Grooming of Multicast Sessions in WDM Ring Networks*

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ABSTRACT

In this paper, we address the problem of routing and wavelength assignment of multicast sessions with sub-wavelength traffic demands. We consider this problem in the scenario of WDM ring networks. In order to support multicasting, individual nodes need to have the capability to duplicate traffic. We consider two different node architectures which perform the duplication in optical and electronic domain, respectively. As traffic duplication at the electronic level is much more expensive than the optical alternative, we study the problem of assigning routes and wavelengths to the multicast sessions so as to minimize electronic copying. The solution to this problem can be divided into three phases - 1. routing of multicast sessions, 2. construction of circles by grouping non-overlapping arcs and 3. grouping these circles onto wavelengths. We propose a heuristic algorithm which implements the routing as well as circle construction phases simultaneously and then groups the circles. We present extensive simulation results to show that our approach leads to much lesser equipment cost than that obtained by routing each multicast session along its minimum spanning tree and then using the best known heuristic for circle construction.[1]

Keywords: Optical WDM ring networks, Routing and wavelength assignment, Multicast sessions, Optical splitter, Traffic grooming, Circle construction

1. INTRODUCTION

Wavelength Division Multiplexed (WDM) optical networks have come to stay as the backbone of the Internet. With each optical link capable of carrying traffic on several wavelengths, each one of which supports traffic in the Gbps range, the bandwidth offered by a WDM network is of the order of Tbps. However, traffic requested by individual connections are still in the Mbps range. Hence, to utilize the available bandwidth efficiently, several connections will have to be grouped onto the same wavelength. This necessitates strategic routing and wavelength assignment (RWA) of each connection because the traffic carried on any wavelength needs to be converted from optical to electronic form whenever a part of that traffic needs to be switched to another wavelength or has to be added/dropped at some node. The cost of the equipment involved in this opto-electronic conversion is the dominant cost in setting up the network.

The problem of RWA of sub-wavelength demands with the objective of minimizing the network cost, called the “traffic grooming” problem, has been studied widely in the literature. Most of the work in this direction has been focused on ring networks,[1–3] with emphasis on minimizing either the number of wavelengths or the number of Add/Drop Multiplexers (ADMs). Work has also been done with the objective of minimizing the overall network cost,[4,5] taking into account factors other than wavelengths and ADMs, which contribute towards the cost of the network. Almost all of this work is restricted to the study of the all-to-all uniform traffic scenario. Later, research was also directed into addressing the traffic grooming problem in the context of dynamically varying traffic[6,7] as well as non-uniform traffic.[8] Recently, there have also been efforts towards solving the traffic grooming problem for mesh networks. This issue has been addressed in both the static[9,10] as well as the dynamic[11,12] traffic scenario. Dynamic grooming is the problem of routing and assigning wavelengths for a new demand, given the current state of the network, whereas in static grooming the traffic demands are known apriori and all of them have to be assigned routes and wavelengths to minimize required resources (wavelengths and ADMs). Static grooming can also be viewed from the angle of maximizing the throughput given the constraints on resources.

*This work was supported by the Department of Science and Technology, New Delhi, India.

The growth in traffic demand over the Internet is primarily due to the increasing popularity of multicast services such as video conferencing and distance learning. As WDM provides the capacity to support these high-bandwidth services, there is an increasing need to implement multicasting efficiently at the optical layer.[13] Efficient designs have been proposed[14,15] for the architecture needed at each node to support multicasting in wavelength-routed networks. The concept of *light-tree* was introduced[16] in the multicast scenario, which is analogous to the lightpath idea used in the context of unicast traffic. To support light-trees, individual nodes need to be equipped with the capability to duplicate an incoming optical signal into two or more copies. Utilizing this concept of light-trees, the problems of designing a logical topology[17] given a set of multicast demands and, routing and wavelength assignment[18] of these sessions have been studied. Since the node architecture which is capable of light splitting is extremely expensive, the multicast RWA problem has also been addressed in the case wherein this capability is available only at a subset of the nodes in the network.[19] The multicast routing problem has also been studied in the scenario of ring networks.[20] A recent survey of the existing work in multicasting in WDM networks is given in.[21] However, all the existing work in multicast routing assumes that the traffic demand of each multicast session is equal to the bandwidth offered by a single wavelength.

In this paper, we address the problem of multicast routing and wavelength assignment in WDM ring networks. Our work takes into account sub-wavelength multicast demands and to the best of our knowledge, ours is the first such work. In other words, we address the traffic grooming problem in ring networks in the multicast scenario. Firstly, we consider two different node architectures for supporting multicasting of sub-wavelength demands. In one, the traffic duplication is done at the optical layer while the other performs the copy in the electronic domain. Since the cost of optical layer splitting is negligible in comparison to splitting at the electronic level, we study the multicast traffic grooming problem with the objective of minimizing the use of the latter capability. We work under the constraint the traffic demand of each session is one unit. To tackle this problem, we divide the solution into three phases - routing of multicast sessions, circle construction (grouping non-overlapping arcs) and grouping of circles onto wavelengths. We suggest a heuristic approach which performs the routing and circle construction in an integrated manner. This approach leads to much lower network cost than that obtained by implementing the routing and circle construction independently. We present extensive simulation results to substantiate this claim.

The rest of the paper is organized as follows. In Section 2, we outline the node architectures required for supporting multicasting of sub-wavelength demands. The issues involved in routing of multicast sessions in ring networks are described in Section 3. The heuristic algorithm we propose for grooming of multicast sessions is presented in Section 4 and then we provide an example in Section 5 to illustrate the working of our heuristic. Results of all the simulations we conducted to measure the performance of our heuristic are given in Section 6. We finally conclude our work in Section 7 along with some directions for future work.

