A Genetic Algorithm for Traffic Grooming in Unidirectional SONET/WDM Rings

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Abstract—In this paper, we have considered the problem of traffic grooming in unidirectional SONET/WDM rings to minimize the numbers of SONET Add-drop multiplexers (SADM) and hence the overall cost of the network. We have proposed an ILP formulation and an efficient genetic algorithm solution to the problem and compared our results with those found in literature.

Index terms—Traffic grooming, SONET Add-drop Multiplexers, Genetic algorithm.

I. INTRODUCTION

Most of today's optical networks are hierarchies of SONET rings. This optical fiber communication is employed with WDM technology where the whole bandwidth of an optical fiber is divided among a number of non-overlapping wavelengths, each of which is capable of carrying high-speed optical data. In recent years, the bandwidth of a wavelength has been increased from 2.5 Gbps (OC-48) to 10 Gbps (OC-192) and likely to be increased up to 40 Gbps (OC-768) in near future [1][2]. Thus the bandwidth capacity on a wavelength is too large for certain traffic requirements. An approach to provide fractional wavelength capacity is to split a wavelength in multiple time slots and multiplex traffic on the wavelength. Therefore each wavelength running at the line rate of OC-N can carry several low-speed OC-M (M ≤ N) traffic channels in TDM fashion. For example, an OC-48 line can carry 16 OC-3 channels. The resulting networks are called WDM-TDM networks or WDM traffic grooming networks. The ratio of N to the smallest value of M is called grooming ratio [1]-[5].

Using WDM technology, multiple rings can be supported on a single fiber ring. In this architecture, each wavelength independently carries a SONET ring. Each SONET ring can further support multiple low-speed streams. At every node a WDM Add/Drop Multiplexer (WADM) adds and drops or bypasses traffic on any wavelength. At each node, there are SONET add/drop multiplexers (SADM) on each wavelength to add/drop low-speed streams [5]. So the number of SADMs per node will increase linearly with the number of wavelengths that a single fiber ring can carry. The cost of SADMs dominates the total cost of the optical network. But in fact, it is not necessary for each node to be equipped with SADMs on each wavelength. An SADM on a wavelength at a node is needed only if there is traffic terminating at this node on this wavelength. So, the problem is to combine different low-speed traffic streams into high-speed traffic streams in such a way that the number of SADMs is minimized [3][4]. This problem is proven to be NP-complete [3]. As far as our knowledge goes, we are the first to propose a genetic algorithm solution to this problem for unidirectional ring topologies. Here, we have restricted ourselves to consider the static traffic pattern only. We have proposed an ILP formulation for the problem and solved it using a genetic algorithm. We have shown that our algorithm produces better results compared to those found in some latest literatures.

The rest of the paper is organized as follows: the next section proposes the ILP formulation of the problem. Section III gives the overview of the genetic algorithm to solve the problem. The results obtained have been shown in section IV. Finally, section V concludes the paper.

II. ILP FORMULATION OF THE TRAFFIC GROOMING PROBLEM

Here we have considered a unidirectional ring network. Let the number of nodes in the ring is N and L is the total number of wavelengths available in a link. Suppose, g is the grooming ratio. An SADM is needed at a node for some wavelength only if some of the traffic contained in that wavelength is originated from, or destined to, that node.

Suppose the N nodes in the network are labeled from 0 to N-1 in a clockwise direction. Wavelengths available are 0 to L-1. We have a set of source-destination node pairs, \( R = \{(s_i, d_i) \mid 0 \leq s_i, d_i \leq N-1, 0 \leq i \leq |R|-1\} \), where each pair \((s_i, d_i)\) denotes requirement of a low speed, unidirectional traffic stream from node \(s_i\) to \(d_i\). The solution of the problem is to find a suitable wavelength assignment \( W = \{l_i \mid 0 \leq l_i \leq L-1, 0 \leq i \leq |R|-1\} \), where wavelength \(l_i\) is assigned to traffic stream \((s_i, d_i)\), such that total number of SADMs needed is minimized. For a wavelength assignment \(|W|\), we can find the total number of SADMs needed. Let \(SADM_{\text{nw}}\) is a binary variable that is true if an SADM is required at node \(n\) for wavelength \(w\), where \(0 \leq n \leq N-1, 0 \leq w \leq L-1\).

\[
SADM_{\text{nw}} = \begin{cases} 
1 & \text{if node } n \text{ needs SADM for wavelength } w. \\
0 & \text{if node } n \text{ doesn't need SADM for wavelength } w.
\end{cases}
\]

We know that an SADM for wavelength \(w\) is needed at node \(n\) only if node \(n\) is the source or destination of any
traffic stream using wavelength \( w \). Hence, we can compute \( SADM_{nw} \) for each \((n, w)\) pair in the following way.

\[
SADM_{nw} = \begin{cases} 
1 & \text{if } [s_i = n \text{ or } d_i = n] \text{ and } l_i = w, \text{ where } (s_i, d_i) \in R, 0 \leq l_i \leq L-1, 0 \leq i \leq |R|-1. \\
0 & \text{otherwise.}
\end{cases}
\]

Therefore total number of SADMs in the ring is given by

\[
\sum_{n=0}^{N-1} \sum_{w=0}^{L-1} SADM_{nw}
\]

The objective is to minimize number of SADMs, i.e.

