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Computation of Regeneration Sites in Survivable Cost-efficient Translucent Optical Networks

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Abstract: Survivability refers to the ability of networks to withstand failures and is one of the most important aspects of network planning and design. If the network is designed to survive failures then it will be capable of providing continuous services without disruption. In this paper, we address the problem of designing translucent optical WDM networks capable of withstanding any arbitrary single fiber-link failure. If an optical signal is propagated beyond a permissible distance also known as optical reach its quality degrades to a level which demands re-amplification, re-shaping and re-timing, a process known as 3R-regeneration. Since employing nodes with regeneration capability incur additional cost, ideally only a subset of the nodes in the network must be identified as regeneration sites. A cost-efficient survivable network design must then ensure that there is minimum number of regeneration sites. Since the Regenerator Placement Problem (RPP) is NP-Hard [1]; we propose heuristics for computing as few regeneration sites as possible to make a translucent network survive the impact of a fiber-link failure. We propose an ILP for getting optimal solution in small networks. We also propose two heuristic strategies namely; Survivable Link based computation of regenerator sites (SLCRS) and Survivable Segment based computation of regenerator sites (SSCRS). We compare the performance of the proposed strategies with some of the existing strategies. Performance comparisons show that our proposed SSCRS can be used to design survivable translucent optical networks with fewer regeneration sites.

Keywords: Link failure, Optical networks, Regeneration sites, Survivable, Translucent.

I. INTRODUCTION

Optical network emerged out in the recent times in the networking arena as a savior to enable us accommodating the growth of high bandwidth traffic which arises due to enormous increase in number of internet users, video conferencing, downloading huge number of large-sized files etc. Wavelength Division Multiplexing (WDM) optical network is a new methodology which multiplexes a group of optical signals into a single optical fiber by using various wavelengths (channels).

The physical impairments diminish the quality of an optical signal disseminating through the optical fiber beyond the optical reach which needs 3R regeneration (re-amplification, re-shaping and re-timing) at proper node positions in WDM optical network (also referred to as translucent optical network). Thus, to establish a lightpath of length greater than the optical reach, it is necessary to place regenerator nodes at proper positions in the translucent optical network. The regenerator nodes have the capability of both O-E-O conversion and wavelength conversion thus making them costly ones and this fact induces the researchers to select as few as possible number of regenerator positions with an objective to maintain connectivity between all node-pairs. A lightpath with at least one regenerator site is called translucent lightpath, otherwise the lightpath is called transparent one. A segment is a span of links which begins either from start node of transmission or regenerator node and terminates at another regenerator node or end node, thus creating more than one transparent lightpath within a translucent path. A translucent lightpath is a valid one if the length of all segments of that lightpath never surpasses the optical reach and they are mutually edge-disjoint.

Minimization of the total number of placed regenerators and selection of their best locations to establish a lightpath between every pair of nodes is known as Regenerator Placement problem (RPP). This problem is an NP-hard one [1]. Routing with Regenerator placement (RRP) problem is closely associated with RPP.

Survivability is a very crucial issue for any network design, which is the proficiency to recover from sudden collapse such as node failure and fiber cuts. The routing through the primary lightpaths are damaged hundreds to thousand times more due to cable cuts as compared to node failures which leads to huge data loss even it happens for a brief period of time. The fault model considered in this paper is a single link failure.

Survivability of a translucent network can be handled in two ways: Link based and Segment based. In case of a link failure, a backup path replaces only faulty link, other links in the lightpath remaining same. Link Survivability schemes are faster in response [2]. Another Approach of Survivability is known as Segment Survivability. In these schemes, a segment is considered to be faulty if one/more than one link(s) within the segment is faulty. Every segment will have its own backup Segment. At the time of failure in a segment, the traffic is shifted over to the backup path of the segment. The advantages of the scheme are fully distributed computing process, capacity efficiency and scalability [2].

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In this paper, our objective is to design a cost-effective survivable translucent optical network with minimum number of regenerators. We propose an Integer Linear Programming model for getting solution in small networks since the proposed problem is NP-Hard one. We also propose two heuristic strategies (i) Survivable Link based Computation of regenerator sites (SLCRS) and (ii) Survivable segment-based Computation of Regenerator sites (SSCRS).

The solution to the proposed problem results to design of a survivable translucent optical network where regenerators are placed in minimum number of positions which is also followed by a routing scheme such that any/total request set can be served assuming the fiber capacity to be infinite.

Rest of the paper consists of the following sections. In section II, we present a literature survey on the sparse placement of regenerators in survivable translucent optical networks. Section III includes the problem definition. In section IV, we include the ILP formulation for the problem mentioned. The various notations and modules used for the proposed heuristics are tabled in section V. The proposed heuristics are presented in section VI. Computational complexity is included in section VII. Section VIII includes the simulation results and performance comparisons. Finally, we conclude in section IX.

II. LITERATURE SURVEY

Different techniques for designing survivable optical networks have been proposed in earlier papers.

In 2003, E. Karasan [3] explore the crisis of developing translucent optical networks consisting of rectifiable, transparent sub-networks. An ILP and also a greedy algorithm has been developed for planning rectifiable sub-networks in translucent optical networks

In 2004, Gangxiang Shen and Wayne D. Grover [4] design and implement capacity-design model for translucent optical networks based on segment-based scheme and associated ILP model has been formulated. The proposed heuristic Survivable Hub Node First (SHNF) algorithm places reduced number of regenerators first (very close to the optimal solution) for large survivable translucent optical networks. They prove that efficiency of the segment-based approach is better than that of the path-based and the link-based approach. They use two heuristics named path-segment restoration (PSR) and shared backup segment protection (SBSP) to plan requires protection capacity.

