in SP and there can be O($sk|R|$) pairs in SP (by Lemma 1). In addition sorting *seqMap* involves comparisons among the c_i components of each [(c_u, c_v,…, c_z), (a, P)] and there can be at most s – 1 such components. When the algorithm begins with a single pair in SP, *findBest*() takes negligible time to return the current best. But the total time for the remaining s calls turns out to be $s(|R|\log|R| + s + |R| + s + s^2k|R|\log sk|R|) \approx s^3k|R|\log sk|R|$ (neglecting smaller terms). The two calls to *findPathSet*() in lines 13 and 19 of Fig. 2 takes O($|V|^2$) and O($|R||V|^2$) time respectively since $|P_{set}| = |V|(|V| - 1)$ where V is the vertex set of the physical topology $G = (V, E)$. Again the two calls to *findPathSet*() can occur at the most s times. Thus the total time for these calls is $s(|V|^2 + |R||V|^2) \approx s|R||V|^2$. Further when the goal pair (a, P) with $a = D$ is reached, the time taken by *updateCost*(),*findOverlaps*() and *assignWav*() takes O($|R|$), O(s) and O($W|E|$) respectively, where W is the number of wavelengths in a fiber link. Thus the total time that H-$RWA1$ can take at the most is $s^3k|R|\log sk|R| + s|R||V|^2 + |R| + s + W|E| \approx s^3k|R|\log sk|R| + s|R||V|^2 + W|E|$ (neglecting smaller terms). Thus H-$RWA1$ can take in the worst case O($s^3k|R|\log sk|R| + s|R||V|^2 + W|E|$) time to complete.

C. HEURISTIC ALGORITHM H-RWA2

The heuristic H-$RWA2$ attempts to find a route for the requested connection (S,D) in a way that the route passes through as few stages of regeneration as possible and in addition, cost of regeneration at regeneration sites is also reduced to the extent possible. The inputs and outputs are the same as those of H-$RWA1$. The method of H-$RWA2$ is almost similar to that of H-$RWA1$, the only difference being that the *findBest*() procedure (line 4 of Fig. 2) is replaced by the procedure *getBest*(). The procedure *getBest*() is discussed next.

Procedure *getBest*(): This procedure is used to obtain the best pair (a, P) presently available in SP having $|P| \leq s$, such that the paths in P will lead to establishment of a lightpath route from S to D satisfying the objective of H-$RWA2$. The inputs to the procedure are SP, s, *regCost* and *cost*. Then every pair (a, P) $\in SP$ with $|P| \leq s$, is associated with a cost which is calculated as follows. The cost of reaching node $a$from S by the paths in P is $|P|$ - 1. The estimated cost *eCost*, of reaching D from a is $\lceil cost[a][D]/d \rceil$. The net cost associated with every (a, P) having $|P| \leq s$ is ($|P|$ - 1 + *eCost*). The best pair (a, P) is chosen as the one whose net cost is minimum.

If two or more pairs have the same net cost then the tie is broken by choosing the one which will lead to reduction of the cost of regeneration at the regeneration sites. This is done by forming sequences out of all pairs (a, P) involved in the tie, modifying the sequences by removing the regeneration sites from every member $< c_i, i >$, generating *seqMap* to map sequences to their corresponding pairs, sorting *seqMap* and finally selecting the pair (a_1, P_1) that corresponds to the first member in the sorted *seqMap* in exactly the same way as described in procedure *findBest*() (sec.V.b). The procedure further removes the chosen best pair (a_1, P_1) from SP. The pair (a_1, P_1) and the updated SP are returned. If no pair (a, P) $\in SP$ has $|P| \leq s$, then the request is considered to be blocked and the procedure returns (*null*, ϕ) and SP.

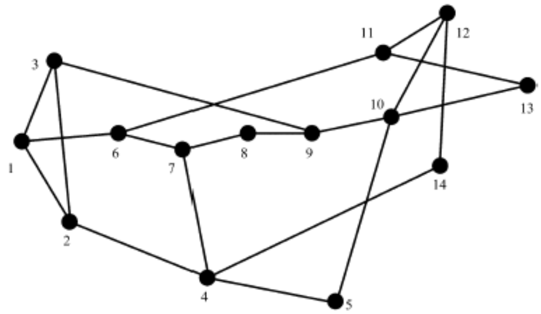

FIGURE 4. 14-node *NSF* network.

