

Optimal Light Trail Design in WDM Optical Networks

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Abstract

The enabling technology for supporting IP centric traffic over optical transport networks evolves as the amount of traffic grows. In this paper, we first review a recently proposed concept called *light trails*. Light trails can enable high speed provisioning, accommodate multi-granularity traffic, support high data rates and offer a good candidate for carrying IP traffic over optical networks. Next, we focus on light trail design. We propose a two-step approach for solving the light trail design problem. The first step is called *traffic matrix preprocessing*, it divides single long hop paths into several shorter paths that satisfy the hop-length constraint. In the second step, the light trail design problem is formulated as an *integer linear programming (ILP)* optimization problem. The results obtained from our experiments show that the resulting light trail network has high wavelength utilization.

I. INTRODUCTION

The rapid growth of IP traffic demand has led to a paradigm shift in the telecommunications industry from voice-optimized to IP-centric networks. It is widely believed that, in the near future, data communications will be based on optical transportation networks (OTNs).

Optical Internet based on wavelength division multiplexing (WDM) has emerged as a dominating trend for providing legacy and future IP services. WDM significantly increases the fiber capacity utilization by dividing the available bandwidth into non-overlapping wavelength channels that matches the peak electronic speed. Connections between users are supported by establishing an all-optical channel, namely *lightpath*, between two end nodes. Signals on lightpaths can be at different rates and use different formats as the signals are never terminated inside the core network. This bit-rate and protocol transparency is a key feature for any backbone network. One challenging problem for this wavelength switched optical network is the huge opto-electronic bandwidth mismatch. The bandwidth on a wavelength is 10 Gbps today and is likely to increase, while the sub-rate traffic connections can vary from STS-1 (51.84 Mbps) to the full wavelength capacity. A wavelength is still a scarce resource, but the majority of resource allocation in the wavelength routing approach is coarse. Once a lightpath is established, the entire wavelength is used

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exclusively by its source and destination node-pair (s-d pair), and no wavelength multiplexing between multiple nodes along the lightpath is allowed. Therefore, the wavelength capacity might be underutilized for IP bursts unless it is filled up by efficiently aggregated traffic.

An alternative to circuit switching is to use optical packet switching (OPS) [1], [2], [3] technology in the backbone. The major advantages of OPS is the flexible and efficient bandwidth usage, which enables the support of diverse services. Pure OPS technology in which packet header recognition and control are performed in all-optical domain is still many years away, and may not become reality. OPS with electronic header processing and control is more realistic for medium-term network scenarios. A practical OPS experiment has already been performed under the European ACT KEOPS (KEys to Optical Packet Switching) project[4]. In KEOPS, the header is sent with data (payload) but at lower bit rate, and the header processing is still in electrical domain. This potentially requires an optical buffering at the input port to allow the header processing circuits to finish the job. At present, the buffering technology is not mature and has to overcome a number of technological constraints, such as the large and varying size of optical buffering. Header processing at high speeds is also an important issue.

Optical burst switching (OBS) [5], [6], [7], [8] is another viable alternative switching technology to transport IP traffic directly over WDM networks. In wavelength switched network, once a lightpath is established, it will remain in place for a relatively long time, perhaps months or even years. In OBS, the goal is to set up a wavelength channel for each single burst to be transmitted. A burst has to be buffered while the control packet is being sent to set up switches and reserve bandwidth for establishing a connection. However since the number of control channels are limited in optical networks, the control channels can be a bottleneck for network performance. Moreover, guard bands are used in each burst to accommodate possible timing jitters along the path from source to destination in OBS. Due to the relatively low speed of optical switching elements, a significant guard time has to be wasted between control and data segments, which results in another significant overhead for OBS. Therefore, taking into account the large ratio between switching delay and IP burst duration, the network might be severely underutilized.

