On the challenges of finding two link-disjoint lightpaths of minimum total weight across an optical network

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The problem of finding two link-disjoint (primary and backup) paths of minimum total weight across a network is referred to as Problem 2DP. For this problem, there exist computationally efficient solving algorithms such as the one developed by Suurballe and Tarjan. Indeed, the latter has become the reference algorithm for solving Problem 2DP in the context of IP networks.

In this paper, we analyze the challenges of developing an algorithm inspired in Suurballe and Tarjan for solving Problem 2DP in the context of wavelength switched optical networks. We examine the challenges under the wavelength continuity constraint as well as in the cases of partial and full wavelength conversion.

Conversely to most previous works in the area, which primarily target the design of protection techniques against multiple link failures, we focus here on providing insight into the algorithmic challenges for efficiently finding two link-disjoint lightpaths of minimum total weight across an optical network.

1. Introduction

Over the last years, optical network technologies have developed in several ways, providing nowadays enormous transmission capacity. With Dense Wavelength Division Multiplexing (DWDM), a single wavelength can now reach several Gbps with tens of wavelengths supported on each fiber, making the latter a cost-effective solution for a transit network infrastructure. Since DWDM networks are prone to link failures, it is necessary to develop appropriate path protection schemes to prevent or reduce as much as possible the data loss in the event of failures. For many network infrastructures, events such as natural disasters (e.g., hurricanes, floods, etc) rarely occur, so simultaneous link failures are uncommon events. For these networks, protection schemes based on the provisioning of two link-disjoint (primary and backup) paths is sufficient in practice.

The algorithms developed by Suurballe [1], and later on by Suurballe and Tarjan [2], in the context of IP networks, have become the reference algorithms for finding two link-disjoint paths of minimum total weight (known as Problem 2DP). In optical networks without wavelength conversion, solving Problem 2DP is much more complex than at the IP layer, since the problem has an additional dimension due to the wavelength space.

Under the wavelength continuity constraint (WCC), Problem 2DP can be seen as a multi-topology problem, where each topology corresponds to one wavelength. This means that, whereas the primary path could be in one topology, its link-disjoint counterpart could be in another—notice that it is not necessary that the two paths use the same wavelength, as long as they are link-disjoint. With wavelength conversion, the number of available link-disjoint paths increases, but the algorithmic challenges in solving Problem 2DP increase as well.

In this paper, we analyze the challenges of developing an algorithm for solving Problem 2DP in the context of wavelength switched optical networks (WSON). We examine the challenges under the WCC, and also under partial and full wavelength conversion capability. Conversely to previous works, where different solutions have been proposed based on iterative invocations of Suurballe and Tarjan's algorithm, our research is focused on the design of algorithms inspired in the latter (e.g., variations of it by changing its search engine), rather than simply reusing it.

The rest of the paper is organized as follows. Section 2 outlines Problem 2DP and shows the application of Suurballe's algorithm through an example. Section 3 presents related work, and Section 4 analyzes the algorithmic challenges in the design of a new algorithm for solving Problem 2DP for optical networks, with and without wavelength conversion. Finally, Section 5 concludes the paper.

2. Two Link-disjoint paths problem: Problem 2DP

With the aim of finding two link-disjoint paths of minimum total weight on a network, the simplest approach is to apply the following two-step algorithm:

Step 1: Employ Dijkstra [3] in order to find the shortest path from the source S to the destination node D.

Step 2: Prune from the network all the links that belong to the path computed, and then find the second path between S and D running Dijkstra again.

If two paths were found, they are certainly link-disjoint and the total weight should be minimal. However, this simple approach fails to find link-disjoint paths in many cases due to what it is usually referred to as the "trap topology" problem. Figure 1 shows this problem, where the above two-step algorithm fails in finding a pair of link-disjoint paths in a network that clearly has a solution, namely, S-E-F-B-D and S-A-G-H-D. Figure 1 shows that after pruning the links found in Step 1 (see that each link is denoted with its cost), S and D become disconnected in the remaining graph, so Step 2 is unable to find the link-disjoint counterpart of the path S-A-B-D found in Step 1.

