A Heuristic Algorithm for Multicast Routing in Sparse-Splitting Optical WDM Networks

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***Abstract*—Multicast routing in optical WDM networks is investigated in the current paper in the presence of optical splitters only at a fraction of the network nodes. This work presents a novel multicast routing algorithm for sparse-splitting networks that is specifically designed for this category of networks. The proposed algorithm is compared with the most efficient multicast routing algorithms for sparse networks that are found in the literature through examples and simulations. Performance results show that the proposed approach achieves an important reduction on the average cost of the calculated multicasting trees, compared to the existing heuristics.**

I. Introduction

Over the last few decades, the size and complexity of telecommunications networks has steadily increased and this increase will continue for the foreseeable future. Fiber-optic communication networks that provide a huge available amount of capacity and low bit-error rates are currently widely used as the telecommunication medium of choice that is able to supply high-speed and reliable communications. Optical networks where the provisioning and fault recovery functionalities are dealt with at the physical layer have been at the forefront of research for several years, especially for unicast applications, and these networks are currently being realized today especially in the backbone arena. However, new traffic requirements are currently emerging for these new types of network architectures, including new high-bandwidth applications (such as video-on-demand, teleconferencing, distance-learning, remote medical diagnostic applications, etc.) that require point-and-click provisioning of multicast sessions in the physical domain [1, 2].

Multicasting in optical networks is realized by the calculation of multicast routing trees and the assignment of a wavelength for the entire tree (or parts of the tree), creating what is referred to in the literature as *light-trees* [3]. If no wavelength converters exist at the network nodes, the same wavelength must be used in all fibers comprising the light-tree [1]; otherwise, if the network nodes have conversion capabilities different parts of the tree can be on different wavelengths. In the current paper it is assumed that each network node has full wavelength conversion, therefore the information can be sent in different wavelengths for each of the light-tree fibers.

The information is transmitted through the light-tree utilizing optical splitters in the network nodes. A light-splitter is a passive device that splits the input optical signal into multiple identical output signals. The nodes that have the ability of light splitting, are called *Multicast-Capable* (MC) nodes. If they do not have this capability, they are called *Multicast Incapable* (MI). Assuming an optical splitter with n outputs, optical splitting reduces the optical power at each splitter output port to $(1/n)^{th}$ of the input power. Thus, since the optical signal power at the photoreceiver needs to be higher than a threshold to be detected, an optical network with a large number of multicast-capable nodes may cause the signal to experience a significant power loss, limiting the reach of the optical signal. To combat this effect, a larger number of optical amplifiers will be required in the network, further adding amplified spontaneous emission (ASE) noise in the system and requiring a worst-case network engineering and design [4]. To limit the impact of optical splitters in the network we can place them at only some of the network nodes (multicast-capable (MC) nodes), resulting in a *sparse-splitting* network [3, 5]. The remaining multicast-incapable (MI) nodes of the network may be *Drop-and-Continue* (DaC) or *Drop-or-Continue* (DoC) nodes. A DaC node can transmit the optical signal to the following node and can also drop it locally as well, while a DoC node can either transmit the optical signal to the following node or drop it locally. Since most of today's optical WDM networks do not have DaC capabilities [6], it is more realistic to assume that MI nodes are DoC, rather than DaC. Therefore, this is the case considered in the current paper.

The problem of multicast routing in sparse-splitting networks is NP-hard, since the NP-hard problem of the Steiner problem in graphs [7] is a special case of it. Therefore, polynomial-time heuristics are used in practice. In the current paper a new multicast routing heuristic algorithm is presented, that was designed specifically for sparse-splitting DoC networks. Is is called *Sparse Splitting Multicast Routing Heuristic* (SSMRH). Its improved performance compared to the existing work in the literature is shown through examples and simulations.

The remaining of the paper is organized as follows: Section

II presents some of the most important sparse splitting multicast routing heuristic algorithms. The proposed algorithm is presented in Section III, while the comparison of the existing and proposed algorithms is given in Section IV. Finally, Section V gives the concluding remarks of the paper, as well as possible future work.

II. Multicast Routing in Networks with Sparse Splitting Capability: Existing Algorithms

There are a number of approaches in the literature on the problem of multicast routing in sparse-splitting mesh optical networks that can be found in [6-14], as well other sources. As it is not possible to compare the proposed solution with all the heuristics in the literature, a few of the heuristics were identified that produce the most efficient solutions amongst the existing works. These heuristics are presented in this section and will be the ones that will be compared with the proposed algorithm for multicast routing in sparse-splitting networks.

