Light-Trail Networks: Design and Survivability

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Abstract— **The light-trail architecture provides a novel solution to address IP-centric issues at the optical layer. By incorporating drop and continue functionality, overlaid with a light-weight control protocol, light-trails enable efficient sharing of network resources, support subwavelength traffic and minimize network costs. In this work, we investigate[1] network design and survivability issues in such networks in the presence of multi-granularity subwavelength traffic subject to non-bifurcation constraints. We first establish the NP-Hardness of the light-trail routing problem by reduction from a Hamiltonian path problem. We propose three heuristics for light-trail network design and study their performance with limited network resources. We observe the effect of tunable and fixed transceiver equipments on network throughput. We observe that our heuristics yield excellent wavelength utilization under moderate to high loads even in the presence of heavily fractional traffic. We propose two additional heuristics for shared and dedicated protection and conclude that with only a modest amount of spare capacity, full protection can be achieved for all single link failures.**

I. INTRODUCTION

In WDM optical networks, the bandwidth request of a traffic stream can be much lower than the capacity of a wavelength. Circuit switched optical networks are provisioned for peak rate traffic due to lack of buffering capabilities and hence may be severely underutilized. Network utilization can be improved by equipping nodes with grooming capabilities that allow efficient packing of low rate streams onto high rate channels. However, grooming brings along with it concerns related to complexity, scalability, delay and transparency. Traffic engineering and statistical multiplexing gains are achievable in optical packet switched networks but high speed optical switches, scalable packet parsing mechanisms and fast and large random access units have not been realizable for large scale commercial deployment. Burst switching provides a hybrid approach between circuit switched and packet switched paradigms, but the requirement of low crossconnect reconfiguration times as compared with the burst duration leads to significant challenges in optical switch design. As a solution to providing high resource utilization and sub-wavelength support, we discuss light-trail technology [1]. The goal of light-trails is to eliminate active switching, and leverage statistical resource multiplexing using a simple hardware and overlaid control protocol. A light-trail is similar to lightpath in that, it requires the establishment of a unidirectional optical circuit between the source and destination. The key difference is that some intermediate nodes can also receive and transmit data on the same channel in a time multiplexed manner.

Figure 1 shows a four node uni-directional light-trail in a ring network, which is a variant of the system suggested in [1]. At every node, the signal passes through a light-trail access unit (LAU) that consists of a splitter, a shutter, a combiner and an amplifier that enables drop-and-continue functionality. A simple medium access control protocol (MAC), discussed in [1], coordinates communication among nodes in the trail. A signal sourced by a node traverses all nodes downstream to it on the trail. At the splitter, a part of the incoming signal power is tapped by the receiver for local processing and the rest of the optical signal is amplified and passed to the shutter. The shutter is a mirror-based optical attenuator that is configured to either block or let the wavelength pass through. If the current node is the last or the first node on the trail, the shutter is configured to block this wavelength. For all intermediate nodes on the trail, the shutter lets the signal pass through. If the signal is not blocked by the shutter, it traverses the combiner before exiting the node. The combiner enables the intermediate nodes to insert its signal on the trail based on the MAC protocol.

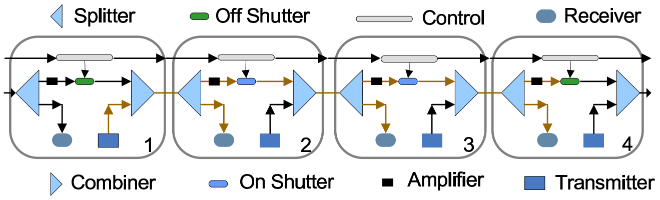

Fig. 1. Data transfer from node 1 to node 4 in a light-trail. The splitter, shutter, combiner, along with a semiconductor optical amplifier constitute the LAU. The arrows in lighter shade show packets transmitted by node 1 to nodes downstream.

The shutters are not reconfigured dynamically for every packet but is done on a longer time scale and this alleviates the requirement for high speed switching. Dynamic traffic is accommodated by setting up new trails, by expanding or contracting existing trails and tearing down unused trails in a distributed manner. An out of band control channel is used to actuate the shutter for dynamic reconfiguration of trails. The crossconnect architecture in a mesh network that allows signals to bypass LAUs of some intermediate nodes is shown in Figure 2 (a) and a sample light-trail network is shown in Figure 2 (b). Readers are referred to [4] for a detailed discussion on light-trail switch and node architecture. Consider a network topology as a directed graph G(V,E), with V as the vertex set and E as the edge set. Let a light-trail instance, which is just a

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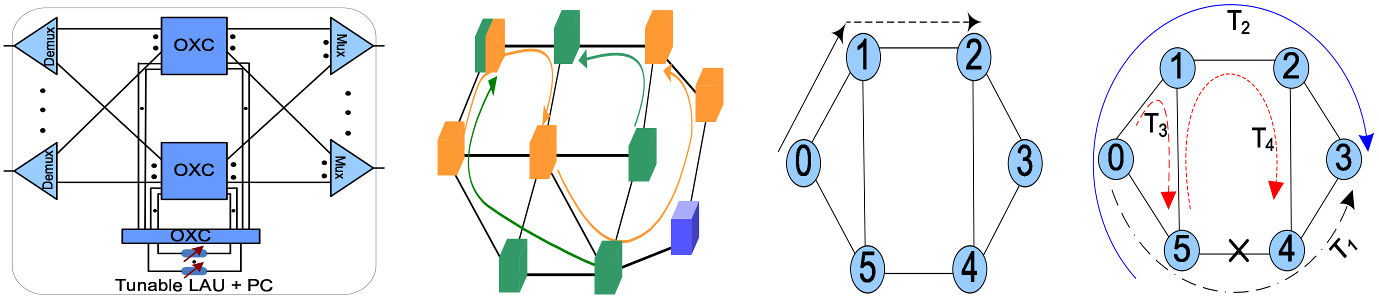

(a) (b) (c) (d)