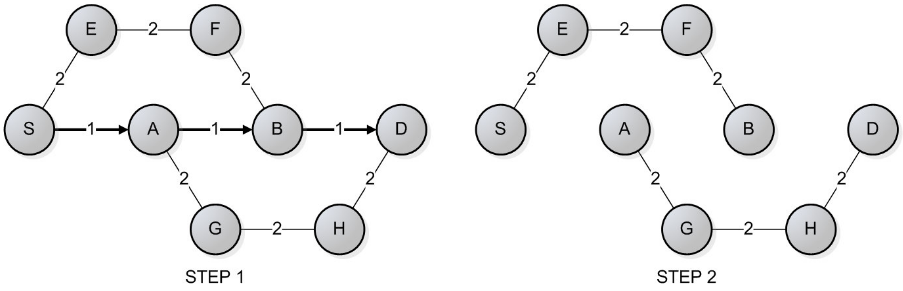

Figure 1: Trap Topology.

In order to address this issue, two algorithms have been proposed.

2.1 Suurballe

The Suurballe's algorithm [1] always finds two link-disjoint paths from a source node S to a destination node D, as long as those paths exist on the network, assuring that the total weight of both paths is the minimum among all pairs of paths in the network. The Suurballe's algorithm works as follows (its application is shown in Figure 2):

Step 1: Apply Dijkstra to find the shortest path p1 between S and D. The result is the path S-A-B-D in Figure 2.

Step 2: Reverse the direction of p1's links and invert their weights.

Step 3: On the new topology, find the shortest path p2 between S and D running Dijkstra again, being the resulting path S-E-F-B-A-G-H-D in Figure 2.

Step 4: Remove all common links between p1 and p2.

Step 5: Using the simple two-step algorithm described above, find the two shortest link-disjoint paths between S and D. In Figure 2: S-A-G-H-D and S-E-F-B-D.

The algorithm runs in O(n^2.log$n$) time, where n is the number of nodes in the network.

