Improved Approaches for Cost-Effective Traffic Grooming in WDM Ring Networks: ILP Formulations, Single-Hop and Multihop Connections *

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Abstract

Traffic grooming is the term used to describe how different traffic streams are packed into higher-speed streams. In a WDM SONET/ring network, each wavelength can carry several lower-rate traffic streams in TDM fashion. The traffic demand, which is an integer multiple of the timeslot capacity, between any two nodes is established on several TDM virtual connections. A virtual connection needs to be added and dropped only at the two end nodes of the connection; as a result, the electronic Add/Drop Multiplexors (ADMs) at intermediate nodes (if there are any) will electronically bypass this timeslot. Instead of having an ADM on every wavelength at every node, it may be possible to have some nodes on some wavelength where no add/drop is needed on any time slot; thus, the total number of ADMs in the networks (and hence the network cost) can be reduced. Under the static traffic pattern, the savings can be maximized by carefully packing the virtual connections into wavelengths. In this work, we allow arbitrary (non-uniform) traffic and we first present a formal mathematical definition of the problem, which turns out to be an integer linear program (ILP). Then, we propose a simulated-annealing-based heuristic algorithm for the case where all the traffic are carried on directly connected virtual connections (referred to as the "single-hop" case). Then, we study the case where a hub node is used to bridge traffic from different wavelengths (referred to as the multihop case). We find the following main results. The simulated-annealing-based approach has been found to achieve the best results so far in most cases relative to other comparable approaches proposed in the literature. In general, a multihop approach can achieve better equipment savings when the grooming ratio is large, but it consumes more bandwidth.

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1 Introduction

SONET ring is a widely deployed optical transport technology because of its high capacity and inherent reliability. In a WDM/SONET ring, each wavelength running at the line rate of OC-N can carry several low-speed OC-M (M≤N) traffic channels in TDM fashion. Note that for non-uniform traffic, each connection can have a different OC-M rate. The traffic demand, which is an integer multiple of the timeslot capacity, between any two nodes is established on several TDM virtual connections. A virtual connection needs to be added and dropped only at the two end nodes of the connection; as a result, the electronic Add/Drop Multiplexors (ADMs) at intermediate nodes (if there are any) will electronically bypass this timeslot. It is possible to have some nodes on some wavelength where no add/drop is necessary in any time-slot, so the electronic equipment can be saved. Figure 1 shows the architecture of a typical node in a WDM SONET-ring network. For some wavelengths (λ1 in this example), since there is no need to add or drop any of its timeslots, they can be optically bypassed at the node. For other wavelengths (λ2 and λ3) where at least one timeslot needs to be added or dropped, an electronic ADM is used.

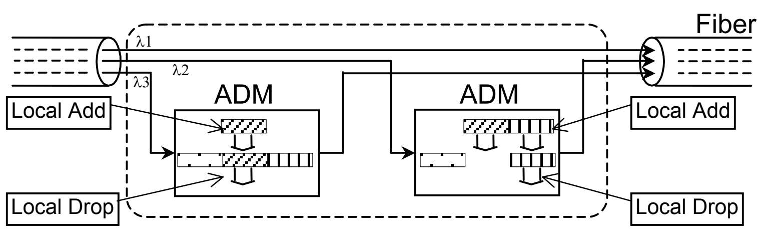


Figure 1. Architecture of a WDM/ring network node.

As shown in the above figure, ADMs do not have the timeslot interchange function. It is also obvious that wavelength interchange is not possible if no additional equipment is used. So there are timeslot-continuity and wavelength-continuity constraints at nodes where only ADMs are used. SONET crossconnect (DXC) can be used at a node to consolidate or segregate sub-channels, but it is relatively expensive.

If a network is not properly designed, more ADMs may be needed to carry the same traffic requirement. This problem is especially undesired in metro-area and enterprise networks where there are few users sharing the cost. In this study, we explore how to minimize the network-wide ADM cost under static (possibly non-uniform) traffic pattern. A special case of using a DXC at a hub node to do grooming is also considered and the cost of the DXC is estimated by the total add/drop cost. Worth mentioning that we are not using the standard terms like BLSR or UPSR to refer to our bi-directional and unidirectional rings but traffic grooming will not affect the protection mechanisms. We are focusing on the network design problem under static traffic pattern, which is expected to be the main operation model for the optical layer [1].