In 2005, Yong Ouyang illustrate [5] the regenerator-segment protection scheme (RSP) for a cost-effective survivable translucent optical network maintaining a dynamic traffic demand. The main achievement of RSP scheme has been noticed in blocking probability computation and fault-recovery time which is less than path protection scheme in all large networks with moderate and less network load. The performance of RSP scheme would be worst for a path with regenerator-segments of smaller sizes.

In 2007, B. Chatelain [6] has designed a novel ILP and a heuristic based on game theoretic approach for constructing translucent optical networks. The simulation results display that the proposed game theoretic approach having reduced time complexity produces solutions very close to the optimal one.

In 2007, N. Shinomiya [7] develops a combined approach adding the advantages of link-based and path-based initiatives. It assures reachability of optical signal for each source destination pair. The simulation results show that for developing large translucent networks a considerable cost reduction of more than 30% is there when compare with a traditional link-based construction.

In 2008, Zhaoyi Pan [8] presents a Tabu Search optimization algorithm and ILP formulation using 1+1 protection scheme with full static traffic demand for designing survivable translucent optical networks. Simulation results demonstrate that the efficiency of the TS algorithm is better than other two existing heuristics - maximum infeasibility reduction (MIR) algorithm and the maximum regeneration demand (MRD) algorithm for large networks in terms of time complexity.

In 2008, N. Sambo [9] explores a new technique for path restoration in translucent optical networks. Two path restoration techniques have been studied. The RSVP-TE signaling protocol and OSPF-TE routing protocol have been utilized by RBS and RAA schemes respectively. The numerical results show that RBS scheme has the same blocking probability as compared to RAA scheme.

In 2009, D. Lucerna [10] formulates a mathematical ILP model for designing survivable small translucent optical networks with guaranteed two link-disjoint lightpaths for all source-destination pairs present in the networks with minimum number of placed regenerators. A new heuristic based on game-theoretic approach has been proposed for large networks also. Here, RPP has been considered as a non-cooperative game and the idea of best response dynamic approach has been used to obtain results which are very closest to the optimal solution. The distribution of Nash equilibria on large network instances has been considered to measure the effectiveness of the proposed heuristic. The simulation results of the proposed heuristic show that instead of non-cooperativeness of game, using Nash equilibria of the model produces very near optimal solution.

In 2010, Dou Wang [11] put forward a heuristic algorithm for searching shortest primary and backup lightpath pair and ILP formulations for getting solution of Route and Wavelength Assignment (RWA) Problem and RPP in translucent WDM optical networks. To improve the efficiency of the heuristic, ILP has been formulated which produced a path protected translucent optical networks with minimum number of regenerators in suitable amount of time for large networks also.

In 2010, Q. Rahman [12] formulated two ILP for shared path protection scheme considering probability of cycles in the dynamic lightpath distribution to design survivable translucent optical networks. The ILP1 is more wide-ranging. The main disadvantage of ILP1 is that it requires an unsatisfactorily lengthy period to finish its execution. The ILP2 is extremely swift but the efficiency is considerably inferior to ILP1.

In 2012, A Beshir presents [13] dedicated (DESRA) and shared (SASRA) protection schemes to design survivable translucent optical networks with reduced number of regenerators. In SASRA heuristic, an active-path-first approach has been adopted for selection of primary and backup lightpaths. The performance of SASRA is significantly better than DESRA.

In 2013, Etzel C. O. Santos [14] proposes the shared path protection schemes to design survivable translucent optical networks. They use two routing algorithms for searching primary and backup lightpaths. They measure the efficiency of their heuristics with respect of blocking probability, protection ratio and vulnerability ratio. The large translucent optical networks create using their heuristic was very robust than transparent optical networks in terms of vulnerability ratio.

In 2014, Q. Rahman [15] formulated an ILP to get most favorable solution to resolve the RPP for large survivable translucent optical networks. A branch-and-cut approach has been recommended for resolving the ILP effectively for large networks. Authors [15] present simulation results for large networks illustrating the better formulation of ILP in terms of time complexity.

In 2015, Juzi Zhao [16] proposes two heuristics for dedicated path protection due to multiple component failures. They explored QoT and SLA aware survivable routing and wavelength assignment problem for dynamic traffic in translucent optical networks. Simulation study is provided.

In 2017, Elias A. Doumith [17] illustrates an exact ILP for constructing survivable translucent optical networks considering the concurrent outcome of four communication impairments. The numerical results show that survivability in translucent optical network could be achieved by selecting reduced number of regenerators to create an M: N shared regenerator pool protection method. In this scenario, for each source-destination pair which needs regeneration, the network administrator calculates numerous routes accompany by effective wavelength passing through various regenerators previously. The numerical results show that for slightly loaded networks, the illustrated method accomplishes similar results to the 1+1 protection scheme. With the growth in network size, the M: N protection approach could be able to produce significantly better results than 1+1 protection approach.