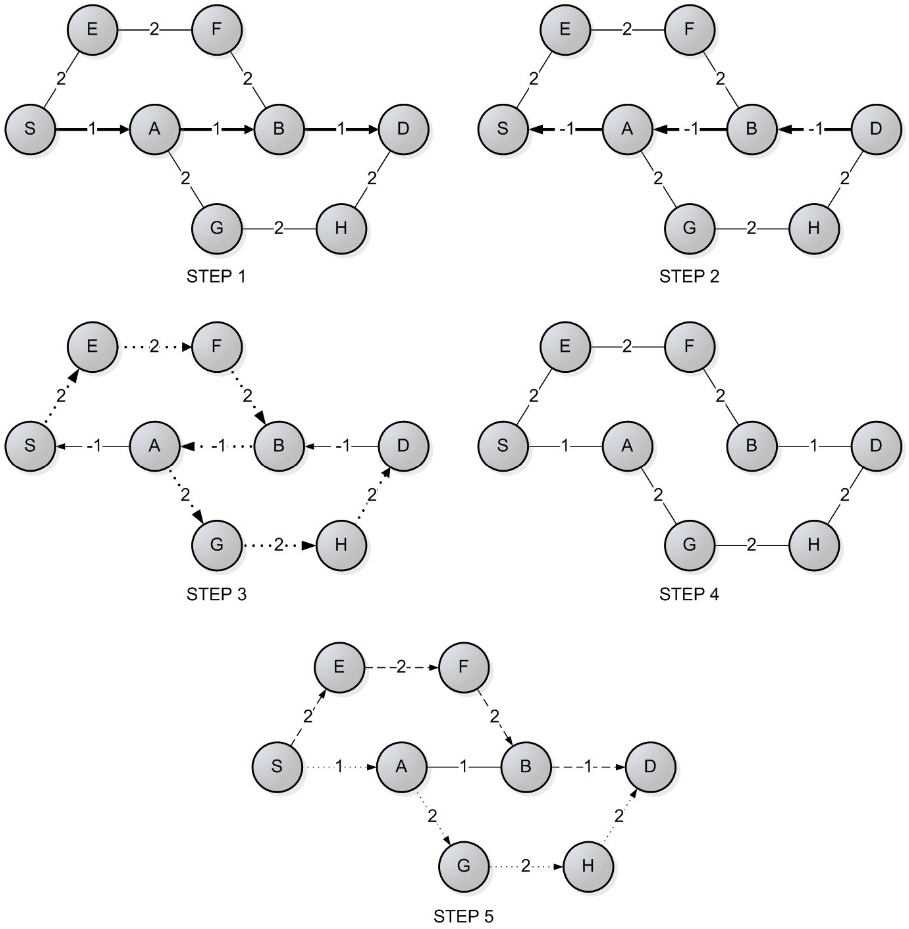

Figure 2: Suurballe's algorithm.

2.2 Suurballe and Tarjan

The algorithm due to Suurballe and Tarjan [2] is a more efficient version of Suurballe's algorithm. It changes some data structures, e.g., it uses a min-heap to store and retrieve the unexplored nodes in order to reduce the second step in Dijkstra. This algorithm is solvable in $O(m.\log_{(1+m/n)} n)$ time using two iterations, where n is the number of nodes and m the number of links in the network (with $m \geq n - 1$).

3. Related Work

In the last years, several research papers have been published addressing Problem 2DP under the WCC [4-9]. Many of them have demonstrated that, constrained to wavelength continuity, Problem 2DP is NP-Complete. Therefore, the existing solutions addressing Problem 2DP in the context of optical networks are based on heuristics, such as the Route-First and Wavelength-Scan Algorithms [7]. The former, first scans all fiber links and increases the cost of a link linearly to the number of wavelengths already in use on the link, so as to enable Suurballe's algorithm to avoid links with fewer free wavelengths. Next, it runs Suurballe and finishes assigning a free wavelength to each of the two paths. The latter, first runs Suurballe's algorithm on every wavelength to find the working and the protection paths on a single wavelength. Then, it chooses the wavelength for which the pair of paths has the minimal total cost. If this step fails, it invokes the simple two-step algorithm (see Section 2) on all wavelengths.

These solutions have one thing in common, i.e., none of them tries to change and improve the core of Suurballe and Tarjan's algorithm. Instead, they propose different (and sometimes inefficient) ways of applying it repeatedly, until a solution is either found or the algorithm gives up. We suspect that better results can be achieved if adaptations to Dijkstra's algorithm are made, since this is the core of the Suurballe's search engine. Furthermore, in the results shown in most available papers in the topic, only the blocking probability of the proposed heuristics is analyzed, so issues such as the set up time are not considered. We consider that other performance metrics must be analyzed, and tested in a real scenario.

4. Challenges within WSON Infrastructures

One of the challenges involved in the connection provisioning within WSON infrastructures is to develop efficient algorithms for dynamically computing routes and assigning wavelengths in a manner which efficiently utilizes the network resources (i.e., wavelength channels), as well as satisfying a specific set of constraints (e.g., computation of two link-disjoint paths, etc.). This is known as the routing and wavelength assignment (RWA) problem [10]. In this context, a key aspect impacting on the complexity and performance of the RWA process is the availability of the wavelength conversion capability. Indeed, the lack of wavelength converters does make the provisioning of connections considerably troublesome. Moreover, such a complexity is at least doubled when for each connection request a pair of link-disjoint paths (working and backup) need to be computed fulfilling the WCC. Such network infrastructures are typically named as Wavelength Selective Networks (WSN). On the other hand, a network wherein either full or partial wavelength converters are available in either all or in specific nodes is referred to as Wavelength Convertible Network (WCN). In the following, we focus on describing the main challenges that the RWA algorithms must address when routing protected connections considering either WSN or WCN scenarios.