1.1. An Example of the Traffic Grooming in a WDM SONET-ring network

Figure 2 shows a five-node network with a uniform traffic request. In this example, we assumed a bi-directional ring with grooming ratio 2 (which may not be practical in a real SONET ring but it is used here for illustration purpose). The total number of bi-directional requests is 10 and each request is 1 unit of sub-channel capacity. The ten bi-directional arcs in Figure 2a ~~illustrated~~ represent all the 10 requests. Fig. 2b and 2c illustrate~~d~~ two ways of organizing the connections on two wavelengths (one and half are actually in use). In Fig. 2.b, there is only bypassing traffic at node 2 of the second ring (outer ring indicated by the dished line) ~~so~~ and nine ADMs are needed to carry all the requests. The number ~~Number~~ of ADMs can be further reduced by simply ~~reconfigure~~ reconfiguring the rings as shown in Fig. 2.c, where the connections between

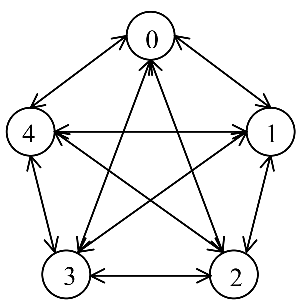


Fig. 2.a. Ten connection requests

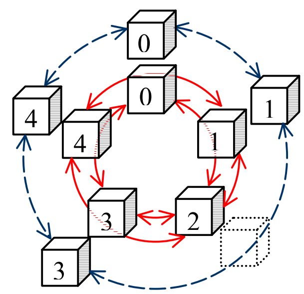


Fig. 2.b. One way of putting the 10 requests on two wavelengths. Nine ADMs are needed. The inner ring

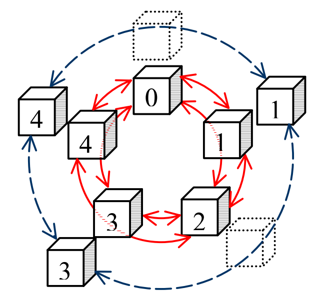


Fig. 2.c. Another way of putting the 10 requests on two wavelengths. Eight ADMs are needed.

Node ADM Sub-channels on two different wavelengths

nodes 1 and 4 on the second ring (1↔4) and part of the first ring (4↔0, 0↔1) ~~are~~ swapped their~~possition~~. positions.

Comment: Is "ring" same as "circle" used later?

1.2 Previous Work and Our Contribution

Table 1 gives a brief review of previous work reported in this area. The various terms used in the table are described below:

- Static ~~or~~ (dynamic) traffic: The traffic pattern will not ~~or~~ (will) change with time~~, respectively~~.
- Uniform (non-uniform) traffic: Traffic demands between any node pair are the same (not the same).
- Single-hop ring: No virtual connection on the ring will be terminated electronically at any intermediate node.
- Multihop ring: Some or all of the virtual connections on the ring may be regenerated electronically at some intermediate nodes.

Figure 2. An example of traffic grooming on a 2-wavelength network and it shows that different strategies can lead to different network cost. Total number of traffic connection is 10 and each request has capacity of one unit.

- Unidirectional (bidirectional) ring: All the traffic on the ring can go along one (both) direction(s).
- Circle: The virtual ring that is established on one timeslot of a wavelength. It has the a capacity of one unit.
- PPWDM: Point-to-point WDM ring (opaque network), in which signals get crossconnected and regenerated at every node.
- Distance-dependent traffic [4]: The nodes farthest apart exchange one unit of traffic, and the inter-node traffic demand increases by one unit as the inter-node distance decreases by one link.
- Egress node: A special node, like the central office of an access network, on the ring where all the traffic terminates at or originates from.

Table 1. Comparision of previous work on traffic grooming on WDM/ring networks.

Source	Traffic assumptions	Ring architecture	Main result
Gerstel [1][2]	• Static, uniform • Non-statistic dynamic and fixed wavelength	• PPWDM (multihop) • Fully-optical ring (single-hop) • Single-hub (multihop) • Double-hub (multihop) • Hierarchical ring (multihop) • Incremental ring (multihop)	• First paper that tries to minimize transceiver cost. • Study of dynamic traffic and fixed lightpath. • Different architectures are compared.
Modiano [3]	• Egress traffic • Static, uniform	• Unidirectional ring with egress node (single-hop) • Bidirectional ring (single-hop)	• Proof of NP-completeness. • Optimal solution for uniform traffic on egress ring. • Lower bound on uniform all-to-all traffic.
Simmons [4][5]	• Static, uniform • Static, distance-dependent traffic	• Bidirectional ring with odd number of nodes (single-hop)	• How to group timeslots. • Maximal savings for some special cases. • Super node model for distance - dependent traffic.
Zhang & Qiao [6]	• Static, uniform traffic • Static, non-uniform traffic	• Unidirectional and bidirectional ring (single-hop)	• Greedy heuristic for grooming arbitrary traffic. • Heuristic for circle construction for non-uniform traffic.
Our work	• Static, uniform traffic • Static, non-uniform traffic	• Unidirectional and bidirectional ring (single-hop) • Single hub (multihop)	• Formal mathematical problem specification (ILP). • Simulated-annealing-based heuristic for traffic grooming • Greedy heuristic for single-hop and multihop grooming.

