REDUCING ELECTRONIC MULTIPLEXING COSTS IN UNIDIRECTIONAL SONET/WDM RING NETWORKS VIA EFFICIENT TRAFFIC GROOMING

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Abstract

We develop traffic grooming algorithms for unidirectional SONET/WDM ring networks. The objective is to assign low rate circuits to wavelengths in a way that minimizes the total cost of electronic equipment (e.g., the number of SONET Add/Drop Multiplexers (ADMs)). When the traffic from all nodes is destined to a single node, and all traffic rates are the same, we obtain a solution that minimizes the number of ADMs. In the more general case of all-to-all uniform traffic we obtain a lower bound on the number of ADMs required, and provide a heuristic algorithm that performs close to that bound. Finally, we consider the use of a hub node, where traffic can be switched between different wavelengths, and obtain an optimal algorithm which minimizes the number of ADMs by efficiently multiplexing and switching the traffic at the hub. Moreover, we show that any solution not using a hub can be transformed into a solution with a hub using fewer or the same number of ADMs.

I. Introduction

Much of today's physical layer network infrastructure is built around Synchronous Optical Network (SONET) rings. Typically, a SONET ring is constructed using fiber (one or two fiber pairs are typically used in order to provide protection) to connect SONET Add Drop Multiplexers (ADMs). Each SONET ADM has the ability to separate a high rate SONET signal into lower rate components. For example, four OC-3 circuits can be multiplexed together into an OC-12 circuit and 16 OC-3's can be multiplexed into an OC-48. The recent emergence of Wavelength Division Multiplexing (WDM) technology has resulted in the ability to support multiple SONET rings on a single fiber pair. Consider, for example, the SONET ring network shown in figure 1, where each wavelength is used to form an OC-48 SONET ring. This network is used to provide OC-3 circuits between nodes and SONET ADMs are used to combine up to 16 OC-3 circuits into a single OC-48 that is carried on a wavelength. With WDM technology providing as many as 32 wavelengths on a fiber, 32 OC-48 rings can be supported per fiber pair instead of just one. This tremendous increase in network capacity, of course, comes at the expense of needing additional electronic multiplexing equipment. With the emergence of WDM technology, the dominant cost component in networks is no longer the cost of fiber but rather the cost of electronics.

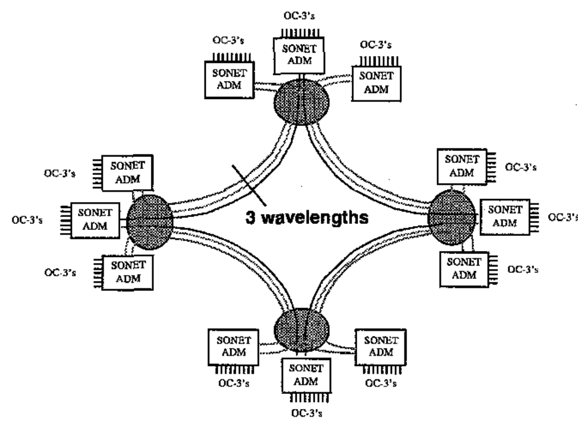

Figure 1. SONET/WDM rings.

The SONET/WDM architecture shown in figure 1 is potentially wasteful of SONET ADMs because every wavelength (ring) requires a SONET ADM at every node. An alternative architecture, shown in figure 2, makes use of WDM Add Drop multiplexers (WADMs) to reduce the number of required SONET ADMs. A WADM at a given node is capable of dropping and adding any number of wavelengths at that node. In order for a node to transmit or receive traffic on a wavelength, the wavelength must be added or dropped at that node and a SONET ADM must be used. Therefore, with a single WADM at each node it is no longer necessary to have a SONET ADM for every wavelength at every node, but rather only for those wavelengths that are used at that node. Therefore, in order to limit the number of SONET ADMs used, it is better to groom traffic in such a way that all of the traffic, to and from a node, is carried on the minimum number of wavelengths. Notice that this is not the same as minimizing the total number of wavelengths used, a problem that has received much attention recently [GER96].