2. NODE ARCHITECTURE

Multicast is the simultaneous transmission of information from one source to multiple destinations. This is bandwidth-efficient because it eliminates the necessity for the source to send an individual copy of the information to each destination. However, this can be implemented only if the individual nodes have the capability to duplicate incoming traffic and forward it on all the outgoing links. In the case of ring networks, since each node has only one outgoing link, the nodes only need to be able to forward an incoming signal in addition to receiving a copy of the signal. This is known as the Drop-and-Continue (DaC) feature.

One possible node architecture that can be used to support the DaC feature for sub-wavelength demands is the one shown in Fig. 1(a). The Receiver Array (RX) first converts the traffic carried by the incoming wavelengths from optical to electronic domain. The electronic switch then switches traffic among different wavelengths. Finally, the Transmitter Array (TX) converts back the traffic from electronic to optical form and is carried out of the node on the outgoing wavelengths. The setup described above is that of an ordinary electronic groomer. To add the DaC capability, another unit (shown as the *Electronic Add/Drop/Copy* in Fig. 1(a)) is required which duplicates the necessary portion of the Add/Drop traffic. Let us call this the *e-DaC* unit. This unit needs to examine the header of each packet which is being added or dropped at that node and selectively duplicate the packets. This involves extremely high overhead as the e-DaC unit will have to handle an extremely large number

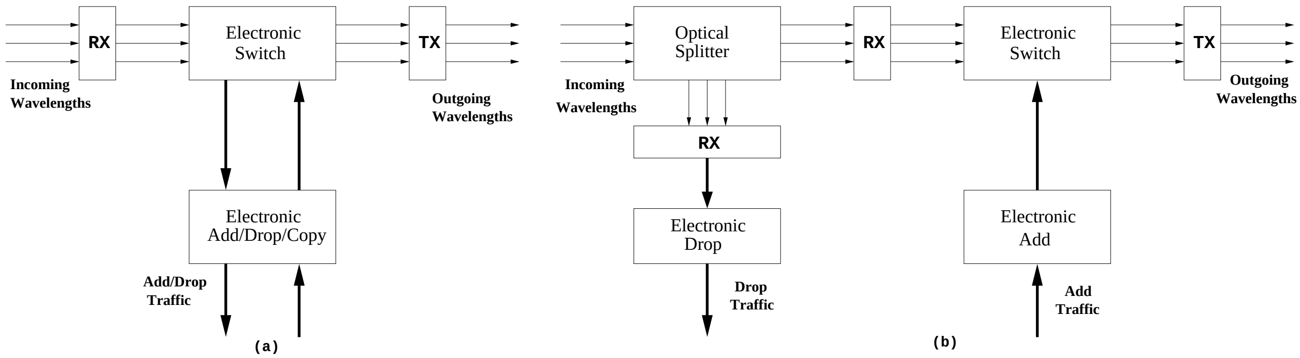


Figure 1. Node architecture which supports multicasting using (a) electronic domain copy (b) optical layer splitting

of packets since the total traffic that needs to be processed at each node is of the order of Gbps. Hence, this node architecture which incorporates the e-DaC unit will be very expensive.

One important point that can be noticed in the above node architecture is that in the case when all the traffic on all the incoming wavelengths needs to be duplicated, the e-DaC unit is redundant as then there is no necessity to examine the header of each individual packet since every packet needs to be duplicated. Clearly, in such a scenario, splitting can be done at the optical layer rather than implementing it at the electronic level. This is the idea behind the design of the second node architecture shown in Fig. 1(b). In this setup (called the *o-DaC* unit), the traffic on all the incoming wavelengths is duplicated by power splitting at the optical layer. Having obtained two copies of the traffic on every wavelength, both the copies are converted to electronic form using Receiver Arrays (RX). All the traffic on one of the copies is completely dropped at that node. The traffic on the other copy is switched along with the add traffic at the node before it is converted back to optical domain and loaded onto the outgoing wavelengths by the Transmitter Array (TX).

The o-DaC node architecture is highly cost-effective in comparison with the e-DaC unit as this obviates the need to examine the header of each packet being added/dropped at a node. Note that optical layer splitting cannot be used irrespective of whether all the traffic on every incoming wavelength needs to be duplicated, as in that case each packet will have to be examined to determine which are the packets that actually need to be forwarded on the outgoing wavelengths. It is also clear from Fig. 1(b) that the o-DaC architecture cannot be utilized at a node if any portion of the add traffic at that node needs to be duplicated. It has to be also noted that the e-DaC architecture significantly simplifies network management in comparison with the o-DaC setup and also, the o-DaC architecture results in power loss. In summary, though the e-DaC unit suffices for traffic grooming in the multicasting scenario, a highly cost-effective alternative would be to also use the o-DaC node architecture at all nodes to groom the wavelengths whose traffic needs to be completely duplicated and no fraction of the add traffic need be replicated.

3. MULTICAST ROUTING

In this section, we provide a brief overview of the issues involved in the routing of multicast sessions in ring networks. For the purpose of our explanation, consider the ring of 10 nodes shown in Fig. 2(a). In this network, 3 possible routes can be assigned to the multicast session with source 1 and destination set $\{5, 8\}$ as shown in Fig. 2(b), Fig. 2(c) and Fig. 2(d). Assuming that $r(i, j, cw)$ and $r(i, j, ccw)$ denote the arc from node i to node j in the clockwise and counter-clockwise direction, respectively, the 3 routes are:

1. $r(1, 5, ccw)$ - This is the Minimum Spanning Tree (MST) route, *i.e.*, the route whose total length is the least.

2. $r(1, 8, ccw) \cup r(1, 5, cw)$ - This is the Shortest Path Tree (SPT) route, *i.e.*, the route along which the maximum distance from the source to any of the destination nodes is the least.

