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Single Shortest Path-based Logical Topologies for Grooming IP Traffic over Wavelength-Routed Networks

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***Abstract*— We consider the problem of designing logical topologies for grooming IP traffic over wavelength-routed networks; in particular non-bifurcated minimum hop routing is used to route IP traffic. We present two approaches to solve this problem. The first approach is a two-step approach where in the first step we solve a mixed integer linear programming (MILP) formulation to determine an initial single shortest path logical topology; this is followed by a pruning approach to find an improved logical topology in the second step. Our second approach is a heuristic solution for moderate size networks. We then consider different performance measures to show the effectiveness of our solution approaches in generating minimum average packet hop-based logical topology.**

***Index Terms*— Grooming, Lightpaths, Virtual Topology, OSPF, Single Shortest Path, Traffic Engineering.**

I. Introduction

Wavelength-routed optical networks employing wavelength division multiplexing (WDM) [1] are considered as potential transport networks for carrying IP traffic. The physical topology of the optical network consists of wavelength routers connected by optical fibers. IP routers are connected to the wavelength routers and these IP routers are inter-connected through optical channels called lightpaths or logical links. These lightpaths form a virtual topology for the IP network which is overlayed over the physical topology. An advantage of WDM is that data can be sent on disjoint wavelengths on a single fiber, thus providing tremendous bandwidth.

In order to utilize this bandwidth more efficiently, several independent traffic streams must be multiplexed into single lightpath, which gives rise to the concept of traffic grooming [2]. In the context of IP over WDM networks, the grooming problem refers to grooming of IP traffic streams into lightpaths. A key bottleneck in the optical network is the limited number of transmitters and receivers available at each node, avoiding the possibility to deploy a fully meshed IP logical topology. Therefore, multiplexing and demultiplexing are not always limited to edge routers. At some core routers, traffic needs to be converted in electrical domain and reconverted in optical domain. These routers can be the bottleneck in the network. Thus, traffic needs to be groomed in such a way that opto-electro-opto(OEO) conversion is minimized. In this paper, we consider minimization of the average number of traffic-weighted logical hops as the objective function, which in effect minimizes the OEO conversion. We have also incorporated the number of available transreceivers at each optical node as a constraint in the problem; thus, we study the impact of number of available transreceivers on the logical topology design.

At the same time, a critical aspect about an intra-domain IP network is that it uses shortest path routing for routing packet traffic between two routers using protocols such as OSPF or IS-IS where the shortest path routing is dictated by the link metric used [8]; furthermore, if there are two paths of equal cost between two IP routers, then equal-cost multipath (ECMP) rule is employed to split traffic. While ECMP is a good functionality in principle, it has been noted that from a network troubleshooting point of view, it is desirable to avoid multiple shortest paths between any two routers [9]; that is, multiple shortest paths can make it difficult for the network administrator to control the traffic flow in the network and identify problems in the network. We want to clarify that we do not take a position whether single-shortest path or ECMP is better for a network provider. We provide our single-shortest path approach as a viable approach for those network providers who may choose or are interested in such a solution due to their internal network management policy.

In this paper, we investigate the problem of generating a virtual IP network topology so that each pair of IP routers have a single shortest path; it is given that the underlaying optical network is node-limited by the number of transmitters and receivers. We assume that the link metric used in the IP network is based on hop count[1]. Our goal is to build a virtual topology in such a way that the average distance between each IP node pairs is minimized, taking into account traffic volume in the IP network. We use virtual topology and logical topology interchangeably in this paper.

Virtual topology design problem for wavelength-routed networks has been extensively studied in the past decade; for example, see [3], [4], [5], [6]. A general approach for the logical topological design problem is to formulate a mixed integer linear programming (MILP) problem, followed by heuristics to solve such formulations for moderate size networks. For a survey of logical topology design algorithm, see [7]. It is worth noting that none of these work however address generating virtual topology that satisfy single-shortest path requirement for all node pairs. The work in [9], [10], [12] have discussed some of the shortcomings associated with using ECMP paths, and presented methods to determine link metric so that ECMP paths can be avoided; it may be noted that these works assume that the virtual topology is given. In an independent work [11], Bley considers single-shortest path routing in the context of network capacity design. To our knowledge, determination of virtual topological design that satisfy single shortest paths requirement has not been addressed in the current literature.