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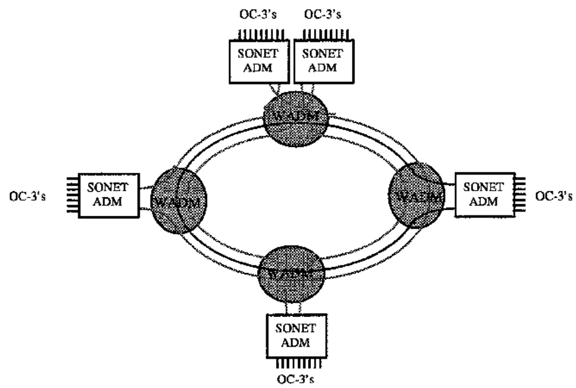

Figure 2. Using WADMs to reduce the number of SONET ADMs.

In this paper we consider a unidirectional WDM ring network with N nodes numbered 1, 2, ..., N distributed on the ring in the clockwise direction. Each node has one WADM and D_i SONET ADMs. Each SONET ADM is used to aggregate **g** low rate circuits onto a single high rate circuit that is carried on a wavelength. For example, each SONET ADM can be used to multiplex 16 OC-3's (g=16) or 4 OC-12's (g=4) onto a single OC-48. The traffic requirement is for r_{ij} low rate circuits between each pair of nodes (i, j), for any i≠j. With a WADM at a given node, a wavelength can bypass that node if there is no traffic to be received or transmitted from that node, which results in the saving of a SONET ADM. The objective is to minimize the total number of SONET ADMs used in the network to support all of the traffic by intelligently assigning traffic to wavelengths.

Most previous work in this area has focused on the virtual topology design problem for known and fixed (static) traffic patterns [BFG90, RS96]. The general problem of virtual topology design can be formulated as a mixed integer programming problem which is known to be difficult. Heuristic algorithms have been developed to design virtual topologies that minimize the number of wavelengths, delays or blocking probabilities.

While the general topology design problem is known to be intractable, the traffic grooming problem is a special instance of the virtual topology design problem for which, in certain circumstances, a solution can be found. For example, [SGS98] considers traffic grooming for a bi-directional ring with uniform traffic. In this paper we describe solutions for unidirectional rings. In Section II we consider the simple case of an egress node from and to which all of the traffic is directed and in Section III we consider the more general case of all-to-all traffic in a ring network. In Section IV we consider the case of a ring network with a hub node, where traffic can be switched between different SONET rings using a SONET cross-connect. We summarize the results with remaining issues in Section V.

II. Egress Node

We start by considering a very simple case of the traffic grooming problem, where all of the traffic on the ring is destined to a single node that we call the egress node. This case is of particular importance in access networks where traffic from the various access nodes on the ring is all destined to the telephone company's central office[1]. Denote the egress node as node 0 and assume that it lies between node N and node 1, as shown in figure 3.

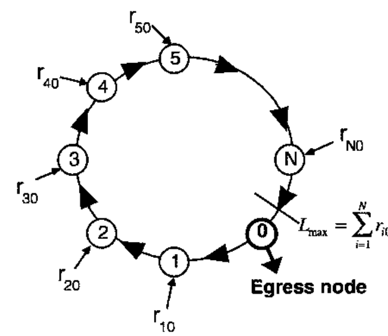

Figure 3. Unidirectional ring network with an egress node

The traffic rate between nodes i and j takes on positive values only when j=0 and i = 1..N. Since the ring is unidirectional, all traffic has to go though the link between node N and node 0. Therefore, link (N, 0) carries the heaviest load $L_{max} = \sum_{i=1}^{N} r_{i0}$. Hence the minimum number of wavelength required to support this load is, $W_{min} = \lceil L_{max}/g \rceil$. Without loss of generality, we can assume $r_{i0} < g$ for all i for the rest of this section [MC98]. The objective of the traffic grooming problem is to assign circuits to wavelengths in such a way that the total number of SONET ADMs in the network is minimized. It was shown in [MC98] that for general values of r_{i0} the problem is NP-complete, hence, the general traffic grooming problem with arbitrary values of r_{ij} is also NP-complete. However, in the special case where all of the r_{i0} are equal (i.e., r_{i0} = r for all i) an exact solution for the minimum number of ADMs required and how they should be assigned to circuits can be found.