A novel heuristic approach *CLR* [18] dealing with the problem of RRP and RPP computes reduced number of regenerators to be placed by generating a shortest path tree (*SPT*) in Translucent Optical Networks which acts as a background for our proposed work in this paper. CLR is described in brief as follows:

Set of reachable Nodes, the nodes at a distance less than or equal to the optical reach from each node $u \in V$, V being the set of nodes are computed. Labels L_u in terms of the number of reachable nodes is associated with each node u. The node with highest label L_{MAX} is denoted as node *MAX*. A Shortest Path Tree G_{SPT} (= (V, E_{SPT})) is constructed by applying Dijkstra's algorithm using node *MAX* as source node where E_{SPT} corresponds to the set of edges in G_{SPT} of the graph *G*. This takes into consideration of the fact that node *MAX* is reachable from maximum number of nodes in the graph. So, location of *MAX* is considered as a site for regenerator placement. $L_{MAX} < (|V|-1)$ implies that all leaf nodes in the *SPT* are not within optical reach from node *MAX*. So, testing is required to check the distance from *MAX* to each leaf node and to place regenerators in proper positions so that all leaf nodes now become reachable from node *MAX*. In similar way, all leaf pairs are now tested and regenerators are placed if necessary. Value of L_{MAX} equals $(|V|-1)$ implicates that all leaf nodes in the *SPT* are within optical reach from node *MAX*. So, checking for all leaf-pairs is now necessary for placement of regenerator nodes. Now, working path for each source-destination pair may be computed using this shortest path tree.

III. PROBLEM DEFINITION

Given a WDM optical network $G = (V, E)$ having sufficient link capacity (number of wavelengths in links) and optical reach, the problem is to design a translucent optical network with minimum number of regenerator sites, capable of serving connections between every pair of source and destination withstanding any single link failure scenario.

IV. ILP FOR OPTIMAL REGENERATOR PLACEMENT ENSURING SURVIVABILITY

Sets

V: Set of nodes in the network
E: Set of links in the network
R: Set of requests for all source-destination pairs *(s-d)*

Parameters

$D_{i,j}$: Length of link $(i, j) \in E$
Src_r: Source for request $r \in R$
Dst_r: Destination for request $r \in R$
M: Optical reach.

Variables

$W_{i,j}^{r}$: A binary variable that equals to 1 if the working path for r^{th} request uses link (i, j); 0 otherwise.
$B_{i,j}^{r}$: A binary variable that equals to 1 if the backup path for r^{th} request uses link (i, j);
0, Otherwise.
A_i : A binary variable that equals to 1 if i^{th} node is used as regenerator.
$X_r^n (Y_r^n)$: A continuous non-negative variable denotes the distance of node n from last regenerator node in primary (backup) path.

Objective: $Minimize \ \sum_{i \in N} A_i$

Subject to:

(i)Flow constraints for working path and backup

$$\sum_{j:(i,j)\in E} W_{i,j}^{r} - \sum_{j:(j,i)\in E} W_{j,i}^{r} = \begin{cases} 1 \ if \ i = Src_r \\ -1 \ if \ i = Dst_r \\ 0 \ otherwise \end{cases} \quad \dots\dots\dots\dots (1)$$

$$\sum_{j:(i,j)\in E} B_{i,j}^{r} - \sum_{j:(j,i)\in E} B_{j,i}^{r} = \begin{cases} 1 \ if \ i = Src_r \\ -1 \ if \ i = Dst_r \\ 0 \ otherwise \end{cases} \quad \dots\dots\dots\dots (2)$$

(ii)For each request, the working and backup paths must be edge-disjoint.

$$W_{i,j}^{r} + B_{i,j}^{r} \leq 1 \ \forall r \in R, \forall i \in N, \forall j \in N \quad \dots\dots\dots\dots (3)$$

(iii)Both primary and backup paths must ensure optical reach constraints. Constraints (4a) and (4b) defines X_r^j and Y_r^j respectively where i^{th} node is the proceeding node of j for each segment of primary and backup paths connecting Src_r and Dst_r.

$$X_r^i + D_{i,j} * W_{i,j}^r - M * \left(1 - W_{i,j}^r + A_j\right) \le X_r^j$$

……………… (4a)

$$Y_r^i + D_{i,j} * B_{i,j}^r - M * \left(1 - B_{i,j}^r + A_j\right) \le Y_r^j$$

……………….. (4b)

$$\forall r \in R, \forall (i,j) \in E, : j \neq Dst_r.$$

Constraints (5a) and (5b) ensure that the length of any segment is within optical reach for primary and backup paths.

$$X_r^i + D_{i,j} * W_{i,j}^r \le M$$

………………….. (5a)

$$Y_r^i + D_{i,j} * B_{i,j}^r \le M$$

……………….. (5b)

$$\forall r \in R, \forall (i,j) \in E.$$

Constraints (6a) and (6b) ensure that if node *i* is used for regeneration, length of segment from
Node *i* is zero.

$$X_r^i \le M * (1 - A_i)$$

……………… (6a)

$$Y_r^i \le M * (1 - A_i)$$

……………… (6b)

$$\forall r \in R, \forall i \in N, : i \neq Dst_r$$

Constraints (7a) and (7b) ensure that length of segment starting from a source node is zero.

$$X_r^i = 0$$

……………… (7a)

$$Y_r^i = 0$$

……………… (7b)

$$\forall r \in R, \forall i \in N, : i = Src_r.$$

V. NOTATIONS, DEFINITION AND MODULES FOR THE PROPOSED HEURISTICS

The notations, definitions and used modules of the proposed heuristics are described as follows:

A. Some Notations

Table 1 describes the various notations used in the two proposed heuristics and their description.