To accommodate sub-rate IP bursts on OTNs is however one of the key and still challenging problems in realizing the future optical Internet. Light trail [9] offers a strong candidate for supporting IP traffic over

optical networks. We study this architecture in more detail and show how it can be effectively used. This paper is devoted to the optimal design of light trails in WDM networks. The rest of the paper is organized as follows. Section II is a brief introduction to light trail concept, light trail node structure, and a summary of light trail properties. A formal statement of light trail design problem is given in Section III, followed by a two-step approach for solving this problem. The results obtained from our experiments are presented in Section IV. Section V presents our conclusions and discusses possible future work.

II. LIGHT TRAIL ARCHITECTURE

Current technologies that transport IP centric traffic in optical networks are often too expensive, due to their reliance on expensive optical and opto-electronic approach. Consumers generate diverse granularity traffic and service providers need technologies that are affordable and seamlessly upgradable. Recently, a concept called *light trail* was proposed to enable IP centric communications at the optical layer [9]. A light trail is a unidirectional *optical bus* between the start node and the end node. It is similar to a lightpath with one important difference that the intermediate nodes can also access this unidirectional trail. In light trails, the wavelength is shared in time and the medium access is arbitrated by control protocol that prevents collisions among the nodes that try to transmit data simultaneously [9], [10].

A. Illustration Example

Consider a 4-node light trail shown in Figure 1, which starts from node 1, passes through node 2, node 3 and ends at node 4. Each of the nodes 1, 2 and 3 are allowed to send data to any of their respective downstream nodes without the need for optical switch reconfiguration. Every node receives the data from the upstream nodes, but only the corresponding destination node(s) will accept the data packets while other nodes will ignore them. An out-of-band control signal carrying information pertaining to the set up, tear down and dimensioning of light trails is dropped and processed at each node in the light trail. Since a light trail is unidirectional, a light trail with N_T nodes offers up to $\binom{N_T}{2}$ optical connections along the trail.

The exclusion of fast switching at packet/burst level, combined with the flexible provisioning for diverse traffic granularity make the light trails superior to conventional circuit and burst switched architecture.

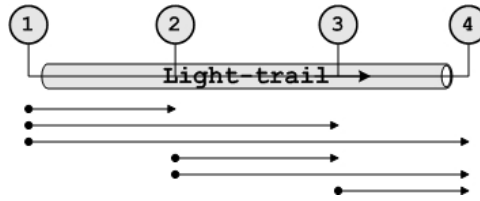


Fig. 1. Illustrative example of traffic streams in a light trail.

B. Node structure

Figure 2 provides a typical node structure in light trail framework [9]. In Figure 2, the multiple wavelengths from the input link are de-multiplexed and then sent to corresponding light trail switches. A portion of the signal power goes to the local receiver, the remaining signal power passes through an optical shutter which is typically an AOTF (Acousto-Optic Tunable Filter).

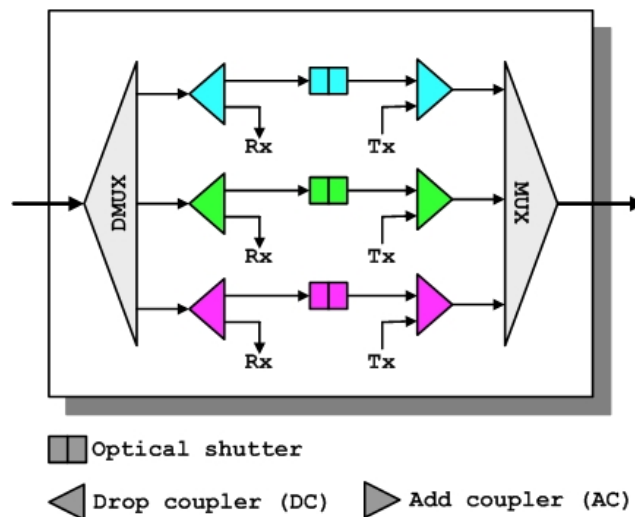


Fig. 2. An example node structure in light trail framework.

Figure 3 gives a connection of four light trail nodes and the corresponding ON/OFF switch configurations. The direction of communication is from node 1 to node 4. The optical shutter is set to *OFF* state at the start and end nodes of the light trail, such that the signal is blocked from travelling further. For an intermediate node along the light trail, the optical shutter is set to *ON* state to allow the signal to pass through the node.