Fig. 2. (a) Incoming signals are directed to the tunable LAUs with power compensation (PC), reinserted back into the OXC and switched out to the right output port. (b) A light-trail network. A node shaded the same color as the wavelength indicates that this node is active on the trail. A node with multiple shades is active on multiple trails and a node with different shade from the wavelength passing through it is inactive on the trail (c) and (d) Example network.

simple path in a graph, be defined by LT_t = $\{v_1,v_2,v_3\}$ such that v_1, v_2, v_3 $\in$ V and (v_1,v_2), (v_2,v_3) $\in$ E. Let R be the request matrix that denotes the value of the request between any node pair. A light-trail is a circuit that carries multiple requests subject to the following constraints:

Containment Constraint: A light-trail can support any connection (v_i,v_j) if v_i, $v_j \in LT_t$ and v_j is downstream of v_i in LT_t. That is, LT_t can possibly support connections given by the containment set LT_t^r = $\{(v_1,v_2), (v_1,v_3), (v_2,v_3), \}$

Capacity Constraint: The sum of request values supported by a light-trail is at most the capacity of a wavelength (C). If C = 5, R_{v_1,v_2} = 3, R_{v_1,v_3} = 3, R_{v_2,v_3} = 2, then LT_t can support one of the following: $\{(v_1,v_2), (v_2,v_3)\}$, $\{(v_1,v_3), (v_2,v_3)\}$, $\{(v_1,v_2)\}$, $\{(v_1,v_3)\}$, or $\{(v_2,v_3)\}$.

Non-bifurcation Constraint: A connection cannot be split across multiple trails. This aspect gains significance in light of the fact that traffic reassembly is complex, expensive and introduces undesirable jitter at the application layer.

The work in [1] proposes light-trails as a solution for handling IP-centric traffic. The crossconnect architecture and mesh network design problem are introduced in [4] but the transceiver resources were assumed to be unconstrained. A testbed implementation of light-trails is presented in [3]. Protection mechanisms in rings deploying light-trails were suggested in [8]. An ILP formulation for survivable routing was provided in [10] but wavelength assignment and multi-granularity traffic were not considered. The above mentioned studies do not quantify the transceiver and wavelength requirements of the more realistic multiple granularity traffic subject to non-bifurcation constraints. None of the work that we are aware of suggests heuristics for providing connection level shared and dedicated protection in the context of large scale light-trail optical networks.

The rest of the paper is organized as follows. Section II provides the motivation for studying the trail routing and wavelength assignment (TRAW) problem and section III presents a formal proof for NP-Hardness of the trail routing problem. Section IV proposes three heuristics for solving TRAW problem. In Section V, possible protection mechanisms are discussed and in section VI, an ILP formulation for the Survivable TRAW (STRAW) problem is presented. In Section VII, two protection heuristics are designed. Section VIII discusses simulation results and finally the paper is concluded with possible future directions in section IX.

II. TRAW MOTIVATION

Consider the network shown in Figure 2(c). Assume that there exists an OC-48 circuit $\{0,1\}$ carrying one OC-12 connection. Now, an additional OC-12 request, (0,2) needs to be accommodated. This can be done in one of three ways. In the first method, a separate lightpath $\{0,1,2\}$ is established to carry the new request in a non-grooming network. In the second method, wavelengths are divided into multiple time slots in a grooming network. Data destined for node 1 and node 2 are multiplexed in time and sent towards node 1. Node 1 demutliplexes the signal, retains the data destined for itself and switches out the rest towards node 2. A third solution employs light-trails. The existing trail $\{0,1\}$ is expanded to $\{0,1,2\}$ by configuring the shutters on node 1 and node 2. Since, the aggregate traffic involved is less than OC-48, the data destined for different destinations can be transmitted in a time multiplexed way. The first solution requires extra transceivers and wavelengths, the second solution requires the presence of grooming switches while the third solution requires LAU units and a MAC protocol.

Non-groomed lightpath networks can be very expensive in terms of transceiver and wavelength requirements in the presence of predominantly subwavelength traffic. Multi-hop electronic grooming (e-grooming) [5] decreases equipment requirements and reduces network costs. When grooming is performed, data needs to be buffered on the intermediate nodes and since processing delay is orders of magnitude higher than transmission delay, latency in such systems can be high. Another drawback with e-grooming is that the entire network has to have a unique upper layer. The bit rates, frame formats, encodings and protocols should be interoperable for the entire network and is hence not transparent. The electronic switch fabric has to operate at higher speeds than the line rate which leads to scalability concerns with increasing optical line rates.

The light-trail solution provides a transparent way of dealing with fractional traffic called o-grooming. By implementing a MAC protocol, it allows a wavelength to be shared by multiple nodes and thereby improves resource utilization and reduces equipment requirements. However, the cost reduction achievable in light-trail networks depend primarily on the routing algorithm used. The trail routing and wavelength assignment problem (TRAW) needs to be solved to identify light-trails required to carry the given traffic on a given physical topology with minimum cost. A tractable algorithm that achieves good resource multiplexing is required to carefully design networks with high bandwidth utilization. It is also important to study the wavelength and transceiver requirements for light-trail networks so as to assess the system capabilities and limitations and compare them with groomed lightpath networks.

The trail routing and wavelength assignment problem can be defined as follows: Given a network and a request matrix, route the trails and identify the minimum number of wavelengths required to carry all the traffic. The wavelength assignment problem was proved to be NP-Complete in [11]. In our current work, we prove that the light-trail routing problem is NP-Hard.

III. TRAIL ROUTING PROBLEM IS NP-HARD

The trail routing problem (TRP) can be defined as follows: Given a network $G'(V, E)$, a request matrix R(V×V), a cost function f : f(e) $\rightarrow c_e$ where $c_e \in \Re$, for every edge $e \in E$, and that the cost of a trail is the sum of the cost of its links, identify the minimum cost trails required to carry R. Define the decision version of the optimization problem as, given, $TRP_d = < G', R, f, k >$, identify if there is a trail assignment in G', to satisfy R, with a cost of at most k using cost function f. TRP_d is in NP since, for a certificate specifying the set of trails satisfying R, we can always check in polynomial time, if the total cost of the trails is at most k. We next prove that TRP_d is NP-Hard by using a reduction technique to show HAM-PATH $\leq_p$ TRP_d. HAM-PATH $\in$ NPC, and finds a hamiltonian path in a graph G, if it exists.