We present two approaches in this paper. First approach consists of two steps: it involves solving a mixed integer linear programming (MILP) formulation to generate an initial logical topology, followed by a pruning heuristic so that the final logical topology has single shortest paths for all demand pairs. A limitation of this approach is the size of the network since an MILP formulation needs to be solved first. Thus, we also present a second, heuristic approach for moderate size networks. In both our approaches, we have considered minimizing the average traffic-weighted hop distance as the objective function. In effect, we groom IP traffic into lightpaths in such a way that OEO conversion is minimum. On the other hand, often a variety of performance measures are of interest to network providers depending on its impact on the network. It is possible that multiple unique minimum-path based topologies exist for a given number of nodes and a particular virtual topology might be more suitable to a network provider compared to other virtual topology depending on performance measures; thus, it is helpful to look at such measures.

The rest of the paper is organized as follows. In section II, we present the problem description. In section III, we discuss some of the regular topologies and discuss some conditions to ensure unique shortest path among all node pairs in a graph. In section IV we present the two-step solution approach. In section V, we present a heuristic to solve the problem for moderate size networks. In section VI, we present results for small and moderate size networks.

[1]We are currently investigating the impact of different link weight systems on virtual topology design; this will be addressed in a follow-up paper.

II. Problem Definition

We consider N number of IP nodes (routers) that are to be interconnected over an optical backbone by setting up bidirectional lightpaths between these IP nodes such that the resulting virtual topology formed by lightpaths has a unique shortest path for every source-destination IP nodes. We assume that all the links (lightpaths) in the virtual IP topology have unit link weight and each IP node has Δ optical transreceivers; thus, each node can have at most Δ incoming and Δ outgoing lightpaths. In the process of designing the logical topology, we want to route each demand through minimum possible hops. In essence, the problem we address is: *what is the best virtual IP topology in terms of minimum value of average number of hops such that there is single shortest path (with hop-count as link metric) among all source-destination pairs?*

Formally, given the following inputs to the problem:

1) N Nodes each equipped with Δ transmitters and receivers,
2) Traffic demand volume between all $N(N-1)$ node pairs for N node network,
3) Link Weights for all possible links (lightpaths) is 1,
4) A single path minimum-hop routing strategy to route IP packets on logical topology,

our aim is to generate a logical topology that minimizes the average traffic-weighted hop distance, such that every demand pair has a unique shortest path.

Before discussing our solution approaches to the above problem, we explore the possibility of using some regular topologies as IP virtual topology. In the next section, we briefly consider two such regular topologies: fully meshed and spanning tree. We also present two conditions which ensure unique minimum-hop paths for all demand pairs in a network.

III. Properties of Single Shortest Path based Topologies

A virtual topology can be represented by an undirected graph since we have assumed that all lightpaths in the virtual topology are bidirectional. The simplest solution to ensure that each source-destination pair has a unique minimum-hop path is to construct a fully connected graph, in effect, making the direct path the shortest path for each demand pair. A fully connected topology also provides a lower bound on the average hop distance (average hop-distance is 1). However, it is often not possible to set up a fully meshed virtual topology due to restriction on the number of transreceivers at each optical node. Moreover, the number of available wavelengths on each fiber imposes a limit on the number of lightpaths.

Another possibility is to set up an IP virtual topology represented by a spanning tree, since this guarantees that unique shortest path (rather unique paths) among all node pairs exist. The number of transreceivers do not pose any restriction on setting up such virtual topology (assuming each optical node has at least 2 transreceivers). However, a spanning tree leads to longer paths in terms of number of hops, leading to high value of the average packet hop distance; this may not be desirable.

Besides the regular topologies described above, we can also construct random topologies, such that each node pair has a single shortest path when hop-count is used as the link metric. Next, we present two conditions which ensure unique minimum-hop paths among all node pairs in an undirected graph. We assume that there is no loop present in the graph. For brevity, we define an *even cycle* in an undirected graph as a cycle with even number of edges (number of edges ≥ 4), and an *odd cycle* as a cycle containing odd number of edges. We also define a cycle as fully connected if all the nodes of the cycle have a link between each other.