A. Special case: $r_{i0} = r < g$ for all i

It is easy to show that, in this case, there exists a minimum ADM solution that does not require traffic from a node to be split onto multiple wavelengths. That is, traffic from any node to the egress node can be carried on a single SONET

[1] For simplicity of presentation, we discuss the egress node case. However, this discussion also apply to the case of an ingress node where all of the traffic comes from one node as well as the case of a single node from and to which all of the traffic is destined.

ring. This is because splitting a node's traffic onto multiple rings requires at least two ADMs (one ADM per ring). Hence, for any assignment with some nodes' traffic being split, an alternative assignment can always be found where traffic from each of those nodes is carried on a separate wavelength using just two ADMs (one at that node and one at the egress node). Of course, the alternative assignment may not use the minimum number of wavelengths, but it will require no additional ADMs. Since, without splitting traffic, we can groom the traffic from at most $\lfloor g/r \rfloor$ nodes on one SONET ring, the number of SONET rings needed is

$$W = \left\lceil \frac{N}{\lfloor g/r \rfloor} \right\rceil .$$

Hence, the minimum number of SONET ADMs M_{min} = N+W, because one ADM is needed at every node (since exactly one wavelength is dropped at each node) plus at the egress node one ADM is needed for each wavelength (since all wavelengths are dropped at the egress node). Note that the resulting number of SONET rings may be larger than the minimum number of rings required (taking the case N=4, g=7, and r=5 as an example). Next we provide a solution that uses the minimum number of ADMs required subject to using the minimum number of SONET rings (or wavelengths).

B. Minimizing the number of ADMs subject to the minimum number of wavelengths

Since, the solution will use the minimum number of wavelengths, W_{min}, the total number of ADMs required will include W_{min} ADMs at the egress node (one for each ring), plus the total number of ADMs at all the regular nodes. Since we are now restricted to using the minimum number of wavelengths, traffic from a node may have to be split onto multiple rings and each node will have one ADM for each SONET ring used to carry its traffic. We say that a *split* occurs when some traffic from a node is divided onto two rings. For example, if traffic from a node is divided onto three rings two splits have occurred. Clearly, for each traffic split, a new ADM is needed. Each node needs one ADM plus an additional ADM for each traffic split at that node. Hence the total number of ADMs needed is equal to W_{min} + N + S where S is the total number of traffic splits over all nodes. Therefore, the minimum number of SONET ADMs subject to minimum number of SONET rings is achieved by minimizing the total number of traffic splits.

Obviously, if all of the traffic can fit on the W_{min} rings with no need for traffic splitting then we have the minimum ADM solution. For each ring with no split traffic, the maximum link load is $L_{ns} = \lfloor g/r \rfloor * r$. Let W_{ns} be the maximum number of rings containing no split traffic, with L_{ns} circuits each. Since, the remaining (W_{min}-W_{ns}) rings contain at most g circuits, we have

$$W_{ns} * L_{ns} + (W_{min} - W_{ns}) * g \geq L_{max} = r * N$$

where $W_{min} = \lceil r*N / g \rceil$. Therefore, the maximum number of rings with no split traffic is given by,

$$W_{ns} = \min\left\{ W_{min}, \left\lfloor \frac{g * W_{min} - L_{max}}{g - L_{ns}} \right\rfloor \right\} .$$

If W_{ns} = W_{min} all of the traffic can be accommodated without any need to split traffic and the optimal solution is found. Hence, in the following we focus on the case where W_{ns}<W_{min}. In this case all of the traffic cannot be accommodated without the need for traffic splitting which implies that there exists at least one traffic-split. The algorithm below assigns circuits to wavelengths in a way that minimizes the number of traffic splits and hence the number of ADMs. The algorithm works for arbitrary positive integer values of g and r and is not restricted to the case of r<g. The algorithm is iterative with the following three steps:

Algorithm:

Step 1: Fill each of W=W_{min} rings with the unsplit traffic from $\lfloor g/r \rfloor$ nodes. The remaining capacity for each of the W rings is g_1= g - $\lfloor g/r \rfloor$ r < r and the traffic from N_1=N- $\lfloor g/r \rfloor$ W nodes still needs to be assigned. Notice that N_1 must be less than W.

