MULTICAST ROUTING HEURISTIC ALGORITHMS IN NON-SPLITTING WDM NETWORKS

Le Dinh Danh

Received: 15 March 2017 / Accepted: 7 June 2017 / Published: July 2017

Abstract: *Multicast at core WDM layer is known as the efficient way of communications to perform data transmission from a source to several destinations. However, due to costly and complicated fabrication of multicast capable switches, multicasting still partly leverages non-splitting devices like TaC cross-connects. This paper investigates multicasting in such context with the objective of minimizing the cost of using wavelengths in network links. Without splitters, a set of light-spiders starting from the multicast source covering all the destinations is known as the traditional solution. This paper argues that the exact solution for the problem is a set of non-elementary spiders called light-spider hierarchies. Two efficient heuristic algorithms are proposed to compute the light-spider hierarchies to illustrate our findings.*

Keywords: *WDM networks, multicast routing, heuristics.*

1. Introduction

Among the optical constraints, the availability of light splitters in the switches is often the most difficult one due to many reasons. First, splitters are expensive and complicated in fabrication. Besides, splitting causes significant power loss. In the ideal case, the power loss is inversely proportional to the number of split signals at the outgoing ports [1]. Also, wavelength converters are still immature. Therefore, we assume neither splitters nor wavelength converters available in this study. Fortunately, multicasting in WDM networks without splitters and wavelength converters is still feasible with the help of Tap-and-Continue (TaC) cross-connects proposed in [2].

In fact, multicasting in non-splitting WDM networks without wavelength converters have been studied in several works [2 -5]. These works were based on either light-paths [3, 4], light-trails [2], or light-forest [5]. However, there is lack of a deep investigation on the best light-structures for the problem as well as efficient algorithms to find them. In addition, all of the above previous works assume the same set of wavelengths available in all the network links, which is not practical. Regarding the optimization objective, these works aimed at minimizing the network resources taking both the number of wavelengths and the wavelength cost into account, with more focus on the number of wavelengths. In practical routing,

Le Dinh Danh
Faculty of Information and Communication Technologies, Hong Duc University
Email: Ledinhdanh@hdu.edu.vn (✉)

however, the wavelengths are occupied and released dynamically, leading to arbitrary wavelengths available in each link at a certain time. In such cases, minimizing the total number of links used is more important than the total number of wavelengths.

This paper aims at filling the gaps in literature works for routing in non-splitting WDM networks. Specifically, first, a general case with arbitrary wavelength distribution is investigated. Second, total link cost is focused instead of number of wavelengths. Third, two heuristic algorithms are proposed. Finally and most importantly, the exact route structure is identified for the problem. Numerous simulations are conducted to support our announced findings. The rest of this chapter is organized as follows. Section 2 defines the problem and related metrics. Section 3 analyses the exact light-structures for the problem. Section 4 presents two heuristic algorithms, followed by their evaluation described in Section 5. Section 6 concludes the paper.

2. Minimum Cost Multicast (MCM) Problem

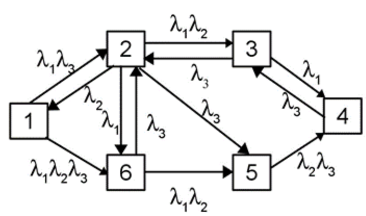


Figure 1. *A WDM network*

A WDM network topology is given by a directed graph $G= (V,A)$, wherein V represents a set of nodes which are all equipped with TaC cross-connects, and A represents a set of directed fibers (links). We assume that there are at most two fibers between every node pair, and each fiber has an arbitrary set of spare wavelengths. Let W be the set of all the possible wavelengths in the network. Since the number of wavelengths can be different in the fibers, we denote $w(l)$ the set of available wavelengths in fiber link $l \in A$: $w(l) \subseteq W$, $\forall\, l \in A$. Also, each fiber l is associated with a positive number $c(l)$ representing the cost of using a wavelength on that fiber (suppose that $c(l)$ is the same for every wavelength in fiber l). Fig. 1 illustrates an example of a WDM network with different distribution of wavelengths in the fibers.