Papers on this topic were first seen appeared in 1998 [1][2][4]. Several network architectures were proposed and compared in [1][2]. This work also provided an example to show that the number of wavelengths and the ADMs cannot be minimized simultaneously for general arbitrary traffic. Studies [3][4][5][6] focused on the single-hop case. In [3], the authors showed that the general traffic-grooming problem is NP-complete. For uniform traffic on a special ring with an egress node, the optimal solution is provided. In [4][5], full mesh connectivity on bidirectional ring with odd number of nodes was considered. An elaborated analysis about how to combine different circles into a wavelength channel was provided and the optimal result was obtained. The work in [6] extended previous discussion to arbitrary traffic, arbitrary number of nodes, and both unidirectional and bidirectional rings. A greedy heuristic was proposed.

In order to improve on previous work, we first provide formal mathematical definitions for the various traffic-grooming problems, which turn out to be integer linear programs (ILPs). Then, we propose a simulated-annealing-based heuristic approach for solving these optimization problems. We believe that this algorithm has achieved the best result so far relative to other approaches. Finally, we discuss the multihop case (with a single hub) where a hub node is used to crossconnect traffic between different wavelengths and timeslots. Comparison of the single-hop and multihop approaches is provided.

2 Problem Definition

Here are the common The notations that we will use throughout this study paper is summarized below.

- N: Number of nodes in the network.
- W w: Number of wavelengths in the network (each wavelength can transmit several circles in time-division fashion).
- C: Grooming ratio, which that is, is the number of circles a wavelength can carry (also, referred to as the grooming ratio).
- $T(t_{ij})$: Non-uniform traffic matrix, in which t_{ij} represents the prescribed traffic from node i to j.
- ${}^{d}V_{ij}^{cw}$: Virtual connection from node i to node j on circle c, wavelength w. The d represents the direction of a connection and it can be either clockwise or counter-clockwise.
- O_i, I_i: In the multihop case, O_i represents the virtual connection that starts from node i and terminates at the hub node. Similarly, I_i represents the virtual connection that starts from the hub node and terminates at node i.
- ADM_i^w: Number of ADMs at node i on wavelength w.
- e: A link on the physical ring.
- c: Sub-channel (or circle).

2.1 Formulation 1: Single-Hop Connections

The traffic-grooming problem on a single-hop bi-directional ring can be mathematically formulated as shown below.

Formulation 1. Mathematical problem formulation for traffic grooming in a single-hop network.

Objective function:	*Minimize* $\sum_i \sum_w ADM_i^w$		
Subject to:	$\sum_w \sum_c \sum_d {}^dV_{ij}^{cw} = t_{ij}$	$\forall i, j$	(Traffic-load constraint)
	$\sum_{{}^de^{cw} \in {}^dV_{ij}^{cw}} {}^dV_{ij}^{cw} \le 1$	$\forall d, e, c, w$	(Channel-capacity constraints)
	$\sum_c \sum_j {}^dV_{ij}^{cw} \le C \cdot ADM_i^w$	$\forall d, i, w$	(Transmitter constraints)
	$\sum_c \sum_i {}^dV_{ij}^{cw} \le C \cdot ADM_j^w$	$\forall d, j, w$	(Receiver constraints)
Bounds:	${}^dV_{ij}^{cw}$ *and* ADM_i^w *are both binary numbers.*		

In the above formulation, ${}^dV_{ij}^{cw}$ represents whether there is a virtual connection (one unit of capacity) from node *i* to node *j* along direction *d* (which can be clockwise or counter clockwise) on circle *c* and wavelength *w*. The t_{ij} represents the total amount of traffic from node *i* to node *j*. ADM_i^w represents whether there is an ADM on wavelength *w* at node *i*. Both ${}^dV_{ij}^{cw}$ and ADM_i^w can be either 0 or 1.

The traffic-load constraint simply states that the number of links from node *i* to node *j* on all circles is equal to the traffic specified in the traffic matrix. (Comment: How can this be? The number of links is dimensionless and the traffic is dimensionless? You have to re word the sentence) In the channel-capacity constraint, ${}^de^{cw}$ represents a *d*-direction link on wavelength *w* and sub-channel *c*. If the virtual connection ${}^dV_{ij}^{cw}$ uses it, (uses what? This link?) we say that ${}^de^{cw} \in {}^dV_{ij}^{cw}$. The channel-capacity constraint requires that a circle carry only one connection on any given link. The last two constraints specify that the number of connections that start and terminate at a node of a ring is bounded by the capacity of the electronic ADM at that node. If there is an ADM, at most C connections can start and terminate there; otherwise, no add/drop can occur.

Unidirectional-ring case can be viewed as a special case of the above formulation, where *d* can only be either clockwise or counter-clockwise. Sometimes, shortest-path routing is required in the bidirectional ring. This requirement can also be accommodated in the above formulation by specifying that ${}^dV_{ij}^{cw}$ will be zero if the distance from node *i* to *j* in the specified direction exceeds $\lceil N/2 \rceil$.