For a given undirected graph G, we construct a network G' as follows. For every vertex in G, introduce a node in G'. Let the number of nodes in G' be m. For every edge in G, introduce two directed edges in G'. Assign a cost function f, which maps every edge in G' to a unit value. Define R such that diagonal elements of R are 0 and the rest are 1. This ensures that every node has a unit traffic to be sent to every other node in the network. Assign the wavelength to have capacity m^2. This allows a single trail to have a capacity greater than the sum of all request sizes. To complete the proof, we show that this transformation is indeed a reduction: the graph G has a hamiltonian path if and only if G' has a trail assignment of cost at most $k = 2m - 2$.

Suppose that G has a hamiltonian path. We claim that a trail assignment of cost at most 2m-2 can be found. G' has some hamiltonian path $T_1 = \{N_1, N_2, .., N_m\}$, since it preserves all the nodes and links in G. Based on the reduction, $T_2 = \{N_m, N_{m-1}, .., N_1\}$ is also a valid hamiltonian path. Since, the capacity of each trail is m^2, T_1 and T_2 can serve all the requests in their respective containment sets. This satisfies all the requests in R and thus, exactly two trails are required. Since the cost of each trail is m-1, the total cost of the assignment is 2m-2.

Suppose that G does not have a hamiltonian path. It can be proved easily that G' also does not have a hamiltonian path. We claim that a trail assignment of cost 2m-2 or less can never be found. For this, we establish a lower bound on the cost of any trail assignment using Lemma 1 (given below) to be 2m-2. From proof of Lemma 2 (given below), in any solution, a node has to appear at least twice. Only in a solution involving hamiltonian paths, it can appear exactly twice. This implies that in a solution not involving hamiltonian paths, there exists at least one node that appears more than twice. The link associated with one of these extra occurrences will add a cost of at least one unit in addition to the cost of the hamiltonian path solution. Hence, the cost of a trail assignment in G' is at least (2m-2)+1 = 2m-1. This completes the reduction.

Lemma 1: The minimum cost trail assignment for a network with m nodes is 2m-2.

This can be proved by induction on the number of nodes of the network. For a two node, two link network, this lemma is easy to see. Assume that the lemma is true for an arbitrary network G'_k with k nodes and the minimum cost assignment is $2k-2$. Consider a network G'_{k+1} with k+1 nodes and suppose a minimum trail assignment S for G'_{k+1} costs less than 2k. We will see how this supposition can lead to a contradiction. Transform G'_{k+1} into a new graph G^o_k such that for some arbitrary $i \in G'_{k+1}$, if $(j, i), (k, i) \in G'_{k+1}, (j, k), (k, j) \in G^o_k$ and i is not present in G^o_k. However, the cost function and traffic are preserved for G^o_k. For G^o_k, based on the transformation, if each occurrence of i is removed from S to form S', the resulting S' is a valid solution and can satisfy all the requests of the k nodes in G^o_k. Since, node i occurred at least twice in S (from Lemma 2), by removing i, the cost of assignment S' is at least two less than the cost of assignment S. Since S costs less than 2k, S' costs less than $2k-2$ which is a contradiction to our assumption about the cost of k node networks. Hence, S costs at least $2k$. This completes the induction step.

Lemma 2: The minimum number of trails required to satisfy R is two.

Consider a trail T and a node $i \in T$. Since T is a unidirectional simple path, there exists no single position in T, where a node can receive from and send to all the other nodes in the network. Since the traffic matrix R has a unit traffic to be sent from node i to every other node and a unit traffic to be received from every other node, i has to appear on at least two different trails to satisfy all it's requests. Suppose, each node appears exactly twice in the solution. Since each node cannot occur more than once in a trail, exactly two trails are required and each trail is a hamiltonian path.

IV. TRAW HEURISTICS

Since TRP is NP-Hard, simple heuristics that yield fast and approximate solutions are required to design large scale optical networks. We propose three such heuristics and the general idea behind the heuristics is outlined below.

1. Select a set of candidate trails
2. Pack each candidate trail and assign it the required network resources
3. Choose the best candidate trail and place it in Γ
4. Update network status and repeat the above three steps until R is completely satisfied

The objective is to pack as many connections as possible onto a single trail to improve wavelength utilization. The output is the list Γ that contains the chosen trails and their assigned resources. The first step selects the set of candidate trails. The second step packs each candidate trail and assigns it the required resources. The three heuristics that we suggest primarily differ in their candidate selection criteria and in the wavelength assignment strategy. The packing mechanism is the same for all heuristics. Recall that each connection is at most the size of wavelength capacity and there could be arbitrary number of connections between a source and a destination. Given a trail t, the containment set LT_t^r is listed out first in a sorted manner. The sorting could be done either in the increasing order or in the decreasing order but we observe that increasing order yields better results on an average. Select all elements in LT_t^r sequentially until choosing one more element violates the capacity of a wavelength. The selected connections can be packed on to the trail and the packing fraction for this trail, which is defined as the ratio of the used capacity to the trail capacity (wavelength capacity) is calculated. The range of the trail, that refers to the number of connections carried by this trail, is computed. A wavelength on every link and a transceiver on every node of the route is assigned to this trail on a first fit basis except in the third heuristic which uses a layered approach as will be explained later. Each of the candidate trails are packed and assigned resources in a way independent of the other candidate trails.