Given a multicast request denoted by $r = (s, D)$, the problem consists in finding a multicast route F starting at the source that spans the destinations D and targeting a given objective function. Without loss of generality, suppose that F consists of K light-structures T_i, $i = 1,\dots,K$, each using a wavelength. The number of wavelengths needed to accommodate the multicast request r is equal to K, i.e., $numwl(F) = K$. The cost of F is the summation of the costs of all the light-structures T_i:

$$\text{cost}(F) = \sum_{i=1}^{K} \text{cost}(T_i) = \sum_{i=1}^{K} \sum_{l \in T_i} c(l)$$

The problem aims at minimizing the combined total cost function expressed as:

$$TotalCost(F) = \Delta * cost(F) + numwl(F) = \Delta * \sum_{i=1}^{K} \sum_{l \in T_i} c(l) + K,\ \Delta > W$$

By choosing $\Delta > W$, the problem aims at minimizing total wavelength link cost first, followed by number of wavelengths.

The multicast route F must comply several constraints. Since there is no wavelength converter, a wavelength should be retained on all the links along a light-structure (*wavelength continuity constraint*), and the light-structures sharing a common link must use different wavelengths (*distinct wavelength constraint*) [7]. Besides, since there is no light splitter, every node (except the multicast source[1]) used in any light-structure should have a degree bounded by two. It is called the *degree constraint.*

3. Exact solutions

Conventionally, the minimum cost multicast route corresponds to tree structure, since there is no redundant edge (arc) created. In non-splitting case, to guarantee this degree constraint, the solution should become a spider-like structure (a spider is a tree with at most one branch vertex [7]). Thus the solution for multicasting without splitters is conventionally a set of light-spiders. However, optical cross-connects allow light signals to be switched using input/output port pairs using a same wavelength as long as no collision occurs. In other words, nodes can be traversed more than once by a route using a wavelength. This makes it possible to realize *non-elementary* routes, as illustrated in Figure 2. Accordingly, three solutions for the request *r=(s,{d_1,d_2})* on the same network condition are possible. Assume that every link is undirected and has unity cost (cost=1). Among possible solutions, light-spider (Fig. 2a) is an *elementary* route; whereas a set of light-paths (Fig. 2b) and a light-trail (Fig. 2c) which are examples of *non-elementary* routes. Obviously, in this context, non-elementary routes are preferred for the cost optimal solution than that of elementary one (light-spider). In the remainder of the paper, we call the mentioned non-elementary routes *light-spider hierarchy*, to distinguish them from elementary light-spider. With this in mind, Theorem 1 gives exact solutions for MCM problem.

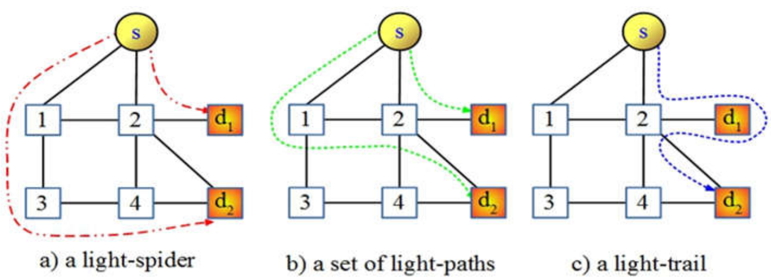


Figure 2. *Different solutions for the multicast request r=(s,{d1,d2})*

Theorem 1. The exact solutions for MCM problem is a set of light-spider-hierarchies.

In the next two sections, two heuristic algorithms to compute the approximate solutions for the MCM problem are presented and evaluated.

---

[1] *Because optical networking allows nodes to be equipped with multiple transmitters, so the multicast source can inject the same wavelength to arbitrary number of successors.*

4. Heuristic algorithms

In this section, we propose two efficient heuristic algorithms for MCM problem.

4.1. Notations

The two proposed heuristic algorithms work on layered graph model [8] instead of topology graph. To support the description of the two heuristic algorithms, we define some used notations as follows.

G'=(V',A'): the layered graph constructed from the topology graph *G=(V,A)*.

r'=(s',D'): the corresponding request of the original request *r=(s,D)* created in the layered graph. We call *s'* the *source*, and *d'* $\in$ *D's ink* in short.