3. $r(1, 8, cw)$ - This is the third possible route.

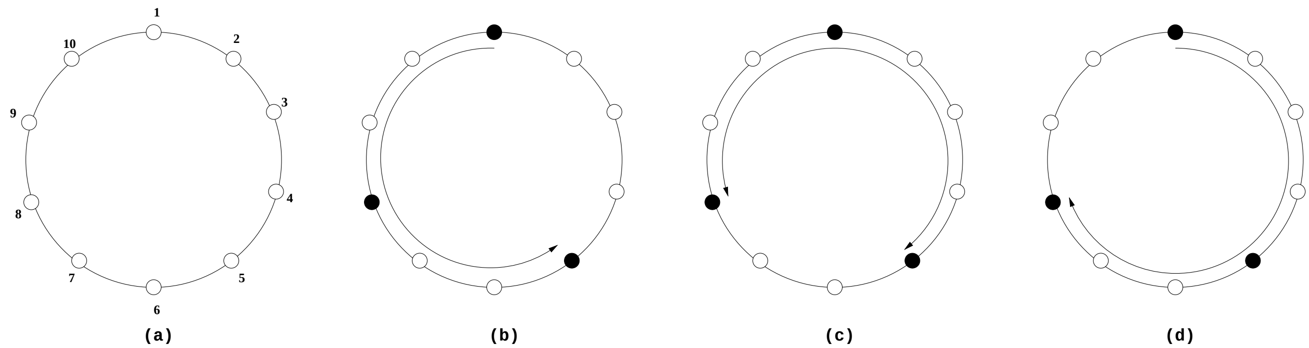


Figure 2. (a) 10 node ring network (b) MST route (c) SPT route (d) Another route

The main point to be noted in the above is that each route can also be represented by the absence of an arc between any two nodes in the set $\{1, 5, 8\}$. So, assuming $\overline{r}(i, j)$ represents the absence of the arc between nodes i and j, the 3 possible routes listed above can also be represented as $\overline{r}(1, 5)$, $\overline{r}(5, 8)$ and $\overline{r}(8, 1)$, respectively. Length of the route $\overline{r}(i, j)$ is given by (10 - length of $r(i, j)$). Hence, $\overline{r}(1, 5)$ represents the MST route as the length of the arc $(1, 5)$ is maximum among the 3 arcs - $(1, 5)$, $(5, 8)$ and $(8, 1)$. Similarly, for the route $\overline{r}(i, j)$, the maximum distance of any node in the destination set from the source is max(length of arc $(1, i)$, length of arc $(1, j)$), which makes $\overline{r}(5, 8)$ the SPT route.

In the general case, consider a ring with n nodes, with the individual nodes named as $N_1, N_2, \ldots, N_n$ (in the clockwise order). Consider a multicast session with source s and destination set D. Let $\{s\} \cup D = \{N_{i_0}, N_{i_1}, \ldots, N_{i_d}\}$, where $i_0 < i_1 < \ldots < i_d$. Since each possible route can be obtained by omitting the arc between some two adjacent nodes in the set $\{s\} \cup D$, the number of routes $= |\{s\} \cup D| = (d+1)$. Each candidate route can be represented in the form $\overline{r}(N_{i_k}, N_{i_{((k+1) \bmod (d+1))}})$ and so, all the $(d+1)$ routes can be enumerated by varying the value of k in the interval $[0, d]$. The length of the route $\overline{r}(N_{i_k}, N_{i_{((k+1) \bmod (d+1))}}) = n -$ length of arc $r(N_{i_k}, N_{i_{((k+1) \bmod (d+1))}}) = n - (n + i_{((k+1) \bmod (d+1))} - i_k) \bmod n = (n + i_k - i_{((k+1) \bmod (d+1))}) \bmod n$. Hence, the MST route is obtained by choosing k such that this value is minimum. Also, the route represented by $\overline{r}(N_{i_k}, N_{i_{((k+1) \bmod (d+1))}})$ is equivalent to the route $r(s, N_{i_k}, cw) \cup r(s, N_{i_{((k+1) \bmod (d+1))}}, ccw)$. Hence, the SPT route is obtained by choosing k such that max(length($r(s, N_{i_k}, cw)$), length ($r(s, N_{i_{((k+1) \bmod (d+1))}}, ccw)$)) is minimum, *i.e.*, $max((n + i_k - i_s) \bmod n, (n + i_s - i_{((k+1) \bmod (d+1))}) \bmod n)$ is minimum, where $s = N_{i_s}$. On the whole, each multicast session can be considered equivalent to the set of arcs $\{r(N_{i_0}, N_{i_1}), r(N_{i_1}, N_{i_2}), \ldots, r(N_{i_d}, N_{i_0})\}$ and assigning a route for it is equivalent to removing exactly one arc from this set. We use this idea of routing in our approach to tackle the traffic grooming problem in the multicast scenario.

4. HEURISTIC SOLUTION

The problem we are addressing in this paper is that of multicast traffic grooming, *i.e.*, given a set of multicast sessions in a ring network, how to assign routes and wavelengths to these sessions with the objective of minimizing the overall network cost. As stated before, we work under the constraint that the traffic demand of each multicast session is one traffic unit. Since unicast traffic grooming for ring networks is NP-complete[2] and as unicast is a special case of multicast with one node in the destination set, the traffic grooming problem in the multicast scenario too is NP-complete. Hence, we propose a heuristic algorithm for the multicast traffic grooming problem in ring networks.