The third step chooses the best of the candidates and adds it to the list Γ. Choice of the best candidate is made keeping in mind the limited availability of transceivers and wavelengths in the network. For every candidate trail, the highest index of the wavelength (I_w) and the transceiver (I_t) allocated in the route are determined. The higher the index for a network resource, the more heavily the resource is used (typically). The parameters taken into account for deciding the best candidates include I_w, I_t, range and packing fraction. Thus, every time, the trail that is likely to correspond to minimum congestion is chosen. Traffic matrix R and used network resources are updated in the fourth step. These resources and requests will not be considered any further while packing candidate trails in the next iteration. The above steps are repeated until each connection has been assigned to a trail.

For all the heuristics below, a list L is required as input. Flloyd Warshall's algorithm is run and shortest routes between all node pairs with nonzero requests are computed. The node pairs are listed in the decreasing order of their shortest route lengths in list L. The specifics of the three heuristics are detailed below.

1) Longest Shortest route first heuristic (LS): Let (s,d) be first element in list L. It has the longest shortest route of length δ. There could be multiple routes between (s,d) and each of these routes could be considered to be a candidate trail. However, for this work, we only consider all possible routes from s to d of length δ to be candidates. Longer routes typically have bigger containment sets and hence may be able to accommodate more requests. Hence, the longest shortest paths are considered first.

Each candidate is packed and a first fit resource allocation is done. The best candidate is chosen with favorable I_w, I_t, packing fraction and range, in that order. The traffic matrix, the network resources and the load of the link are updated. The load of a link (i,j) is defined as $L_{i,j} = \eta\ w_{i,j}$ where $w_{i,j}$ is the number of trails traversing link (i,j) currently and η is a parameter that can be tuned to achieve good performance. The candidate trails for next node pair in list L for the next iteration are identified by running shortest path algorithm considering current network load. By varying the load on the links dynamically for every iteration, congestion is minimized. The LS heuristic is a variant of the method proposed in [4] to include transceiver constraints, multi-granularity traffic and link load considerations.

2) Best Fit heuristic (BF): The candidate trails correspond to all routes in L. Each of these trails are packed and assigned the necessary network resources. While choosing the best candidate, preference is given to the candidate with favorable I_w, I_t, packing fraction and range, in that order. The traffic matrix, network resources and link loads are updated as specified in LS heuristic. The current list L is removed and the routes between all node pairs are recomputed based on the current load and stored again in list L for the next iteration.

3) Layered Graph heuristic (LG): In this heuristic, we view the WDM network as a multi layered network, one for each wavelength. We assume that each layer looks identical since resources are provisioned uniformly. There exists no wavelength conversion (no ladders) to hop from one layer to another. The first element (s,d) is considered and the candidate trails correspond to the routes between s and d on each layer. Packing of each trail is done as in previous two heuristics. Preference is given to I_t, packing fraction, and range, in that order. Once a trail is chosen on a particular wavelength, the links corresponding to that route are removed from that layer. The next node pair in L is considered for next iteration.

The candidate set for BF heuristic is relatively large and hence has higher time complexity when compared to the other two. The LG heuristic maintains a network for every wavelength and has relatively higher space complexity. The LS heuristic is the simplest both in terms of space and time and will be fast and efficient for large scale networks, though the results produced are not as good as the other heuristics.

V. STRAW MOTIVATION

Survivable network design has been a well researched topic in the area of lightpath networks [9]. Network survivability refers to the ability of the network to recover from node, link or equipment failures. Network resilience is vital considering the implications of failure on a WDM network of vast transport and switching capacities. The failure due to a fiber cut is not unusual and hence we study survivability mechanisms in the context of light-trail networks.

The original service route of a connection is called the primary trail. When a failure occurs on the primary trail, the connections on the trail get re-routed over backup trails. The survivability techniques can be broadly classified into two: protection and restoration. Protection refers to designing networks with spare capacities (wavelengths) so as to tolerate specific kinds of failure. For restoration, spare capacities are not provisioned in advance. In the event of a failure, an online mechanism is invoked that searches for spare capacities in the network through which the backup trail can be routed. Restoration is more efficient than protection in terms of resource utilization but is complex. Protection is better in terms of the ability to provide service guarantees.

Protection and restoration techniques can be further classified as link-based or connection-based in light-trail networks. In link-based protection, the connections are rerouted around the failed component. Nodes in the detour route let this trail bypass their LAUs. As observed in lightpaths [9], link-based protection is unattractive for trails as well, since the backup trails are be usually longer and the choice of backup trails is limited. Due to the absence of wavelength conversion, the wavelength continuity constraint should be adhered to which may lead to significant capacity overhead. Besides, handling node failures is not possible with the link-based approach.

In a connection-based approach, a backup trail is assigned to every primary connection. The backup capacity can be shared or dedicated. In the dedicated protection scheme (DP), data can be assumed to be sent on the primary and backup trails simultaneously. The destination uses the signal that has better quality. In the shared protection scheme (SP), the backup capacity is shared among multiple backup connections whose primaries do not fail together. As opposed to dedicated scheme, the backup capacities are reserved and used only in the case of a failure. DP requires more spare capacity than SP but is fast since the destination has to simply switch to the backup trail in the event of a failure. SP requires a complex protection switching mechanism that configures the crossconnects on the intermediate nodes to route the connection on the backup trail in the case of a failure.

If a link on a trail is cut, only connections traversing the cut gets affected. For instance, in a trail $\{0,1,2\}$ serving connections (0,1) and (0,2), only connection (0,2) is affected when link (1,2) fails. The protection mechanism could depend on the fault location or could be independent of it. In a failure dependent scenario, only the affected connections on a trail are rerouted and the backup route can use all the links except the one that failed. In a failure independent scenario, all the connections on the trail get rerouted and the rerouted connections cannot traverse any of the links traversed by the primary trail. While fault dependent failure is more resource effective, the fault independent failure is easier to design. All connections between a node pair traversing a single primary trail could be routed on multiple backup trails or be restricted to just one single backup trail. The signaling mechanism for the latter is simpler due to its course granularity but requires more spare capacity. The former mechanism is more fine granular, flexible and resource-efficient.