MC_SET: the set of copies of the original source s in all the layers.

CONN_SET: the set of connectors, which can be used to grow the current hierarchy *H*. For the aforementioned degree constraint, not all the vertices in *H* but a subset of them can be used to grow the hierarchy. They include the *s'*, copies of the original source *s, MC_SET* and leaf-nodes in *H*.

SPT(c,D'): the shortest path tree from source *c* to set *D'*.

P(u,v): the shortest path from *u* to *v*.

pred(d'): the predecessor of sink *d'* $\in$ *D'* in the shortest path from *s'* to a sink *d'*.

4.2. Nearest Destination First Algorithm

Nearest Destination First (NDF) algorithm employs the basic idea of the Minimum Path Heuristic [6], which constructs an approximate Steiner tree from an initial vertex by iteratively adding a destination together with the shortest path (one at a time) until all the destinations reached. However, to satisfy the aforementioned degree constraint, MPH is modified in NDF heuristic to compute a valid route.

Given a WDM network modeled by a topology graph *G=(V,A)*, and a multicast request *r=(s,D),* NDF computes a minimum cost route for the corresponding request *r'=(s',D')* on layered graph *G'=(V',A')*. The algorithm returns a multicast route (*hierarchy*) *H* rooted at the source s' and spans the *sinks* D' = {d'_1,d'_2,.., d'_D}. After pruning pseudo vertices and arcs from H, the resulting hierarchy H consists of a set of light-spider-hierarchies (LSHs). Each of these LSHs is located in a different layer, using a distinct wavelength. The description of NDF is given in the Algorithm 1.

Initially, *H* consists of only the source *s'*. At each iteration, the algorithm searches for the nearest sink *d'* (line 11) from *CONN_SET* in the current hierarchy *H* to all the *unreached* sinks *d'*$\in$*D'*. This is done by gathering set *CONN_SET* as a virtual source *c*, and then creating a shortest path tree from *c* to the sinks in *D'* (line 7). Then the algorithm adds all vertices and arcs in the path *P(c, pred(d'))* to *H*, then removes the arcs in the path *P(c,d')* from the layered graph *G'*, and update *CONN_SET* (lines 15-18). The algorithm terminates when there is no reachable destination remaining, or equivalently, H cannot be extended. To obtain the final multicast route, the final step prunes all the pseudo vertices (source and sinks) and the relevant pseudo arcs. The result is a set of LSHs routed at the source duplicates. Obviously, the resulting hierarchy respects all the aforementioned constraint. One example to illustrate the algorithm is shown in Figure 4.

4.3. Critical Destination First Algorithm

NDF algorithm always chooses the nearest sink to extend the current hierarchy. However, there are cases in which this policy is not effective. Let us see Fig.4 for an example. The network is shown in Figure 4a, with the request $r=(s, \{d_1, d_2, d_3\}$. The corresponding layered graph with attached link costs are shown in Figure 4b. According to NDF, the first sink should be d'_3 with the shortest path computed in layer 1: $(s',s^1,2^1,4^1,5^1,d^1{}_3,d'_3)$ with length (cost) of 4. For the next iteration, only d'_1 can be reached (through layer 2) with the corresponding shortest path $(s',s^2,1^2,4^2,6^2,d^2{}_1,d'_1)$ with length of 8. The algorithm terminates and d'_2 is not routed (Fig.4c)!.

Now we see that d'_2 has a least number of incoming arcs (1 in this case). Naturally, it should be chosen first since it has the least probability to be routed. Suppose that we choose d'_2 first, the corresponding shortest path is $(s', s^1, 2^1, 4^1, 5^1, d^1{}_2, d'_2)$ with the length of 5 is added to the hierarchy. To choose the next sink between d'_1 and d'_3, since they have the same number of incoming links, the nearest one from the current hierarchy should be chosen.

So the next sink should be d'_3, and the corresponding shortest path $(d^1{}_2,5^1,d^1{}_3,d'_3)$ with the length of 3. Finally, the last sink $d'_1$and the shortest path $(s', s^2, 1^2, 4^2, 6^2, d^2{}_1, d'_1)$ with the length of 8 is added to the hierarchy, resulting in the solution that reaches all the sinks with total cost of 16 as shown in Figure 4d.