4.1 Wavelength Selective Networks

The migration of the current optical transport networks towards all-optical infrastructures is due to two drivers, namely, the huge capacity provided by the WDM technology, and the mature and cost-effective all-optical switches (e.g., OXCs). Besides increasing the transport capacity, all-optical transport networks also yield important benefits such as network cost reduction (i.e., elimination of the optical/electronic/optical - OEO conversions when switching), transparency to the signal bit rates and traffic formats, etc. [11]. On the other hand, due to the lack of OEO conversions, and to the high cost of the current all-optical wavelength converters, the lightpaths to be established are subject to meet the well-known WCC. In other words, all the optical connections to be set up are required to allocate the same wavelength channel on each link between the source and the destination nodes. Otherwise, the entire optical connection is blocked.

In the context of dedicated path protection within WSN, as mentioned above, for each connection request, the RWA algorithm is the responsible to jointly compute a pair of working and backup paths that must satisfy independently the WCC. In this work, we consider 1:1 dedicated protection which allows selecting different wavelength channels per lightpath. As depicted in Fig. 3, for a connection request between node 1 and node 7, the working path is established through the path formed by the nodes 1, 3, 5 and 7, and allocating the wavelength channel 1. On the other hand, the backup path is set up through the path composed by nodes 1, 2, 6, and 7, and occupying the wavelength channel 2.

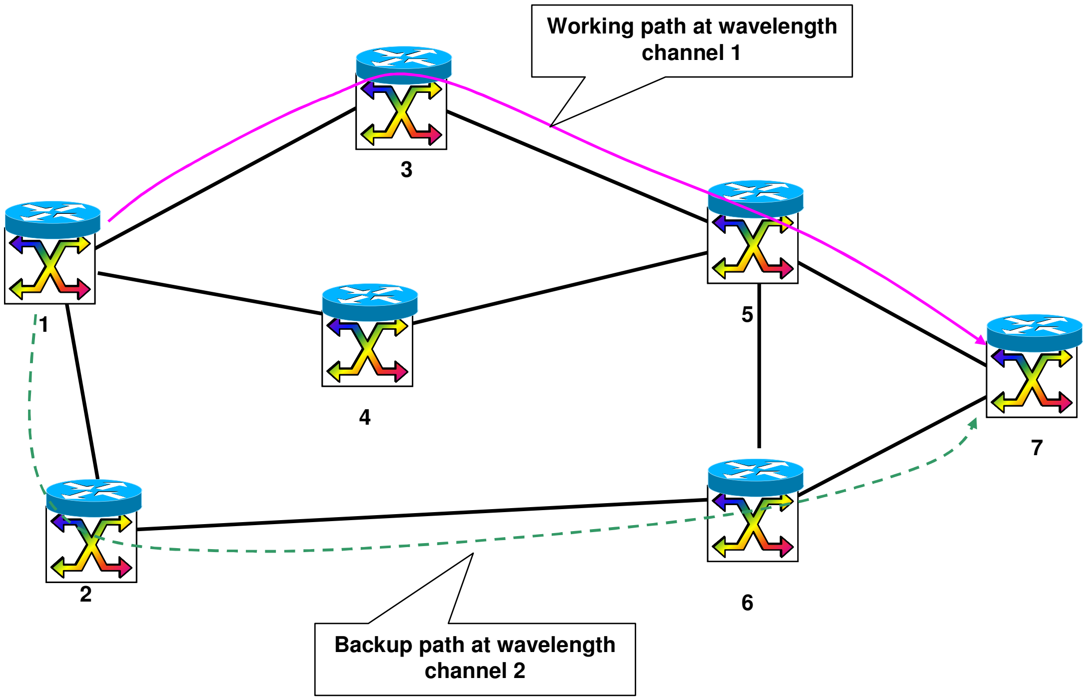

Figure 3: Example of working / backup path provisioning within WSN.

It is worth noting that in this scenario, the distributed / centralized path computation entity (RWA algorithm) needs to be aware of not only the network topology to compute a pair of link disjoint paths for each connection request, but also the wavelength channel availability of every network link to fulfill the WCC. If this information is disseminated using control protocols, such control protocols need to be extended. Then, the objective of the RWA algorithm aims at serving each connection request fulfilling these constraints at the same time that the network resources in terms of wavelength channels are optimized.