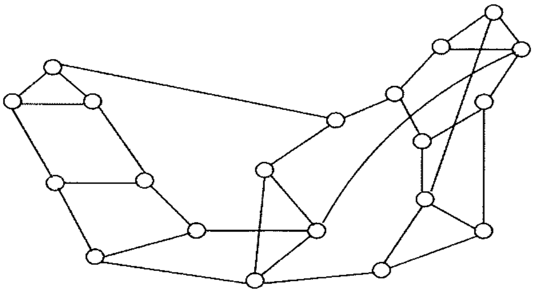

FIGURE 5. 20-node *ARPANET*.

The worst case complexity of H-$RWA2$ is same as that of H-$RWA1$ i.e. O($s^3k|R|\log sk|R| + s|R||V|^2 + W|E|$).

VI. PERFORMANCE COMPARISONS

We compare our schemes H-$RWA1$ and H-$RWA2$ with the heuristic presented in [15] which also address the problem of dynamic RWA in translucent optical networks. We use the name H-RWA for the RWA heuristic in [15]. Comparisons are carried out with programs written in ANSI C++, executed using Ubuntu 16.04 LTS 64-bit operating system in Intel Core i3 CPU M 380 @ 2.53GHz × 4 processor with 3GB RAM. We use the 14-node *NSF* network shown in Fig. 4 and the 20-node ARPANET shown in Fig. 5 for the simulation experiments. The results from simulation experiments are also compared with the optimal values obtained by solving the ILP. The ILP is solved using ILOG CPLEX 12.8.

The $k$paths in P_{ab} for $\forall a, b \in V$ were computed using Yen's algorithm [31]. We compute 5 paths ($k = 5$) within optical reach between every node pair. The length of a fiber link in the two networks used for simulation is chosen randomly between 200 and 1200 miles. The optical reach of an optical signal typically ranges from 500 to 2000 miles [3].

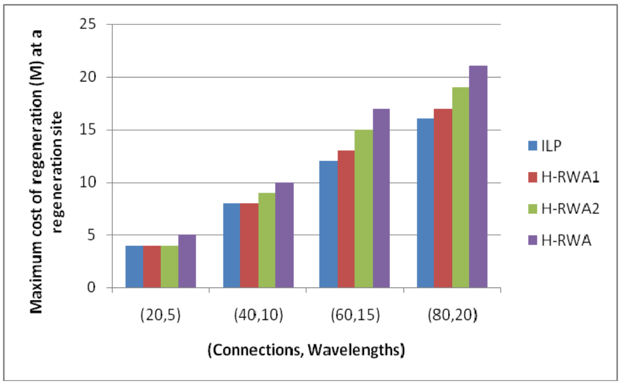

FIGURE 6. **Comparison of maximum cost of regeneration (*M*) at a regeneration site computed by *ILP* and the three heuristics for different experiments in *NSF* network.**

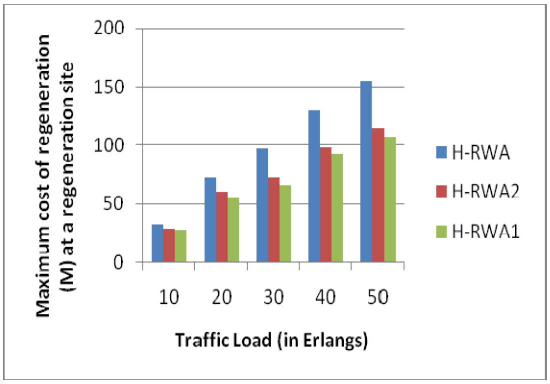

FIGURE 7. **Comparison of maximum cost of regeneration at a regeneration site computed by the three heuristics in *NSF* network.**