B. Definition

Optical Reach Constrained (ORC) Path: The lightpath $P_{i,j}$ connecting the nodes *i* and *j* in *G* is referred to as an Optical Reach Constrained (ORC) Path for a particular source destination pair *(i, j)* if for each $TS_{i,j}^m$ in $P_{i,j}$ the following relation holds:

$W_{TS_{i,j}^m} \le M$, $2 \le m \le k-1$, where *k* is the number of nodes present in the lightpath $P_{i,j}$.

C. List of modules used in the proposed heuristics

Module *MAX_LEAF* () is called to modify the paths from MAX node to all leaf nodes into ORC path by placing regenerator(s) at proper position if necessary.

Module *LEAF_LEAF* () is invoked to convert all paths from leaf to leaf of the G_{SPT} into ORC paths by placing regenerator(s) at proper positions if necessary.

Module Test () is used to check whether the already existing regenerators (in the intermediate stage during computation) are sufficient to consider it the backup lightpath as an ORC one.

Module Place_Re () is called to select the appropriate new positions for placing the regenerator(s).

Table 1 Notations used

Notations	Descriptions
M	Optical Reach Distance
$W_{P_{i,j}}$	Weight of the lightpath $P_{i,j}$
$TS_{i,j}^m$	m^{th} transparent segment in the lightpath $P_{i,j}$
n	Total number of segments present in Shortest Path Tree.
G_{SPT}	A Shortest Path Tree created on graph *G* considering *MAX* node as the source node and all the other nodes as destination nodes.
$W_{TS_{i,j}^m}$	Weight of the m^{th} transparent segment connecting the nodes *i* and *j*.
b	Total count of those paths from *MAX* to leaf node whose length is greater than *M*.
h	Total count of paths from leaf node to leaf node whose length is greater than *M*.

VI. PROPOSED WORK

We propose two heuristic approaches to solve the problem described in section 3; Heuristic SSCRS (Survivable Segment based computation of regenerator sites) and Heuristic SLCRS (Survivable Link based computation of regenerator sites).

The computation of regenerator sites using heuristic SSCRS is based upon the computation of backup segments with reduced number of regenerator sites. Fig. 1 shows the flowchart of the proposed heuristic SSCRS. We apply the Heuristic CLR on graph *G*. Then total number of Segments (n) in the produced *SPT* has been counted. We compute the available number of shortest backup segments for each primary segment present in the *SPT*. Then we initialize a counter C as zero. After this we sort these segments in ascending order of available number of backup segments and create a list list_b_path to store them. Then if C is less than or equal to n then we select the segments with least number of backup segments from the list list_b_path. Then we apply module Test () to check whether the already existing regenerators (output of heuristic CLR) are sufficient to make it an ORC segment. If Test () module is not sufficient to convert it into an ORC segment, then we call module Place_Re () to place reduced number of regenerators in the selected segment from the list list_b_path. After placement of reduced number of regenerators in the selected segment from the list list_b_path, the segment will be deleted from the list list_b_list. Then we increment the counter C by one. We continue the checking whether C is less than or equal to n. If it is true then we repeat the above-mentioned procedure again to place the reduced number of regenerators in the remaining segment with least number of backup segments present in the list list_b_path one by one.

We stop the execution of the heuristic SSCRS after placing the reduced number of regenerators in n number of backup segments so that for each primary ORC segment one ORC backup segment must be present in the graph *G* ensuring reduced number of placed regenerators.

