Efficient Algorithms for Physically-Disjoint Routing in Survivable GMPLS/ASTN Networks*

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Abstract

With the advent of intelligent multilayer networks, like GMPLS, connections can be protected against failures effectively; however, to capitalize the advantages, novel sophisticated routing methods are needed. This paper addresses the task of finding path-pairs in a survivable multilayer network in order to ensure high availability for each connection. Known methods (like running a shortest path algorithm twice) either do not guarantee physical disjointness (SRLG constraints) or may not find solution even if it exists. Besides the Integer Linear Program based approach that yields a solution with minimal total cost, we propose a heuristic method to solve the problem, and extend it to (1) minimize the number of spans used by both working and protection paths, (2) to find the weighted working path while ensuring the existence of a protection path, and (3) to find more than one backup paths for high priority traffic. It is shown with numerous simulations that our proposed method finds solution for significantly (up to 35%) more node pairs than traditional methods, while the running time is only slightly increased. Furthermore, it yields connection availabilities close to the optimum.

*P. Laborczi is supported through a European Community Marie Curie Fellowship. T. Cinkler is supported by the János Bólyai foundation. This research has partially been supported by the Hungarian National Science Fund (OTKA grants D42211 and 42559).

1 Introduction

The design, configuration, reliability and protection issues of Wavelength Division Multiplexing (WDM) networks are being discussed intensively in the literature, e.g., in [1, 2, 3, 4, 5]. However, most existing networks are integrated in a multilayer network architecture, that means several combinations of the architecture IP-over-ATM-over-SDH-over-WDM. This four layer architecture makes today core network architecture ineffective. The vision "IP directly over WDM" promises the elimination of unnecessary network layers leading to network cost and complexity reduction [6]. Such technology is the Generalized Multiprotocol Label Switching (GMPLS) [7, 8, 9] that defines common control plane for a heterogeneous network (e.g. IP/MPLS routers, ATM switches, SDH/SONET elements, optical devices etc.) in order to efficiently and cooperatively respond to traffic demands and network reconfiguration. Although GMPLS can support different network scenarios, in this paper we refer to two-layer network architecture, explicitly IP/MPLS over WDM architecture. GMPLS allows sharing information between the WDM and IP layers while enabling IP traffic to directly access the WDM channels. Therefore, such an IP-over-WDM architecture can effectively coordinate label switched path (LSP) determination and protection to deliver optimal performance [6].

In the literature several problems arising in multilayer networks are discussed. In [10] and [11] Bhandari designs an algorithm for the shortest pair of physically-disjoint paths between a given pair of nodes. He takes two special cases of the problem (fork configuration and express link) into account. However, other configurations may occur that are not covered by these works and demands can be blocked even if physically disjoint path could be found. A major problem with protection of multilayer networks is a scenario when multiple upper-layer links (shared risk link group - SRLG [12]) are torn down simultaneously due to a single lower layer failure. In [13] a tabu search based algorithm is proposed that maps upper layer links into lower layer channels and prevents three types of failure propagation. In [14] the ILP formulation of protection at the upper (electrical) and at the lower (optical) layer are given. In this paper, dynamic IP connections are realized by MPLS label switched paths (LSPs) that are mapped into static λ paths of the WDM layer. To our opinion, it is reasonable to configure only the MPLS layer dynamically and assuming the mapping and the routing in the WDM layer static because of the following reasons:

o In transport networks the aggregated traffic is relatively steady and predictable.

o In case of high loads a well configured static routing has the best performance.

o Due to dynamic behaviour the paths can become quite long that deteriorates the throughput. This is a particular problem if more than one layer is dynamic.

o This was the idea in ATM dynamic VCCs over a static VPC system, or in telephony networks, dynamic 64 kbit/s "circuits" over a static VC system.

o Hardly any wavelength path can be terminated to reuse its wavelength links in more efficient way, since in its very large capacity there is almost always some minor traffic leaking through it that will hinder us in terminating it.