Theorem *1: If an undirected graph does not have any even cycle, all node pairs in the graph will have unique shortest path with hop-count as link metric.*

Proof: We prove this result by contradiction. Suppose that at least one demand pair has two shortest paths and each of these paths has k hops. These two shortest paths in turn will form an *even cycle* containing $2k$ links in the graph. However, the graph does not have any *even cycle*. Hence, the graph has unique shortest paths for all node pairs. ■

Theorem *2: If all the even cycles in an undirected graph are fully connected, all node pairs in the graph will have unique minimum hop path with hop-count as link metric.*

Proof: We prove this result also by contradiction. Suppose that at least one demand pair has two shortest paths and each of these path has k hops. This, in turn, will form an *even cycle* containing $2k$ links in the graph. Since, we have assumed that there are no loops in the graph, therefore k has to be ≥ 2. However, all the even cycles in the graph are fully connected and thus all the node pairs of this *even cycle* have unique shortest path(direct path) between them. Consequently our starting assumption of multiple shortest path does not satisfy. Hence, the graph has unique minimum-hop paths for all node pairs. ■

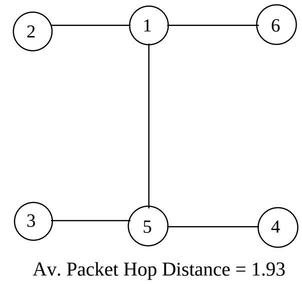

Fig. 1. Spanning tree logical topology for SN-I

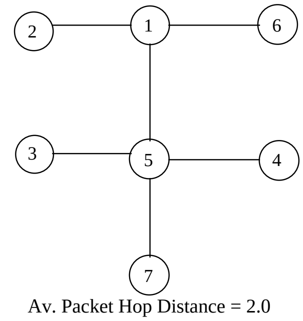

Fig. 2. Spanning tree logical topology for SN-II

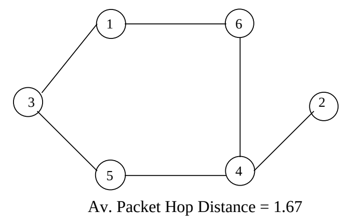

Fig. 3. Single Shortest Path logical topology for SN-I

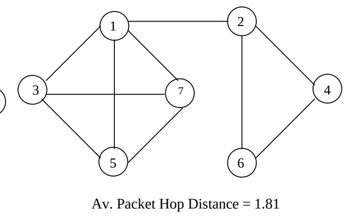

Fig. 4. Single Shortest Path logical topology for SN-II

We consider two sample networks SN-I (6 Nodes) and SN-II (7 Nodes) to represent the two scenarios presented in Theorem 1 and 2. We also show the spanning tree-based logical topology for these two networks. We assume that each optical node has 3 transreceivers in SN-I and 4 transreceivers for SN-II, and all node pairs have uniform demand volume among them. For both the sample networks, it is not possible to set up fully meshed virtual topology due to restriction on the number of transreceivers. Figure 1 and Figure 2 show the spanning tree based logical topology for SN-I and SN-II. Figure 3 and Figure 4 show the logical topology for SN-I and SN-II corresponding to two scenarios presented in Theorem 1 and 2, respectively. The logical topologies in Figure 3 and Figure 4 give a lower value on the average packet hop distance compared to spanning tree topologies.

Theorem 1 and 2 give only two scenarios when an undirected graph will have unique minimum-hop paths for all node pairs. There are other possible scenarios when the graph satisfies the unique shortest path condition. For example, it is possible to have unique minimum-hop paths for all node pairs in the presence of partially connected even cycles. At this point, we are not aware of any necessary condition that will ensure single minimum hop paths for all node pairs in an undirected graph.

Theorem 1 and 2 provide the impetus for the solution approach presented in the next section.