Step 2: Fill the remaining capacity g_1 of each of N_1 rings by the traffic from each of the remaining N_1 nodes. The remaining traffic of each of N_1 nodes becomes r_1 = r-g_1.

Step 3: Now, there are W_1=W-N_1 rings that each has capacity g_1 left, and N_1 nodes that each has traffic r_1 left. Update W:=W_1, g:=g_1, N:=N_1, and r:=r_1 and repeat Steps 1-3 until the traffic from all nodes has been assigned (i.e., r_i=0).

Proof of optimality is based on showing that any other assignment can be converted into the one given by this algorithm without using additional ADMs. The proof is omitted due to space limitation[2]. Next we consider the more general case of a ring network with traffic between all node pairs.

III. All-to-All Uniform Traffic

In this section we consider the more general case of all-to-all traffic in the ring. Since the solution to the general problem is NP-complete, we consider a more limited case of uniform traffic. That is, r_{ij} = r for all i≠j, where r is some positive integer representing the number of low rate circuits between each pair of nodes. Again, the traffic granularity, g, is equal to the number of low rate circuits that can fit on a single SONET ring (or wavelength).

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[2] The algorithm and its optimality proof are provided by Zhuangbo Tang of AT&T, 101 Crawfords Corner Rd., Holmdel, NJ 07733.

We begin with a few definitions that will help our discussion. Let the node load be the number of low rate circuits originating or terminating at a node, then $L_d = (N-1)\,r$. Let the link load be the number of low rate circuits traversing a link. Clearly, $L = N(N-1)r/2$, because there are $N(N-1)/2$ node pairs each with r circuits between each pair. Now a lower bound on the number of ADMs needed is given by $M \geq \lceil L_d / g \rceil N$. This number is simply the minimum number of wavelengths required to carry the traffic to and from a node multiplied by the number of nodes, since an ADM is needed when a wavelength is dropped at a node requires an ADM. Of course this minimum may not be achievable. A tighter lower bound is provided in the next section. The minimum number of wavelengths required to carry all of the traffic in the network is equal to the link load divided by g, i.e., $W_{min} = \lceil L/ g \rceil$. This minimum can be achieved by dropping every wavelengths at every node and would require W_{min} ADMs at each node yielding an upper bound on the minimum number of ADMs, hence, $M \leq W_{min} * N$.

A. Lower Bound on number of ADMs (r=1)

We obtain a lower bound on the number of ADMs by finding the most efficient ways to carry traffic between nodes on the same wavelength. That is, we determine the maximum average number of circuits that can be supported by an ADM, and use that number to lower bound the number of ADMs required in the network. In this section we restrict our discussion to the case of r=1, however our approach can be generalized to other values of r. For a given wavelength, with n nodes (and n ADMs), we classify the traffic into two classes. In the first class, which we call "all-to-all traffic" a circuit is set-up between every pair of nodes. With n nodes on the wavelength, the total number of circuits is n(n-1)/2 using n ADMs. Since at most g circuits can be supported on a wavelength, n(n-1)/2, must be less than or equal to g. In the second class, which we call "cross traffic", the nodes on the wavelength are divided into 2 groups of size n_1 and n_2 where $n_1 + n_2 = n$, and a circuit is set-up between every node in one group and every node in the other group. For "cross traffic" the link load is $n_1 * n_2$, and again this load must be less than or equal to g. For a given value of n, the link load is maximized when $n_1 = \lfloor n/2 \rfloor$. Note that with all-to-all traffic among a group of nodes all of the circuits between members of those groups are established. While with cross traffic, only those circuits between members of the two groups are established but circuits between the nodes within each of the groups remain unassigned.

Also notice that for a given number of ADMs, "all-to-all traffic" assignments can carry more circuits than "cross traffic" assignments. This is because with cross traffic on average n/4 circuits are supported per ADM while with all-to-all traffic on average (n-1)/2 circuits are supported per ADM. For particular values of g, this concept can be used to generate a lower bound on the number of ADMs. For example we demonstrate this approach for g=4.