TABLE 1. **Execution time (in seconds) for the ILP and the three heuristics.**

(Connections, Wavelengths)	ILP	*H-RWA*1	*H-RWA*2	*H-RWA*
(20,5)	7.2	0.89	0.42	0.28
(40,10)	36.5	2.6	1.54	1.12
(60,15)	112.3	4.17	2.34	2.12
(80,20)	234.7	5.83	3.53	2.82

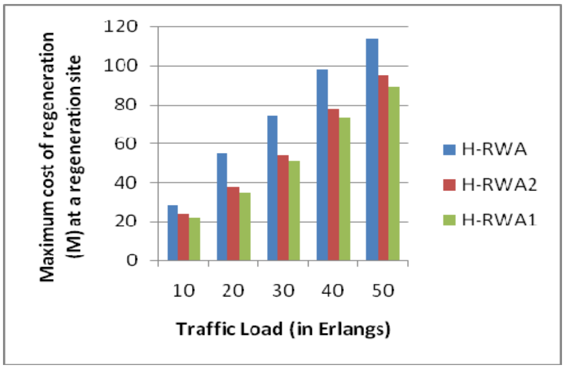

FIGURE 8. **Comparison of maximum cost of regeneration at a regeneration site computed by the three heuristics in *ARPANET*.**

In a way similar to the works [5], [11], [15] and [29] we assume that the optical reach for the physical topology is known and assume this as 1500 miles. The regeneration sites for the two networks are computed from the heuristics of [29]. We assume that all fiber links have the same number of wavelengths and (T, R) pairs are the only resources available at regeneration sites for regeneration of an optical signal. This assumption is also made in [14].

We first compare the maximum cost of regeneration (M) that occurs at a regeneration site computed by H-*RWA*1, H-*RWA*2 and H-*RWA* with that of the ILP. Comparisons are carried out by admitting 20, 40, 60 and 80 dynamic connections into the system. Fig. 6 shows the comparison of the values of M for the NSF network. In all these experiments the value of M computed by H-*RWA*1 differed with that of the optimal by at most 1.

Execution times (in seconds) for the ILP and the three heuristics, for different experiments in NSF network are shown in Table 1. The entries in Table 1 suggest, that our proposed H-*RWA*1 is able to compute near-optimal solutions, in a small fraction of time needed to compute the optimal solutions by the ILP. However, the time taken by H-RWA1 and H-RWA2 is slightly more than that of H-RWA because of the extra computation that occurs in the *findBest*() and *getBest*() procedures of the two heuristics respectively.

The three heuristics are compared by assuming 1000 calls to arrive dynamically for experiments conducted in each of the two networks. The source and destination pairs for connections are chosen randomly. We assume the arrival process for connections to follow Poisson distribution and exponential holding time for connection durations. We varied the traffic load in the network by changing the arrival and the service rates. The traffic load is the ratio of arrival rate to the service rate.

Comparisons of the maximum cost of regeneration (M) at a regeneration site, in non-blocking conditions for different traffic loads in the two networks are shown in Fig. 7 and Fig. 8. The figures show that in each experiment a substantial decrease in M value resulted by using the proposed heuristics in comparison to H-*RWA*. Over all experiments that were conducted, average(maximum) percentage decrease in M values using *H-RWA2* and *H-RWA1* over *H-RWA* in NSF network are 21.08(26.45)% and 26.65(32.98)% respectively whereas in ARPANET these values are 21.85(30.90)% and 27.26(37.36)% respectively.

Table 2 and Table 3 compare the standard deviation (S.D.) of regeneration costs at regeneration sites in the two networks. The results show that the proposed heuristics perform better than H-*RWA*. The low value of S.D. in every experiment signifies that regenerations occurred more uniformly at the regeneration sites in our heuristics than that of H-*RWA*.

Comparisons of connection blocking probability (*CBP*) on varying the number of wavelengths in links (W) but with fixed number of regeneration resources (N) and segments (s) in routes for the two networks are shown in Fig. 9 and Fig. 10.

TABLE 2. Standard deviation of regeneration costs at regeneration sites in NSF network.