4.2 Wavelength Convertible Networks

The utilization of full or sparse wavelength converters at a given set of nodes drastically relaxed the complexity of establishing the connections within WSON networks. Indeed, the WCC is considered the main cause for connection blocking in such scenarios. Nevertheless, in WCN, a lightpath may use as many wavelength channels as links are forming the entire path. To do this, it is required that each node of the route has at least an available wavelength converter.

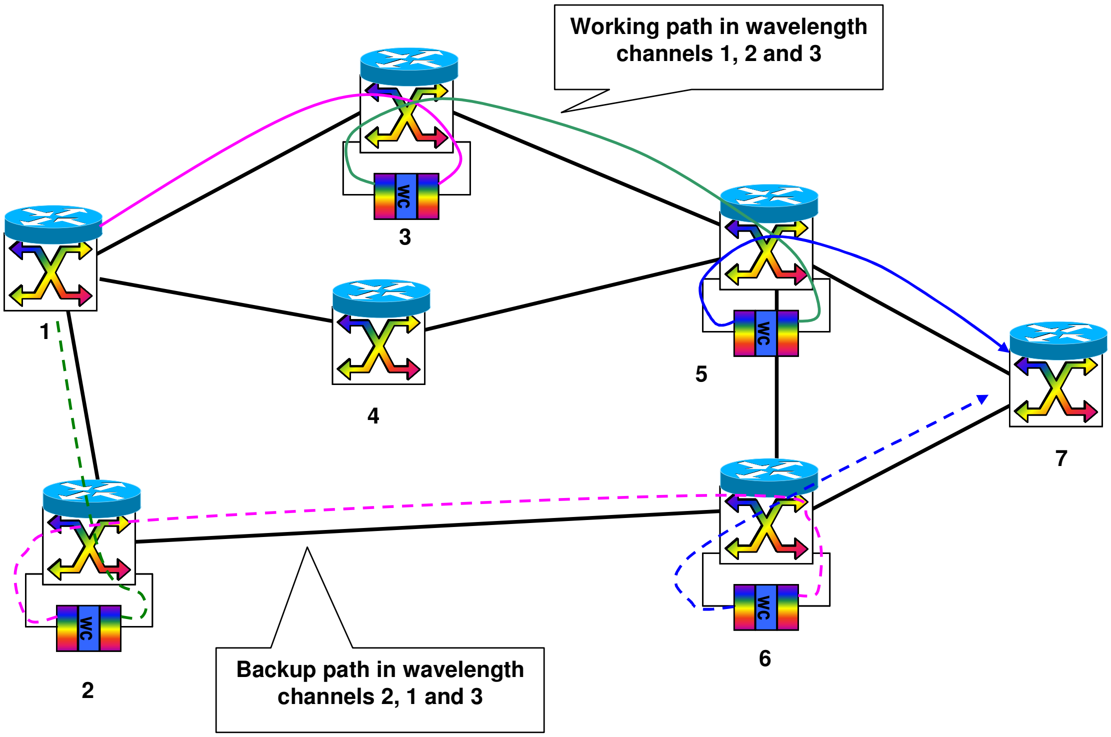

Figure 4: Example of working / backup path provisioning within WCN.

In Fig. 4, we show the same example as above but within a WCN scenario. One may observe that both the working and backup paths are provisioned using different wavelengths on each traversed link. Of course, this reduces both the complexity of the RWA algorithm and the connection blocking when establishing lightpaths. Furthermore, if the network nodes are equipped with full wavelength converters in each network link, the problem of the wavelength assignment is not an issue. Indeed, the RWA algorithm is reduced to the computation of a pair of link-disjoint paths, which is optimally obtained through the Suurballe and Tarjan algorithm as described in section 2. However, if either the full wavelength conversion capability is sparse among all the network nodes, or the wavelength converters are only available in a limited number of links at each node, the RWA algorithm needs to be aware of the topology, the wavelength availability and the wavelength converter utilization in order to route the connections. In turn, the information regarding converter availability must be obtained, by means of control protocol extensions, if appropriate. Recall that if no available wavelength converters can be used, the WCC must be satisfied. Likewise in the WSN scenario, the goal of the RWA algorithm is to jointly compute a pair of link disjoints paths at the same time that the network resources in terms of wavelength channels and wavelength regenerators are optimized.