2.2 Formulation 2: Multihop ~~Method~~Connections

A multihop ring uses a DXC to do sub-channel consolidation or segregation at a hub node. In this study, we simplify the cost calculation by using the following equivalent architecture instead. The hub node has as many ADMs as there are wavelengths. All connections that are passing through it can be terminated and switched to any wavelengths and timeslots. A connection can go through the hub node at most once. The formulation for the unidirectional, single-hub ring case is shown below in formulation 2. Bi-directional formulation for the single-hub-based multihop network is also available. We omit it here since it is a straightforward extension of the following formulations.

Objective function: $$\text{Minimize } \sum_i \sum_w ADM_i^w$$

Subject to:

$$\sum_w \sum_c \Big(\sum_{j(j>i)} V_{ij}^{cw} + O_i^{cw} \Big) = \sum_j t_{ij} \qquad \cdots\cdots \forall i$$

$$\sum_w \sum_c \Big(\sum_{i(j>i)} V_{ij}^{cw} + I_j^{cw} \Big) = \sum_i t_{ij} \qquad \cdots\cdots \forall j \qquad \text{(Traffic-load constraint)}$$

$$\sum_{e^{cw} \in V_{ij}^{cw}} V_{ij}^{cw} + \sum_{i<e^{cw}} O_i^{cw} + \sum_{j>e^{cw}} I_j^{cw} \le 1 \qquad \cdots\cdots \forall e, c, w \quad \text{(Channel-capacity constraint)}$$

$$\sum_c \sum_j V_{ij}^{cw} + \sum_c O_i^{cw} \le C \cdot ADM_i^w \qquad \cdots \forall i, w \qquad \textit{(Transmitter constraint)}$$

$$\sum_c \sum_i V_{ij}^{cw} + \sum_c I_j^{cw} \le C \cdot ADM_i^w \qquad \cdots \forall j, w \qquad \textit{(Receiver constraint)}$$

Bounds: *All* V_{ij}^{cw}, O_i^{cw}, I_i^{cw} *and* ADM_i^{cw} *are binary numbers.*

Formulation 2. Mathematical problem formulation for traffic grooming in a single-hub multi-hop network.

In the above formulation, O_i^{cw} represents the virtual connection from node *i* to the hub node on circle *c,* wavelength *w.* Similarly, the notation I_i^{cw} represent the connection that starts from the hub node and terminates at node i. The condition *(j>i)* means the virtual connection that starts from node *i* and ends at node *j* without going through the hub node. The notion $i<e^{cw}$ means the following: if *s* is the start node of link e^{cw} and *t* is the end node, then *i* is ~~at~~ upstream of *t*. Similarly, $j>e^{cw}$ means that *j* is ~~at~~ downstream of *s*. The traffic-load constraint needs to be broken into two parts for the multihop case. The first part in the multihop formulation specifies the following fact: any virtual connection that starts from node *i* will either terminate before it reaches the hub node or will terminate at the hub node. Similarly, the second traffic-load constraint states that any virtual connection that terminates at node *i* is either coming from the hub node or from some node downstream of the hub node. ~~The explanations~~ Explanation of the other constraints ~~are the same as~~ is analogous to the single-hop case.

3 Solving the ILPs Directly

We attempted to solve the ILPs directly under the current restriction that a SONET/ring has a ~~maximal~~ maximum size of 16 nodes. The case of uniform ~~Uniform~~ traffic on single-hop, unidirectional ring was chosen to demonstrate ~~for demonstration to give audience a feeling of~~ how fast the ~~ILPs can be solved~~ method yields a solution, although our formulation is capable of solving non-uniform traffic cases (examples of which will be given in 5.1.2~~.~~). A commercially available ILP solver ("CPLEX") was used. Table 2 shows the computational time and the optimal solution. For small networks, i.e., 6 nodes or less, the ILP solver ~~can find~~ found the optimal solution in a reasonably short time of a few seconds to a few hours. When the network size grows beyond 6 nodes, the solver ~~was found to take~~ took more than 6 hours to discover the ~~optimal~~ optimum for some cases. ~~(showed as question marks in Table 2).~~ (comment. Replace question marks in the table woth ">6 hrs.") When the network size is larger than 7 or 8 nodes, we need to turn to heuristics. Table 3 provides some ~~additional~~ detailed information about the performance of this method. ~~-~~When we give the ILP solver a time limit of half-hour for each problem, it usually fails to find even one feasible solution when network size is larger than 8 nodes. Notice that when the grooming ratio is large enough so that one wavelength is enough to carry all the traffic~~s~~, traffic grooming does not have practical meaning anymore since an ADM is needed at each node.