Number of connections	S.D. for *H-RWA*1	S.D. FOR *H-RWA*2	S.D. of *H-RWA*
100	4.5	5.2	9.9
200	8.9	9.2	22.6
300	8.87	10.3	30.5
400	9.3	11.87	38
500	11.85	12.6	43

TABLE 3. Standard deviation of regeneration costs at regeneration sites in ARPANET.

Number of connections	S.D. for *H-RWA*1	S.D. FOR *H-RWA*2	S.D. of *H-RWA*
100	5.7	5.95	7.58
200	9.8	11	14.3
300	12.5	13.6	19
400	16.6	17.5	26.5
500	20.1	22.6	32.2

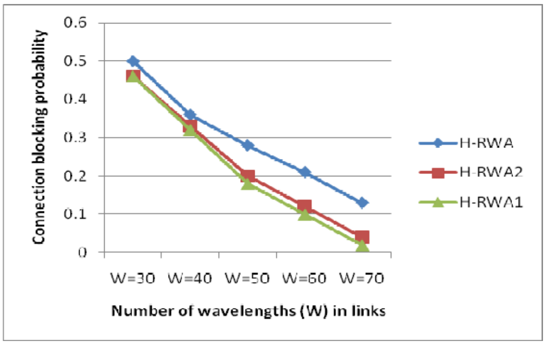

FIGURE 9. Comparison of *CBP* with *N* = 80 and *s* = 4 in *NSF* network when number of wavelengths in links is varied.

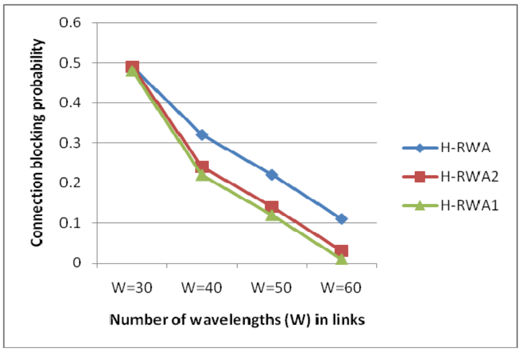

FIGURE 10. Comparison of *CBP* with *N* = 80 and *s* = 4 in *ARPANET* when number of wavelengths in links is varied.

Comparisons are shown for a traffic load of 50 Erlangs in the two networks with $N = 80$ and $s = 4$. It can be observed that as W is increased, *CBP* decreases for all the three algorithms but the proposed algorithms provide much superior blocking performance compared to *H-RWA*. Over all experiments that were conducted, average percentage decrease in *CBP* using *H-RWA*2 and *H-RWA*1 over *H-RWA* is 31.39 % and 38.36 % respectively in NSF network and 33.52 % and 42.41 % respectively in ARPANET. The proposed *H-RWA*1 outperforms others in terms of *CBP* for every experiment that is conducted. This is because employing *H-RWA*1 results in computation of paths between every S and D in a way that reduces the number regenerations that occurs at regeneration sites and hence results in a balanced traversal of the links that leads to a regeneration site.

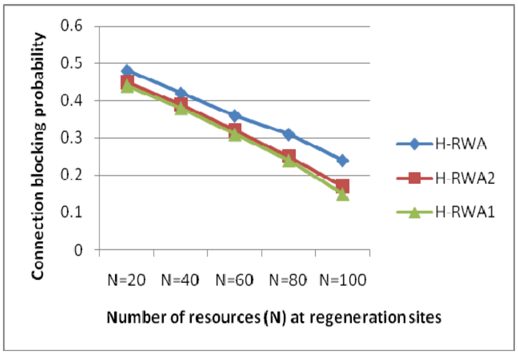

FIGURE 11. Comparison of *CBP* when resources at regeneration sites (*N*) are varied with *s* = 2 in *NSF* network.

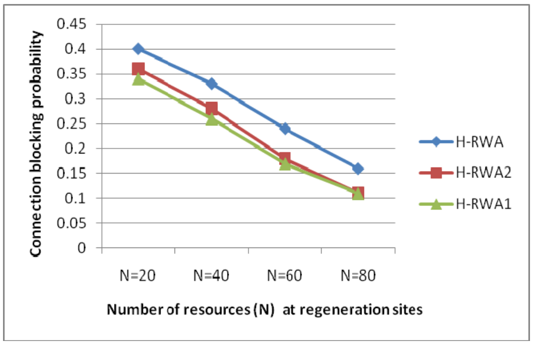

FIGURE 12. Comparison of *CBP* when resources at regeneration sites (*N*) are varied with *s* = 2 in *ARPANET*.

