Survivable Cross-Layer Virtual Topology Design Using a Hyper-Heuristic Approach

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ABSTRACT
In optical WDM networks, designing survivable virtual topologies is a critical problem since a fiber failure may result in a serious amount of data loss. We propose a novel hyper-heuristic approach based on ant colony optimization for solving the survivable cross-layer virtual topology design problem efficiently. To increase the scale-up, a flow-deviation method is used. The experimental results show that our approach can solve the problem for single-link failure in a reasonable amount of time, i.e., 20 minutes on average. Moreover, for double-link failure situations, our approach can still be used to design survivable virtual topologies in approximately 30 minutes without any change in the algorithm.
Keywords: Survivable virtual topology design, Multiple-link failure, Hyper-heuristics, Ant colony optimization

1. INTRODUCTION

In this study, we solve the survivable virtual topology (VT) design problem in optical WDM networks, where the physical topology and the packet traffic intensities between nodes are given. We determine a set of lightpaths (forming the VT), route these lightpaths on the physical topology, so that any fiber failure does not disconnect the VT, assign wavelengths, and route the packet traffic. We assume that the number of wavelengths and transceivers per node are limited. Both the single-link and double-link failure scenarios are considered.

Most studies in literature consider only the survivable VT mapping subproblem [1]. Only two studies address the design problem: a tabu search heuristic [2] and an ILP formulation [3]. The tabu search heuristic in [2] is constrained with small nodal degrees (2,3,4,5) of VTs, and the ILP method in [3] can solve small problem instances up to 4 node physical topologies, optimally. To the best of our knowledge, this is the first study considering double-link failure situations for the survivable VT design problem. Due to the NP-complete nature of the problem, classical optimization techniques, such as greedy local search heuristics provide highly suboptimal solutions to the whole survivable VT design problem, especially for large instances. In this study, we propose a HH method based on ant colony optimization (ACO) [5].

A hyper-heuristic (HH) [4] is a method used to select between the low-level heuristics (LLH) at each step of an optimization process. This way, the best features of different simple greedy heuristics which are used as LLHs, can be combined. Our previous study [6] showed that the ACO-based HH approach solves the survivable VT design problem for large size networks with a 100% success rate. However, it did not include any mechanisms to improve scale-up. In this study, we adapt a flow-deviation method to the ACO-based HH approach, to balance the traffic flow over lightpaths.

Many fibers in a network may share the same resource (duct, conduit, etc). Therefore, the failure of a resource will result in a failure of more than one physical link at an instant. In this study, we explore the performance of our HH approach for both single and double-link failures. We should stress that, the proposed approach can be applied to the multiple-link failure problem instances without any modifications. The only change is the survivability control routine which has a complexity of $O(n^2)$ for double-link failure cases, whereas it is $O(n)$ for cases with single-link failure. However, since the search algorithm is not changed, run times will not be affected considerably. The experimental results show that our approach can solve the problem for both single-link and double-link failures in a reasonable amount of time, i.e., 20 minutes and 30 minutes on average, respectively.

2. PROPOSED HH SOLUTION TO THE PROBLEM

Many different heuristics can be defined for each problem domain. However, each of these heuristics has its own weaknesses and strengths. The main purpose of HHs is to combine the best features of these different heuristics. In HHs terminology, these heuristics are referred to as LLHs, and a high-level heuristic is used to select between these LLHs at each step of an optimization process.

The survivable VT design problem is composed of subproblems [7] that can be solved separately. However, these are not independent problems and solving them sequentially may degrade the quality of the overall result considerably. Therefore, in this study, we handle the survivable VT design problem as a whole, by using a HH approach. In a preliminary study [6], we evaluated the performance of different heuristic selection methods, i.e., evolutionary algorithms (EA), adaptive iterated constructive search (AICS), and simulated annealing (SA). The results showed that ACO outperforms the other HH approaches based on EA, AICS and SA. Therefore, in this study we use the ACO based HH approach. The formal problem definition and the details of our approach are briefly explained in the following sections.

2.1. Formal Problem Definition

The survivable VT design problem is defined as follows:
Given:

- Physical topology: Nodes and physical links that connect the nodes
- Average traffic rates between each node pair
- Maximum number of lightpaths that can be established on a node, i.e., the number of transceivers per node
- Lightpath bandwidth capacity

Find:

- A collection of lightpaths to be established as a VT
- A survivable mapping (routing of the lightpaths over the physical topology, and wavelength assignment)
- A suitable routing of the packet traffic over the VT

The detailed ILP formulation for the survivable VT design problem can be found in [3]. Based on this formulation, the objective is to minimize the resource usage of the network, i.e., the total number of wavelength-links used in the physical topology. A wavelength-link is defined as a wavelength used on a physical link.