A. On-Tree MC Node First (OTMCF) and Nearest MC Node First (NMCF) Heuristics

The On-Tree MC Node First (OTMCF) and Nearest MC Node First (NMCF) heuristic algorithms that were created for DoC networks are presented in [6]. For both heuristics the following pre-processing takes place.

Initially, a multicast-capable (MC) network M_G is derived from the original network G as follows:

1) All the MC nodes in network graph G are included as its vertex set, say W.
2) If there is a path between two MC nodes in G, these two MC nodes are connected in M_G.
3) The link cost from node i to node j in graph M_G is set to the cost of the minimum-weight path from node i to node j in G, for all $i, j \in W$.

Subsequently, the *Auxiliary Network Transformation (ANT)* is performed as follows:

1) The MC network graph M_G of the original network graph G is determined.
2) A Steiner tree heuristic is applied to graph M_G to generate a minimum-cost tree T_R for multicast session R.
3) The resulting light-tree T is obtained by substituting each link, say (i, j), in T_R with the corresponding minimum-cost path from node i to node j in G.

Finally, the multicast tree can be derived by the following two algorithms that utilize *ANT*:

On-Tree MC node First (OTMCF) Heuristic: This approach attempts to minimize the cost of an MC tree. An MC tree is constructed by first including all the MC nodes to which group members are directly connected, and then expanded as follows: the MI nodes to which the remaining members are directly connected join the tree through the nearest on-tree MC nodes.

Nearest MC node First (NMCF) Heuristic: This approach attempts to minimize the cost of MI nodes which join the MC tree. The set of MC nodes used to construct an MC tree consists of all the MC nodes directly connected to the destinations of the group and the MC nodes which are the nearest to the MI nodes connected to the remaining destinations. NMCF expands on-tree MC nodes in such a way that each MC node nearest to each MI node in the group must also be on-tree.

B. Cost-Effective Multicasting Using Splitters (MUS) Heuristic

This algorithm is presented in [8] and was also created for DoC networks. According to a given graph G, an auxiliary graph $G'(M, E')$ is created that consists of MC nodes only (set M), where the cost of a link in E' is the cost of the corresponding shortest path in the original graph. An initial Steiner tree T is then created that consists of the source node and the destination nodes that are MC. Let M_{onTree} be the set of MC destinations, and M_{remain} the set of the rest of the destinations in a given session. The latter are MI nodes and are not as of yet connected to the tree. The procedure presented next is then followed for the connection of the M_{remain} nodes on the initial tree T.

1) For each node in M_{remain}, find the MC node in M_{onTree} that it can connect to via the shortest path.
2) Select the shortest path among the corresponding paths and add it to tree T.
3) If an MC node exists on the shortest path, then the MC node is added to M_{onTree}.
4) The MI node connected to T is excluded from the set M_{remain}.
5) Repeat the above steps until M_{remain} is an empty set.

MUS is similar to NMCF with two basic improvements that make it more efficient. The first one is that, after the addition of a path that connects a MI destination to the tree, the unconnected MI destinations are checked whether they can be connected efficiently (i.e., with low cost) through any MC nodes belonging to this path (whereas NMCF ignores these nodes). The second one is that, using MUS, the MI destinations are connected in increasing order according to the cost of the shortest path between them and the tree, while in NMCF this is not taken into account.

III. Multicast Routing in Networks with Sparse Splitting Capability: Proposed Heuristic Algorithm

A. Sparse Splitting Multicast Routing Heuristic (SSMRH)

A new multicast routing algorithm for sparse splitting networks called Sparse Splitting Multicast Routing Heuristic (SSMRH) is proposed in this section and it consists of the following steps (D is the destination set):

1) Calculate the multicast tree, using the MUS algorithm.
2) Calculate the cost c of the resulting tree.
3) For each MC node MC_i not belonging to the current tree:

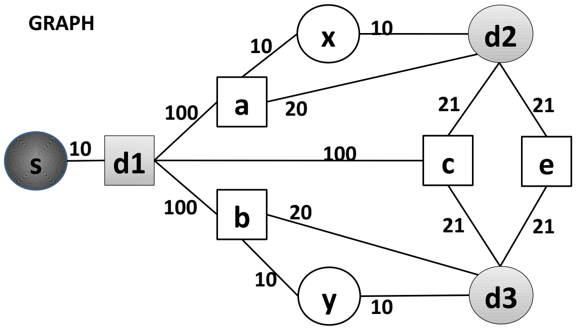

Fig. 1. Network Graph.