We next compare the algorithms in terms of connection blocking probability (*CBP*) when the number of regeneration resources (N) at regeneration sites varies with a given number of segments (s) in lightpath route. Comparisons are shown for a traffic load of 50 erlangs with $W = 60$ in NSF network and $W = 50$ in ARPANET respectively. The comparisons of *CBP* in NSF network for $s = 2$ and $s = 3$ are shown in Fig. 11 and Fig. 13 respectively whereas for ARPANET it is shown in Fig. 12 and Fig. 14 respectively. It can be observed that as $N$is increased for a given value of s, *CBP* decreases for all the three algorithms but the proposed algorithms performs better. Over all experiments that were conducted in NSF network for s =2, the average percentage decrease in *CBP* using *H-RWA*2 and *H-RWA*1 over *H-RWA* is 14.60 % and 18.36 % respectively. For s =3 the same using *H-RWA*2 and *H-RWA*1 over *H-RWA* is 29.22% and 36.02 % respectively. Over all experiments that were conducted in ARPANET for s =2, the average percentage decrease in *CBP* using *H-RWA*2 and *H-RWA*1 over *H-RWA* is 20.35 % and 24.15 % respectively.

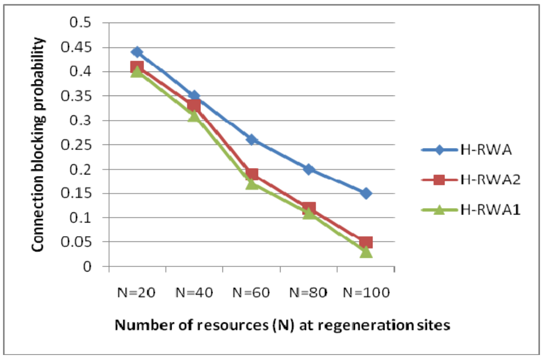

FIGURE 13. **Comparison of *CBP* when resources at regeneration sites (*N*) are varied with $s = 3$ in *NSF* network.**

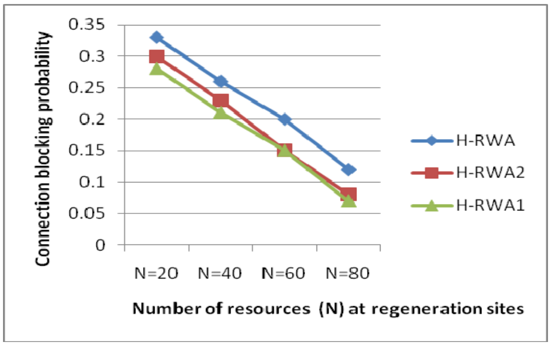

FIGURE 14. **Comparison of *CBP* when resources at regeneration sites (*N*) are varied with $s = 3$ in *ARPANET*.**

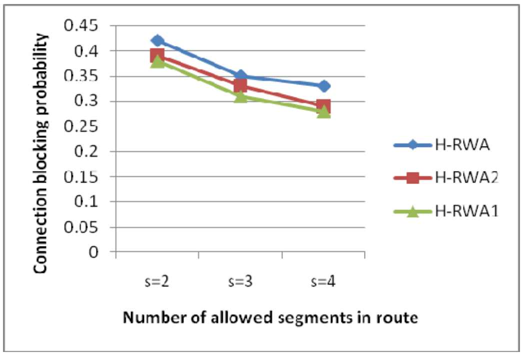

FIGURE 15. **Comparison of *CBP* when allowable segments (*s*) in lightpath routes are varied with $N = 40$ in *NSF* network.**