We thereby obtain a unidirectional light trail from the start node to the end node. No switch reconfigu-

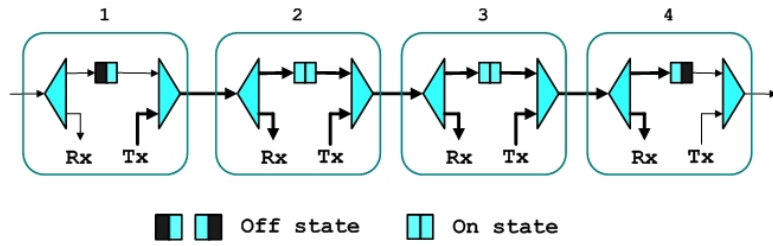


Fig. 3. An example node structure in light trail framework.

ration is required after the initial light trail setup. Due to the power loss within the light trail, which mainly comes from the power splitting at each node, the length of a light trail is limited and can be estimated in terms of hop-length. The expected length of a light trail is 5 hops [9].

C. Light Trail Characteristics

In contrast to OBS, we do not need to configure any switches when using light trails to carry IP bursts. This leads to an excellent provisioning time [9]. Moreover, the major advantage of using light trails for burst traffic, as compare to OBS, is the improved wavelength utilization. Utilization is defined as the ratio of capacity used over time for actual data transmission to the total reserved capacity. The study in [9] shows that the utilization in OBS is severely degraded comparing to that in light trails as the network load increases. More specifically, the utilization of light trails is an order of magnitude better than that in OBS under similar conditions.

Multicasting in optical layer is another salient feature of light trail architecture. Nodes in a light trail are able to send the same quanta of information to a set of downstream nodes without the need for a special processing or control arbitration.

In general, the light trail offers a technologically exclusive solution that enables a number of salient features and is practical. It exhibits a set of properties that distinguishes and differentiates from other platforms. The following three characteristic properties of light trails make possible this differentiation:

- Light trails are built using mature components that are configured in such a way that allows extremely fast provisioning of network resources. This allows for dynamic control for the fluctuating bandwidth requirements.
- Light trails offer a method to group a set of nodes at the physical layer to create optical multicasting -

a key feature for the success of many applications.

- The maturity of components leads to the implementation of light trails in a cost effective manner resulting in economically viable solutions for mass deployment.

III. LIGHT TRAIL DESIGN

To identify a set of light trails to carry the given traffic is one of the key issues in light trail WDM networks design phase. Moreover, the performance of light trail in terms of wavelength utilization also depends on the location of the light trails.

A. Problem statement

The goal of this section is to develop an effective method to groom traffic in light trail architecture and come up with a set of light trails. The light trail design problem is stated as follows: *Given graph $G(V, E)$, where $|V| = N$, and traffic matrix $T_{N \times N}$, how to define a minimum number of light trails to carry the given traffic.* Once the light trails are established, routing would be straightforward, hence we focus on light trail design in this paper.

B. A two-step approach

Our approach consists of two steps. The first step is called *traffic matrix preprocessing*. As stated earlier, due to the power losses on the lines, a long light trail may not be advisable. The length of a light trail is limited and can be estimated in terms of hop-length, denoted by BL . According to the study in [9] the expected hop-length of a light trail is 5. In this step, we recursively divide a single long hop traffic into multiple hops.

The second step is to solve an ILP optimization problem, with the given network topology and refined traffic matrix obtained from step one. The objective is to find a minimum number of light trails that are required for the system.

C. Step I: Traffic matrix preprocessing

In the preprocessing of the traffic matrix, a single long hop traffic is divided into multiple hops to satisfy the hop-length constraint. For a given a network physical topology $G(V, E)$, with N nodes and E links,

we apply Dijkstra's shortest path algorithm to find the shortest path between all s-d pairs. This forms a distance matrix $D_{N \times N} = \{d_{ij}\}$, where d_{ij} denotes the physical distance from node i to node j .