IV. Solution Approach

In this section, we present a two step solution approach for the virtual topology design problem stated in section II. In the first step, we solve a mixed integer linear problem formulation (see section IV-A). This formulation considers scenarios presented in Theorem 1 and 2 as constraints, and uses minimizing the average packet hop distance as the objective function. The formulation chooses either one of the two scenarios depending on the feasibility of constraints. In effect, this formulation leads to the single shortest path logical topology with hop-count as link metric. However, as pointed out in the previous section, the two scenarios do not give a necessary condition to ensure unique minimum-hop paths for all demand pairs. Therefore, the formulation does not necessarily gives the best logical topology in term of the objective function. We call the logical topology generated from the solution of this formulation as the *initial topology*. In the second step, our approach starts with the initial topology generated in the first step and uses a pruning approach (see section IV-B) to generate an improved logical topology. We refer to this solution approach as $\mathbf{SA1}$. The notation for this solution approach is described in Table I.

TABLE I
Notations used in Solution Approach

V	:	Set of nodes in the Network
$\mathcal{D}$	:	Set of origin-destination demand pairs in the network
$\mathcal{L}$	:	Set of candidate links (lightpaths) in the Network
h_d	:	Traffic demand volume for demand pair $d \in \mathcal{D}$
P_d	:	Set of candidate paths for $d \in \mathcal{D}$
$a_{\ell v}$	:	1 if link $\ell \in \mathcal{L}$ originates or terminates at node $v \in V$
δ^{ℓ}_{dj}	:	1 if path $j \in \mathcal{P}_d$ of demand $d \in \mathcal{D}$ uses link $\ell \in \mathcal{L}$, 0 otherwise
Δ	:	Number of transreceivers at each node
o_ℓ, t_ℓ	:	Originating and Terminating Node of Link $\ell \in \mathcal{L}$
$h(o_\ell, t_\ell)$	:	Traffic demand volume between originating and terminating nodes of link $\ell \in \mathcal{L}$
$NL(v)$	:	Number of lightpaths as node $v \in V$
U	:	Set of all subsets of V, such that each subset contains even number of nodes
$\mathcal{C}_s$	:	Set of subsets of $\mathcal{L}$, where each subset contains even number of links connecting nodes of $S \in U$; such that these links form an even cycle.
y_s	:	binary parameter to enforce one of the two constraints to meet unique shortest path requirements described in Theorem 1 and 2
Decision Variables:		
b_ℓ	:	1, if link $\ell \in \mathcal{L}$ is included in the logical topology and 0 otherwise
u_{dj}	:	1, if demand $d \in \mathcal{D}$ uses path $j \in \mathcal{P}_d$ and 0 otherwise

A. Formulation

We assume that V, $\mathcal{D}$, h_d and Δ are given. We consider all $N(N-1)/2$ undirected links in a N node network in the initial set of candidate links $\mathcal{L}$. With information about sets V and $\mathcal{L}$, we can find information about $a_{\ell v}$, U and $\mathcal{C}_S$. We generate set $\mathcal{P}_d$ for each demand pair using a k-shortest path algorithm. Binary parameter y_s is used to enforce one of the two constraints to meet unique shortest path requirements described in Theorem 1 and 2.

We now present our formulation which will be referred to as the $\mathbf{MTD}$ problem:

$$\bar{F} = \min_{\{u_{dj}, b_\ell\}} \frac{1}{\sum_{d\in\mathcal{D}} h_d} \sum_{\ell\in\mathcal{L}} \sum_{d\in\mathcal{D}} \sum_{j\in\mathcal{P}_d} \delta^{\ell}_{dj} u_{dj} h_d \quad (1)$$

subject to

$$\sum_{j\in\mathcal{P}_d} u_{dj} = 1, \quad d \in \mathcal{D} \quad (2a)$$

$$\sum_{j\in\mathcal{P}_d} \delta^{\ell}_{dj} u_{dj} \leq b_\ell, \quad d \in \mathcal{D}, \ \ell \in \mathcal{L} \quad (2b)$$

$$\sum_{\ell\in\mathcal{L}} a_{\ell v} b_\ell \leq \Delta, \quad v \in V \quad (2c)$$