	C=3		C=4		C=12	
	T(s)	N_{ADM}	T(s)	N_{ADM}	T(s)	N_{ADM}
N=4	1	7	2	7	0	4
N=5	471	12	45	10	0	5
N=6	?	?	9783	15	191	9
N=7	?	?	?	?	549	12

Table 2. Computational time (in seconds) and optimal solution for the single-hop case. ~~Question mark~~ The notation >6 hrs. indicates that "CPLEX" failed to obtain an optimal result ~~in~~ within 6 hours. This test is obtained from a HP-Visualize B132l machine running UNIX. For the case N=4, 5 and C=12 (shaded cells), no grooming is needed since one wavelength can carry all the traffic.

4 Heuristics

The general traffic-grooming problem is NP-complete [3]. Solving the ILP directly is not practical even for moderate-size networks because of the long solution time. Although a simple greedy heuristic has been provided in [5], we propose alternative approaches to discover improved results. Specifically, we propose a simulated-annealing algorithm for single-hop connections and a simple greedy heuristic for multihop connections.

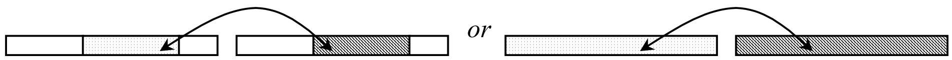
4.1 Simulated Annealing for Single-Hop Connections

To reduce the complexity, the traffic-grooming problem is usually ~~divided into two components~~ addressed in two steps (as in [4][5][6]). In the first step, the traffic demands are assigned to circles. In the second step, a traffic-grooming algorithm is employed to reorganize the circles or connections on wavelengths. We adopted the same strategy and our first step heuristic is ~~build~~ built upon the wavelength-assignment algorithm proposed in [6] for reducing wavelength consumption. An important ~~practice~~ practical concern is whether or not the heuristic is a good foundation for our second step ~~heuristic~~? It has been shown in [1] that it is not always possible to minimize simultaneously both the number~~s~~ of wavelengths and the ADMs. ~~is not always possible to be minimized simultaneously~~. Both our ILP (discussed in section 2 and 3) and heuristic (will be discussed in this section) have the potential to find the true ~~optimal~~ optimum when there are more than enough wavelengths. Indeed, it is possible ~~Although there are chances~~ that the heuristic gives us less number of wavelengths than necessary to minimize the ADM usage, but ~~the chance is low~~ this possibility is small. Further~~-~~more, the emphasis of this study is on comparing different second step heuristics. ~~, so the heuristic is adequate~~. Our second step heuristic randomly chooses some virtual connections in the network and changes their position. Using the simulated annealing technique to help accelerate the process of branch-and-bance (?) Comment: Is this brancj-and-bound? to find a good solution. The implementation of simulated annealing follows the Monte Carlo method [6] referred to as the *Metropolis Algorithm.* The algorithm is ~~depicted~~ described below:

In this implementation, “perturb” means to randomly pick two circles on different wavelengths, swapping part of them or the whole circles (illustrated in the comment of the pseudo-code). The chance for doing partial swapping is chosen to be very small. Whenever the criterion for doing partial swapping is satisfied, we go ahead to check if there are segments in the two circles that are swappable (if swapped, they do not break any existing connections). If the result is no, we simply swap the whole circles. The consequence of the perturbation may or may not be helpful to bring down the ADM usage. If the perturbation helps, we will accept the perturbation; otherwise, we will calculate *exp(-Δcost/control)* and compare it with a random number. The perturbation will still be accepted if the random number is smaller. After repeating the above process for certain times, we consider the system reached equilibrium state and go on to decrease the *control* variable (the temperature). The process will be terminated when the *control* variable satisfies predefined criterion.

Comments on the box below. Add a preamble identifying the variables and their data types. The circle assignment heuristicis not adequately explained either in the text ort in the program segment. This is crucial. Yout readers are not likely to know all the nuances of SA. Pl. work on this. Actually, I would like to see that you rewrite the next paragraph and do it in conjunctionwith the revisions to the program segment above. If it takes an extra few lines, so be it. Explain what part is swapped. When is a paret of the circle swapped and when is a whole circle swapped?

```
do { // iterate around all states
        do {//accept ANN_CONST*C times
                //randomly pick two circles, swap part or all of them
                dcost=perturb(); //
```




```
                if (Δcost<0 || (Δcost>0 && exp(-Δcost/control)>rand[0,1))){
                        accept_change();// accepted the change
                        chain++;
                }
                else reject_change();
        }while (chain<ANN_CONST*C);
        control = control*DEC_CONST;
} while (control>END);
```