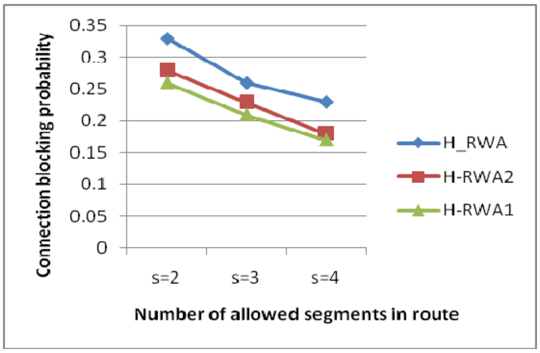

FIGURE 16. **Comparison of *CBP* when allowable segments (*s*) in lightpath routes are varied with $N = 40$ in *ARPANET*.**

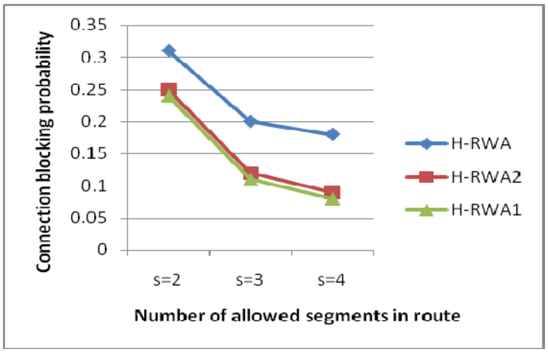

FIGURE 17. **Comparison of *CBP* when allowable segments (*s*) in lightpath routes are varied with $N = 80$ in *NSF* network.**

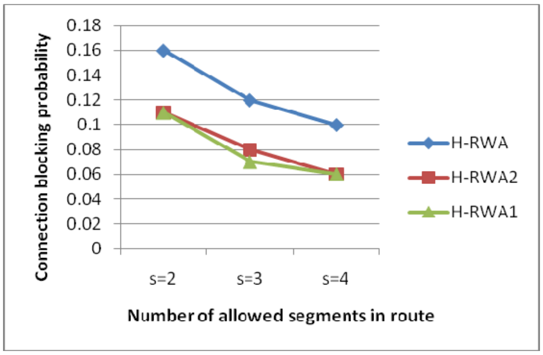

FIGURE 18. **Comparison of *CBP* when allowable segments (*s*) in lightpath routes are varied with $N = 80$ in *ARPANET*.**

For s =3 the same using H-$RWA2$ and H-$RWA1$ over H-RWA is 19.74 % and 25.26 % respectively.

The connection blocking probability (*CBP*) for the three algorithms is then compared by varying the number of segments (s) in a lightpath route for a given number of resources at regeneration sites (N). Comparisons are shown for a traffic load of 50 erlangs with $W = 60$ in NSF network and $W = 50$ in ARPANET respectively. The comparisons are shown for NSF network in Fig. 15 and Fig. 17 for $N = 40$ and $N = 80$ respectively. The same is shown for ARPANET in Fig. 16 and Fig. 18 for $N = 40$ and $N = 80$ respectively. It can be observed that as $s$is increased for a given value of N, *CPB* decreases for all the three algorithms but the proposed algorithms performs better. Over all experiments that were conducted in NSF network for $N = 40$, the average percentage decrease in *CBP* using H-$RWA2$ and H-$RWA1$ over H-RWA is 8.32 % and 12.03 % respectively. For $N = 80$, the same using H-$RWA2$ and H-$RWA1$ over H-RWA is 36.45 % and 41.04 % respectively. Over all experiments that were conducted in ARPANET for $N = 40$, the average percentage decrease in *CBP* using H-$RWA2$ and H-$RWA1$ over H-RWA is 16.14 % and 22.17 % respectively. For $N = 80$, the same using H-$RWA2$ and H-$RWA1$ over H-RWA is 34.86 % and 37.63 % respectively.