We assume that both the e-DaC as well as the o-DaC units are present at all the nodes in the ring. At each node, the o-DaC unit is used to groom the incoming wavelengths on which all the traffic needs to be duplicated and the traffic that is added need not be duplicated. The e-DaC setup grooms the remaining wavelengths at each node. At any particular node, the number of wavelengths groomed by the e-DaC/o-DaC node architecture is the number of ports required on the e-DaC/o-DaC unit at that node. As already discussed in Section 2, the cost of the o-DaC setup is negligible compared to the e-DaC unit. Hence, we consider only the number of grooming ports required on the e-DaC unit as a measure of the network cost. So, the objective of our heuristic is to minimize the total number of ports required on the e-DaC setup across all nodes.

The solution to the multicast traffic grooming problem in rings can be divided into three phases:

1. Routing - As described in the previous section, a multicast session can be assigned one of $(d+1)$ possible routes, where d is the cardinality of the destination set. So, for each multicast session, we need to determine which one of these $(d+1)$ routes must be chosen.

2. Circle construction - Once the route has been assigned for a multicast session, the route can be split into arcs with endpoints in the set $\{s\} \cup D$. The reasoning behind this is that since the wavelength which has been assigned to this route has to pass through the groomer at the source node as well as at all the destination nodes, the route can also be switched to another wavelength at these nodes without any additional cost (Note that in both the node architectures described in Section 2, the traffic on any incoming wavelength which passes through the groomer can be switched to a different outgoing wavelength). So, the routes identified for all the multicast sessions can be split into arcs. These arcs can then be grouped into circles, *i.e.*, the set of arcs can be partitioned such that no two overlapping arcs are in the same partition.

3. Grouping of circles - Finally, having grouped the arcs obtained after routing into circles, each one of these circles needs to be assigned a wavelength. Alternatively, the circles have to be grouped into disjoint sets with each partition being assigned to a distinct wavelength. So, the number of wavelengths required is equal to the number of partitions. The grouping of circles has to be done under the constraint that the number of circles in any partition must not be greater than the groom factor. This phase is identical to that in the case of unicast traffic.[1]

One possible approach to solving the problem under consideration is to solve each of the three phases independently. Each of the three phases can be solved as near-optimally as possible. So, in the routing phase, each multicast session can be assigned its Minimum Spanning Tree (MST) route. In the case when more than one MST route exists, the route for which the maximum distance from any of the destination nodes to the source node is minimum, *i.e.*, the shortest path route among the MST routes can be chosen. Each of these routes can be split into arcs at the source node and the destination nodes. Since all the arcs of all the routes can be grouped independently into circles, each arc can be considered equivalent to a unicast and the circle construction for unicast traffic can be applied to these arcs. The best algorithm existing in the literature for circle construction in the unicast scenario is that proposed by Zhang and Qiao.[1] Since our objective is to minimize the total number of e-DaC ports consumed, the circle construction algorithm which minimizes the number of ADMs must be used. Finally, these circles can be grouped into wavelengths using the circle grooming algorithm given in the same work.[1] Though this approach, which we call the MST Routing with Unicast Circle construction (MRUC) algorithm, attempts to solve each of the three phases near-optimally, clearly nothing can be said about the optimality of the overall solution.

We attempt to improve on the above approach by choosing the route for each session using the information of which are the other sessions that also need to be routed. So, instead of choosing the MST route independently for each session, we try to assign the route to each session so that it will share e-DaCs with other sessions. Based on this intent, we follow an approach wherein routing is performed as circle construction proceeds. So, as the circles are being formed, the routes are decided so as to ensure sharing of e-DaCs. As mentioned in Section 3, our algorithm uses the equivalent notation for each multicast session as a set of arcs. Also, as discussed earlier, the length of the MST route for any session is equal to (number of nodes in the ring - length of the longest arc in the set representation of the session). We now extend this definition to any set of arcs, *i.e.*, the length of the MST of a set of arcs is equal to (sum of the lengths of all the arcs in the set - length of the longest arc in the set).

Given a n node ring network wherein M multicast sessions need to be established, our heuristic algorithm, called the Combined Routing and Circle construction (CRC) algorithm, works as follows:

1. Initialize $CircleNum$ to 1 and the current circle to $\{\}$. Also, for $k = 1 \ldots M$, initialize set A_k to the set representation of session k.

2. Evaluate the length of the MST for each set A_k and determine the value of k for which the value is maximum. Remove the shortest arc from that set and add it to the current circle. If the length of the MST $= 0$ for all values of k, then the algorithm terminates.

3. In each set A_k, determine the subset of arcs C_k which can be added to the current circle without creating more than one gap in the circle. If more than one possible subset exists, choose the one with greatest sum of lengths of the arcs.

4. For every k for which $C_k = A_k$, two cases need to be considered:

   (a) If adding all the arcs in C_k to the current circle completes the circle, then identify the longest arc R in the set C_k.

   (b) Else, identify the arc R in C_k such that even if instead of C_k, all the arcs in $C_k - \{R\}$ are added to the current circle, more than one gap will not be created in the circle.

   Set $C_k = C_k - \{R\}$.

5. For each k, evaluate the sum of the lengths of the arcs in C_k and determine the value of k for which this sum is maximum. Let this value of k be k' (choose one at random in the case of a tie). If C_k is empty for all values of k, then skip to step 7.