In our current work, we study dedicated and shared, connection-level, failure independent protection. We investigate the additional costs (in terms of wavelengths) required to design a network that can survive all single link failures as opposed to designing one with no protection. We explain a simple illustrative example to see why STRAW problem is hard. Consider a trail T_1 = $\{0, 5, 4, 3\}$ in the network shown in Figure 2(d) that serves requests $\{(0, 5), (5, 4), (0, 3), (5, 3)\}$. Each request is OC-12 and the capacity of a trail is OC-48. The backup trails corresponding to this would be $T_2 = \{5, 0, 1, 2, 3\}, T_3 = \{0, 1, 5\}$ and $T_4 = \{5, 1, 2, 4\}$. T_2 protects connections (5,3) and (0,3) while T_3 and T_4 protect connections (0,5) and (5,4) respectively. The number of wavelength links required without protection is 3 while the number of wavelength links required with protection is 9. While there is two-fold increase in the number of wavelengths required, the trails T_2, T_3 and T_4 are significantly underutilized. The objective is to find edge-disjoint trails for every connection and at the same time maintain significant utilization on all the trails which is a challenging problem.

Towards this end, we first formulate an ILP to solve the STRAW problem. Since the ILP is computationally intractable for large scale networks, we design efficient heuristics that yield approximate solutions. Our conclusion based on our simulation is that with modest amount of spare capacity, 100 % single link failure recovery can be achieved.

VI. ILP FORMULATION

We formulate an integer linear program to solve the maximize throughput problem for TRWA and the minimize cost problem for STRWA. Given a directed network topology G(V,E), where V is the node set, E is the link set and given the traffic matrix R, design the network to optimize one of the objectives (1) Max throughput TRWA: Given the number of wavelengths on each link (W) and the number of transceivers on each node (X), identify the routing and wavelength assignment so as to maximize network throughput.(b) Min cost STRWA: Identify the minimum network resources required to route and assign wavelengths for primary and backup route for every connection so as to survive all single link failures. We make the following assumptions. The topology G is 2-connected. All links are bi-directional. All nodes are equipped with tunabltransceiversrs and wideband receivers. Wavelength conversion capabilities are not present in the network. Individual connections between any node pair are sub-wavelength and is subject to non-bifurcation constraints. If multiple connections exist between a node pair, each one can be routed through a different path. We assume the presence of an out of band communication mechanism that allows all the nodes active in a trail to know about a failure that happens on any link traversed by this trail. Dedicated protection scheme is assumed and the protection mechanism is failure independent. We describe our notation, give a maximize throughput formulation for STRWA and modify it to solve the above two problems.

N - number of nodes in the network (data)
C - capacity of a wavelength (data)
W - number of wavelengths on each link of capacity C (data)
LT - set of possible light-trails in the network (data)
LT_t - an instance of a light-trail $LT_t \in LT$ (data)
LT_t^r - set of requests that can be supported by LT_t based only on the containment constraint (data)
$LT_t^{i,j}$ - 1 if trail LT_t traverses link (i, j), 0 otherwise (data)
t, t_1, t_2 =1..$\|LT\|$ - number assigned to each light-trail(index)
I_{t_1,t_2} - 1 if t_1 and t_2 share at least one link, 0 otherwise (data)

$\lambda = 1..W$ - number assigned to each wavelength (index)
$i, j = 1..N$ - nodes in the network (index)
α - a very large number (say, 1000) (data)
$\Phi_{i,j}^{k,y}$ - 1 if k^{th} OC-y from i to j is carried by the network, 0 otherwise (variable)
$P_{i,j,t}^{k,y}$ - 1 if k^{th} OC-y from i to j is carried by the network, 0 otherwise (variable)
$S_{i,j,t}^{k,y}$ - 1 if k^{th} OC-y from i to j is carried by the network, 0 otherwise (variable)
T_t^{λ} - 1 if wavelength λ is assigned to trail t, 0 otherwise (variable)
TX_t^i - 1 if node i on trail t needs a transmitter, 0 otherwise (variable)
RX_t^i - 1 if node i on trail t needs a receiver, 0 otherwise (variable)
U_{λ} - 1 if wavelength λ is used, 0 otherwise (variable)
N_{λ} - number of wavelengths used in the network (variable)
T_t - number of instance of trail LT_t (variable)
T_{max} - number of trails on the maxim loaded link (variable)

$$\textbf{Maximize} \sum_{i,j} \sum_{k,y} \Phi_{i,j}^{k,y} \tag{1}$$

Subject to constraints

$$\sum_{t}^{(i,j)\in LT_t^r} P_{i,j,t}^{k,y} = \Phi_{i,j}^{k,y} \quad \forall k, y, i, j \tag{2}$$

$$\sum_{t}^{(i,j)\in LT_t^r} S_{i,j,t}^{k,y} = \Phi_{i,j}^{k,y} \quad \forall k, y, i, j \tag{3}$$

$$\sum_{(i,j)\in LT_t^r} \sum_{k,y} y P_{i,j,t}^{k,y} + y S_{i,j,t}^{k,y} \quad \leq \quad T_t\ C \quad \forall t \tag{4}$$

$$(P_{i,j,t_1}^{k,y} + S_{i,j,t_2}^{k,y})(1 - I_{t_1,t_2}) \leq 1 \quad \forall k, y, i, j, t_1, t_2 \tag{5}$$

$$T_t \leq \sum_{(i,j)} \sum_{k,y} P_{i,j,t}^{k,y} + S_{i,j,t}^{k,y} \quad \forall t \tag{6}$$

$$\sum_{\lambda} T_t^{\lambda} = T_t \quad \forall t \tag{7}$$

$$\sum_{t} T_t^{\lambda} \leq 1 \quad \forall \lambda, \{t : LT_t^{p,q} = 1, \forall (p,q) \in E\} \tag{8}$$

$$TX_t^i \geq P_{i,j,t}^{k,y} + S_{i,j,t}^{k,y} \quad \forall k, y, t, i, \forall (i,j) \in LT_t^r \tag{9}$$