The length of a light trail is a main constraint due to the loss both at nodes and over the links. Let BL be the maximum length of a light trail. For traffic between s-d pair (i, j) , where $d_{ij} > BL$, it is not possible to accommodate this traffic on a direct light trail. Thus this traffic will need to go through multiple hops. Here one light trail is counted as one "hop". This necessitates the first step in our approach, namely *traffic matrix preprocessing*.

Let $T_{N \times N} = \{t_{ij}\}$ denote the estimated traffic matrix. Traffic matrix pre-processing will return a modified traffic matrix that satisfies: $T_{N \times N} = \{t_{ij} : d_{ij} \leq BL, \forall t_{ij} > 0\}$. Figure 4 provides the pseudo code for traffic matrix preprocessing algorithm.

<p>INPUT: Graph $G = (V, E)$ and a traffic matrix $T_{N \times N}$.</p> <p>OUTPUT: Rearranged traffic matrix $T_{N \times N}$ and the distance matrix $D_{N \times N}$.</p> <p>ALGORITHM: <i>Step 0:</i> Apply Dijkstra's shortest path algorithm, calculate distance matrix $D_{N \times N}$. <i>While</i> (find $(i, j) : t_{ij} > 0, d_{ij} > BL$) { 1. Pick an intermediate node k: $k = \arg \min_{v \in V} \{d_{vj} d_{iv} \leq BL\}$; 2. Update traffic matrix $T_{N \times N}$: (a) $t_{ik} \leftarrow t_{ik} + t_{ij}$; (b) $t_{kj} \leftarrow t_{kj} + t_{ij}$; (c) $t_{ij} \leftarrow 0$. } }</p>
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Fig. 4. L-bus establishment step 1: Traffic matrix preprocessing

In this step, the traffic on s-d pair (i, j) with $d_{ij} > BL$, will be reallocated on multiple hops. The goal is to find a node k such that path from node i to node k forms the first hop which is less than BL in distance. A next intermediate node k is found recursively for the source node. Among all possible intermediate nodes, k is chosen to be as close to the destination node as possible, as shown in step 1 in Figure 4. This is done in order to reduce the number of hops that the original traffic has to take.

After the preprocessing of the traffic matrix, each non-zero element in the modified traffic matrix would have corresponding distance less than BL , which is the maximum length allowed for a light trail.

D. Step II: ILP formulation

Given the network topology $G(V, E)$, and the traffic matrix obtained from *step I*, we first list all possible paths with the hop-length limit constraint for each s-d node pair, this can be accomplished by applying *breadth first search* for each node. These eligible paths form a set of all possible light trails. Among all these possible choices, we then chose an optimal set of paths to form the light trail network, such that the total number of light trails are minimized. This problem is formulated as an ILP optimization problem. We also assume that each request can not be divided into different parts and transferred separately.

E. Notations

E.1 Parameters

For the given directed graph $G(V, E)$, $N = |V|$, let LT be the set of all the possible light trails within hop-length limit BL , and $l = 1, 2, \dots, |LT|$ be the number assigned to each light trail in the LT .

Let C denote the full-wavelength capacity which is represented as an integer which is a multiple of smallest capacity requests. The smallest capacity request is denoted as 1. The integer entry in traffic matrix $T_{N \times N}$, represented by t_{ij} , denotes the requested capacity from node i to node j .

We assume the network is a single fiber network. In the absence of wavelength converters, the wavelength continuity constraints still need to be hold for light trail networks. Here, we do not impose constraints on the number of wavelengths available per link. Yet, as we will see later, the number of wavelengths required for establishing the light trails is not high.

E.2 Variables

- μ_{st}^l : binary variable, route indicator, takes value of 1 if request (s, t) takes light trail l ; zero otherwise. This also implies that node s and t are on trail l and s is t 's upstream node.
- δ^l : binary variable, light trail usage indicator, takes value of 1 if trail l is used by any request; zero otherwise.