6. Add all the arcs in $C_{k'}$ to the current circle. Set $A_{k'} = A_{k'} - C_{k'}$ and go back to step 3.

7. Increment $CircleNum$ and initialize the new circle to $\{\}$. Go back to step 2.

We now elucidate some of the key features of the CRC heuristic and give the reasoning behind some of its steps. Since the objective is to minimize the total number of e-DaC ports, the CRC algorithm never forms a circle with more than one gap. This ensures sharing of e-DaCs as every arc in each circle shares a common endpoint with at least one other arc in that circle. The algorithm starts off with the arcs set representation of each multicast session and keeps moving arcs from these sets into circles until exactly one arc remains in each set. Therefore, since the length of the MST of a set which has only one arc is equal to 0, the algorithm terminates when the length of the MST is equal to 0 for all sets. Also, step 4 of the algorithm is required to ensure that from any set all the arcs are not removed. The cases $4(a)$ and $4(b)$ are shown in Fig. 3. At any stage, the length of the MST of the set A_k is equal to the minimum sum of the lengths of the arcs that need to be added to some circle in order for the routing of the session k to be complete. Hence, whenever a new circle is initialized, we choose the set whose length of MST is maximum as the arcs in sets with lesser value of MST will more easily fit into the gaps remaining later. Moreover, we add the shortest arc from this chosen set to the new circle because ideally, we would like each session to be assigned its MST route, which would require the longest arc in each set

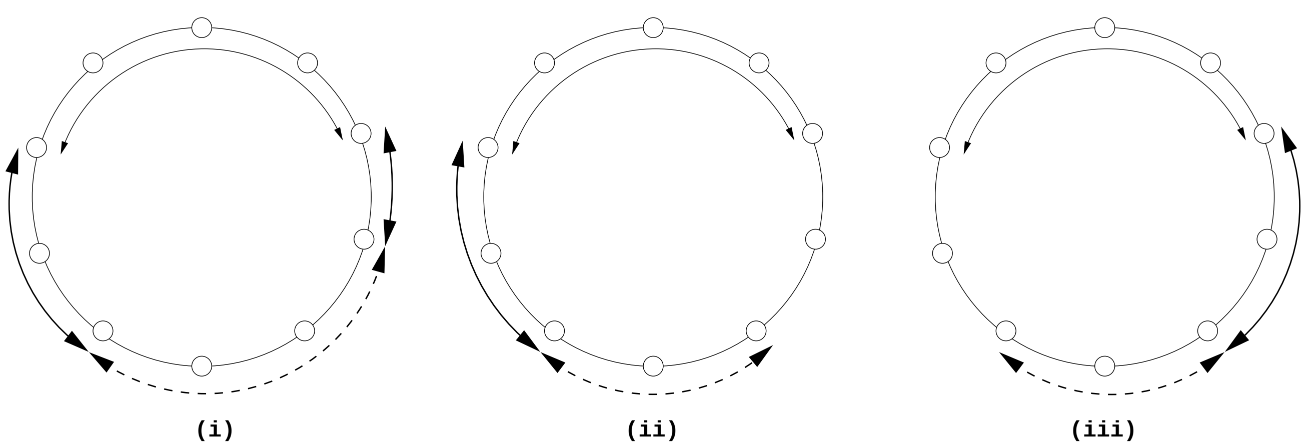


Figure 3. (i) Example of case 4(a) (ii) & (iii) Examples of case 4(b)

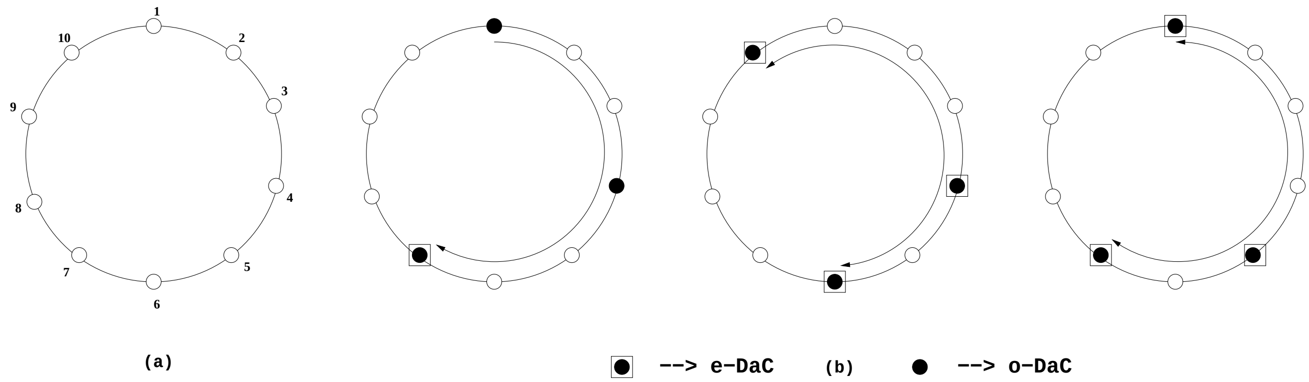


Figure 4. (a) Example ring network (b) The circles obtained by MST routing followed by unicast circle construction

to be left behind at the end of the algorithm. Also, for the same reason, the longest arc is removed in step $4(a)$. Though followed by the MRUC algorithm as well, the approach of using arcs between consecutive nodes in the set $s \cup D$ itself helps in reducing the number of e-DaC ports as traffic of any session need not be switched across wavelengths at any intermediate node.

The CRC algorithm can also be used for routing and circle construction for unicast traffic as a unicast is a special case of a multicast with $|D| = 1$. In this case, the CRC algorithm reduces to a minor variation of the circle construction algorithm presented by Zhang and Qiao[1] with the objective of minimizing the number of ADMs. Their algorithm works by considering arcs in the decreasing order of arc length and when an arc comes up for consideration, if it cannot be added to any circle without forming a gap, that arc is added to a list called the $GapMaker$ list. The arcs in the $GapMaker$ list are considered for routing only after no arcs remain outside the $GapMaker$ list, whereas the CRC algorithm for unicast traffic is equivalent to considering the arcs in the $GapMaker$ list for routing in each iteration, not only at the end. In most cases, this variation does not lead to much difference in overall cost.