$$\sum_{\ell\in\mathcal{L}(S)} b_\ell \geq |\frac{S(S-1)}{2}| \ (1 - y_S), \quad S \in U \quad (2d)$$

$$\sum_{\ell\in R} b_\ell \leq |S| - y_S, \quad R \in \mathcal{C}_S, \ S \in U \quad (2e)$$

$$u_{dj} \in \{0,1\}, \quad b_\ell \in \{0,1\}. \quad (2f)$$

Objective function (1) minimizes the average traffic-weighted hop distance. Since, we do not pose any constraint on the capacity of the logical link, the objective function ensures that the entire demand volume for each demand is allocated to the minimum-hop path. The first constraint is to ensure that only one path is used to carry each demand. The second constraint ensures that a particular link has a flow only if it is selected as a lightpath in the virtual topology. The third constraints says that the number of lightpaths originating (terminating) from (on) a node are less than the number of transreceivers available at that node. The last two constraints say that if an even cycle is present in the logical topology, it is fully connected, thereby ensuring the existence of unique minimum-hop paths among all demand pairs (Theorem 2). If the value of $y_S = 0$, constraint (2d) ensures that all nodes of set S are fully connected. On the other hand, if $y_S = 1$, constraint (2e) ensures that nodes of set S do not form an even cycle. For the purpose of this paper, we have not incorporated routing of lightpaths on the physical topology of the optical network. Thus, information about the physical topology is not required to be included in the formulation.

The solution of this formulation results in a virtual topology such that each source-destination pair has a unique shortest path. We denote the set containing the links of this virtual topology by E_1. Formally, we define $E_1 = \{\ell \in \mathcal{L} | b_\ell = 1\}$. The objective function value ($\bar{F}$) obtained after solving this formulation is maintained as f_{Best}; this is required for the second step of this approach.

B. Pruning Approach

The pruning approach starts with the initial topology generated by the $\mathbf{MTD}$ problem as the "starting" virtual topology. At every iteration, we select one of the link from this virtual topology and prune it. Then, we generate a new virtual topology which satisfies the unique shortest path constraint. The procedure for generating the new logical topology at every iteration is given in Algorithm 2 (referred to as $\mathbf{UT}()$). It may be noted that we need to ensure that the logical topology remains connected. Thus, we prune the selected link only if there is(are) an alternate path(s) to carry the demand between originating and terminating nodes of the link. At the end of each iteration, we store the best topology in terms of the average number of traffic-weighted hops. We formally present our entire algorithm in $\mathbf{Algorithm\ 1}$ (also referred to as $\mathbf{ILTD}$).

Observe that in Algorithm 2, we prune only those links which are part of even cycle(s), since we know from Theorem 1 that links which are not part of any even cycle will not be on any of the shortest paths for the demands with multiple shortest paths. In effect, by breaking the even cycle at every step, we reduce the number of shortest paths for all the demands that uses this link on at least one of the shortest paths in the current logical topology.

Algorithm 1 $Pruning\ Approach\ (ILTD)$

$E_2 = \{\ell \in \mathcal{L} | \ell \in E_1\}$ and $k = 1$
while $(k \leq |E_1|)$ **do**
  Define the set $E_3 = \mathcal{L} \setminus \{\ell \in \mathcal{L} | \ell \in E_1\}$
  Select $\ell \in E_1$, such that $h(o_\ell, t_\ell)$ is k^{th} largest demand volume
  if (Removing ℓ from E_1 does not make logical topology unconnected) **then**
    $E_1 = E_1 \setminus \{\ell\}$ and $NL(o_\ell) --$, $NL(t_\ell) --$
    $f_{Current} = UT(E_3)$
    if (If $f_{Current} \geq f_{Best}$) **then**
      $E_1 = E_2$ and $k \leftarrow k + 1$
    else
      $f_{Best} = f_{Current}$, $E_2 = E_1$ and $k = 1$
  else
    $k \leftarrow k + 1$