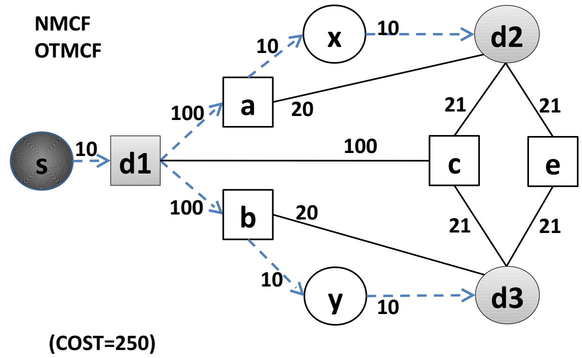

Fig. 2. Tree Obtained by NMCF and OTMCF.

a) Add that MC node to D.
b) Calculate the multicast tree, using MUS.
c) Calculate the cost c_i of the resulting tree.
d) Remove the MC node from D.

4) Find ${c_i}^{min}$. If ${c_i}^{min} \geq c$, go to Step 5. Else,
   a) $c = {c_i}^{min}$.
   b) Add the corresponding MC node permanently to D and return to Step 3.
5) Calculate the multicast tree for the new D, using the MUS heuristic algorithm.

The SSMRH algorithm works as follows: each one of the MC nodes that are not part of the multicasting tree derived by the MUS heuristic algorithm, is added *temporarily* in the destination set $\{D\}$, the new tree is calculated and the MC node is removed from $\{D\}$. The MC node that, if added in $\{D\}$, gives the tree with the least cost, is added *permanently* into $\{D\}$. The procedure is repeated until no further cost reduction can be succeeded.

SSMRH algorithm uses MUS as its basis and applies a recursive procedure to improve the solution obtained by the latter. Therefore, for every case, it gives at least as good solution as MUS, i.e., it never finds a tree that has cost greater than the one derived by MUS.

B. Example of the SSMRH Heuristic

An example where the SSMRH heuristic algorithm has improved performance compared to the aforementioned existing algorithms is shown in Figures 1-4. In this example, the network is considered as DoC, s is the source node, d_1, d_2, d_3 are the destination nodes, and square-shaped nodes are the MC nodes.

In this example, SSMRH locates MC node C, which can lead to a lower-cost tree if added in $\{D\}$ compared to the rest of the heuristics, resulting in a tree with less cost compared to the results of the NMCF, OTMCF, and MUS heuristic algorithms.

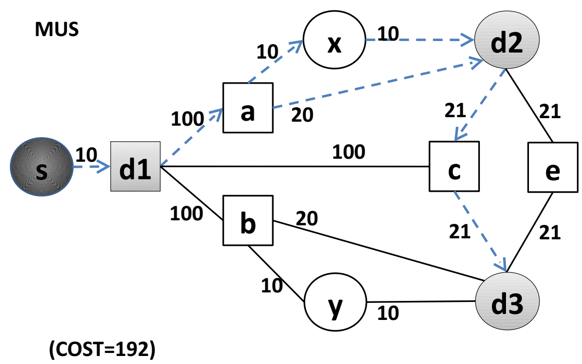

Fig. 3. Tree Obtained by MUS.

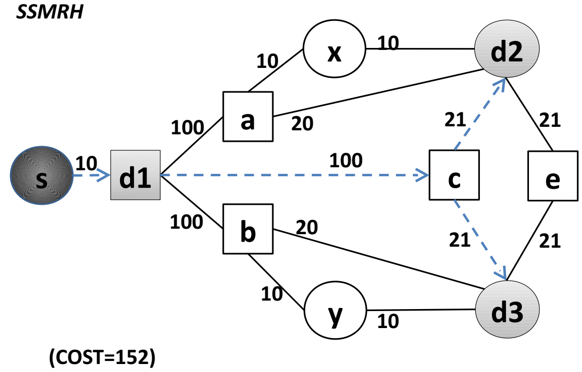

Fig. 4. Tree Obtained by SSMRH.