After utilizing the CRC algorithm for routing and circle construction, we use the algorithm given in[1] for circle grooming. The ADM in their problem setting is equivalent to our e-DaC unit, in terms of cost-contributor. In every circle, an e-DaC is required at a node if either some traffic which need not be copied is being dropped or if some traffic which needs to be duplicated is being added. While grouping the circles onto wavelengths, a wavelength must pass through the e-DaC unit at a node if that wavelength has been assigned to some circle which requires an e-DaC at that node. So, the circle grooming algorithm, intended to minimize the number of ADMs in the unicast traffic scenario, minimizes the total number of e-DaC ports required in our problem setting.

5. ILLUSTRATIVE EXAMPLE

Having presented a detailed explanation of our heuristic algorithm in the previous section, we now describe the working of both the MRUC as well as the CRC algorithm with an example. Consider the 10 node ring network shown in Fig. 4(a) wherein the groom factor is 2. Three multicast sessions need to be established which are $(1 \rightarrow \{4, 7\}), (4 \rightarrow \{6, 10\})$ and $(5 \rightarrow \{1, 7\})$. When the MST routing with Unicast Circle construction (MRUC) algorithm is used, 3 circles are obtained (shown in Fig. 4(b)) with each circle having the MST route for one of the sessions. Since the groom factor is 2, the circle grooming algorithm[1] groups the circles into 2 wavelengths, requiring a total of 7 e-DaC grooming ports.

On the other hand, the Combined Routing and Circle construction (CRC) algorithm begins execution with the 3 arc sets - $A_1 = \{r(1, 4), r(4, 7), r(7, 1)\}, A_2 = \{r(4, 6), r(6, 10), r(10, 4)\}$ and $A_3 = \{r(1, 5), r(5, 7), r(7, 1)\}$.

(a) The length of the MST of all the three sets is 6 and so, the shortest arc in the first set, *i.e.*, $r(1, 4)$ is added to the first circle. The subsets of each set which can be added to the current circle without creating more than one gap are - $C_1 = \{r(4, 7), r(7, 1)\}, C_2 = \{r(4, 6), r(6, 10)\}, C_3 = \{r(5, 7), (7, 1)\}$. However, $C_1 = A_1$ and also, adding the arcs in C_1 completes the current circle. So, the longest arc in C_1, $r(7, 1)$ is removed

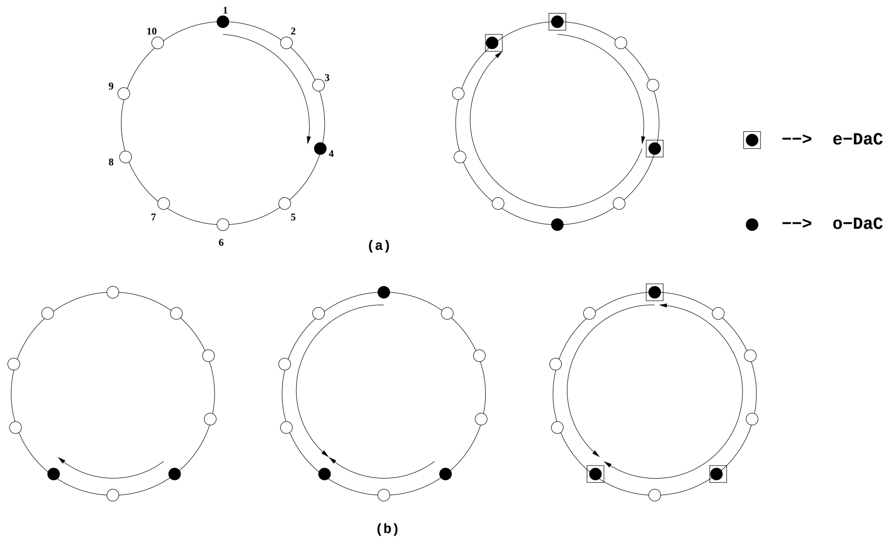


Figure 5. Formation of (a) first circle and (b) second circle by CRC algorithm

from C_1. The sum of the lengths of the arcs in C_1, C_2 and C_3 are 3, 6 and 6, respectively. Since there is a tie between C_2 and C_3, the former is chosen at random and all the arcs in C_2 are added to the current circle.

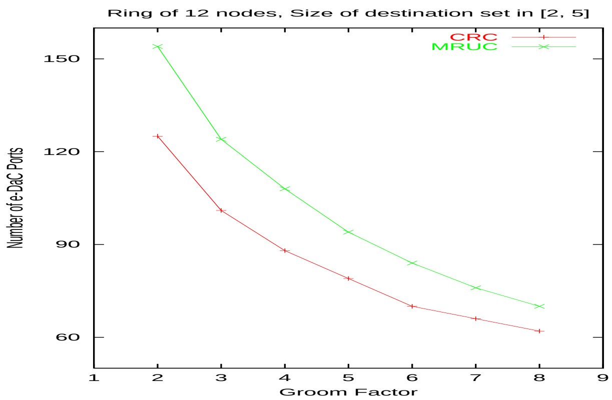
(b) Now, the contents of the three arc sets are - $A_1 = \{r(4,7), r(7,1)\}, A_2 = \{r(10,4)\}$ and $A_3 = \{r(1,5), r(5,7), r(7,1)\}$. Since no arc from any of the three sets can be added to the current circle, a new circle is initialized. The lengths of the MST of the three sets are 3, 0 and 6, respectively. So, the shortest arc in A_3, $r(5,7)$ is added to the current circle. Again determining the subsets of each of the three sets which can be added without creating more than one gap, $C_1 = \{r(7,1)\}, C_2 = \{\}$ and $C_3 = \{r(1,5), r(7,1)\}$. Since $C_3 = A_3$ and adding all the arcs in C_3 completes the current circle, the longest arc in C_3, $r(7,1)$ is removed. So, the sum of the lengths of the arcs in C_1, C_2 and C_3 are 4, 0 and 4, respectively. At random, C_1 is chosen and hence, the arc $r(7,1)$ is added to the circle. Yet again determining C_1, C_2 and C_3, the first two are empty, while $C_3 = \{r(1,5)\}$. So, arc $r(1,5)$ is added to the circle.