Algorithm 2 $Updating\ Logical\ Topology\ (UT(E_3))$

while $(\ell \in E_3)$ **do**
  Select the $\ell \in E_3$ such that $h(o_\ell, t_\ell)$ is maximum
  $E_3 = E_3 \setminus \{\ell\}$
  if $(NL(o_\ell) \leq \Delta - 1) and (NL(t_\ell) \leq \Delta - 1)$ **then**
    $E_1 = E_1 \cup \{\ell\}$ and $NL(o_\ell) ++$, $NL(t_\ell) ++$
while All the demands do not have unique shortest paths **do**
  if (Removing any $\ell \in E_1$ leads to unique shortest paths for all node pairs) **then**
    Select ℓ
  else
    Select the $\ell \in E_1$ such that maximum number of even cycles use ℓ
  $E_1 = E_1 \setminus \{\ell\}$ and $NL(o_\ell) --$, $NL(t_\ell) --$
$f_{Current} =$ Average Packet Hop distance
return $f_{Current}$

V. Solution for Moderate Size Networks

The solution approach presented in the previous section requires solving $\mathbf{MTD}$ in the first step. The $\mathbf{MTD}$ problem is NP-hard, and therefore computationally intractable even for moderate size networks. In this section, we provide a heuristic solution to generate virtual topology for moderate size networks. This approach generates a virtual topology in three steps as follows:

1) Construct a spanning tree as initial logical topology.

2) Starting with the initial logical topology, generate an updated logical topology without any even cycles.
3) Use the pruning approach discussed in Section IV-B to generate an improved logical topology.

We refer to this approach as $\mathbf{SA2}$. We describe below the first two steps; note that the third step is already described in Section IV-B.

A. Generating Spanning Tree

To generate a spanning tree, we initially consider that the current logical topology consists only of nodes and no links, and that each node is a separate tree. Next, we select the node pairs in the order of increasing demand volume between the node pair and place a link between them, if they are in different trees. We check the number of paths between the two nodes in the current logical topology to determine if they are in separate trees. If the nodes are in separate trees, the number of paths between these nodes will be zero. We continue the process until we check all $N(N-1)/2$ node pairs. We define set E_1 such that it contains all the links of the spanning tree generated in this step. We refer to this approach of generating spanning tree as $\mathbf{SPT}$.

B. Generating logical topology without Even Cycles

We use an iterative procedure to update the spanning tree based logical topology generated in the first step such that the updated logical topology has no even cycles. To check for even cycles, we examine the number of links in all the paths between any two nodes in the current logical topology. If all the paths between between any two nodes have even number of links (> 1), adding a link between these nodes will not create an even cycle. At every iteration, we prune one link from the current topology and add a new link such that it does not create even cycles. At the end of iteration, we store the best topology in terms of the average number of traffic-weighted hops. We know from Theorem 1, that such a topology has unique minimum hop path for all node pairs in the network. We use the virtual topology resulting from second step as the ”starting” virtual topology in the final step of the approach (which is already described in Section IV-B).

VI. Numerical Results

In this section, we evaluate the performance of the two solution approaches presented in Section IV and Section V. We have implemented Formulation $\mathbf{MTD}$ and pruning heuristic using C^{++} and CPLEX callable libraries.

A. Performance Measures

In our study, we consider the following performance measures to evaluate the solutions obtained from our approaches:

- Average Packet Hop Distance (HD): It captures the average number of hops taken by an IP packet from source to destination. A lower value of HD ensures minimal electronic processing at intermediate routers. For a fully connected logical topology, HD will be 1.0. On the other hand, a spanning tree based logical topology will lead to a high value of HD.
- Number of Lightpaths (NLP): It captures the number of lightpaths in a logical topology. For a fully connected logical topology, NLP will be equal to $N(N-1)/2$, while a spanning tree based logical topology will have NLP value equal to $N-1$ for a N node network. A higher value of NLP translates into more number of wavelengths on each fiber.

B. Small Topology Results

For the first set of studies, we consider 3 experimental networks of 5(EN-I), 6(EN-II) and 7(EN-III) nodes. We consider that demand volume between all node pairs is uniformly distributed between 50 and 150. We have generated a reasonably large set of possible paths $\mathcal{P}_d$ for each demand d. Figure 5 shows the logical topologies for the experimental networks, that we arrive at as a result of the first solution approach ($\mathbf{SA1}$). These topologies were generated under the constraint that each node has 3 transreceivers(Δ). The largest network we could solve using SA1 approach was a 7 node network.