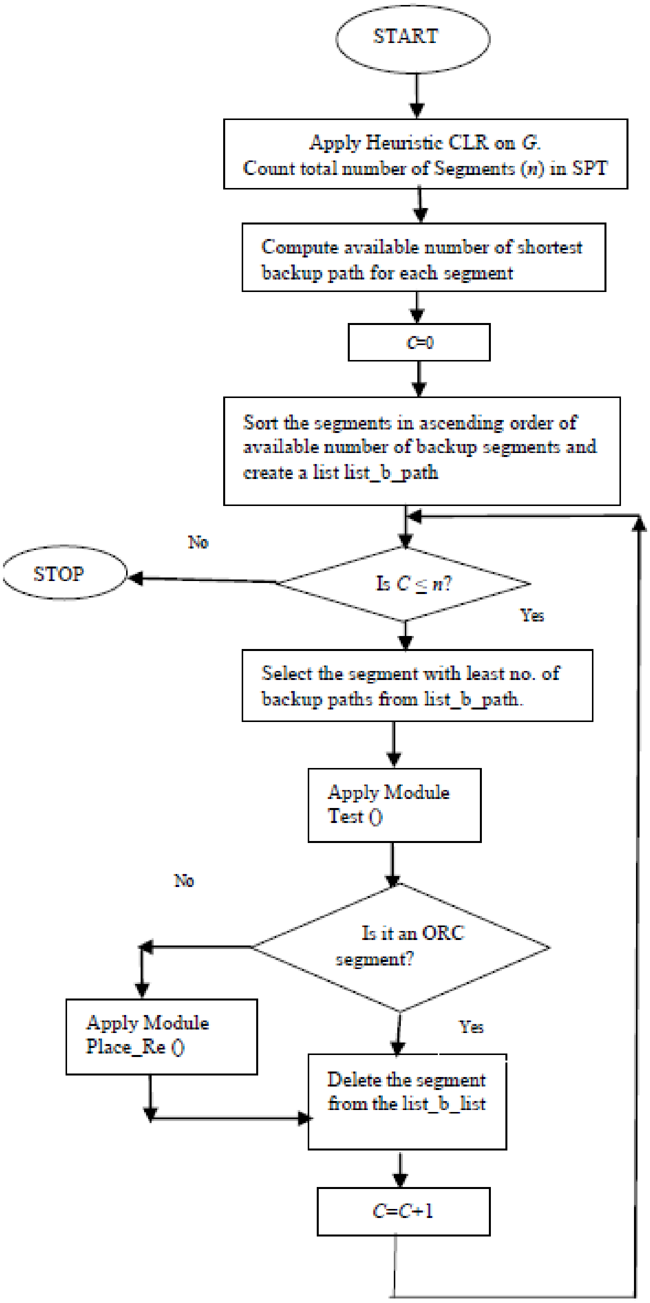

Fig. 1: Flowchart of the heuristic SSCRS

The heuristic SLCRS is based upon removing each link only once and selecting the regenerator sites using heuristic CLR on the modified network. Fig. 2 shows the flowchart of the proposed heuristic SLCRS. We take a counter COUNT and initialize it to zero. We also take a set *S* which is initialized as NULL. Then we remove a link one by one from graph *G* considering all other links present in the graph *G* to create *G'*. Then we increment COUNT by one. We check whether COUNT is less than or equal to the number of edges of the graph *G*. If it is true then we apply heuristic CLR on the graph *G'* to place reduced number of N_R regenerators on graph G'. Then, we do union the set S and N_R. We repeat the above-mentioned procedure until COUNT is less than or equal to the number of edges of the graph *G*.

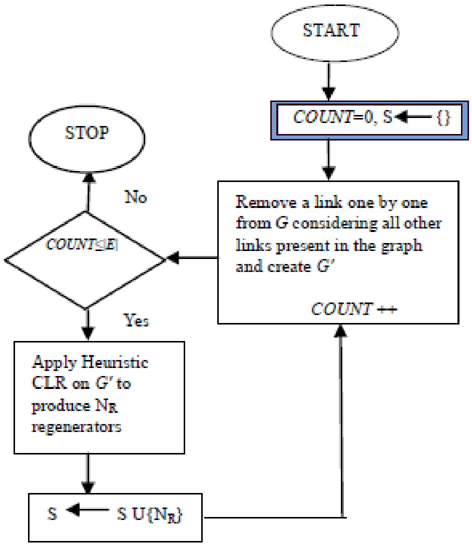

Fig. 2: Flowchart of the heuristic SLCRS

A. Heuristic Survivable Segment based computation of regenerator sites (SSCRS): A case study

Fig. 3 shows a network with 7 nodes and 10 links. The distances between the nodes are represented in miles. Optical reach is considered as 2000 miles.

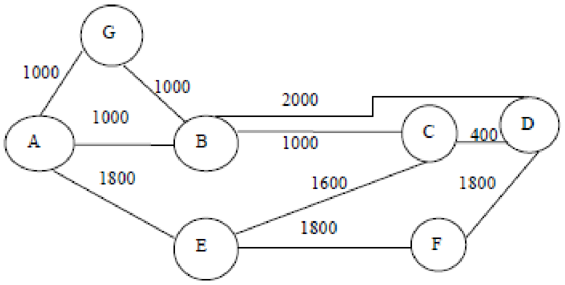

Fig. 3: Long haul optical network with distances between the nodes in miles.

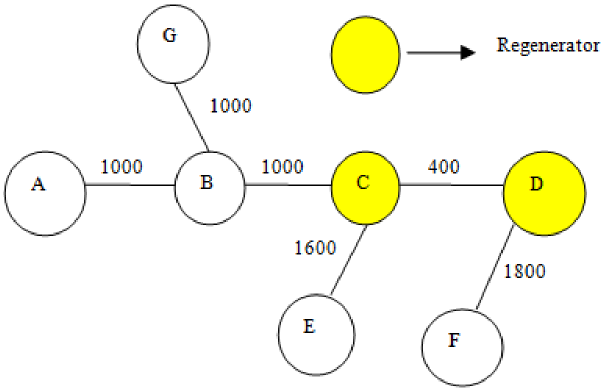

Fig. 4: G_{SPT} obtained using CLR.

Fig. 4 shows the G_{SPT} with reduced number of regenerator sites obtained from Fig.3 using heuristic CLR. The selected reduced numbers of regenerator sites are node C and node D.

We assume that all primary segments are available in G_{SPT} as shown in Fig. 4. Respective Backup segments are obtained from the graph G (in Fig. 3).

In G_{SPT} already regenerators are placed in nodes C and D considering M=2000.

The following section describes a case study of Heuristic SSCRS.

The segments of G_{SPT} in Fig. 4 are A-B-C, G-B-C, C-D, C-E and D-F.

Following are the Link-Disjoint next shortest segments (available in graph *G*) sorted in ascending order according to number of backup segments for each primary segment in G_{SPT} of Fig. 4.

(i) **Segment G-B-C: Only One** Link-Disjoint next shortest path except primary path for segment G-C is G-A-E-C: Cost-(1000+1800+1600) = 4400.

