ABSTRACT

Fault tolerance or survivability is an issue of primary importance in the design of the wide area optical backbones of tomorrow. With the current mismatch of bandwidth available from individual wavelength channels and typical bandwidth demands, it is also widely recognized that grooming of subwavelength traffic into the full-wavelength channels is an indispensable component of optical network design. The topic of survivability in optical networks that carry subwavelength traffic has recently started receiving attention. We consider the common basis on which grooming effectiveness and protection efficiency can be considered, and develop a design approach in keeping with this consideration. We formulate the joint problem of protection and grooming, and offer a heuristic algorithm to solve this problem. In offering numerical simulation results for our algorithms, we make the important observation that a disjoint sequential consideration of the two problems leads to solutions that are inefficient in the joint sense, a deficiency that our heuristic algorithm can correct.

1. INTRODUCTION

Recent advances such as Wavelength Division Multiplexing (WDM) and Wavelength Routing make optical networking the technology of choice for tomorrow’s backbone networks. In such networks, lightpaths are formed by optical switching, on which traffic is carried by electronic routing. Survivability or the ability to continue to fulfill QoS guarantees under partial failure of network equipment is of paramount importance in backbone networks [1], [2]. At the same time, the design of strategies to carry subwavelength traffic components to minimize Opto-Electro-Optic (OEO) equipment required at intermediate nodes has become an important research area known as traffic grooming in the last few years [3].

Early work in the area of joint survivability and grooming has started [4]–[8], but as yet a clear consensus has not emerged as to what the grooming problem should be understood to be when survivability concerns exist in the network. One approach to treating protection design for networks carrying subwavelength traffic is to view the problem as a traditional protection problem, considering the grooming aspect to be limited to a tool for multiplexing multiple subwavelength protection traffic together onto the wavelength in order to minimize amount of protection capacity. In that case, the performance of the proposed design is measured in the reduction of spare resources required for a given blocking probability or restoration ratio (or the reduction of blocking probability for a given amount of spare resources). However, as recognized in traffic grooming literature, minimizing the network cost in terms of OEO processing capability required may be more important in networks which carry subwavelength traffic than, say, minimizing the number of wavelengths used.

Our Contribution: We consider a network design problem with static traffic matrix and required protection. In integrating the grooming and protection concerns, we focus on the fact that at a conceptual level, the objective of protection design and the grooming design is similar in the sense that both try to minimize the total network cost. If grooming and protection design were to be separated, then the natural approach to network design would be to first reserve some fraction of the network resources systematically for protection, then design the best grooming solution (with the usual grooming objective of cost minimization) on the rest, finally to design the best protection scheme with the reserved resources for the working paths, considering only full wavelength scenarios. The value of our research lies in the following: we show that from this base case, we can increase the resource utilization by leveraging our knowledge of the subwavelength nature of the traffic, thus satisfying both grooming and protection design concerns.

2. PROBLEM DEFINITION

In a network with subwavelength traffic, DXCs are deployed along with OXCs to enable grooming by extracting and electronically switching individual lower-speed streams aggregated inside lightpaths. An instance of the traffic grooming problem is given by a physical topology graph \( G = (V, E) \), a traffic matrix \( T = [t_{sd}] \), the of wavelengths limit \( W \) on each fiber link, and the bandwidth \( C \) of each wavelength channel. \( C \) and \( t_{sd} \) are expressed as integer multiples of some base rate. Conceptually, a feasible solution to the grooming problem is composed of the following components: (i) The virtual topology to be implemented, with Routing and Wavelength Assignment (RWA) for each lightpath in the virtual topology, together referred to as \( T \), and (ii) Routing \( G \) of traffic components \( t_{sd} \) on the lightpaths. The OEO grooming cost is measured either in amount of actual traffic OEO routed, or the number of DXC ports required; and either by totaling over all network nodes, or the maximum among the nodes. Details of these cost functions can be found in [3], [9]. When 100% protection is required in the design, the solution \( (T, G) \) must also specify one or more protection routing for every subwavelength traffic component. The topology of the network after removing the failed components is called the survivor physical topology, or simply the survivor topology. Thus under the failure of the single directed link pair \( l_f \), the survivor topology is the graph \( G' = (V, E\setminus l_f) \). Under each failure
The algorithm may be seen to operate in three phases: Figures 1 and 6 present the algorithm. At a very high level, call the Selective Subwavelength Protection Heuristic (SSPH).

There are some choices the protection designer is faced with that are especially relevant in this special context.

**Granularity of protection:** Whether the protected entity is the physical fiber link, the lightpath (i.e. virtual link), or the subwavelength traffic component. In general, finer granularity leads to better protection, but higher computational cost, and more complicated Operation and Management (OAM).

**Failure-dependence:** Whether backup routes are specified separately for each possible failure that causes this route to fail, or whether a single backup is specified that is applicable to all failures that affect the route. Again, the tradeoff is between efficiency and simplicity.

The important goals for the design are:

**Minimize subwavelength computation:** Since there are many more subwavelength components than lightpaths, protection design at subwavelength level can cause a large increase in computational requirement over full-wavelength protection; this must be avoided.