E.3 ILP formulation

1. Objective:

$$\min \sum_l c^l \times \delta^l. \quad (1)$$

When $c^l = 1$, the objective is to minimize the number of light trails that are required in the network. When c^l is defined as the *hop-length* of light trail l , the problem becomes to minimize the total wavelength-links in the networks, which represent the total reserved capacity in the networks. This can be used to optimize the wavelength capacity utilization, while it might consume more light trails.

2. Assignment constraint: Each request is assigned to one and only one light trail.

$$\sum_l \mu_{st}^l = 1 \quad \forall (s, t) : t_{st} \in T, t_{st} > 0 \quad (2)$$

3. Light trail capacity constraint: The aggregated request capacity on a light trail should not exceed the full wavelength capacity.

$$\sum_{(s,t)} \mu_{st}^l t_{st} \leq C \quad (3)$$

4. Light trail usage constraint: If any of the s-d pair is assigned on light trail l , δ^l is set to 1; otherwise, if none of the s-d pairs picked light trail l , $\delta^l = 0$. Recall that δ^l is a binary variable.

$$\delta^l \geq \mu_{st}^l \quad \forall (s, t) : t_{st} \in T \quad (4)$$

$$\delta^l \in \{0, 1\} \quad (5)$$

F. Discussions

The light trail design is a challenging problem for the following reasons.

First, in order to use a wavelength fully, one would like to *groom* near full-wavelength capacity traffic onto the wavelength. This is similar to a normal traffic grooming problem, which is often formulated as a *knapsack problem* and it is known to be an NP-complete problem. However, we cannot simply set up a light trail for any set of traffic requests that add up to C . For example, given that $t_{12} + t_{13} + t_{16} = C$, it

might not be possible to establish the desired light trail due to the physical hop-length constraint. Hence, the light trail hop-length limit also adds to the complexity of the problem.

Second, the ILP formulation of the light trail design problem is similar to the *bin packing* problem which is an NP-hard problem. However, if we treat light trails as the "bins", and elements in the given traffic matrix as the "items" in bin packing problem, this problem differs from a normal bin packing problem due to a potential physical route constraint that an item cannot be put in any of the given bins, but only a sub-set of the bins. More specifically, an s-d pair can be assigned to the routes which satisfy: 1) node s and t belong to the route; 2) node s is the upstream node of node d along the route. Hence, the approximate algorithms for solving normal bin packing problems cannot be directly applied here for solving this light trail design problem.

IV. NUMERICAL RESULTS

This section presents numerical results of the above ILP formulations on physical topologies given in Figure 5. To simplify the problem, we assume each physical link is bidirectional with the same length.

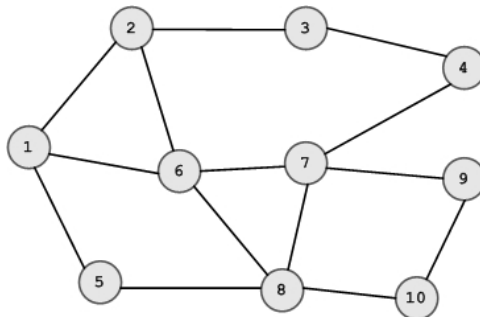


Fig. 5. A 10-node example network.

Table I provides a randomly generated traffic matrix for this illustration example. The integer numbers indicates the request capacity in unit of OC-1 (51.84 Mbps), while the entire wavelength capacity is OC-48. Here we only take fractional wavelength capacity into consideration for the study of grooming. Intuitively, if every s-d pair requires capacity greater than half of the full wavelength capacity, no two requests can be groomed on a light trail. In general, the reason light trail is employed is that most of the s-d pairs requires a small fractional capacity of the full wavelength. Hence, we randomly generate request between 0 and 11 as shown in Table I.