Consequently, the protection tasks can be effectively coordinated in the upper (IP) layer [15]. However, cooperation of different types of network layers raises the question how to route and protect the demands (commodities) in the upper network layers [16, 17, 18].

There exist two main approaches to protect the traffic of multilayer networks. In case of *Protection at the Lower Layer (PLL)* the network is protected in the lowest possible layer by equipment of this layer, e.g., the resilience is carried out in the layer as near to the origin of the failure as possible. The WDM layer supplies protected λ paths for the links of the IP layer. (In this paper, we use the terms *span* and *link* for the lower (WDM) and upper (IP) layers, respectively.) The other approach is *Protection at the Upper Layer (PUL)* that recovers failures in the layer closest to the origin of the traffic. Applying this approach failures happening in the lower layer are recovered in the upper layer. In case of overlay model the IP node detects that the signal does not arrive within a certain time from the WDM layer. In case of peer model IP node receives a control signal from the common control plane after a failure occurs. Obviously, the working and protection paths should be disjoint of each other in the lower layer as well.

An exhaustive comparison of the two approaches, according to resilience time and installation costs can be found in [18]. PLL is cheaper and faster, while PUL ensures better granularity that means:

o For demands having different reliability requirements connections of different reliability can be established.

o The uppermost layer protects against all failures in lower layers, thus the cooperation of different layers can be avoided, which ensures simpler functionality.

o Even thousands of LSPs can use a single 2.5 Gb/s WDM link. In case of protection in the upper layer they have to be restored one by one. Although this causes slower operation, these paths utilize the network more efficiently [18].

Detailed explanation of these protection strategies can be found in [16, 17, 18].

1.1 Disjoint Routing in the Upper Layer

An efficient way of enhancing the availability of a connection is to find two physically disjoint paths. In this paper we deal with disjoint routing of one upper layer demand. The task is to find for each demand one working path and one protection path. The task should be carried out fast in order to be applicable in a dynamic environment. This is not as simple as in case of one layer because both the mapping [20] and the lower layer capacity constraints are to be taken into consideration. Routing in the upper layer can fail because of two reasons: (1) Due to capacity constraints: In this case the routing fails because it cannot be routed within available lower layer capacities. (2) Due to disjointness: In this case the routing fails because there exists no pair of paths that are disjoint in the lower layer, i.e., which do not cause failure propagation. Capacity constraints are always to be respected (all links are temporarily deleted that would be overloaded if they were used by the demand), but disjointness constraints can be avoided in order to achieve higher throughput. In the later case the price for higher throughput can be the deterioration of availability. In many cases minimum level of availability is assigned for higher priority traffic. In this case it can be necessary to define more than one protection paths for demands with higher priority in order to achieve higher availability.

We study two cases: the *“disjoint or blocking”* case is most often used in the literature that will simply block the new demand if a totally disjoint path-pair does not exist. We introduce the *“disjoint or joint”* approach for GMPLS networks that minimizes the number of physical spans commonly used by the upper layer working and protection paths. Furthermore, the *asymmetrically weighted pair of disjoint paths* [19] is extended for multilayer networks. It can be proved that these problems are algorithmically very complex (NP-hard). We characterize the algorithm on the one hand by its running time and on the other hand by the quality, i.e., success rate in the *disjoint or blocking* case, while by the number of commonly used spans and by the availability in the *disjoint or joint* case. Furthermore, we indicate the length of the paths. We give methods based on Integer Linear Program (ILP), and an Extension of Dijkstra's shortest path algorithm (ED) to solve the above problems. The running time and quality is compared with Dijkstra's and Suurballe's algorithm [19, 21], commonly used in the literature. ILP yields optimal solution but its running time can be very long (exponential). It is shown that ED is a very good compromise between running time and quality.

2 Integer Linear Programming (ILP)

We consider routing of one demand and assume that the topologies of both layers and the mapping between layers are known. Let $G(V, E)$ denote the directed graph where V is the set of nodes (vertices) while E the set of directed upper layer links (edges) of the GMPLS network. Let c_{kl} denote the cost of using edge $kl \in E$, x_{kl} and y_{kl} take the value 1 if link $kl \in E$ is used by the working and by the protection path, respectively, otherwise they are 0. Furthermore, we denote the set of lower layer edges (spans) by E_1.