(ii) **Segment D-F: Only One** Link-Disjoint next shortest path except primary path for segment D-F is D-C-E-F: Cost-(400+1600+1800) = 3800.

(iii) **Segment A-B-C: Two** Link-Disjoint next shortest paths except primary path for segment A-C are
  a) A-E-C: Cost-(1800+1600) = 3400 (Next Shortest disjoint path)
  b) A-G-B-D-C: Cost (1000+1000+2000+400) = 4400
  Backup segment A-E-C is less costly than the other one A-G-B-D-C.

(iv) **Segment C-D: Two** Link-Disjoint next shortest paths except primary path for segment C-D are
  a) C-B-D: Cost-(1000+2000) = 3000 (Next Shortest disjoint path)
  b) C-E-F-D: Cost-(1600+1800+1800) = 5200
  Backup segment C-B-D is less costly than the other one C-E-F-D.

(v) **Segment C-E: Two** Link-Disjoint next shortest paths except primary path for segment C-E are
  a) C-B-A-E: Cost-(1000+1000+1800) = 3800(Next Shortest disjoint path)
  b) C-D-F-E: Cost-(400+1800+1800) = 4000

Backup segment C-B-A-E is less costly than the other one C-D-F-E.

The segments G-B-C and D-F with only one backup segment are selected first for placement of regenerator(s). Then we select segments A-B-C, C-D and C-E one by one by selecting link-disjoint back-up path of each segment having least cost for placement of regenerators.

All dotted links of any color indicates the link of G_{SPT}.

1. Segment G-B-C (Only backup segment is G-A-E-C)

To compute the link-disjoint path for the segment G-B-C, distances of GB and BC are set to ∞ temporarily. So, this leads to select G-A-E-C as only one next shortest link-disjoint segment (Backup segment) for segment G-B-C (Fig. 3) which is shown in Fig. 5.

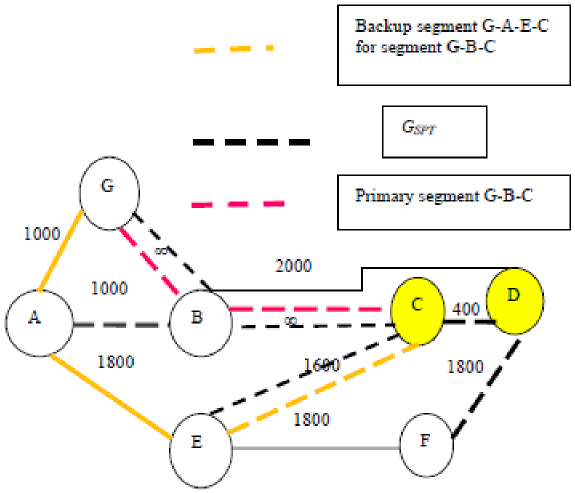

Fig. 5: Only Backup Segment G-A-E-C for segment G-B-C.

Fig. 6 shows placements of regenerators due to only Backup Segment G-A-E-C of segment G-B-C. In the Backup Path G-A-E-C, the appropriate regenerator positions are A and E.

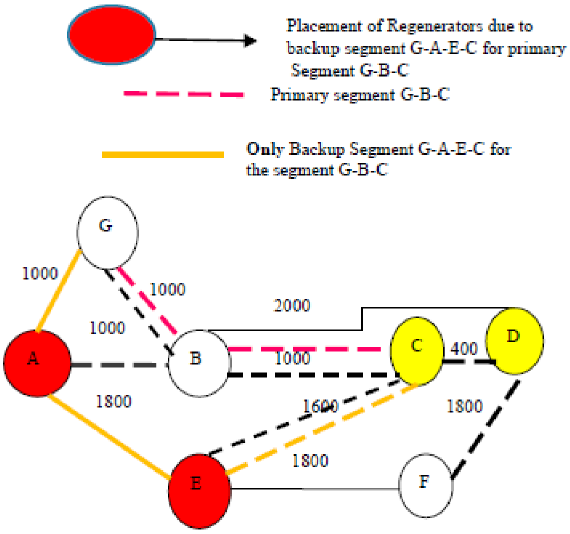

Fig. 6: Placement of Regenerators due to alternate segment G-A-E-C for the primary segment G-B-C.

2. Segment D-F (only backup segment is D-C-E-F)

Following same procedure as done for the segment G-B-C, we find that no new regenerator needs to be placed.

3. Segment A-B-C (Backup segments are A-E-C and A-G-B-D-C)

We select the less costly backup segment A-E-C.

Backup Segment A-E-C

Fig. 7 shows the primary segment A-B-C. No new regenerator needs to be placed for the backup segment A-E-C since the path is an ORC one.

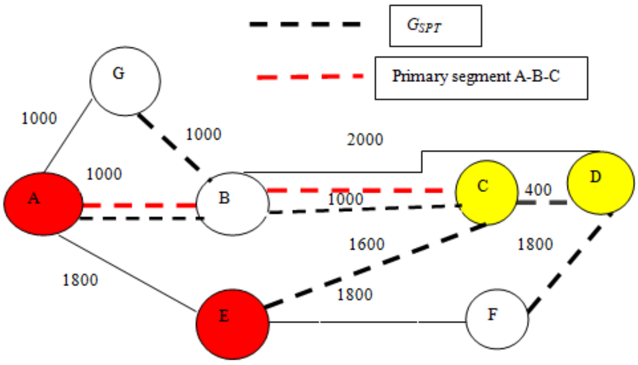

Fig. 7: Primary segment A-B-C

The same procedure is continued iteratively for all other primary segments until all the backup lightpaths for all primary lightpaths become ORC lightpaths.