**Avoid disruption to unaffected traffic:** Since individual subwavelength traffic components in general traverse multiple lightpaths, and individual lightpaths in general traverse multiple fiber links, propagating the failure could cause a large amount of rearrangement if not guarded against.

**Provide tunability:** Allow the network provider to decide what fraction of available resources should be used for protection design.

3. **Heuristic Approach**

With these considerations in mind, we present the following heuristic approach for the entire design problem, which we call the Selective Subwavelength Protection Heuristic (SSPH). Figures 1 and 6 present the algorithm. At a very high level, the algorithm may be seen to operate in three phases:

1. Obtain a working traffic solution \((T, G)\) with a given number of working wavelengths.
2. Obtain a full-wavelength protection solution with 100% restoration guarantee for the lightpaths of \(T\). This solution is failure-independent, but includes only routing for the backup lightpaths, and not wavelength assignment.
3. The third phase is the bulk of the algorithm. Attempt to color the lightpaths in a failure-dependent manner; i.e. for each failure scenario, attempt to find a valid wavelength assignment for the backup lightpaths that must be created under this failure. Terminate such lightpaths electronically at intermediate node(s) if this is necessary to find valid coloring. This step can increase the OEO cost of the protection solution. For each failure, find the traffic components that have suffered increase in OEO, and attempt to find alternate end-to-end subwavelength protection routes for them.

This high level view of SSPH is shown in Figure 1. Circles indicate algorithms and boxes indicate data. Bold and normal lines indicate failure-independent and failure-dependent processing respectively. The physical topology and required grooming parameters are input to the algorithm, as well as \(w_p\), the number of wavelengths on each fiber link that are to be reserved for protection purposes. The subwavelength rerouting operation is not necessarily carried out for each failure scenario: in Figure 1 we show it as being unnecessary for failure scenario #2, because the full-wavelength protection scheme for this failure does not increase the electronic switching cost above that of the working solution. In this case the full wavelength solution after the failure-dependent wavelength assignment is also the final solution.

Rather than repeating effort in well-investigated areas, we have adapted existing heuristics with good performance for (i) working traffic grooming and (ii) full-wavelength protection. The traffic grooming algorithm used in Phase 1 above was modeled after the Maximize Single-hop Traffic (MST) algorithm from [10]. A modified version of Dijkstra’s algorithm designed to maximize single-hop transport for traffic components was used to route the lightpaths. An innovation we used was as follows: while no more than \(W - w_p\) wavelengths are allowed to be used on any fiber link by the working traffic solution, we allow any of the \(W\) colors to be used in assigning wavelengths to the working lightpaths. On the virtual topology so obtained, traffic components were routed using shortest logical (lightpath) hops routing. In Phase 2, a simple heuristic following [11] was used. Weight assignment is not performed at this stage. Each fiber is guaranteed to have \(w_p\) free wavelengths by the definition of Phase 1, there may be additional free wavelengths on some fibers that were not used by Phase 1.

Phase 3 is the subwavelength tuning phase. The details of the algorithm in this phase are presented in Figure 6 as pseudocode. For lack of space we cannot describe it fully. Broadly, it has two parts. First, coloring the protection lightpaths that a particular failure generates (lines 5-13 of Figure 6), terminating and re-originating them at intermediate nodes if necessary (lines 15-24). Second, the subwavelength rerouting of traffic components which flow over lightpaths that have been “broken” in the above step (lines 25-31). This second part embodies our desire to limit grooming cost even for protection traffic; however, by our choice of traffic components, we seek to limit it \(only\) to the extent that the working solution \(achieved\), not beyond.

There are several points of interest in the SSPH algorithm as presented above, all of which derive from the integrated design aspects of the algorithm.

1. We know by experience that wavelength assignment is the more constraining part of RWA. Allowing the working path design to use all \(W\) colors, as well as deferring wavelength
increased computation required due to the failure-dependent fraction of the subwavelength components only for a rerouting. The extra computation is performed as possible, which is much faster and less disruptive than approach may be offset by this selectivity. Figure 2 provides an illustration of this; traffic components for which OEO does not rearrange, less obviously, SSPH attempts to minimize which tends to offset the local characteristic of the shortest path design somewhat.

3. The success of Phase 3 is due to two reasons. In any grooming solution, typically the lightpaths often carry less than the capacity of the full wavelength. This subwavelength slack can be found and utilized by lines 27-31 of Figure 6. Secondly, the reserved bandwidth for protection is made available by the formation of the protection lightpaths, possibly broken (lines 5-24).

4. Obviously, traffic that was not utilizing the failed link is not rearranged. Less obviously, SSPH attempts to minimize disruption for the rest of the traffic as well. Even though all traffic that was flowing over the failed link must be rearranged, this rearrangement is restricted to OXC reconfiguration as far as possible, which is much faster and less disruptive than reconfiguration of DXCs.

5. SSPH minimizes extra computation for subwavelength rerouting. The extra computation is performed only for a fraction of the subwavelength components. Note that even the increased computation required due to the failure-dependent approach may be offset by this selectivity. Figure 2 provides an illustration of this; traffic components for which OEO does not change also did not incur subwavelength computation.