Minimize \[
\sum_{n=0}^{N-1} \sum_{w=0}^{L-1} SADM_{nw}
\]

There are some certain constraints that we have to consider. First of all, \( 0 \leq SADM_{nw} \leq 1, \) and \( SADM_{nw} \) is integer variable. The other constraint is that no wavelength at any link should be overloaded, i.e. maximum number of traffic streams that pass through it should be less than or equal to the grooming ratio \( g \).

The link from node \( n \) to \((n+1) \mod N\) is traversed by all low speed traffic streams \((s_i, d_i) \in R\), where \((s_i \leq n < d_i)\) or \((n < d_i < s_i)\) or \((d_i < s_i \leq n)\). Therefore, the load on wavelength \( w \) on link \( n \rightarrow ((n+1) \mod N) \) is given by the cardinality of the set

\[
LD_{nw} = \{(s_i, d_i) \mid (0 \leq s_i \leq n < d_i \leq N-1) \text{ or } (0 \leq n < d_i < s_i \leq N-1) \text{ or } (0 \leq d_i < s_i \leq n \leq N-1)\} \text{ and } |l_i = w|, (s_i, d_i) \in R, 0 \leq l_i \leq L-1, 0 \leq i \leq |R|-1
\]

Hence, the load constraint will be:

\[
\forall n, w \quad (0 \leq n \leq N-1, 0 \leq w \leq L-1) \Rightarrow |LD_{nw}| \leq g.
\]

Thus, the problem of minimization of SADMs in unidirectional SONET/WDM ring via traffic grooming can be given as,

Given integers \( N > 0, L > 0, g > 0 \) and Request set \( R = \{(s_i, d_i) \mid (0 \leq s_i \leq N-1, 0 \leq i \leq |R|-1), \) find a suitable wavelength assignment \( W = \{l_i \mid 0 \leq l_i \leq L-1, 0 \leq i \leq |R|-1\} \), so that,

\[
\sum_{n=0}^{N-1} \sum_{w=0}^{L-1} SADM_{nw}
\]

is minimized

Subject to:

1. \( 0 \leq SADM_{nw} \leq 1, \) and \( SADM_{nw} \) is integer variable,

2. \( \forall n, w \quad (0 \leq n \leq N-1, 0 \leq w \leq L-1) \Rightarrow |LD_{nw}| \leq g. \)

III. GENETIC ALGORITHM FOR THE TRAFFIC GROOMING PROBLEM

Genetic algorithms are robust and stochastic search procedures based on the principles of natural genetics and evolutionary theory of genes. The algorithm starts by initializing a population of potential solutions encoded into strings called chromosomes. Each solution has some fitness value based on which the fittest parents that would be used for reproduction are found (survival of the fittest). The new generation is created by applying genetic operators like crossover (exchange of information among parents) and mutation (sudden small change in a parent) on selected parents. Thus the quality of population is improved as the number of generations increases. The process continues until some specific criterion is made or the solution converges to some optimized value.

A. Solution representation

Here, we have encoded the solution to integer strings. In the previous section we depicted that input set of source-destination pairs is the set \( R=\{(s_i, d_i) \mid 0 \leq s_i, d_i \leq N-1, 0 \leq i \leq |R|-1\} \), where each pair \((s_i, d_i)\) denotes requirement of a low speed, unidirectional traffic stream from node \( s_i \) to \( d_i \). We have to find out suitable wavelength assignment such that total number of SADMs required is minimized. We can represent the solution as an integer string \( W=\{l_i \mid 0 \leq l_i \leq L-1, 0 \leq i \leq |R|-1\} \), where wavelength \( l_i \) is assigned to traffic stream \((s_i, d_i)\). The fitness value (objective function of the ILP), i.e. the total number of SADMs required, for each solution can be calculated as shown in the previous section. We do not explicitly check the validity of a string whether it satisfies the constraint that a wavelength on a link can support maximum \( g \) (grooming ratio) numbers of low speed traffic streams, rather the fitness function is converted into an unconstrained form, by adding a penalty term greater than \( L \times N \) (maximum number of SADMs in the ring) times the number of violations, to the objective function. Thus while minimizing the fitness values, the solutions violating the constraint are automatically ruled out of the contest.