2.2. Solution to the Survivable VT Design Problem

In hyper-heuristics, it is crucial to design a solution representation that is well-suited to the problem. In this study, we represent a solution candidate as an array of integer values showing the order of LLHs to be used to select lightpaths for the VT to be established. We define 3 different LLHs: Add a lightpath between nodes: 1) with maximum single direction traffic demand (MAX_SNG), 2) with maximum bidirectional total traffic demand (MAX_TOT), and 3) selected randomly (RND). Therefore, the integer values on the solution array can be 1,2, or 3. The solution array length is equal to the maximum number of lightpaths that can be established, i.e., $number\ of\ transceivers\ on\ each\ node * number\ of\ nodes/2$.

To illustrate the representation, consider a network with 6 nodes and 3 transceivers per node. Then, each solution candidate length is 6*3/2=9. If a solution candidate is represented with an array of [2 1 1 3 2 3 2 2 2], this means first a lightpath will be added using the second LLH, then the next two using the first, continuing with the third, second, ... LLHs. While adding the lightpaths, if the lightpath added according to the corresponding LLH results in using more than the existing number of transceivers in one or both ends, this lightpath is not added to the VT and the algorithm continues with the next LLH in the solution array. The algorithm establishes lightpaths until either the end of the solution array is reached or until no traffic remains in the traffic matrix.

Initially, each ant in the ACO-based HH iteratively adds a random LLH to its partial solution. The solution construction terminates when the solution array of the ant equals to the maximum number of lightpaths. No constraint is applied to the solution in the construction phase of the solution array. There is no heuristic information, so, the solution construction only depends on the pheromone trail. The pheromone trails τ_{ij} we use in this paper refer to the desirability of using the j^{th} LLH to add the i^{th} lightpath. Pheromone trails are initialized using the initial random solutions of the ants and are modified each time all ants have constructed a solution. We use the elitist ant system (EAS) as the ACO variation.

After each ant generates its solution candidate, the corresponding VT is determined. If the generated VT is not at least 2-connected (at least 2 link disjoint paths exist between each node pair), new lightpaths are added subject to the transceiver capacity until the VT becomes at least 2-connected. The nodes whose degree is less than two are selected and lightpaths are added between these nodes and other nodes considering maximum traffic demand. Next, the best mapping for the VT is found using ACO-M [1]. Then, the packet traffic is routed through the shortest paths starting from the node pair with the largest traffic demand. Finally, the quality of the resulting solution is evaluated.

In HHs, the quality of the solutions is determined through a fitness function. In this study, the fitness of a solution is measured as the total number of wavelength-links used throughout the network, which is referred to as resource usage. The objective of the survivable VT design problem is to minimize this resource usage while considering the survivability and the capacity constraints. Resource usage is the total number of wavelength-links used in the physical topology. An infeasible solution can either be penalized by adding a value to the fitness function, or can be discarded. In our HH algorithms, if a solution is found to be infeasible during the phases of creating a VT and routing the lightpaths, it is discarded. In the next stage, if the traffic cannot be routed over the VT, the fitness of the solution is penalized by a value proportional to the amount of traffic that cannot be routed.

To increase the scale-up of the solution, the flow-deviation method [8] is applied to the best solution obtained in the end. The aim in flow deviation is to balance the traffic load on lightpaths. After the traffic is routed through shortest paths, new weights are assigned to the lightpaths considering the traffic flow passed through them. The new