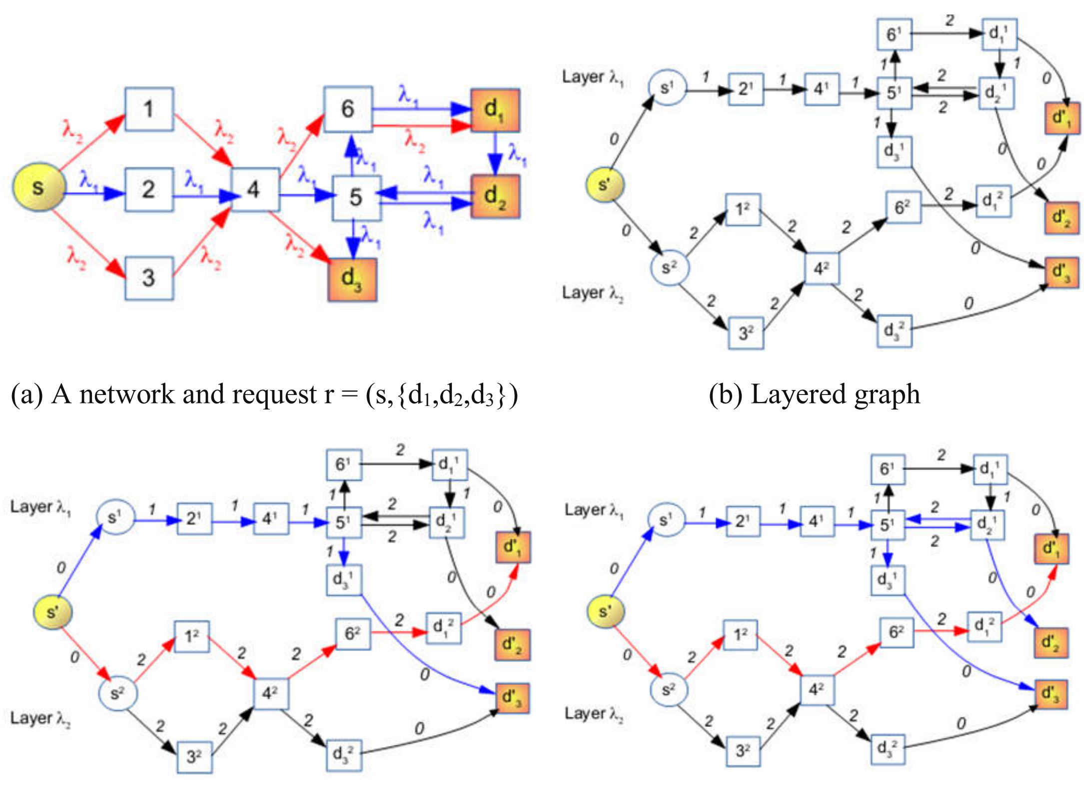
Algorithm 1 Nearest Destination First Algorithm

Input: A topology graph $G = (V, A)$, a set of wavelengths W, a multicast request $r = (s, D)$
Output: A minimum cost hierarchy H

Construct the layered graph $G' = (V', A')$ from G, and the multicast request $r' = (s', D')$ from r
$MC\_SET \leftarrow \{s^1\} \cup \{s^2\} \cup \ldots \cup \{s^{|W|}\}$
$CONN\_SET \leftarrow \{s'\} \cup MC\_SET$
$H \leftarrow \{s'\}$
while $(D' \neq \emptyset)$ **do**
  Gather set CONN_SET as a virtual source c
  Compute in G' the shortest path tree $SPT(c, D')$
  if $(SPT(c, D') = \emptyset)$ **then**
    break
  end if
  Find the nearest sink d' from c
  $H \leftarrow H \cup P(c, pred(d'))$
  $D' \leftarrow D' \setminus \{d'\}$
  $A' \leftarrow A' \setminus \{\text{arcs in } P(c, d')\}$
  $CONN\_SET \leftarrow CONN\_SET \cup \{pred(d')\}$
  if $(c \notin MC\_SET)$ **then**
    $CONN\_SET \leftarrow CONN\_SET \setminus \{c\}$
  end if
end while
Prune all the pseudo vertices and relevant pseudo arcs from H
return H