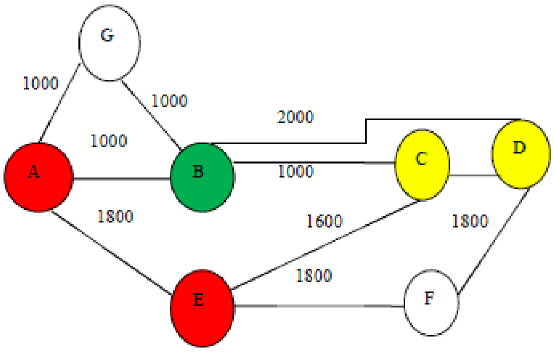

Fig. 8: Regenerator placement after applying Heuristic SSCRS

Fig. 8 shows the network after placement of regenerators which connects every source destination pairs of nodes simultaneously considering the fibre capacity to be infinite. In this connection, we like to infer that each primary path is available in G_{SPT} and corresponding backup path can be constructed by using the backup segments which are used for regenerator placements. Say, for the primary path A-B-C-D the backup path is A-G-B-D constructed from the backup segments A-G-B and B-D.

Table 2 shows the results of heuristic SSCRS for the graph in Fig.3.

Primary Segments	NODE A	NODE B	NODE C	NODE D	NODE E	NODE F	NODE G	Remarks
G-B-C	√				√			√ indicates newly selected regenerator sites.
D-F	*				*			
A-B-C					√			
C-D		√						
C-E	*	*						* indicates already existing regenerator sites.
Heuristic CLR			√	√				
The selected regenerator sites of Fig.3 for SSCRS approach	√	√	√	√	√			

Table 2 Regeneration sites placement during execution of SSCRS

B. Heuristic Survivable Link based computation of regenerator sites (SLCRS): A case study

In this section, we describe heuristic SLCRS which is designed for survivability using link failure in translucent optical networks using a case study.

Table 3 shows the result of the heuristic SLCRS for Fig.3. First, the link A-G from the Graph G in Fig.3 has been removed to produce the modified network. Then we apply heuristic CLR on the modified network to get the node positions for regenerator placement on G'. Node positions are selected which is shown in Fig. 9. Then we add the link A-G in G' to get back the original graph G in Fig.3. The above procedure is repeated for all the links present in the Fig.3.

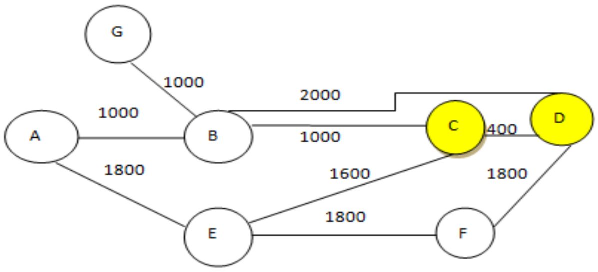

Fig. 9: Modified graph G' after applying CLR in Fig.3

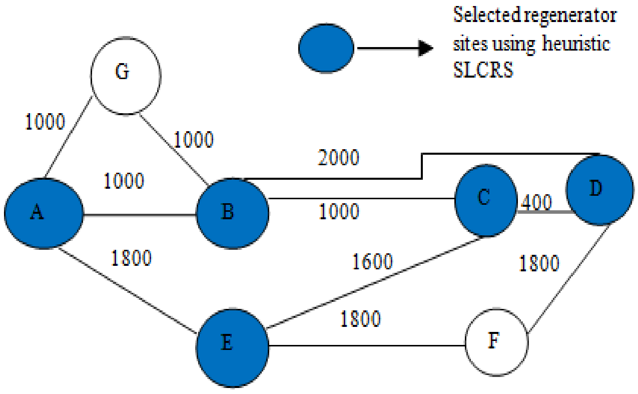

Fig. 10: Final graph with regenerator sites using heuristic SLCRS

Fig.10. shows the final regenerator sites selected using heuristic SLCRS which connects every source destination pair of nodes simultaneously considering the fiber capacity to be infinite. Table 3 shows the results of SLCRS for the graph in Fig.3

Table 3 Regeneration sites placement during execution of SLCRS

Removed Links	NODEA	NODE B	NODEC	NODED	NODE E	NODE F	NODEG
A-G			√	√			
A-B		√	√	√			
A-E			√	√			
B-C		√		√			
B-G	√		√	√			
B-D			√	√			
C-D		√	√		√		
C-E	√	√		√			
D-F			√		√		
E-F			√	√			
The selected regenerator sites of Fig.3 for SLCRS approach	√	√	√	√	√		

VII. COMPUTATIONAL COMPLEXITY

Worst-case complexities of the heuristic SSCRS and SLCRS have been computed. The worst-case time complexity of heuristic SSCRS is O (|*m*|*|*q*|*|*E*|*log|*V*| + $|V|^3$log|*V*|), where m is the number of segments present in the G_{SPT} and q is the degree of node *i* in each segment (*i, j*) where degree of node *i* ≤ degree of node *j*. The worst-case time complexity of heuristic SSCRS is O ($|V|^3$*log|*V*|).