VII. CONCLUSION

In this paper, we study the problem of minimizing cost of regeneration at regeneration sites during dynamic establishment of lightpaths in translucent optical networks, taking into account OSSP. To the best of our knowledge this problem was not addressed earlier. Earlier works however studied the problem of dynamic lightpath establishment by performing RWA of connections through minimum stages of regeneration, thereby minimizing the total cost of regeneration. We have proposed an ILP formulation to address the problem and then proposed two efficient heuristics. The proposed heuristics outperformed an existing heuristic in every experiment that was performed. Our heuristic $H\text{-}RWA1$ was able to provide the best results. Blocking performance was studied extensively through simulation experiments. At first, blocking performance was studied by varying the number of wavelengths in links but keeping number of segments and regenerating resources fixed, it was then studied by keeping the number of segments fixed while varying the number of regeneration resources at regeneration sites and it was studied further by varying the number of segments with a given number of regeneration resources at regeneration sites. In every experiment where blocking performance was studied, our heuristics outperformed the existing one. The results of this work show that minimizing the cost of regeneration at regeneration sites in presence of fixed regeneration site locations can be a better choice of objective to address than focusing on minimizing the stages of regeneration in lightpath routes during dynamic lightpath establishment. If the objective is primarily to minimize stages of regeneration in lightpath routes, this work shows how it should be carried out by proposing $H\text{-}RWA2$ to improve blocking performance.

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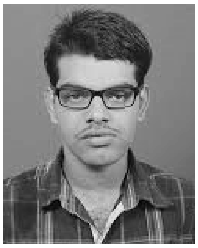
IRA NATH received the B.Tech. degree in computer science and engineering and the M.Tech. degree in software engineering from the Maulana Abul Kalam Azad University of Technology (formerly West Bengal University of Technology), India, in 2005 and 2008, respectively. She is currently pursuing the Ph.D. degree in computer science and technology with Indian Institute of Engineering Science and Technology (IIEST), Shibpur, India. She is currently an Assistant Professor with the Department of Computer Science and Engineering, JIS College of Engineering, India. Her research interests include regenerator placement, survivability, and routing and wavelength assignment in translucent WDM optical networks.

VISHAL DEY received the B.Tech. degree in computer science and technology from the Indian Institute of Engineering Science and Technology, Shibpur, India, in 2018. He is currently pursuing the Ph.D. degree with The Ohio State University, USA. He was a Summer Intern with Nanyang Technological University, Singapore, from May 2017 to July 2017. He is currently a Graduate Research Assistant with The Ohio State University, USA. His research interests include high performance computing and WDM optical network design.



JOY HALDER received the B.Tech. degree in computer science and engineering from the West Bengal University of Technology, India, in 2014, and the M.Tech. degree in computer science from the University of Kalyani, India, in 2016. He is currently pursuing the Ph.D. degree with the Department of Computer Science and Technology, Indian Institute of Engineering Science and Technology, Shibpur, India. His research interests include survivability and routing in optical networks.

MONISH CHATTERJEE received the Ph.D. degree in computer science and engineering from Jadavpur University, India, in 2012, and the M.E. degree in computer science and technology from the Indian Institute of Engineering Science and Technology (IIEST) [formerly Bengal Engineering and Science University (BESU)-one of the oldest pioneering engineering institutes in India], Shibpur, India, in 2000. He is currently an Associate Professor and the Head of the Department of Computer Science and Engineering, Asansol Engineering College, India. He started his career as a software engineer in the IT industry but after a short period he subsequently switched over to academia. He has 17 years of teaching experience and 2 years of IT industry experience. He has publications in refereed international journals and IEEE international conference proceedings. He has chaired sessions. His research interests include routing, regenerator allocation, traffic grooming, and survivability in WDM optical networks and elastic optical networks. He has been a member of technical program committee of many IEEE international conferences and workshops.

UMA BHATTACHARYA received the Ph.D. degree in computer science from the University of Calcutta, India, in 1995. She is currently a Professor with the Department of Computer Science and Technology, Indian Institute of Engineering Science and Technology (formerly Bengal Engineering and Science University), Shibpur, India. She was a Postdoctoral Fellow with Windsor University, Canada, in 1998. She was Commonwealth Fellow of Sheffield Hallam University, U.K., spent six months, from 2002 to 2003. Being the U.K.–India Networking Awardee, she was with Northumbria University, U.K., in 2005, funded by Royal Society, U.K., and the Department of Science and Technology (DST), India. Her research interests include optical networks, interconnection networks, and fault tolerance.

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