From the above observation, it is more beneficial to give higher priority to the sinks with lower incoming degree when extending the current hierarchy. We call these sinks *critical destinations*, and the incoming degree *critical degree*, since the incoming degree of a sink indicates the reachability of it from the source *s'* (Fig.4b). The least critical degree sink is thus the most critical destination. This gives rise to the new policy, i.e., choosing the most critical destination first, and hence the name: Critical Destination First (CDF) heuristic. When there are multiple sinks having the same critical degree, the nearest one from the current hierarchy will be chosen first as in NDF.

Basically, CDF has the same framework as NDF, except that instead of finding a nearest sink of *D'*, CDF finds the most critical sink from *D'*. This difference leads to two other different points in the description of CDF algorithm. The first point comes from the possibility that the shortest path *P(c,pred(d'))* may contain destination duplicates which are associated with some sinks. If so, the corresponding sinks must be removed from *D'*. The second different point is that the algorithm should update the reachability of all the affected sinks whenever *P(c,pred(d'))* has been added. These points are dealt using efficient technique in implementation in such a way that the complexity of CDF is the same order as NDF. For space limit, however, the description of CDF and all technical details are omitted in this paper.



(a) A network and request r = (s,{d_1,d_2,d_3})

(b) Layered graph

(c) NDF solution: d'_2 is blocked!

(d) CDF solution: all destinations are routed!

Figure 4. *Illustration of the two heuristics*

5. Performance evaluation

5.1. Performance metrics

This work considers the case with arbitrary distribution of the wavelengths in the links. Hence, in the cases with limited available wavelengths, it is possible that not all the destinations routed for a given multicast request. Two blocking models are taken into account: *full destination blocking* and *partial destination blocking* [9]. Accordingly, under full destination blocking model, a multicast request is established if the source can reach to all the destinations. In this case, the appropriate metric to evaluate the solutions is the request blocking probability (RBP), i.e., the ratio of the number of requests blocked to the total number of requests arrived. For full destination blocking model, the destination blocking probability (DBP), i.e., the ratio between the destinations blocked and the total number of destinations of the request is calculated.

5.2. Simulation settings

The simulations are run on random network topologies *G= (V,A)*, with random distribution of wavelengths in each arc. $|V|$ is chosen in (50,100,150), $W = 10$, and $|D|$ varies in (10%, 20%; …, 90%) of $|V|$. For each $|D|$, we run 1000 instances, then calculate the 95% confident intervals for all the mean values of the above-defined blocking probability metrics (DBP and RBP).

5.3. Results and discussion

For space limit, only result for the case with $|V|$=100 is displayed in Figure 5, but the tendency is the same for the other cases. Among the algorithms, CDF-LSH outperforms the others when always achieving lowest DBP as well as RBP. NDF-LSH appears close to CDF-LSH on DBP but it is by far higher on RBP. Comparing LSH with LS solutions over all the conducted simulations, LSHs are always better than LSs whatever heuristics are employed. In particular, with NDF algorithm, NDF-LSH profits 4.5% (on average) lower on DBP, and 18% on RBP compared with NDF-LS. Similarly, the corresponding gains of 6.5% and 21.5% obtained when comparing CDF-LSH with CDF-LS. Especially, based on the same LSH solutions, CDF-LSH works better than NDF-LSH when achieving 18% lower RBP, 1% lower DBP.