The worst-case time complexity of heuristic SLCRS is O (|*E*|*$|V|^3$*log|*V*|).

We have compared our heuristics SSCRS & SLCRS with two other heuristics SHNF [4] (segment based) & SASRA [13] (link based). The complexity of SHNF is O ($n|E|^4$), where n is the number of segments present in the graph [4]. The complexity of SASRA is O ($|V|^2$log|*V*| +|*V*||*E*|) [13].

So, in segment-based approach our heuristic SSCRS has less worst-case complexity compared to SHNF. In link-based approach our heuristic SLCRS has greater complexity than that in SASRA.

Lemma: Heuristic SSCRS performs better than Heuristic SLCRS

Proof: In SSCRS, first of all, one G_{SPT} has been formed by applying heuristic CLR by placing N_R number of regenerators on primary paths. From this G_{SPT}, available numbers of segments (say *m*) are selected. For each segment, link-disjoint all backup segments are considered. Amongst these the backup segment with least cost are considered for placing least number of regenerators (say W_1) along with N_R number of already placed in the network. For selecting the link-disjoint backup segment of the next segment (out of m number of segments) the same procedure has been applied considering ($W_1 + N_R$) numbers of regenerators are already placed in the network. This will help in reducing the number of regenerators to be placed in the network for survivability.

On the other hand, in SLCRS, after removing 1st link from the network *G*, N_{RE_1} regenerators will be selected for the modified network applying heuristic CLR. In heuristic SLCRS, after removing each link from the network *G*, a new set of regenerators are selected without considering the presence of previously selected regenerators. The selected regenerators using SLCRS method for a network with |*E*| number of links will be $(N_{RE_1} \cup N_{RE_2} \cup \ldots\ldots \cup N_{RE_{|E|}})$. So, total count of number of regenerators to be placed in SLCRS is always greater than those to be placed in the network using SSCRS.

Approach SSCRS is also better than the approach from the point of view of survivability since SSCRS supports single/ multiple link failures present in the segment whereas SLCRS supports single link fault only.

VIII. PERFORMANCE COMPARISONS

We use the two heuristics SASRA [13] (link based) and SHNF [4] (segment based) for performance comparisons. The simulation is carried out in Windows 8 platform. We conducted extensive simulations to evaluate the efficiency of our heuristics using two different realistic networks; 14 nodes NSF Network [4] and 21 nodes ARPA2 Network [4]. We have used IBM ILOG CPLEX optimization studio (12.6.8) for running the ILP formulation. The heuristic algorithms are implemented using C programming language.

Optimal results obtained from the ILP are compared with all the heuristics SSCRS, SLCRS, SASRA and SHNF for small sized networks i.e. 14 nodes NSF network. Optimal result remains intractable when we use 21 nodes ARPA2 network [4].

Table 4 Total number of regenerating sites for NSFNET Network by using different approaches

Optical Reach	Total number of regenerating sites				
	Segment based		Link based		Optimal
	SSCRS	SHNF	SLCRS	SASRA	
189	10	10	12	13	9
250	6	7	10	11	6
350	4	4	12	12	4
450	2	2	5	6	2
550	1	1	3	3	1

Table 4 gives the number of regenerating sites obtained by the heuristics SSCRS, SLCRS, SASRA, SHNF and optimal results obtained by running ILP for different optical reaches in NSFNET Network.

Table 5 Total number of regenerating sites for ARPA2 Network using different approaches

Optical Reach	Total number of regenerating sites			
	Segment based		Link based	
	SSCRS	SHNF	SLCRS	SASRA
109	14	14	17	17
200	7	8	11	10
300	5	5	8	8
400	2	2	7	7
500	1	2	3	4
600	1	1	3	2

Table 5 gives the number of regenerating sites obtained by the heuristics SSCRS, SLCRS, SASRA, and SHNF for different optical reaches in ARPA2 Network. For large sized ARPA2 network, optimal solution is not tractable one and hence absent in Table 5.

Some Observations

It has been observed from Table 4, Table 5 and computational complexity [section VII] that

[1] SSCRS provides significantly better performance than SLCRS between two proposed approaches in this paper.

[2] Segment based approaches shows far better performance than link-based approaches.

[3] Segment based both the approaches show result close to the optimal one. SSCRS gives slightly better performance than SHNF. But worst-case complexity of our proposed approach SSCRS is better than SHNF.

Both the comparisons done for NSFNET and ARPA2 networks show that the algorithm SSCRS gives the best performance compared to other heuristics.

IX. CONCLUSION

In the proposed work, the problem of designing the survivable translucent networks as well as the selection of minimum number of regenerating sites for making network cost efficient have been addressed to overcome the problem of physical impairments with least cost. Regenerator placement problem along with survivability is NP-hard [4] one. We propose an ILP for getting optimal solution which becomes intractable as the network size grows. This leads us to propose two heuristics SSCRS (segment-based approach) and SLCRS (link-based approach). The performance of SSCRS is significantly better than that of SLCRS. Segment based heuristic SSCRS is compared with another existing segment based one SHNF and link based heuristic SLCRS is compared with another existing link based one SASRA. Simulation results show us that segment-based approach gives far better results (near optimal) in comparison to link based approaches. Our proposed segment based heuristic SSCRS has less time complexity than the existing SHNF thus proving the efficacy of SSCRS.

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