	1	2	3	4	5	6	7	8	9	10
1	0	5	11	10	4	5	4	6	6	10
2	8	0	5	5	1	3	1	11	7	2
3	3	0	0	3	0	2	9	4	10	9
4	8	2	11	0	11	6	11	6	9	4
5	11	7	7	6	0	11	3	2	9	9
6	8	9	7	5	4	0	11	8	10	9
7	9	7	11	9	1	10	0	4	11	2
8	6	0	10	4	2	4	4	0	2	9
9	2	9	10	2	6	9	9	8	0	9
10	11	0	10	0	8	10	8	11	4	0

TABLE I
TRAFFIC MATRIX FOR A 10-NODE NETWORK

A. *Light trail hop-length limit: $BL = 4$*

We use CPLEX Linear Optimizer 7.0 [11] to solve the ILP formulation proposed in III-D. Assume the hop-length limit $BL = 4$, from the topology we can observe that all s-d pairs have paths within this hop-length limit, hence, the *traffic matrix preprocessing* will not make any change of the given traffic matrix. (We experiment with step I in Section IV-B). Since we perform experiments mainly on small fractional wavelength requests, the number of wavelengths on each link is not a critical constraint. For this example, $W = 4$ is sufficient, although we do not put constraint on number of wavelengths. Table II presents the results from solving the ILP formulation with hop-length limit $BL = 4$.

TABLE II
ILP SOLUTION: RESULTING LIGHT TRAILS $BL = 4$

No.	L_B	Accommodated $s - d$ pairs	Load
1	{2, 3, 4, 7, 9}	(2,3) (2,4) (2,7) (2,9) (3,9) (4,9) (7,9)	48
2	{2, 6, 8, 10, 9}	(2,6) (2,8) (2,10) (6,10) (8,9) (10,9)	31
3	{3, 4, 7, 6, 1}	(3,6) (4,6) (6,1) (7,1) (7,6)	35
4	{3, 4, 7, 8, 10}	(3,4) (3,7) (3,8) (3,10) (4,7) (4,8) (4,10) (7,10)	48
5	{4, 3, 2, 1, 5}	(1,5) (2,1) (2,5) (3,1) (4,1) (4,2) (4,3) (4,5)	48
6	{5, 1, 2, 3, 4}	(1,2) (1,3) (1,4) (5,2) (5,3) (5,4)	46
7	{5, 1, 6, 7, 9}	(1,6) (1,7) (1,9) (5,6) (5,7) (5,9) (6,9)	48
8	{5, 1, 6, 8, 10}	(1,8) (1,10) (5,1) (5,8) (5,10) (8,10)	47
9	{9, 10, 8, 5, 1}	(8,1) (8,5) (9,1) (9,8) (9,10) (10,1) (10,5)	46
10	{9, 7, 4, 3, 2}	(7,2) (7,3) (7,4) (9,2) (9,3) (9,4)	48
11	{9, 7, 6, 8, 5}	(6,5) (6,8) (7,5) (7,8) (9,5) (9,6) (9,7)	41
12	{10, 8, 6, 2, 3}	(6,2) (6,3) (8,3) (10,3) (10,8)	47
13	{10, 8, 6, 7, 4}	(6,4) (6,7) (8,4) (8,6) (8,7) (10,6) (10,7)	46

Table II shows the 13 light trails that are needed to carry the given traffic. The traffic assignment obtained from solving ILP formulation is also listed. For each light trail, the summation of all the traffic requests on it calculated as shown in the right most column in Table II. It can be seen that most of the light trails are fully or almost fully occupied, hence, the resource utilization is quite high.

B. Light trail hop-length limit: $BL = 3$

We also performed experiments by changing the hop-length limits to $BL = 3$. In the network topology shown in Figure 5, the shortest paths between node 3 and node 10 have hop-length of 4. Therefore, the request between these two nodes cannot be accommodated on single light trails. The *traffic matrix preprocessing* heuristic re-arrange the original traffic $t_{3,10}$ onto $t_{3,8}$ and $t_{8,10}$. Similarly, the request from node 10 to node 3 is aggregated onto node-pair (10, 2) and (2, 3). The resulting traffic matrix is shown in Table III.