$$\sum_{t} TX_t^i \leq N_t \quad \forall i \in LT_t \tag{10}$$

$$RX_t^i \geq P_{i,j,t}^{k,y} + S_{i,j,t}^{k,y} \quad \forall k, y, t, i, \forall (j,i) \in LT_t^r \tag{11}$$

$$\sum_{t} RX_t^i \leq N_t \quad \forall i \in LT_t \tag{12}$$

$$U_{\lambda} \geq \sum_{t} T_t^{\lambda} / \alpha \quad \forall \lambda \tag{13}$$

$$N_{\lambda} \geq \lambda\ U_{\lambda} \quad \forall \lambda \tag{14}$$

$$P_{i,j,t}^{k,y},\ S_{i,j,t}^{k,y},\ \Phi_{i,j}^{k,y},\ T_t^{\lambda},\ TX_t^i,\ RX_t^i, U_{\lambda} \in (0,1)$$

$$\mathrm{N}_{\lambda}\ T_t \in I \tag{15}$$

Equation (1) maximizes the throughput. Equation (2) and (3) reserve a primary and backup trail for every connection that is accepted in the network. Equation (4) ensures that the sum of the capacities of all the primary and backup connections in a trail do not exceed the capacity of the trail. Equation (5) prevents the primary and secondary trail from sharing any link and equation (6) discards any trail that does not carry any request. Equation (7) allocates a wavelength for every trail and equation (8) prevents any two trails sharing the same edge from being assigned the same wavelength. Equations (9) and (11) count the number of transceiver equipments required on each node. A communication equipment is used on a trail only if a primary or a backup connection to or from the node is served by that trail. Equations (10) and (12) ensure that the number of communication equipments required do not exceed what is provisioned. While equation (13) keeps track of the wavelengths that are used, equation (14) identifies the wavelength of maximum index that has been already assigned.
(1) TRWA: If aloccurrenceses of $S_{i,j,t}^{k,y}$ are removed from the above formulation, and equations (3) and (5) are discarded, the resulting formulation models max throughput TRWA problem.
(2) STRWA: If we set $\Phi_{i,j}^{k,y} = 1 \quad \forall k, y, i, j$ as an additional constraint and change the objective function to $C_{\lambda} N_{\lambda} + C_t N_t$, where C_t and C_{λ} are the costs of the transceivers and a wavelength respectively, the above formulation models min cost STRWA problem.

VII. STRAW HEURISTICS

Heuristics for protection in large-scale lightpath networks was studied in [6], [7]. We propose two heuristics to solve the min cost problem in large-scale survivable light-trail networks. For our heuristics, we decouple the routing and wavelength assignment problems. Though this may lead to discrepancy between the approximate results and the optimal solution, our heuristic is simple and fast while an attempt to solve the combined problem becomes intractable for large networks. The output of our heuristic is a primary trail and a backup trail for every connection and the wavelengths assigned to them.

We first describe our routing and coloring heuristic which are common to both the protection schemes. For wavelength assignment, an auxiliary graph is obtained based on the results from the routing step. The rules for generating the auxiliary graph are different for dedicated and shared protection but the coloring heuristic used is the same. We describe the routing and coloring heuristic and the auxiliary graph generation rules.

A. Routing

We study connection-based failure independent protection and hence, for every connection, a primary route and a secondary route that is link disjoint with the primary route is identified. To find link disjoint routes, the heuristic method suggested in [6] is used. We define the term backup containment set for a trail. A backup connection $(v_i,\ v_j)$ is said to be in the backup containment set of trail t, if node v_j is downstream of node v_i on trail t and if the trail t is edge disjoint with the primary trail of this connection.

Candidate backup trail packing is done in the following way. We list all the connections in the backup containment set of the trail in increasing order of request sizes. We pack all the elements from the left until taking one more would defy the capacity constraints of the backup trail. Next, we assign a wavelength and transceivers to this trail on a first fit basis. We now explain the procedure for primary and backup routing.

We list the shortest routes between all node pairs with nonzero request in list P, which corresponds to the candidate primary trails listed in Step 1 of Table I. For every candidate primary route in P, we list the corresponding candidate edge disjoint secondary route in list S. By giving P as input to one of the heuristics in section IV, we assign a primary trail to every connection and place the primary trails in list Γ_p.

We pack all the candidate backup trails in S as explained above and choose the best backup trail and place in Γ_b. The best backup trail is the one with the highest packing fraction. Wavelength index and range are other metrics used to break possible ties. S is packed again and the next best candidate is selected. This step is repeated until each connection is assigned a backup trail. The backup trails are placed in list Γ_b.

B. Wavelength Assignment

After all primaries and secondaries are routed on the graph, each trail needs to be assigned a wavelength according to the wavelength assignment and continuity constraints. We construct an auxiliary graph, G', such that each light-trail in the system is represented by a node in G'. An undirected edge between two nodes is introduced in G' if the trails are required to have different colors. The nodes in the auxiliary graph are colored using the standard largest-first algorithm.

C. Auxiliary graph generation

1) Dedicated Trail Protection (DP): The auxiliary graph G' required for coloring is generated as follows. For every trail $t \in \Gamma_p$ and Γ_v, introduce a vertex in G'. An edge is introduced between two vertices if the corresponding two trails share at least one link in the network.

2) Shared Trail Protection (SP): The auxiliary graph G' is generated as follows. Consider two primary trails t_1 and $t_2 \in \Gamma_p$. Suppose primary trail t_1 carries connections c_1^1 through c_m^1. Let the backup trails corresponding to each connection be b_1^1 through b_m^1 with not all of them necessarily distinct. Let primary trail t_2 carry connections c_1^2 through c_n^2. Let their corresponding backup trails be b_1^2 through b_n^2 with not all of them necessarily distinct. For every trail obtained from the routing step, introduce a vertex in G'. Edges are introduced in graph G' based on the rules defined below.