Algorithm 1 General flow for flow-deviation method

```
route traffic through shortest paths using actual link costs
for a predefined number of steps do
    assign new weights to the lightpaths considering the traffic flow passed through them
    for each node pair, reroute some portion of traffic demand using new shortest paths
end for
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weights are calculated using the equation, $W_{ij} = \frac{C_{ij}}{\gamma(C_{ij}-F_{ij})^2}$, where C_{ij} is the bandwidth capacity of the lightpath between nodes i and j, F_{ij} is the traffic flow routed through the lightpath between nodes i and j, and γ is the total traffic demand throughout the network. Then, the traffic amount of $\alpha * \gamma_{ij}$ for each node pair is routed again using shortest paths according to the new lightpath weights. γ_{ij} is the amount of traffic demand between nodes i and j, and α is the parameter to determine the proportion of traffic demand that will be rerouted. This reroute operation is repeated for a predefined number of steps. The flow-deviation method is given in Algorithm 1.

3. PERFORMANCE EVALUATION

The performance of the proposed HH approach is measured on a 24-node 43-link telco network given in Figure 1. For the experiments, we use 20 different randomly generated traffic matrices, where, 70% of the traffic is uniformly distributed over the range [0, 0.5 Gbps] and 30% of the traffic is uniformly distributed over the range [0, 5 Gbps]. The lightpath channel capacity is chosen as 40 Gbps.

First, we apply the flow deviation to the solutions. In Figure 2, the traffic flow on each lightpath is given both before the flow deviation and after the flow deviation. The figure clearly indicates that traffic flow is balanced after flow deviation.

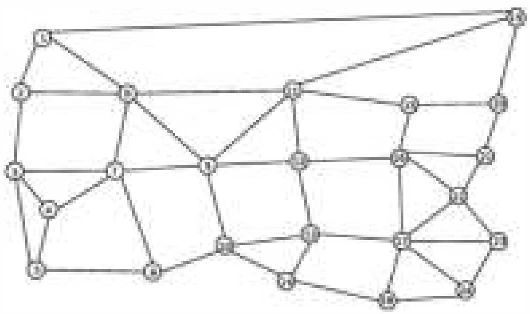

Figure 1. 24-node 43-link network topology

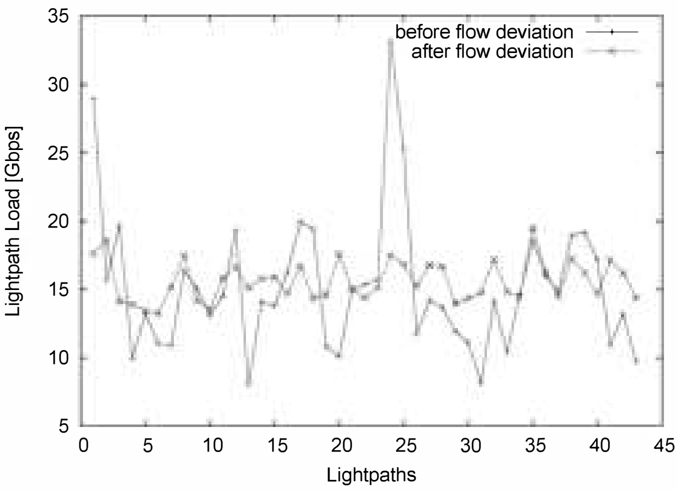

Figure 2. Traffic flow on lightpaths before & after flow deviation

We tested different α values, i.e., 0.1, 0.2, and 0.3, used in flow-deviation applied for 100 steps to see its effect on the solution quality when there is a single-link failure. The results given in Table 1 are the averages of resource usages (RU) and scale-ups (SU) obtained after 20 runs for 20 different traffic matrices (a total of 400 results) using the corresponding α value. Table 1 shows no significant difference between different α values, and therefore, we chose 0.2.

Table 1. Effect of α for flow deviation (single-link failure case). Success rate is 100%.

$\alpha = 0.1$		$\alpha = 0.2$		$\alpha = 0.3$	
RU	SU	RU	SU	RU	SU
144	1.69	144	1.70	144	1.64

The proposed ACO-based HH solves the survivable VT design problem for single-link failures with a 100% success rate in 23 minutes on average. Success rate is defined as the percentage of program runs in which a feasible solution for the problem is found. We also tested this method to see its performance when there is a double-link failure in the physical topology. The results of these experiments are shown in Table 2. The first observation is that, the success rate of our approach decreases when there is a double-link failure, as expected. However, it should be noted that, to solve the problem with double-link failures, our approach can still be used without any modification. The decrease in success rate led us to see how it is affected with the number of shortest paths used to route lightpaths (*sp-test*) and the maximum search time for an ant (*time-test*) in ACO-M. First we conducted the *sp-test*, in which, we tried different number of precalculated shortest paths. The values in columns between 2 and 6 of Table 2 are the averages of 20 algorithm runs for each of the 20 traffic matrices (total 400 runs). In order to isolate the effect of the maximum search time for an ant in the *time-test*, we omitted 4 traffic matrices for which no feasible solutions were found in the *sp-test*. Since the run time of the algorithm increases directly proportional with the increase in the maximum search time for an ant in ACO-M, in *time-test*, the algorithm is run 10 times for each traffic matrix. The last 3 columns in Table 2 show the results for these 16*10=160 tests.

Table 2 shows that the increase in both the number of shortest paths and the maximum search time result in an increase in success rate. Since there is a considerable increase in success rate, the increase in run time when we use larger number of shortest paths can be tolerable up to 25 shortest paths. On the other hand, the run time increases directly proportional with maximum search times for an ant in ACO-M, while the success rate increase is not the same. As a result, using 25 shortest paths to route lightpaths and 10 seconds as a maximum search time for an ant in ACO-M are found to be a good set of parameters.

Table 2. Effect of number of shortest paths (sp) used for routing lightpaths and maximum search time (st) for an ant in ACO-M (double-link failure case)

	# of sp used for routing lightpaths (ant search time: 10sec)					**search time for an ant (# of sp: 15)**		
	10	15	20	25	50	10sec	15sec	20sec
success rate	14%	19%	28%	40%	48%	23%	25%	29%
resource usage	223	220	214	216	219	211	214	211
scale-up	2.83	2.85	2.69	2.75	2.71	2.74	2.85	2.77
run time (in mins)	24	27	28	34	55	24	33	47

4. CONCLUSION

The hyper-heuristic approach proposed for the survivable VT design problem solves this cross-layer design problem for large-size networks with intensive traffic demands with a 100% success rate for single-link failure situations. The results show that, our approach can be easily applied to the double-link failure situations without any modification in the algorithm. As a future work, we will examine the performance of our approach by comparing it with the study proposed in literature.

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