In the above implementation, as the computation goes on and the *control* variable goes down in value, the chance of having a "good perturbation" and accepting a "bad perturbation" will decrease, so the time spent in lower temperature is much longer than in higher temperature. (Comment: Rewrite the previous sentence. The way it stands is contradicting itself. Also, you used the word temperature for the first time. Explain what temperature is in one sentence so people who are new to SA are not lost) The constants ANN_CONST and DEC_CONST are critical for the performance. ANN_CONST decides how long we have to wait before we consider that the system has reached its equilibrium. DEC_CONST decides how fast we lower the temperature. After playing around with these parameter values, we finally adopted ANN_CONST to be between 4 and 20 depending on the size of the search space, (comment: Is 4 for smaller search space and 20 for larger search space? How did you estimate the size of the search space?))and DEC_CONST = 0.95 for best results for our numerical examples. The start temperature is found to be important for some cases. We will not recommend very high circle-assignment heuristic in the first step ~~serves~~ as a pre-grooming heuristic, which puts similar connections as close to one another as possible; thus, a very high starting temperature can counter-balance the effort of the first step and prolong the convergence process. Some special hand-crafting techniques are also needed when implementing the *perturb()* function, details of which are skipped here. These techniques are mainly used to increase the convergence speed of the algorithm. (Comemnt: I suggest that you go ahead and describe the special techniques to improve convergence.)

Although the simulated annealing based heuristic adopted ~~the~~ a two-step strategy, it is intrinsically different from the greedy heuristic [5] in that it always has the potential to find the true optimal. For the greedy heuristic, the second step can only regroup the circles but not to change the existing circles. This is one of the major reasons for getting only a sub-optimal solution. The simulated-annealing based second step heuristic provides a chance to change the circles so it can jump out of ~~the~~ traps created by local minima in the search space.

4.2 Greedy Heuristic for the Multihop ~~Method~~ Connections

A greedy heuristic is proposed for the multihop method. It puts all the traffic on circles sequentially, and then it applies the following algorithm:

```
while (the number of ADMs and the number of wavelengths can be reduced) {
        Establish connection on the shortest path;
        Wavelength_Combining();
        Segmen_Swapping();
}
```

In the above psudo code, the Wavelength_Combining function checks the? two wavelengths link by link. If the total load on any link will not exceed the wavelength capacity, then it combines them. The Segment_Swapping function finds the underutilized links in different wavelengths and combines them into one wavelength through segment swapping.

5 Illustrative Numerical Results and Comparisons

5.1 Single-Hop ~~Approach~~ Case (This implies that you are going to do Multi-hop case later. But you deleted that section. So change the title to 5.1 Single-Hop Case: Uniform Traffic and the next section 5.2 Single-Hop Case: Non-uniform Traffic)

5.1.1 Uniform Traffic

The uniform-traffic case has been well studied before in the literature so they provide a good reference to evaluate our algorithms. Table 3 shows the required number of ADMs from the different algorithms for the single-hop case (Formulation 1) for an unidirectional ring. For each value of the grooming ratio (C), the first row shows the lower bound calculated by the algorithm proposed in [5]. The second row shows the result from solving our ILP solver, given half an hour for each value (a question mark means that the ILP solver failed to obtain a feasible solution within half an hour). The third row shows the result from our simulated-annealing heuristic, and the fourth row shows the result from the greedy heuristic in [5]. The simulated-annealing algorithm was run for 30 trials and the best result was chosen. Table 4 shows comparison results for the bidirectional ring.

We noticed that, most of the time, the simulated-annealing approach achieves better results than the greedy heuristic. Sometimes, it even reaches the lower bound. Even for the one case where the greedy method ~~showed~~ gave a better result (N=16, C=48), we believe that the simulated-annealing algorithm might have done a better job if it ~~was~~ were given more time. In this study, all algorithms started from the same network configurations (step 1 heuristic results), but the simulated-annealing algorithm can always be started from the greedy result if we choose to do so and this will guarantee equal or better results. ~~To calculate all the simulated annealing results in the Table 3, the~~ The computational time for all 30 trials (see Simulated annealing results in Table 3) was a little less than 100 minutes on a 200 MHz Pentium machine running Windows NT. ~~The fact that the simulated-annealing algorithm outperforms the simple greedy algorithm is not surprising since it tried more possibilities and consumed more computational time.~~ (You cannot compare the these two: SA was applied to single-hop and Greedy to Multi-hop. We have apples and oranges, don't we?) In [4], the authors provided a more elaborate~~d~~ algorithm for the special case of uniform traffic on bidirectional rings. Although claimed to be optimal, our simulated-annealing based heuristic does find a better solution for the case N=9 and C=4. (Comment: Are you saying that the result reported in [4] was claimed to be better than SA, and now you feel that SA is at least better for the case of N=9, and C=4?) Our algorithm saved one more ADM. The reason for this difference is that the algorithm in [4] will always try to fill occupied wavelengths first before it examines new wavelength. For this special case (N=9, C=4), 3 wavelengths are needed to carry all traffics and the optimal occurs when two wavelengths are filled with 3 circles and one with 4 circles, which is out of the search space for the algorithm in [4]. However, for our algorithm, this is a natural result. (Comment: Now I am confused. Which one is better? And why? Pl. sit with me and we can re-write this part.)