1. t_1 is disjoint with b_1^1 through b_m^1, by definition. Hence, there is no edge between t_1 and any of b_1^1 through b_m^1. The same applies for t_2 and its backup trails.
2. If t_1 fails, all connections on t_1 are routed on its corresponding backup trails. Consider b_1^1 through b_m^1 pairwise. If the individual trails in a chosen pair are distinct and if they share a common link, introduce an edge between them. The same applies for the relation betwen t_2 and its backup trails.
3. If t_1 and t_2 are disjoint, there exists no edge between t_1 and t_2. An edge is not introduced between trails α and β, $\alpha \in \{b_1^1,..,b_m^1\}$, $\beta \in \{b_1^2,..,b_n^2\}$ in this step even if α and β share a link. This is because, t_1 and t_2 will not fail simultaneously and hence their backup trails will not be activated simultaneously.
4. If t_1 and t_2 overlap on a link, then introduce an edge between them. An edge is introduced between trails α and β, $\alpha \in \{b_1^1,..,b_m^1\}$, $\beta \in \{b_1^2,..,b_n^2\}$ if α and β share a link.
5. If t_1 overlaps with a backup trail of t_2, i.e, $\beta \in \{b_1^2,..,b_n^2\}$, introduce an edge between t_1 and β. Similarly if t_2 overlaps with a backup trail of t_1, introduce an edge between them.

VIII. SIMULATION RESULTS

We discuss results obtained from ILP for our max throughput and min cost formulation. CPLEX 8.1.0 was used to solve the integer program for the network shown in Figure 2(c). The capacity of a wavelength is OC-48. The requests between a node pair are of three granularities - OC-1, OC-3 and OC-12 and are uniformly distributed in the range (0,1), (0,1) and (2,3) respectively leading to a total offered traffic of 925 units.

In Figure 3(b), T refers to the number of tunable transceivers per node, W, the number of wavelengths per link, and R, the total offered traffic. We can see from Figure 3(b) that when $T = 2$, throughput increases with W but saturates beyond $W = 8$. This is because there are not enough transceivers to set up the connections that are blocked. When T is increased to 3, all connections are accepted when $W = 5$. Figure 3 (c) presents the minimum cost resource requirements for survivable network design under dedicated connection-based, failure-independent protection scheme. While the network with no protection needs $T = 3$ and $W = 5$ to accept all the traffic, the survivable network design requires $T = 11$ and $W = 8$, showing a significant increase in the redundancy requirement. When the offered traffic is reduced, the resource requirement is also reduced as expected.

Next, we present the TRAW and STRAW heuristic results for the 25 node test network shown in Figure 3(a). The capacity of a wavelength is OC-48. The connections between any node pair are OC-1, OC-3 and OC-12 and the number of such connections are uniformly distributed in the range (0,12), (0,4) and (0,2) respectively. Figure 4(a) plots throughput as a function of number of tunable transceivers per node for the BF, LS and LG heuristics when 15 wavelengths are provisioned per link. It is seen that a maximum of about 80 % throughput is obtained using any of the heuristics. This is because the number of wavelengths in the link are not sufficient to establish the blocked connections. Any increase in the number of transceivers does not help accept more connections. It is seen that BF heuristic curve raises much faster than the other two and saturates first. This suggests that the wavelength requirement for BF heuristic is high and the transceiver requirement is low. The performance of LS and LG heuristics are a little lower for lower values of T but saturates at a higher throughput value.

Figure 3(b) shows throughput as a function of number of wavelengths per link when 25 transceivers are provisioned per node. While BF heuristic can achieves close to 90 % throughput, the other heuristics saturate at about 78%. As observed earlier, the transceiver requirement for BF is low while for the others, it is high. So, when the system is transceiver limited, BF is able to outperform the other heuristics.

To achieve 100 % throughput for the current example when transceivers are not constrained, LS, BF and LG required 19, 22 and 17 wavelengths per link respectively. In general, the wavelength requirements of LG heuristic and transceiver requirements of BF heuristic were observed to be low for various scenarios. Since BF heuristic typically explores more set of candidate trails, it is able to achieve better reduction in the number of transceivers. LS is a layered approach that naturally considers routes other than shortest routes on the original network if the corresponding wavelength is not available on the shortest route. This allows the first fit wavelength allocation process to be more effective and helps conserve wavelengths.

In Figure 5(a), throughput is plotted as a function of number of wavelengths per link for the fixed transceiver and tunable transceiver case. Since tunable transceivers are expensive, the exact amount of savings generated by a tunable transceiver needs to be quantified to justify their higher deployment costs. We quantify this savings with all the heuristics, but, we show only the representative results using BF heuristics to prevent graph from getting cluttered. An array of fixed transceivers contains a transmitter and receiver on every wavelength and we use two such arrays per node. For the tunable case, we use 33 transceivers per node. On an average, about 216 connections can be sourced by a node and hence the transceiver requirement can be expected to be high. When 22 wavelengths per link are used, the number of transceivers in the fixed case is 44 but is still unable to achieve 100 % throughput, while using tunable transceivers, all the traffic are accepted.

Figure 5(b) plots the average utilization of a wavelength as a function of load for various heuristics. We define the load as follows. For a node pair, every connection is established corresponding to the above mentioned distribution with a probability p. We call p the load of the system and it indicates the amount of traffic in the network. When load is 0.1, the corresponding aggregate traffic is 1198 units and when load is 1, the aggregate network traffic is 14,571 OC-1 units in the example network. It is seen that BF heuristic has the lowest utilization and hence requires more wavelengths to accept all traffic. LG heuristic shows the best performance and about 90% of the wavelength is utilized at maximum load. Such high utilizations in the presence of heavily fractional traffic leads to significant wavelength savings.

Figure 6 shows the number of wavelengths required as a function of load (as defined above) for networks with and without protection. As expected, networks without protection require the least amount of resources. Shared protection outperforms dedicated protection significantly. When the aggregate traffic in the network is about 14,571 units, the maximum number of wavelengths required by BF heuristic is 22, while that for shared protection, it is 37. For dedicated protection, 51 wavelengths are required. A redundancy of about 100 % is required for shared protection and about 200 % is required for dedicated protection.