In summary, SSPH is a simple but powerful protection design heuristic which combines the best of both worlds in more than one sense: it combines full-wavelength and subwavelength protection, incurring the additional computation cost for subwavelength protection only when needed; it combines failure-independent and failure-dependent approaches; and it reflects both the traffic grooming and the protection objectives in terms of resource utilization.

4. NUMERICAL RESULTS

In investigating the performance of our approach by numerical simulations, we used two physical topologies, the 24-node NSFNet and a 16 node mesh torus. Each arc consists of a directed link pair. Traffic matrices were generated by randomly setting each \( E^{(ad)} \) using the uniform distribution between 0 and \( C \). This created light load traffic patterns (around 40%). Traffic matrices of higher average link load (around 80%) were generated by scaling up the light load traffic patterns. It was verified that the resultant traffic patterns remained topology-unspecific by analyzing with Arena 5.0. For the NSFNet topology, the number of working wavelengths were 20, and the number of protection wavelengths varied from 10 to 15. For the torus, 6 working wavelength and 3 to 6 protection wavelengths were used. The value of \( C \) was fixed at 48 for all the experiments.

We investigated the behavior of the algorithm for various grooming metrics relating to OEO. In particular, we studied increases in both the amount of electronic processing (EP), and the number of lightpaths originating or terminating at a node (degree), under restoration scenarios. We studied these quantities both as totals over the network and at the node where the maximum occurred; and both as averages over failure scenarios and for the failure for which the maximum such increase occurred. It is clear that all these quantities are of importance from the point of practical network design. The total OEO performed over the network is a measure of the total cost of the network; on the other hand, the maximum increase of OEO cost at a node determines the cost of overprovisioning the DXCs at each node, when each node must be deployed with the same equipment. We present a small relevant subset of the results we have obtained.

In Figures 2 and 3, we present some detailed view of the results. Figure 2 shows the total EP in the network and Figure 3 shows the total number of new lightpaths that have
5. CONCLUSION

We have proposed an algorithm for protecting subwave-length traffic without sacrificing the performance of the grooming of subwavelength traffic. The computational cost of this algorithm is quite modest and numerical results show that it has good performance. There are various ways in which our approach could be extended, and we expect this area to generate more original contribution in the near future.

REFERENCES


SSPH Algorithm - Failure-dependent Part

Input: The inputs of the overall problem instance. In addition, a single directed fiber link pair $l_f$ whose failure is being considered, the working solution $(T, G)$, the protection routing for each lightpath which traversed $l_f$ in $T$.

Output: The set $L$ of protection lightpaths that must actually be established under this failure, together with RWA for each such lightpath, new mapping $G'$ of the traffic components of the traffic matrix $T$ over the union of the survivor virtual topology and $L$.

1. begin
2. Initialize the set $L$ to an empty set.
3. Initialize the set $G'$ to the set of all traffic components that did not traverse either of the links $l_f$, together with their routing in $G$.
4. Form the set $L$ of lightpaths that traversed one of the links $l_f$, according to $T$, with their protection routing. Sort the lightpaths in $L$ in decreasing order of traffic carried by them, according to $G$. Break ties arbitrarily.
5. repeat
6. Pick the first lightpath $l$ in $L$.
7. Form the set of colors that are free over all links of the protection route of $l$.
8. if the set is not empty,
9. Color $l$ with the first color in the set
10. Add $l$ to the set $L$.
11. Remove $l$ from the set $L$.
12. until the end of set $L$ is reached
13. // At this stage, we have colored some or all lightpaths // of $L$ without having to break them
14. Save a copy of $L$ in $L_{br}$.
15. while the set $L$ is not empty,
16. Pick the first lightpath $l$ in $L$.
17. Set $i$ ← the source of $l$.
18. repeat
19. Find the color that can color $l$ from $i$ for the largest number of hops, till some node $j$.
20. Add a lightpath from $i$ to $j$ with this color, with routing like the corresponding part of $l$, to the set $L$.
21. Set $i ← j$.
22. until $i$ is equal to the destination of $l$
23. Remove $l$ from the set $L$.
24. endwhile // of line 14
25. // At this stage, we have colored all lightpaths, but possibly // at the cost of increasing OEO for some traffic
26. // If so, resort to subwavelength rerouting to improve OEO
27. Form the set $R$ of traffic components which traversed some lightpath in $L_{br}$, according to $(T, G)$.
28. Sort the traffic components in $R$ in decreasing order of magnitude.
29. repeat
30. Pick the first traffic component $t$ in $R$.
31. Let $T_r$ denote the survivor virtual topology under the failure of $l_f$. Route $t$ on the shortest logical hop path on $(T_r ∪ L')$, retaining feasibility with $G'$.
32. Add $t$ to $G'$ with this logical routing.
33. Remove $t$ from the set $T'$.
34. until the set $R$ is empty
35. Delete any lightpaths that now carry no traffic.
36. end // of the failure-dependent algorithm

Fig. 6. Details of Step 3 of the SSPH Algorithm