(c) When the three subsets are re-determined, obviously all of them are empty as the current circle is complete. So, a new circle is initialized. However, the current status of the three arc sets is - $A_1 = \{r(4,7)\}, A_2 = \{r(10,4)\}$ and $A_3 = \{r(7,1)\}$. Since each set has only one arc, the length of the MST of all the three sets is 0 and so, the algorithm terminates. The 2 circles obtained are groomed onto one wavelength and a total of 5 e-DaC grooming ports are required.

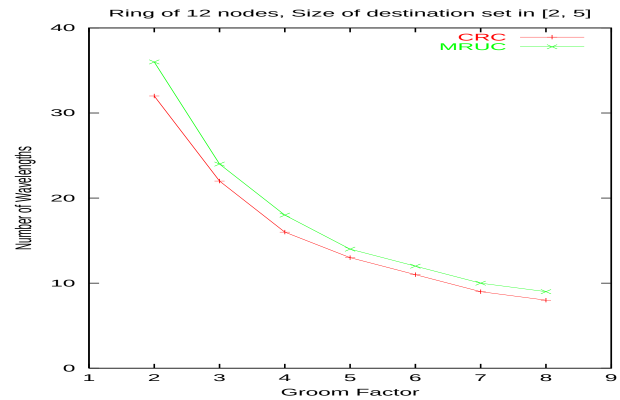
Finally, the routes assigned to the three sessions are $r(1,4,ccw) \cup r(1,7,cw)$, $r(4,10,ccw)$ and $r(5,1,cw) \cup r(5,7,ccw)$, respectively. The route assigned to the first session is not a MST route, whereas the second session, which has two possible MST routes, is assigned the MST route which is not the shortest path route. On the other hand, the third session, which also has two possible MST routes, is assigned the MST route which is the shortest path route. So, this example demonstrated how the CRC algorithm determined the route for each session while constructing the circles, which led to a saving of 2 e-DaC ports. Though the number of wavelengths is not considered to contribute towards the network cost in our problem setting, this example showed that efficient routing and circle construction by the CRC algorithm also leads to lesser number of circles, which in turn leads to lesser number of wavelengths.

6. SIMULATION RESULTS

We conducted several simulations to study the performance of the CRC algorithm, especially in comparison with that of the MRUC algorithm. The performance of either heuristic was evaluated in terms of the overall network



(a)



(b)

Figure 6. Variation of (a) Number of e-DaC ports and (b) Number of wavelengths, with groom factor

cost, measured in terms of the total number of e-DaC grooming ports, minimizing which is the objective of the multicast traffic grooming problem we considered. Also, the number of wavelengths required by either algorithm was measured because in the unicast traffic scenario, minimizing the number of ADMs has been determined to have a strong correlation with minimizing the number of wavelengths.[2] Moreover, number of wavelengths also contributes to the network cost.

6.1. Generation of Sessions

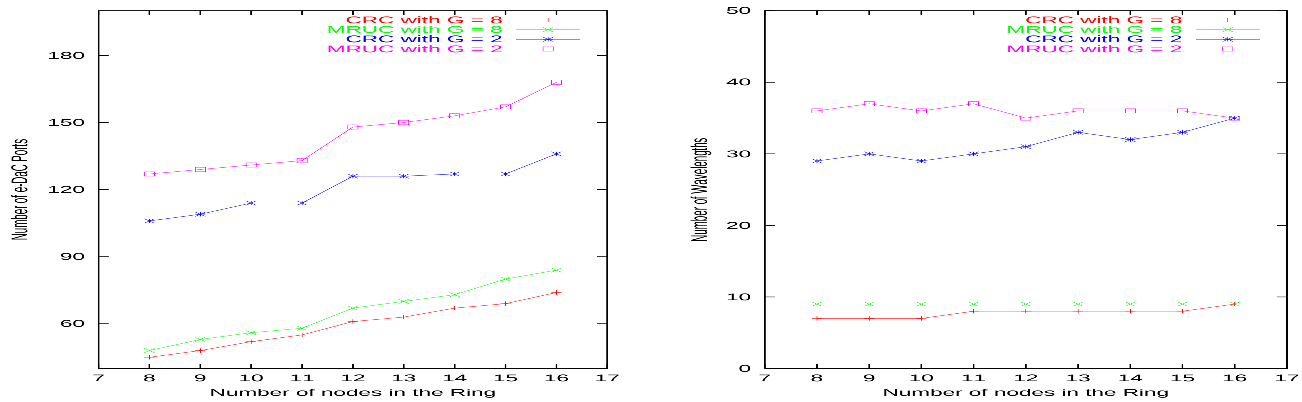
While generating a multicast session for a n node ring network, each of the n nodes was given equal probability of being the source node for the session. In most cases, the size of the destination set was generated as a uniformly distributed random number in the range 2 to 5. After the size of the destination set was determined to be d, the nodes in the destination set were then chosen such that every subset of size d of the n nodes was equally probable of being the destination set. This was achieved by the following iterative process. The first node was chosen with each of the n nodes having equal probability of being picked. Then, each of the remaining $n - 1$ nodes was given equal probability of being the second node. This process was continued till all the d nodes were chosen.

6.2. Variation with Groom Factor

Firstly, we compared the performance of the two approaches with respect to variation in the groom factor G. We considered a 12 node ring network and varied the value of G from 2 to 8. Both the number of e-DaC ports required as well as the number of wavelengths required by each algorithm was averaged over 10 sets of multicast sessions, each one of which consisted of 100 sessions. As shown in Fig. 6, the CRC algorithm not only leads to lesser network cost in terms of number of e-DaC ports but also requires lesser number of wavelengths than the MRUC algorithm.