IX. CONCLUSIONS AND FUTURE WORK

This study is focused on network design and survivability in light-trail networks. We proved that the trail routing problem is NP-Hard and formulated an ILP for the TRAW and STRAW problems. We proposed three heuristics for design of networks with limited wavelength and transceiver resources. We observed that our heuristics lead to excellent wavelength utilization of upto 90 % even in the presence of heavily fractional traffic subject to non-bifurcation constraints. We quantified the savings achieved using tunable transceivers as compared with fixed transceivers. We discussed possible protection mechanisms in light-trail networks, reasoned why STRAW is a hard problem and designed heuristics for dedicated and shared protection. We found that, with dedicated protection, about 200 % redundancy may be required. Shared protection performs much better and full protection can be achieved in the presence of single link failures with less than 100 % redundancy.

Our current survivability work considers trails that carry primary connections alone or secondary connections alone. Our ILP results suggest that some optimal solutions involve trails that multiplex both primary and secondary connections. For instance, assume a trail t of capacity 48 units packed with 36 units of primary traffic. The 12 units spare capacity can carry a backup connection c of size 12 units if c is in the backup containment set of t. This spare capacity can also be shared. If two backup connections of size 12 units each conform to the backup containment set of t, then both could share the 12 units spare capacity on t, if their corresponding primaries will not fail together. We intend to pursue this research further. Our work considers static problem while the dynamic scenario would be interesting to solve. Our next step would be to compare light-trails with lightpaths, and quantify the trade-offs involved.

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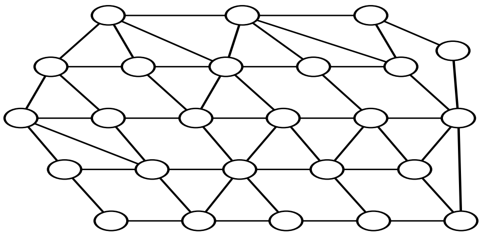


(a)

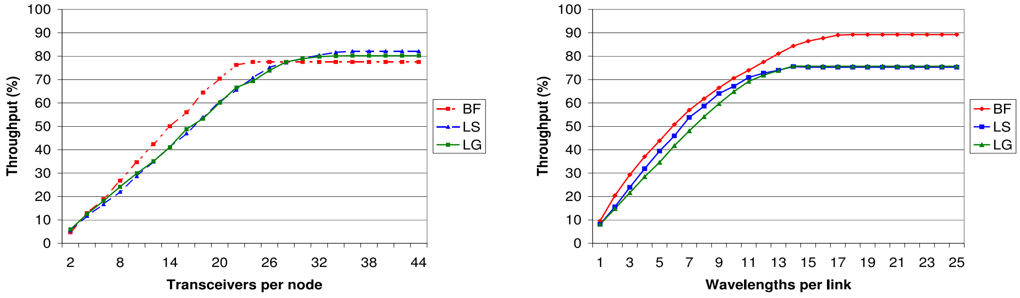
T	W	$Throughput(\%)$
2	6	81.41
2	7	82.38
2	8	83.14
2	12	83.14
3	4	92.21
3	5	100

(b)

R	W	T
194	4	5
406	6	6
751	8	7
925	8	11

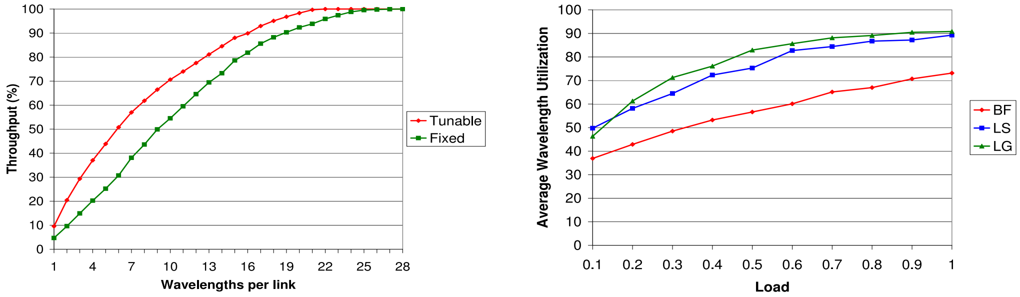
(c)

Fig. 3. (a) 25 node network for simulation study (b) ILP results for max throughput TRAW formulation on the six node network shown in Figure 2(c) with aggregate traffic of 925 OC-1 units (c) ILP results for min cost STRAW formulation on the same six node network.



(a) (b)

Fig. 4. (a) Throughput as a function of number of transceivers per node for 15 wavelengths per link. (b) Throughput as a function of number of wavelengths per link for 25 tunable transceivers per node



(a) (b)

Fig. 5. (a) Throughput as a function of number of wavelengths per link for tunable (35 per node) and fixed transceivers (2 arrays per wavelength per node) using BF heuristic. (b) Average wavelength utilization due to o-grooming as a function of load.

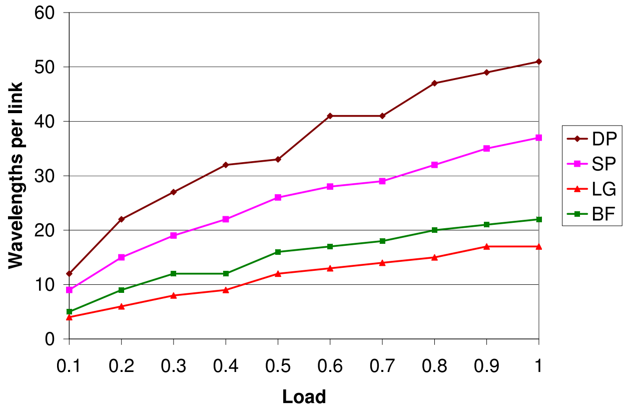


Fig. 6. Wavelength requirement comparison among networks with no protection, dedicated protection and shared protection for a maximum aggregate traffic of 14,571 OC-1 units.

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