		N=4	N=5	N=6	N=7	N=8	N=9	N=10	N=11	N=12	N=13	N=14	N=15	N=16
C=3	Lower Bound	6	11	15	21	29	36	45	56	66	78	92	105	120
	ILP	7	12	18	28	46	?	?	?	?	?	?	?	?
	Simulated Annealing	7	12	17	21	31	36	48	57	69	78	95	105	124
	Greedy	7	12	17	26	35	44	56	67	81	98	113	131	152
C=4	Lower Bound	6	10	15	21	28	36	45	55	66	78	91	105	120
	ILP	7	10	15	27	31	?	?	?	?	?	?	?	?
	Simulated Annealing	7	10	15	21	28	36	45	55	66	78	91	105	120
	Greedy	7	11	17	23	30	37	48	60	72	84	99	112	130
C=12	Lower Bound	4	5	9	11	15	18	23	28	33	39	46	53	60
	ILP	4	5	9	13	18	?	?	?	?	?	?	?	?
	Simulated Annealing	4	5	9	12	16	18	24	30	36	39	49	57	64
	Greedy	4	5	10	13	18	19	27	33	41	49	56	69	73
C=16	Lower Bound	4	5	6	10	12	16	18	23	28	33	37	42	48
	ILP	4	5	6	11	14	18	?	?	?	?	?	?	?

	Simulated Annealing	4	5	6	11	14	18	20	26	33	37	42	46	57
	Greedy	4	5	6	13	15	20	21	30	35	42	48	58	65
C=48	Lower Bound	4	5	6	7	8	9	10	15	17	19	21	26	29
	ILP	4	5	6	7	8	9	10	?	?	?	?	?	?
	Simulated Annealing	4	5	6	7	8	9	10	16	19	22	24	31	37
	Greedy	4	5	6	7	8	9	10	19	23	24	25	31	34
C=64	Lower Bound	4	5	6	7	8	9	10	11	15	18	20	22	24
	ILP	4	5	6	7	8	9	10	11	?	?	?	?	?
	Simulated Annealing	4	5	6	7	8	9	10	11	15	19	22	25	28
	Greedy	4	5	6	7	8	9	10	11	15	25	26	27	28

Table 3. Results from different approaches to solve the traffic-grooming problem in an unidirectional ring with uniform traffic and single-hop connections. Question marks represent the cases where the ILP solver could not find a feasible solution within a half-hour time limit. Note that the simulated-annealing algorithm reaches better results than the greedy algorithm, even reaching the lower bound sometimes. Shaded data means that all traffic can be carried on one wavelength, so no "traffic grooming" is necessary. Lightly shaded data indicates the only situation where Greedy was found to outperform simulated annealing in our experiments.

5.1.2 Non-Uniform Traffic

For handling non-uniform traffic, we first show an example, which is small enough to be solved by an ILP solver in a reasonable amount of time. We picked a 4-node unidirectional-ring network with a random traffic matrix: {{0, 1, 8, 4}, {12, 0, 3, 9}, {1, 2, 0, 2}, {4, 1, 7, 0}}. (Comment: Show this trafficmatrix in matrix format and number the nodes). For example, in this traffic matrix, if nodes are numbered 0 through 3, then the traffic demand from node 1 to node 3 is 9 units. The grooming ratio C (or wavelength capacity) of this network is chosen to be 3. We ~~run~~ ran all the three programs, i.e., ILP, Simulated Annealing, and Greedy. After a 6-hour time limit, ILP gives the result: 15 wavelengths and 31 ADMs (it may not be optimal); Simulated Annealing gives the same result in about 2 seconds; while Greedy gives 33 ADMs in negligible time. (Comment: List these items) Our experiment indicates that the ILP usually cannot handle networks larger than 6 nodes when given non-uniform traffic. Results from simulated-annealing are shown in Fig. 3. In the figure, each wavelength is drawn as three lines (recall that C=3) representing the three circles. The four nodes on the ring are denoted as node 0~3. As an example, the 8 units of traffic from node 0 to node 2 are carried by wavelength 4, wavelength 9, and part of wavelength 7 (timeslots 2 and 3) (shown in bold in Fig. 3).

Notice that the traffic matrix is highly asymmetric which is very ~~practical in~~ realistic representation of today's data networks and is very different from most of the previous work on traffic grooming. In the above example, suppose the wavelength capacity is OC-3, then traffic demand from node 0 to node 2 equals OC-8, which can be two OC-3 and two OC-1 connections (as was shown in Fig. 3). One demand may have to be transmitted on different wavelengths if needed, e.g., the OC-8 traffic from a single user may be transmitted over three OC-3 wavelengths.