Next, we present values of performance metrics for experimental networks in Tables II- IV for increasing number of available transreceivers at each node. We compare our results with results for a spanning tree based logical topology. The formulation presented in section IV-A for $\mathbf{MTD}$ problem can be modified to generate an optimal spanning tree by replacing the last two constraints with the following constraints [13]:

$$\sum_{\ell \in \mathcal{L}(S)} b_\ell \;\leq\; |S| - 1, \qquad S \subset V \tag{3a}$$

$$\sum_{\ell \in \mathcal{L}} b_\ell \;=\; |V|, \tag{3b}$$

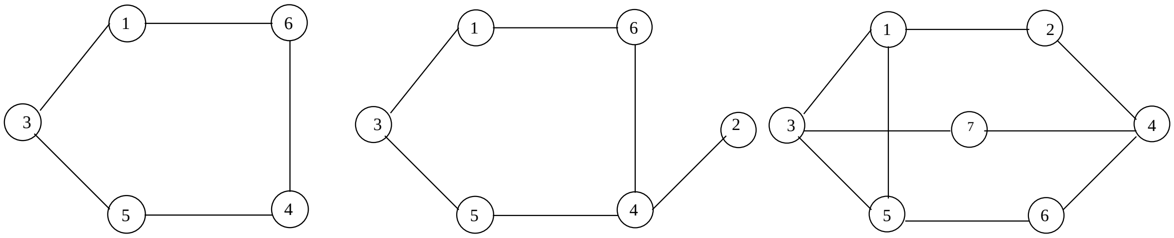

Fig. 5. Small Logical Topologies: EN-I, EN-II and EN-III

TABLE II
RESULTS FOR EN-I

	OST		SA1	
Δ	HD	NLP	HD	NLP
2	1.78	4	1.44	5
3	1.65	4	1.44	5
4	1.65	4	1.0	10

TABLE III
RESULTS FOR EN-II

	OST		SA1	
Δ	HD	NLP	HD	NLP
2	2.10	5	2.10	5
3	1.85	5	1.56	6
4	1.85	5	1.39	8
5	1.85	5	1.0	15

TABLE IV
RESULTS FOR EN-III

	OST		SA1	
Δ	HD	NLP	HD	NLP
2	2.46	6	1.93	7
3	2.11	6	1.51	9
4	2.10	6	1.50	9
5	2.10	6	1.40	12
6	2.10	6	1.0	21

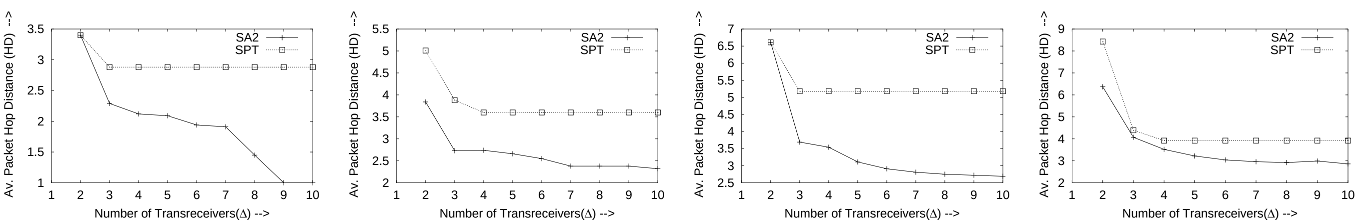

Fig. 6. HD value for Increasing Number of transreceivers for SA2 and SPT for RN-I, RN-II, RN-III and RN-IV