5. Conclusions and Future Work

In this paper, we have analyzed the challenges for finding two link-disjoint lightpaths of minimum total weight across an optical network (this is known as Problem 2DP). We have described the strengths of Suurballe and Tarjan's algorithm for solving Problem 2DP in the context of IP networks, and we have also outlined the most relevant proposals addressing Problem 2DP in an optical network scenario. We have examined the RWA problem under the WCC as well as in an optical network with either partial or full wavelength conversion capability. We have shown that in an optical network with full wavelength conversion capability, the RWA could be solved using Suurballe and Tarjan, but in scenarios subject to the WCC or to partial wavelength conversion, the latter is not sufficient. Indeed, most of the existing heuristics to solve Problem 2DP without full wavelength conversion propose inefficient iterations of Suurballe and Tarjan's algorithm.

We argue that more effective and efficient solutions can be developed by improving the core of Suurballe and Tarjan's algorithm, rather than looking at different ways of applying the latter. Our future work will focus on developing enhanced versions of Suurballe and Tarjan's algorithm especially adapted for optical networks without full wavelength conversion capability. We also plan to test and validate our algorithms on a real optical infrastructure.

Acknowledgements

This work was partially funded by the MICINN (Spanish Ministry of Science and Innovation) under contract TEC2008-02552-E/TEC.

References

[1] Remesh Bhandari, "Survivable Networks – Algorithms for Diverse Routing," Kluwer Academic Publishers.

[2] J. W. Suurballe and R. E. Tarjan, “A quick method for finding shortest pairs of disjoint paths,” Networks, vol. 14, pp. 325-336, 1984.

[3] E.W. Dijkstra, "A note on two problems in connection with graphs," Numberische Mathematik. 1 (1959) 269-271.

[4] S. Tanwir and D. Seshadri, "Dynamic Path Protection Algorithms for WDM networks: Survey and Performance Comparison," http://dutta.csc.ncsu.edu/csc775_fall06/wrap/final_project_deliverables/deepa_savera.pdf.

[5] S. Yuan and J. P. Jue, “Dynamic lightpath protection in WDM mesh networks under wavelength continuity constraint,” IEEE GLOBECOM 2004, vol. 3, pp. 2019 – 2023, November 2004.

[6] A. S. Reid Andersen, Fan Chung and G. Xue, “On disjoint path pairs with wavelength continuity constraint in WDM networks,” IEEE INFOCOM 2004, Hong Kong, China, p. 10, March 2004.

[7] S. Yuan and J. P. Jue, "Dynamic path protection in WDM mesh networks under wavelength-continuity and risk-disjoint constraints," Technical Report, no. UTDCS-26-04, University of Texas at Dallas.

[8] S. Yuan and J. P. Jue, "Dynamic lightpath protection in WDM mesh networks under risk-disjoint constraint," IEEE GLOBECOM 2004, vol. 3, pp. 1770 – 1774, November 2004.

[9] D. Xu, Y. Chen, Y. Xiong, C. Qiao, and X. He, "On the complexity of and algorithms for finding the shortest path with a disjoint counterpart," IEEE/ACM Trans. Networking, vol. 14, no. 1, pp. 147–158, Feb. 2006.

[10] H. Zang, J. P. Jue, B. Mukherjee, "A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks", Opt. Networks Mag, vol. 1, no. 1, pp. 47-60, Jan. 2000.

[11] R. Ramaswami, "Optical networking technologies: what worked and what didn't", IEEE Commun. Mag., vol. 44, no. 9, pp. 132-139, Sept. 2006.