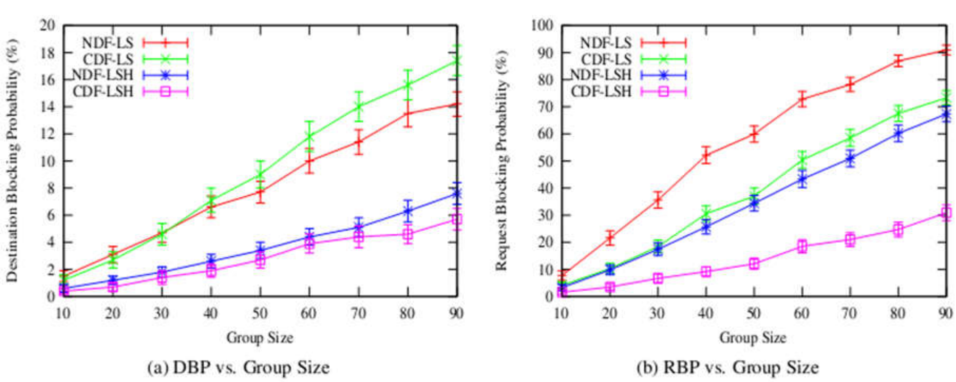


Figure 5. *Performances of algorithms on 100-node random graphs with W= 10*

In short, the LSH solutions are always better than LS counterparts; and the CDF algorithm outperforms NDF. The results are expected and explainable. On one hand, by permitting vertices to be visited more than once, LSH allows to make full use of all the available wavelengths in the links while respecting the three aforementioned constraints. Consequently, more destinations can be reached with a limited available links and wavelengths, it in turn results in better blocking probability. On the other hand, CDF gives high priority to the most critical destinations to extend the hierarchy. Naturally, the most critical destinations will not be abandoned whenever there is a chance. Meanwhile NDF always chooses the nearest one, which may leave some destinations unreached even if there are many other choices.

6. Conclusion

The paper proposed two cost-effective heuristics for the MCM problem: Nearest Destination First and Critical Destination First. These algorithms aim at minimizing the total cost for a given multicast request under the arbitrary availability of wavelengths in non-splitting networks. The two algorithms are designed to compute minimum-cost light-spider hierarchies based on the auxiliary layered graph model. They are different in the way of choosing the candidate destinations. NDF always chooses the nearest destinations at each iteration, while CDF selects the critical destinations first. The performances of the two heuristics are compared with each other. They show that, taking the critical degree of the destinations into account, particularly choosing the most critical destination to route first, results in a better solution under arbitrary wavelength configuration. Once again, the simulation results confirm that light-spider-hierarchies outperform light-spiders counterpart in supporting multicast in non-splitting networks.

References

[1] M. Ali and J. S. Deogun (2000), *Power-efficient design of multicast wavelength-routed networks*, Selected Areas in Communications, IEEE Journal on, vol. 18, no. 10, pp. 1852 -1862.

[2] M. Ali and J. S. Deogun (2000), *Cost-effective implementation of multicasting in wavelength-routed networks*, EEE/OSA Journal of Lightwave Technology, vol. 18, pp. 1628 -1638.

[3] R. Libeskind-Hadas (2000), *Efficient collective communication in WDM networks with a power budget*, in Computer Communications and Networks, 2000. Proceedings. 9th International Conference on, pp. 612 -616.

[4] S. Yan and J. Deogun (2003), *Multi-drop path model for multicast routing and wavelength assignment*, Information Sciences, vol. 149, no. 1, pp. 113 -134.

[5] D.-R. Din (2009), *Heuristic Algorithms for Finding Light-Forest of Multicast Routing on WDM Network*, Information Science and Engineering, vol. 25, pp. 83 -103.

[6] H. Takahashi and A. Matsuyama (1980), *An approximate solution for the Steiner problem in graphs*, Mathematica Japonica, vol. 24, pp. 573 -577.

[7] L. Gargano, P. Hell, L. Stacho, and U. Vaccaro (2002), *Spanning trees with bounded number of branch vertices*, in Automata, Languages and Programming, pp. 355 -365, Springer.

[8] C. Chen and S. Banerjee (1996), *A new model for optimal routing and wavelength assignment in wavelength division multiplexed optical networks*, in INFOCOM '96. Fifteenth Annual Joint Conference of the IEEE Computer Societies. Networking the Next Generation. Proceedings IEEE, vol. 1, pp. 164 -171, March 1996.

[9] Dinh Danh Le, Fen Zhou, and Miklos Molnar (2015), *Minimizing Blocking Probability for MCRWA problem in WDM Networks: Exact Solutions and Heuristic Algorithms*, Journal of Optical Communications and Networking (JOCN). Vol. 7, Iss. 1, pp. 36-48.