<u>Example:</u> g=4 (e.g., OC-12 circuits on an OC-48 ring)

It can be shown that with g=4 the most efficient circuit assignment requires 1 ADM per circuit. There are three ways in which circuits can be assigned to wavelengths requiring 1 ADM per circuit:

- 3 nodes per wavelength with all-to-all traffic between the nodes, for a link load of 3 using 3 ADMs.
- 4 nodes with cross traffic between pairs of nodes, for a link load of 4 using 4 ADMs.
- 4 nodes with all-to-all traffic between 3 nodes and cross traffic between the fourth node and one of the three nodes, for a link load of 4 using 4 ADMs.

It can be shown that any other way of assigning circuits to wavelengths would use more ADMs per circuit on average. Notice, also, that due to the maximum link load of 4 circuits per wavelength, many assignments are not possible. For example all-to-all traffic among four nodes results in a link load of 6 which cannot be supported on a single wavelength.

In all three cases, we can support one circuit per ADM on average. It can be easily determined that no other assignment can be more efficient. Hence, no matter how circuits are assigned, we need at least one ADM per circuit, leading to the following lower bound on the number of ADMs.

LB (g=4) = (total link load L circuits) / (1 ADM/circuit)
= N(N-1)/2.

Similarly, this approach can be extended to obtain lower bounds for other values of g. A plot of this lower bound with g=16 is shown in figure 4. Next we discuss heuristic algorithms that attempt to assign circuits to rings in order to minimize the number of ADMs required.

B. First Heuristic Algorithm

This algorithm attempts to maximize the number of nodes that only require one ADM, then of the remaining nodes maximize the number of nodes with two ADMs and so on. A node needs k ADMs if it is on k wavelengths. Let, M_k be the number of nodes with k ADMs (k=1 to W_{min}). Then, the algorithms maximizes M_1, then maximizes M_2 ..., maximizes M_{wmin-1}. Clearly, the motivation of the algorithm is that by maximizing the number of nodes that use fewer ADMs we ultimately reduce the total number of ADMs used. It can be shown that M_i, i = 1, 2, ..., W_{min}, is given by [MC98],

$$M_i = \max \{H \text{ s.t. } \textstyle\sum_{h=0 \text{ to } H}(N-1-h) \leq i*g\} - \sum_{k=1 \text{ to } i-1} M_k.$$

The algorithm fills each wavelength before assigning traffic to a new wavelength, hence it always uses the minimum number of wavelengths W_{min} and is optimal for $W_{min} \leq 2$. For cases where $W_{min} > 2$, the algorithm is clearly not optimal. This is because by maximizing the number of nodes with only a single ADM, the algorithm forces all other nodes to use their ADMs inefficiently. However, the algorithm results in substantial savings over a system where all wavelengths are dropped at all nodes as would be the case if no WADMs were used. The next algorithm, however, results in much more substantial savings in ADMs.

C. Second Heuristic Algorithm

This algorithm attempts to assign nodes to wavelength by efficiently packing the wavelengths. The algorithm is as follows:

Let $n = \lfloor \sqrt{g} \rfloor$ and divide N into $G = \lceil N/n \rceil$ groups of n nodes, where the last group has only n_l = (N mod n) nodes. We assign different pairs of groups to each wavelength with cross traffic between the two groups. By design, the cross traffic between two groups of size $n = \lfloor \sqrt{g} \rfloor$ is less than g circuits and can fit on a wavelength. In order to accommodate all of the cross traffic between the G groups a total of G(G-1)/2 wavelengths are needed. The remaining traffic is the all-to-all traffic within each group and is fit on the existing wavelengths if possible, otherwise on additional wavelengths. We illustrate the idea with the following example.

Example: g=4 (OC-12's on an OC-48 ring)

Since g=4 we divide the N nodes into groups of 2 and have the following two cases:

1) N even => G = N/2

G(G-1)/2 wavelengths can be filled with cross traffic between different pairs of groups. The all-to-all traffic would require additional $\lceil G/4 \rceil = \lceil N/8 \rceil$ wavelengths with four groups on each wavelength. Hence, each node requires G=N/2 ADMs for a total of $N^2/2$ ADMs.