	1	2	3	4	5	6	7	8	9	10
1	0	5	11	10	4	5	4	6	6	10
2	8	0	15	5	1	3	1	11	7	2
3	3	0	0	3	0	2	9	13	10	0
4	8	2	11	0	11	6	11	6	9	4
5	11	7	7	6	0	11	3	2	9	9
6	8	9	7	5	4	0	11	8	10	9
7	9	7	11	9	1	10	0	4	11	2
8	6	0	10	4	2	4	4	0	2	18
9	2	9	10	2	6	9	9	8	0	9
10	11	10	0	0	8	10	8	11	4	0

TABLE III

TRAFFIC MATRIX FOR A 10-NODE NETWORK: AFTER TRAFFIC MATRIX PREPROCESSING

The second step is to solve the ILP formulation with this modified traffic matrix. The results show that a minimum of 25 light trails are required in the network. The detailed results are omitted due to space limit. The common thing between results in IV-A and IV-B is only the longest paths are chosen as light trails. This is due to the objective function that we designed is to minimize the number of light trails. The program stops search as the number of light trails cannot be further reduced, even though it is possible to substitute some light trails with shorter paths.

The total capacity required for establishing light trails obtained in Section IV-A (with $BL = 4$) is the total wavelength-link production of the light trails. Since all the 13 light trails have hop-length of 4, the total required capacity is $13 \times 4 \times C = 52C$, where C denotes the full wavelength capacity. Similarly, the total capacity reserved in light trails obtained in Section IV-B (with $BL = 3$) is $25 \times 3 \times C = 75C$. In this experiment, much more capacity is reserved in light trail network with smaller hop-length limit for carrying the same traffic matrix. The is also due to the objective function that minimizing only the number of light trails. To change the objective function to minimize the total *wavelength-links* would help to increase the

wavelength utilization, however, more light trails might be employed in this scenario. To make a trade-off between the number of light trails and the wavelength utilization and optimize the network-wide cost would be a practical engineering problem.

C. Possible LP relaxation

Since the ILP formulation proposed in Section III-D is similar to a *bin packing* problem, LP relaxation might not be a very effective means to solve this problem.

However, when the traffic matrix is uniform, or the variation among different requests are small enough that they can be approximately treated as uniform traffic, LP relaxation can be used for obtaining fast solutions. This can be achieved by modifying ILP formulation as follows, and the rest of the formulation proposed in Section III-D remains the same.

$$\sum_{(s,t)} \mu_{st}^l \leq \lfloor C/t \rfloor \quad (6)$$

where t_{st} is the uniform traffic request.

$$0 \leq \delta^l \leq 1 \quad (7)$$

$$0 \leq \mu_{st}^l \leq 1 \quad (8)$$

In this formulation, the coefficient matrix of the variables is totally unimodular, hence, the LP relaxation still yields integer solutions. This can be applied to solve light trail design problem where the traffic requests have similar capacities.

V. CONCLUSIONS

The concept of light trails has been proposed as a novel architecture designed for carrying finer granularity bursty IP traffic. The fast access of lightpath communication and the flexible dynamic sub-wavelength provisioning make light trail architecture a strong candidate for transporting IP traffic over optical networks.

Light trail design problem is one of the key issues to effectively implement the concept of light trails. We propose a two-step approach for designing minimum number of light trails required in the network. The first step is *traffic matrix preprocessing* - a heuristic algorithm which divides a single long hop into multiple short hops that satisfy the light trail hop-length constraint. The second step is to solve an ILP formulation to obtaining an optimal set of light trails for carrying the given traffic. Numerical results obtained by using our algorithms are presented, and it is shown that by employing the concept of light trails, the wavelength utilization can be significantly improved in the cases where most requests are of small fractional wavelength capacity. Another observation is that with the objective to minimize the total number of light trails, only the longest paths are selected to be light trails. This can be used to develop fast approximate algorithms for solving light trail design problem.

Although the results are obtained from given static traffic, they help to understand the complexity of the problem, and provides a lower bound for this minimization problem. We are working on effective approximation algorithms for optimal light trail design in WDM networks.

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