Complexity of the SSMRH Heuristic

The complexity of the proposed heuristic algorithm for a network that consists of V nodes, where X of them are multicast capable, and the set of the source and destinations of multicast group has size K, is derived as follows:

- MUS has time complexity equal to $O(KV^2)$. Therefore:
  - Complexity of step 1: $O(KV^2)$
  - Complexity of step 3: $O(XKV^2)$
- Step 3 is repeated at most X times.

Therefore SSMRH has complexity $O(X^2KV^2)$.

IV. Performance Evaluation

The performance of the proposed heuristic algorithm was evaluated through simulations. The network graph was randomly created, it consisted of 50 nodes and 200 links, and it was undirected (i.e., every connection was bidirectional). A random cost varying from 1 to 100 was assigned to each network link. Let the *nominal distance* (d^{ij}_{nom}) between two nodes i and j be defined as $d^{ij}_{nom} = |i - j|$. The constraint that every arc that was added in the graph had to connect nodes that satisfy $d^{ij}_{nom} \leq 5 \; \forall i, j$, was used for the random graph creation. The reason is that the graph must simulate a real telecommunications network, where most of the nodes that are interconnected belong to the same geographical area. The simulation was repeated for various possible multicast group sizes, from $D = 5$ to $D = 25$ (D stands for the number of destinations), with a step equal to 5. The experiment was executed 5000 times for every multicast group size to extract the average cost of the derived trees, while the source and destinations of the multicast connections were distributed uniformly across the network. The cost of the multicasting tree was calculated using the existing heuristic algorithms (OTMCF, NMCF, MUS) as well as the proposed SSMRH heuristic.

Let the percentage of the network MC nodes denoted by P. The aforementioned procedure was repeated for $P = 10, 20, 30, 40, 50$. The MC nodes were allocated to the network nodes according to their degree (in decreasing order). Clearly, there are a number of other methods that can be utilized for MC node placement. This topic is currently being investigated but it is not addressed in this work as this paper dealt only with the routing problem assuming that the MC nodes were already placed. The results of the simulations are given in Figures 5-9.

It is clear that the proposed algorithm outperforms the existing ones (i.e., the average cost of the resulting trees is less), regardless of the percentage of the MC nodes. The cost reduction that SSMRH achieves, compared to the existing algorithms, is bigger for networks with low percentage of MC nodes, where the proposed technique is more efficient in identifying MC nodes that can be included in the tree in order to reduce its cost. For example, for the case of Figure 5 (i.e., where 10% of the network nodes were MC), SSMRH gave multicasting trees that had on the average 19% lower cost (averaged over every multicast group size considered in the simulation) compared to the best solution obtained by the rest of the heuristics.

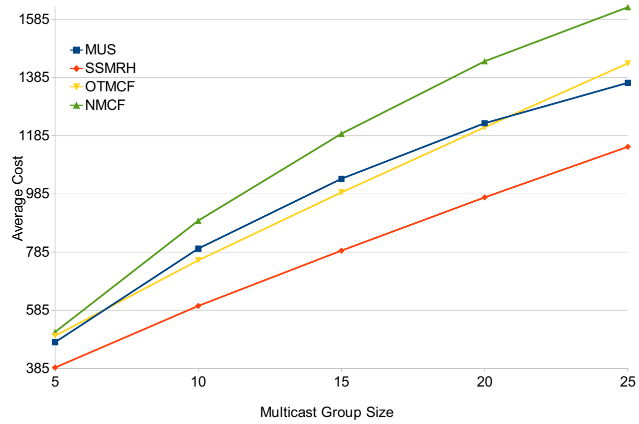

Fig. 5. Average Cost for Different Multicast Group Sizes (10% of the Network Nodes are MC).

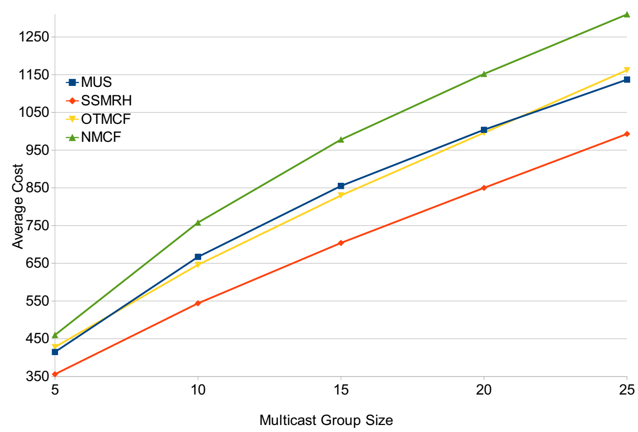

Fig. 6. Average Cost for Different Multicast Group Sizes (20% of the Network Nodes are MC)).