2) N odd => G = (N+1)/2

The first G-1=(N-1)/2 groups have 2 nodes and the last group has only 1 node. (G-1)(G-2)/2 wavelengths can be filled with cross traffic between different pair of groups from the first G-1 groups. An additional $\lceil (G-1)/2 \rceil$ wavelengths can be used for cross-traffic with the node from the last group, where each wavelength has two groups (four nodes) from the first (G-1) groups and the node from the last group. If one of the wavelength in the previous step is not full (i.e., (G-1)/2 is not an integer), it can be used for the all-to-all traffic within 2 of the first G-1 groups. The remaining all-to-all traffic can be handled by assigning 4 groups to each wavelength. So the number of ADMs at each node is G = (N+1)/2 except for the last node which uses $\lceil (G-1)/2 \rceil = \lceil (N-1)/4 \rceil$ ADMs. Hence, the total number of ADMs used when N is odd equals $(N-1)(N+1)/2 + \lceil (N-1)/4 \rceil = (N^2-1)/2 + \lceil (N-1)/4 \rceil$.

Putting it all together the total number of ADMs required with g=4 is,

$$\#ADM\ (g=4) = (N-1 \bmod 2) * N^2/2 + (N \bmod 2) * ((N^2-1)/2 + \lceil (N-1)/4 \rceil).$$

In both cases, since all the wavelengths except the last one are filled with 4 circuit, the resulting assignment only uses W_{min} wavelengths. However, for general g the algorithm may result in number of wavelengths that is more than W_{min}, but not too far from W_{min}.

D. Performance Comparison

In figure 4 we plot the number of ADMs vs. the number of nodes on the WDM ring for g=16 (OC-3 circuits on an OC-48 ring). Plotted in the figure are the lower bound in section III, the number of ADMs used by the first and second heuristic algorithms, the number of ADMs that would be used if all wavelengths were dropped at every node (no grooming) and lastly, the best solution that we have been able to find via exhaustive search. As one can see from the figure, the result of the second heuristic algorithm are very close to the lower bound and almost mirror the best solution. In figure 5 we plot the percentage of ADM savings that can be achieved using the second heuristic algorithm over dropping all of the wavelengths at every node. As one can see from the figure, the most savings are achieved when g=1. This, in fact, is a trivial case because each wavelength can only carry the traffic between two nodes and hence should only be dropped at those two nodes. It is interesting to note, however, that in general it appears that greater savings can be achieved with smaller values of g. This is due to the fact that when g is small each wavelength can be filled with traffic from just a few nodes while when s is large it takes traffic from many nodes to fill a wavelength.

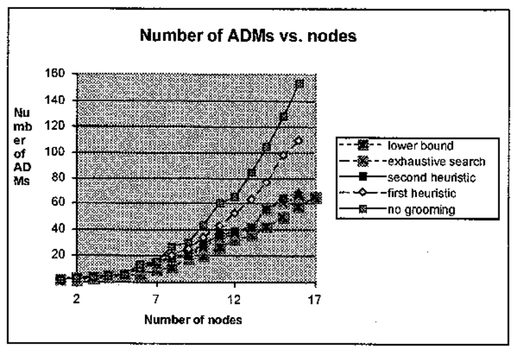

Figure 4. Comparison of heuristic algorithms (g=16, r=1).

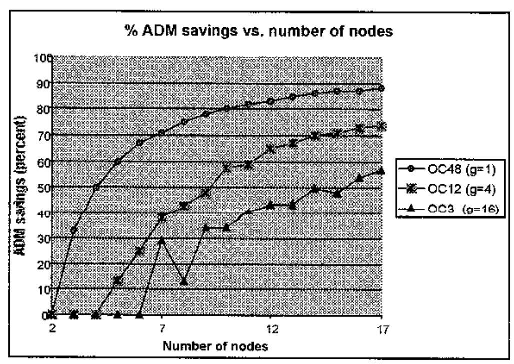

Figure 5. ADM savings due to grooming.