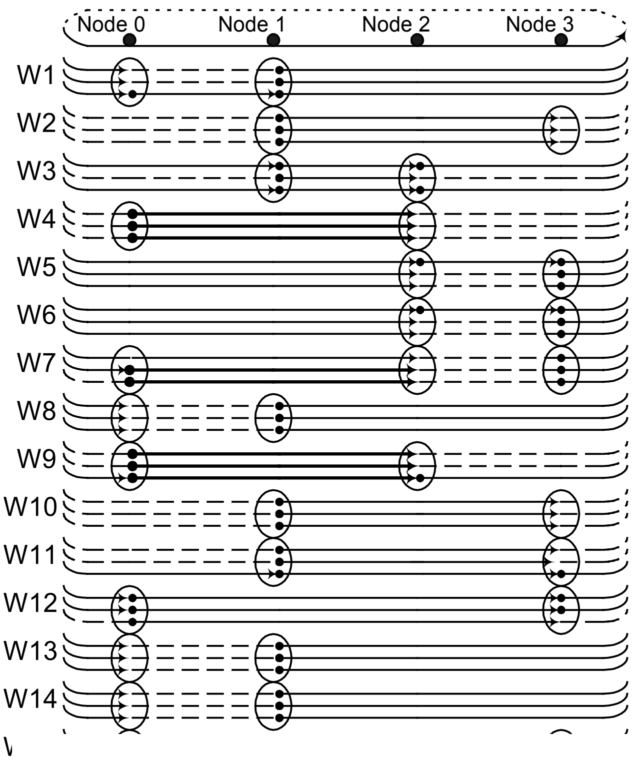


Figure 3. Non-uniform traffic example. Dots and arrows represent the start and the end of a connection. Circles represent ADMs.

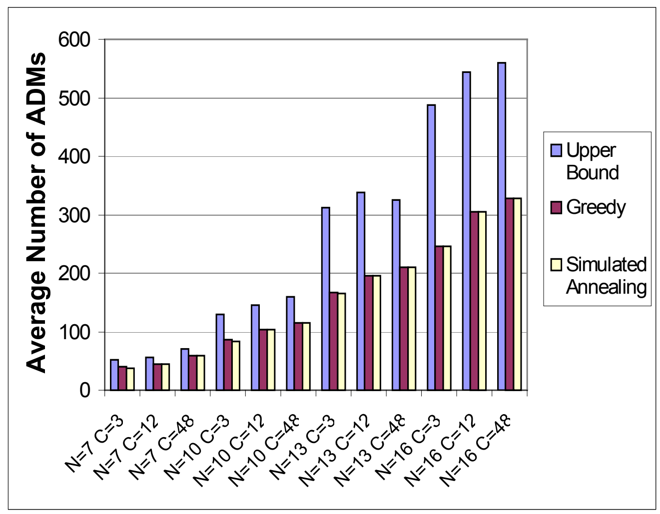


Figure 4. Statistical result-comparison for non-uniform traffic on a bidirectional ring.

Figures 4 shows a statistical ~~result~~ comparison~~s~~ of results for the bidirectional ring. The results are calculated in the following way: for each ring size and each wavelength capacity, 30 random traffic matrices were generated. The traffic demand between any node pair is uniformly distributed between 0 and twice wavelength capacity (t_{ij} = rand(0, 2×C)). Three values are calculated for each traffic matrix, namely, the upper bound (no grooming), result from the greedy approach, and result from the simulated-annealing approach. Then, the average number of ADMs is shown in the figures for each approach.

These -results show that both traffic grooming algorithms achieved very good savings. Although still visible in some cases, but the benefit of simulated-annealing based approach is not that significant. One reason is that the traffic load given to the network is much heavier and they are unregulated. Unregulated traffic causes "bubbles" (unusable segments) in single-hop networks. The two reasons combined to bring the number of circles to tens and even hundreds, this in turn increases the searching space dramatically. By increasing the computation time, this problem can be partially resolved. (Comment: Needs rewriting of this last sentence)

Why did you remove the multi-hop case? Would you rather discuss only the single-hop case and skip completely the Multi-hop case? Both the reviewers raised a question about the different way these two cases are treated. It is worthwhile that we talk about this.

6 Conclusion

In this study, we first provided the formal mathematical specifications of the traffic-grooming problem in several ring networks, i.e., single-hop and multihop (with a single hub) cases of unidirectional and bidirectional rings. Then, we proposed a simulated-annealing-based traffic-grooming algorithm for the single-hop case and a greedy heuristic for the multihop case. The simulated-annealing based heuristic overcomes the sub-optimal problem caused by the two-step strategy in previous greedy heuristic. We believe that the simulated-annealing algorithm has reached the best result so far. It was also showed that, for non-uniform traffic, the greedy approach usually is good enough when compared with the simulated-annealing algorithm. The multihop approach could achieve more ADM savings when the grooming ratio is neither too small nor too large, but it usually results in more wavelength usage due to the prolonged connection length in our algorithm and it is expected to be improved in our future work.

Here we should also talk about the benefit of this study in the longer term. Why is this study necessary? Just to save money? What is the impact of this on scalability? Reliability? Etc.

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