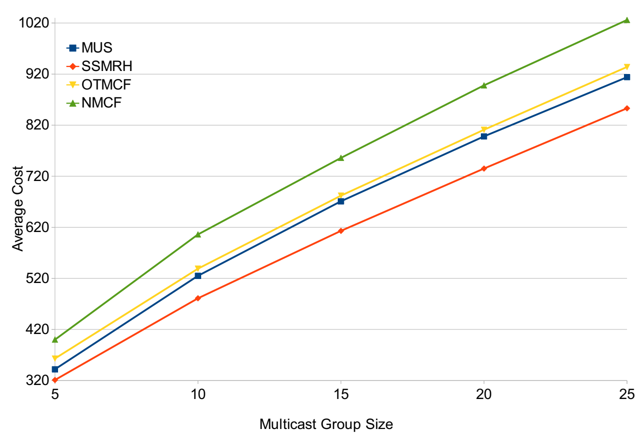

Fig. 7. Average Cost for Different Multicast Group Sizes (30% of the Network Nodes are MC)).

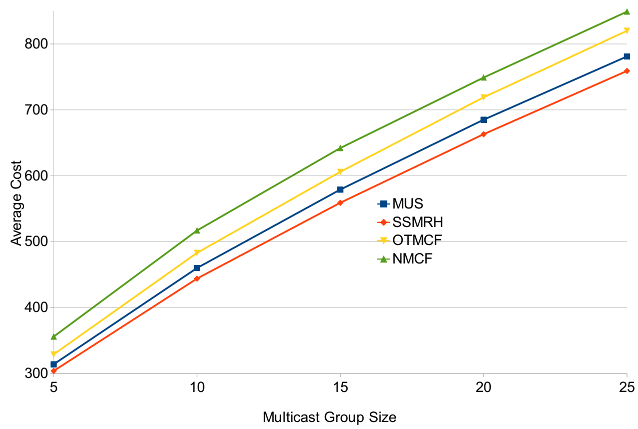

Fig. 8. Average Cost for Different Multicast Group Sizes (40% of the Network Nodes are MC)).

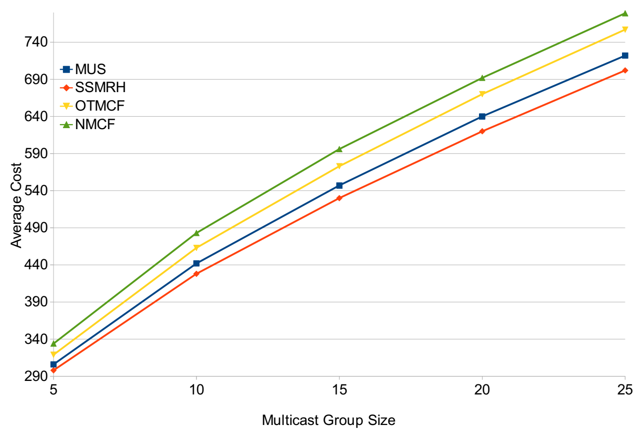

Fig. 9. Average Cost for Different Multicast Group Sizes (50% of the Network Nodes are MC)).

V. Conclusions

In the current paper the problem of multicast routing in networks with sparse splitting capabilities was investigated. A new heuristic algorithm, called Sparse Splitting Multicast Routing Heuristic (SSMRH), was presented. It was shown through an example and simulations that the proposed algorithm outperforms the most efficient existing approaches, in terms of average cost of the calculated multicasting trees. This improvement is more pronounced for networks with low percentage of MC nodes.

Current follow-up work focuses on the placement of optical splitters as well as on the provisioning of survivable multicast calls in sparse-splitting optical networks. The case of DaC sparse-splitting networks is also studied as well. Although most of today's networks do not have this capability, future networks will possibly have it. Therefore, efficient multicast routing algorithms must be developed for this case as well. A performance comparison between the case of networks with DoC and DaC MI nodes is also the subject of current research.

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