IV. Using a hub with a SONET cross-connect

Here we allow one node to have a SONET cross-connect, say node N. We denote this node as a hub. A hub can take a circuit from one SONET ring and switch it to another ring. Again, we focus on the case with all-to-all uniform traffic where $r_{ij} = r$ for all $i \neq j$, and we assume that $L_d = r\,(N-1) \leq g$ (i.e., all of the traffic to and from a node can be carried on one wavelength).

Theorem 1: The optimal solution with one hub is either as good as or better than the optimal solution not using a hub in terms of minimizing the total number of ADMs.

Proof: Let node N be the hub node and consider any solution where node N is not on every wavelength, there exists a corresponding solution with the hub on every wavelength using the same or fewer ADMs. Since the hub node is also a regular node, every node has traffic going from and to the hub. Therefore each of the nodes on those wavelength(s) without the hub must have at least two ADMs (one on some wavelength without the hub and one on some wavelength with the hub). Since the traffic from each node can be carried on a separate wavelength through the hub using just two ADMs, any assignment not using the hub can be transformed into an assignment with the hub present on every wavelength using no additional ADMs. Of course, this solution does not use the minimum number of wavelengths. A further reduction in the number of ADMs can be obtained by packing the wavelengths optimally as we show next for the case of r=1.

A. Optimal Algorithm when r=1 and $L_d = N-1 \leq g$

With the same argument as used for the egress node case [MC98], it can be shown that there exists a minimum ADM solution such that no traffic to and from a node is split onto two rings. This means that only one ADM is needed for every node except the hub, which has W ADMs, where W is the number of wavelengths used. This reduces the problem to minimizing W, which is equivalent to maximizing the number of nodes carried on a wavelength. Let K be the maximum number of nodes on a wavelength (including the hub node), then each wavelength with K nodes needs to carry two types of traffic. Traffic within the K nodes that does not need to go through the hub, of which there are K(K-1)/2 circuits; and traffic between the K-1 (excluding the hub) nodes and the remaining N-K nodes not on the same wavelengths of which there are (K-1)(N-K) circuits. This combined traffic load must be less than or equal to g, hence, K(K-1)/2 + (K-1)(N-K) must be less than g. Expanding this expression and using the quadratic formula we obtain,

$$K = \left\lfloor N + \frac{1}{2} - \frac{\sqrt{4N^2 - 4N - 8g + 1}}{2} \right\rfloor.$$

It can be shown that as long as K is less than N (K=N corresponds to the case of W=1 where all the traffic can be carried on one wavelength), the above expression yields a real value for K. The corresponding number of wavelength is $W = \lceil (N-1)/(K-1) \rceil$ and the corresponding number of ADMs M = W+N-1, which is optimal.

V. Conclusions

This paper studies the problem of assigning circuits to wavelengths with the objective of minimizing the cost of electronic multiplexing equipment. In particular, we consider the special case of SONET/WDM ring networks, and attempt to minimize the number of SONET ADMs. While the general problem is NP-complete, we are able to obtain encouraging results for some special cases where circuit rates are the same. In particular, in the case of an egress node we obtain the solution that minimizes the number of ADMs as well as a solution that minimizes the number of ADMs subject to using the minimum number of wavelengths. For all-to-all traffic we obtain a lower bound on the number of ADMs and simple heuristic algorithms that performs close to that bound. Finally, we consider the use of a hub node where traffic can be switched between the SONET rings and show that, for the case where all of the traffic to and from a node can be carried on a single wavelength, a solution using a hub node always requires fewer or the same number of ADMs compared to a solution not using a hub node. We also obtain the optimal solution using a hub node and the corresponding minimum number of ADMs.

Yet, the work of this paper is preliminary and considers only a select number of special cases. Many interesting problems remain to be solved. For example, we still need to find the optimal solution and the optimal algorithm in the all-to-all uniform traffic case. Also, the benefits of using one or more hubs with a cross-connect require further study. Ultimately, this work should be extended to the more general case of non-uniform traffic and other forms of electronic multiplexing (e.g., ATM switch).

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