6.3. Variation with Size of Ring

Next, we compared the CRC algorithm with the MRUC algorithm over rings of various sizes, with the number of nodes in the ring varying from 8 to 16. Here too, every value was obtained by averaging over 10 sets of 100 multicast sessions each. We performed this simulation with $G = 2$ and $G = 8$ to compare the performance in both the dense as well as sparse traffic scenarios, respectively. In either situation, the CRC algorithm required lesser number of e-DaC grooming ports. Also, yet again, our approach requires lesser number of wavelengths. The results of these simulations are shown in Fig. 7.



(a) (b)

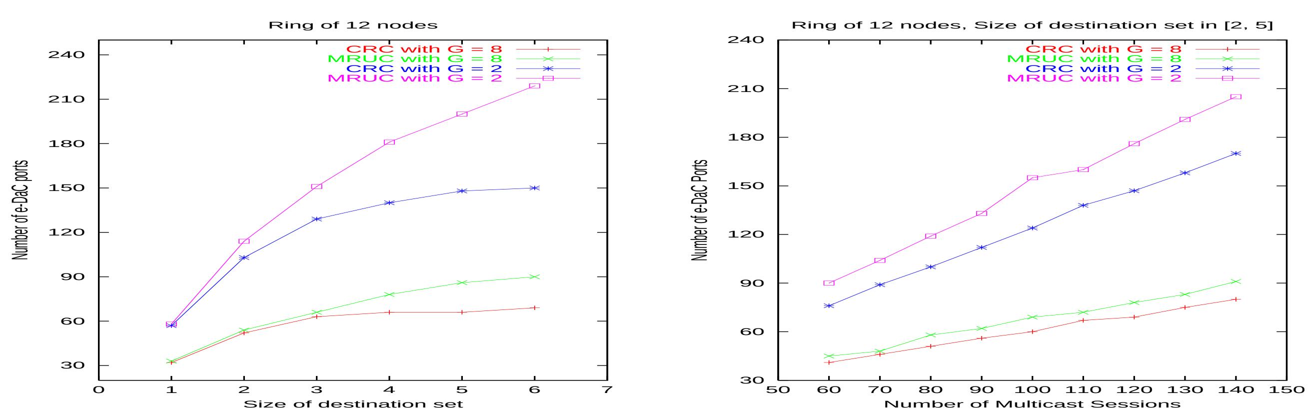
Figure 7. Variation of (a) Number of e-DaC ports and (b) Number of wavelengths, with the number of nodes in the ring

6.4. Variation with Traffic Load

Finally, we studied the network cost yielded by the two algorithms in the context of varying traffic load. The traffic load was varied in two ways on a 12 node ring network - 1. Making the size of the destination set of each session a constant and varying this constant, 2. Varying the number of multicast sessions that need to be established. Again, each value was averaged over 10 sets of sessions and the values were determined for both the $G = 2$ and $G = 8$ cases. The results obtained (Fig. 8(a) and Fig. 8(b)) demonstrated that irrespective of the traffic load, the CRC algorithm requires lesser number of e-DaC ports compared to the MRUC algorithm. Also, the coincidence of points when the size of the destination set for all sessions is fixed at 1 re-affirms our claim that in the unicast case, the CRC algorithm reduces to a minor variation of the circle construction algorithm presented in.[1]

6.5. Analysis of Results

The results obtained also clearly displayed that the combined routing and circle construction approach followed in the CRC algorithm we proposed yields much lesser network cost in comparison with the alternative approach of the MRUC algorithm. In fact, our algorithm gives significant reduction in network cost in dense traffic scenarios as illustrated in the results presented. This can be solely attributed to the fact that while determining



(a) (b)

Figure 8. Variation of Number of e-DaC ports with (a) Size of destination set and (b) Number of multicast sessions

the route for any session the CRC algorithm uses the information of which are the other multicast sessions that also need to be established. While the MRUC algorithm assigns routes to the sessions and then forms circles independently, the CRC algorithm determines the route for every session while forming circles so that the routes can be chosen so as to ensure sharing of e-DaC ports. Also, both the CRC algorithm as well as the circle construction heuristic[1] used in the MRUC algorithm build circles which have at most one gap. Hence, if an arc does not share an endpoint with any arc in any circle, a new circle has to be created. This implies that efficient sharing of e-DaCs also leads to lesser number of wavelengths, which was demonstrated in the results of our simulations. In summary, the CRC algorithm achieved its objective of providing lesser network cost than the MRUC algorithm.

7. CONCLUSION

In this paper, we addressed the problem of routing and wavelength assignment of sub-wavelength multicast sessions in WDM ring networks. We proposed two node architectures, e-DaC and o-DaC, for supporting multicasting of sub-wavelength demands, wherein the former performs traffic duplication in the electronic domain whereas the latter does the same by power splitting at the optical layer. Having identified the three stages involved in solving the multicast traffic grooming problem, we presented a heuristic approach which performs routing of multicast sessions as well as circle construction simultaneously. Finally, we provided extensive simulation results to demonstrate the superiority of our approach in comparison with the alternative approach of performing routing and circle construction independently.

We are currently developing an ILP formulation for the multicast traffic grooming problem considered in this paper. We intend to extend this ILP formulation as well as the CRC algorithm to work in the case when each multicast session can have an arbitrary traffic demand. Also, we need to consider the alternative problem setting with the maximum number of wavelengths as an additional resource constraint in the static as well as dynamic scenario, with the objective as maximizing throughput and minimizing blocking probability, respectively. Another significant improvement we are currently working on is to address the multicast traffic grooming problem in the context of mesh networks.

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