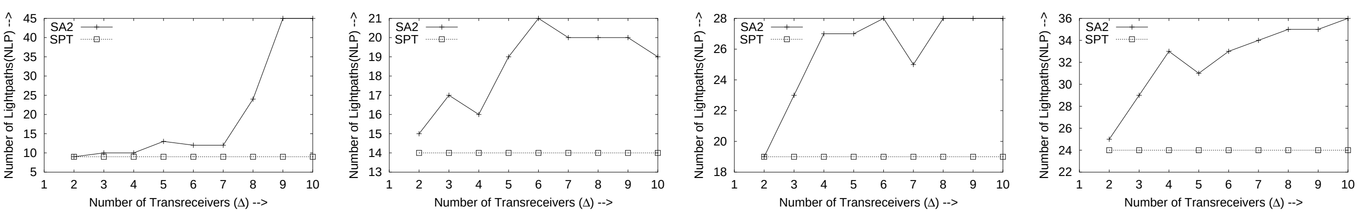

Fig. 7. NLP value for Increasing Number of Transreceivers for SA2 and SPT for RN-I, RN-II, RN-III and RN-IV

In an N-node network, constraint (3a) ensures that the logical topology is acyclic while constraint (3b) ensures that there will be exactly $N-1$ lightpaths. We denote this modified formulation as **OST**. For all the experimental networks, SA1 approach was successful in generating virtual topology with the HD significantly lower compared to spanning tree based logical topology. The improvement in HD comes at the cost of increase in NLP; however, the increase in NLP is not significant except for the last row in the Tables II- IV, which represents a fully meshed virtual topology.

To compare the two solution approaches SA1 and SA2 presented in this paper, we also solved the problem for experimental networks using SA2 approach. For EN-I and EN-II, we find the exact same results from both approaches. However, for EN-III, results from SA2 were inferior to that of SA1. This can be attributed to the fact that in SA1, the initial logical topology gives optimal solution satisfying one of the two conditions presented in Theorem 1 and 2, while in SA2 a spanning tree is used as the initial logical topology.

C. Results for Moderate Size Networks

Next, we evaluate the performance of **SA2** for moderate size networks. We consider 4 networks with number of nodes equal to 10 (RN-I), 15 (RN-II), 20 (RN-III) and 25 (RN-IV). We assume that traffic demand between each pair of nodes is uniformly distributed between 50 and 150. We compare our results with the results for spanning tree based logical topology generated at the first step (SPT) of SA2 approach. We present results for these networks in Figure 6 and 7.

In Figure 6, we present the value of HD metric for increasing number of transreceivers (Δ) at each node while in Figure 7, we present the value of NLP metric with increasing number of transreceivers (Δ). We run the experiment for the value of Δ from 2 to 10 in increments of 1. We observed a similar trend in the values of HD and NLP, as we observed for SA1. HD remains almost constant for increasing value of Δ for SPT, as after certain number of transreceivers, increasing the number of transreceivers does not change the spanning tree topology. On the other hand, HD decreases rapidly with increasing value of Δ for SA2. Similarly, NLP increases with increasing Δ for SA2. However, NLP is independent of the value of Δ in case of SPT, since a spanning tree must have exactly $N - 1$ links for an N node network irrespective of the number of transreceivers.

For some instances, NLP decreases with increase in Δ. This can be attributed to the fact that our solution approach does not take the number of lightpaths in consideration. Recall that we are interested in finding a solution that minimizes the average packet hop distance. With higher number of transreceivers, SA2 generates logical topologies such that more number of demand pairs with high traffic volume have direct paths between source and destination. In doing so, it is possible that the number of lightpaths originating and terminating on some nodes exhaust the number of transreceivers at these nodes, while some nodes are source and sink of very few lightpaths. Overall, this, in turn, can lead to fewer number of lightpaths but still giving lower value of HD.

VII. Conclusion and Future Work

In this work, we explore the problem of generating logical topologies for grooming IP traffic over wavelength-routed IP networks such that all source-destination pairs in the resulting logical topology have unique shortest paths. The objective of minimizing the average traffic-weighted hop-distance ensures that the solution requires minimum OEO conversion. We have also presented two conditions that ensure unique minimum-hop paths. We then proposed a two step solution approach to solve problems that work for small topologies and a heuristic approach for moderate size networks. Through numerical studies, we have observed that our solution approaches are successful in generating logical topologies which give acceptable value for various performance measures. As ongoing research work, we are currently investigating the impact of different link metric system on logical topology design problem.

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