Example:

Input set:

\( R = \{(2,3), (6,2), (1,8), (5,6), (2,4), (3,6)\} \)

Solution representation:

\( W = \{3 \ 8 \ 3 \ 2 \ 2 \ 1 \} \)

B. Initial population

The initial population is generated by creating a number of individual solutions (strings). Each string is generated by random assignment of wavelengths to each traffic stream of the input set \( R \).

C. Selection operator

Here, we use the tournament method of selection, in which a number of strings are picked up randomly from the current generation and from among them; we chose the best solution to act as a parent. The other parent is always the best solution of the previous generation. The genetic operators are applied on the parents to produce the offspring solutions.

D. Crossover operation

The crossover operation is used to exchange genetic materials between two parents. Here we have used the
single point crossover, which produces two children from two parents. This operation is performed in the following way. A random crossover point is generated between 0 and maximum chromosome length of the solution. This point divides each solution in two parts. The corresponding parts of the parent chromosomes are swapped to produce two new offsprings.

**Example:**

Parent1: **1 3 5 2 3 6 7 4 1**  
Parent2: **3 4 5 2 5 7 1 5**  
Crossover point: 5  
Offspring1: **1 3 5 2 3 | 5 7 1 5**  
Offspring2: **3 4 5 2 2 | 6 7 4 1**

**E. Mutation operator**

A random mutation point between 0 and maximum chromosome length is selected and another wavelength is assigned instead of the current wavelength at that point with some probability called the *mutation probability*.

**Example:**

Chromosome: **1 3 5 2 3 6 7 4 1**  
Mutation point: 4  
New assignment to 4th wavelength (2): 8  
New chromosome: **1 3 5 8 3 6 7 4 1**

A new offspring solution obtained by crossover or mutation operation is retained in the population, if its fitness value is better than the worst fitted solution in the population, otherwise the solution is rejected [6].

**F. An improvement to the genetic algorithm for All-to-all unitary traffic**

In this sub-section, we will present an improvement over the aforementioned genetic algorithm by adding an extra constraint. This improvement works best in case of all-to-all unitary traffic. In this case, if the input set \( R \) contains a source destination pair \( (s, d) \), then it will also contain the pair \( (d, s) \). The additional constraint is that, both these pair is assigned the same wavelength. The rationale for this is that, this assignment will create a circle and SADM saving is maximum when such a circle is created, because a circle needs two SADMs, one at node \( s \), and the other at node \( d \). If two different wavelengths are used, then a total of four SADMs are needed, two SADMs at each node. Hence, while generating a string, we apply this additional constraint with the expectation of getting better performance. Let us denote this improved algorithm as GA*.

**IV. RESULTS AND DISCUSSIONS**

In this section we have presented the results of our algorithm and made comparisons with two other results found in [3] and [4]. In [3], Modiano presented a heuristic algorithm for the same problem, whereas, in [4], a Reactive Local Search (RLS) algorithm has been presented. We tested the performances of the algorithms for all-to-all unitary traffic case, i.e., traffic requirement is exactly 1 for each pair of nodes. Hence the input set of traffic requirements \( R \) can be calculated as:

\[
\begin{align*}
For \ s &= 0, 1, 2, 3, \ldots, N-1 \\
For \ d &= 0, 1, 2, 3, \ldots, N-1 \\
If \ s \neq d \ then \ R &= R \cup \{(s, d)\} \ End if \\
End for \\
End for
\end{align*}
\]

For example, for a SONET ring with 3 nodes, the input set of lightpaths will be:

\( R = \{(1,2), (2,1), (1,0), (0,1), (2,0), (0,2)\} \)

We have run our algorithm upto 10,000 generations to get the results and it takes near about 1 minute on a 1.7 GHz Pentium IV computer with 128 MB RAM running Windows Me operating system. The execution time does not depend on number of nodes of the ring.

In Fig. 1, we have shown the comparison among Modiano’s algorithm, the RLS algorithm, our Genetic Algorithm (GA) and GA* for all-to-all unitary traffic in unidirectional rings. The graphs represent the number of SADMs required for certain number of nodes. The number of nodes varies from 8 to 16, as most of the SONET ring contains a maximum of 16 nodes. We have shown the graphs for grooming ratio \( g = 4 \). We have also given the graphs for optimal number of SADMs required. From the graph it is clear that our algorithm performs better than Modiano’s algorithm in all the cases. GA* and RLS give optimal result for \( g = 4 \).

![Fig. 1: Performance of algorithms for g = 4](image)

Fig. 2 shows the graphs comparing the above four algorithms for grooming ratio \( g = 16 \). Here we can see that the improved GA, i.e., GA* performs better than the other algorithms and its performance is near optimal.
V. CONCLUSIONS

In this paper we have presented a genetic algorithm for the traffic grooming problem in unidirectional SONET/WDM rings to minimize the number of SADMs required. We have also given an improvement over the genetic algorithm for all-to-all unitary traffic. We have shown that our algorithm performs better than other heuristic and reactive search techniques found in recent literature.

VI. REFERENCES