The flow conservation indicator is defined for all nodes $k \in V$ as follows:

$$f(k) = \begin{cases} 1 & \text{if } k \text{ is the source of the demand} \\ -1 & \text{if } k \text{ is the sink of the demand} \\ 0 & \text{otherwise} \end{cases}$$

2.1 The *“Disjoint or Blocking”* Approach

In this case the task is to find two physically disjoint paths with minimum total cost.

Objective:

$$\min \sum_{kl \in E} (x_{kl} + y_{kl}) c_{kl} \tag{1}$$

Constraints:

$$\sum_{\{l:\ kl \in E\}} x_{kl} - \sum_{\{m:\ mk \in E\}} x_{mk} = f(k) \tag{2}$$

for all nodes $k \in V$

$$\sum_{\{l:\ kl \in E\}} y_{kl} - \sum_{\{m:\ mk \in E\}} y_{mk} = f(k) \tag{3}$$

for all nodes $k \in V$

$$x_{kl} + y_{mn} \le 1 \tag{4}$$

for all link-pairs $kl, mn \in E$, of which paths use at least one common span.

$$x_{kl} \in \{0, 1\}, y_{kl} \in \{0, 1\}, \text{for all links } kl \in E \tag{5}$$

The objective is to minimize the edge costs used by the working and protection paths. Previous studies pointed out (e.g. [22]) that in a dynamic routing environment for each link the cost of the link is to be set to the reciprocal of the free capacity on the link in order to minimize the blocking probability. Equations (2) and (3) are flow-conservation constraints for working and protection paths and Constraints (4) ensure path-diversity in the lower layer.

The drawback of this approach is that if no solution is found the request is blocked. Therefore, a second approach is proposed that always finds two paths (if the network is connected); however, they may use common spans.

2.2 The *“Disjoint or Joint”* Approach

In this case the Objective (1) is modified to minimize the number of lower layer edges that are used both by the working and by the protection paths:

$$\min \beta \sum_{e \in E_1} b_e + \sum_{kl \in E} (x_{kl} + y_{kl}) c_{kl} \tag{6}$$

where $b_e \in \{0, 1\}$ takes the value 1 if span $e \in E_1$ is used by both, the working and the protection path of a demand, otherwise it is 0. β is a large number (e.g., $1000\overline{c_{kl}}$) to put larger weight on the left component of the sum.

Let $\Phi_1(kl, mn)$ denote the set of lower layer edges that are used by both upper layer links kl and mn. Using this, Equation (4) is modified as follows to take common spans into account:

$$x_{kl} + y_{mn} \le 1 + \sum_{e \in \Phi_1(kl, mn)} b_e \tag{7}$$

for all link-pairs $kl, mn \in E$ using at least one common span.

2.3 Weighted Working Paths

In many cases a network operator's aim is not only to reduce the total cost of the path pair but to optimise with weighting on one of the paths (usually on the working path). This is called the *asymmetrically weighted pair of disjoint paths* where the objective of the optimisation is the sum $\alpha cost(P_1) + cost(P_2)$, where $cost(P_1)$ and $cost(P_2)$ are the cost of the working path and of the protection path, respectively. Parameter α is the weight of the working path, which is determined by the protection strategy. In other words the consumption of network resources by the working path is α times more important than that of the protection path.

In [19] the problem has been proved to be **NP**-complete and several heuristics have been proposed based on k-shortest paths searching, Suurballe's algorithm, Integer Linear Programming (ILP), Linear Relaxation (LR), and Minimum Cost Network Flow (MCNF) algorithm to achieve best performance in polynomial time. The heuristic methods presented in [19] can be appropriately applied to multilayer networks as well. Here, we extend this approach to multilayer networks by formulating it as an ILP.

In this case Objective (6) will be as follows:

$$min\ \beta \sum_{e \in E_1} b_e + \sum_{(k,l) \in E} (\alpha x_{kl} + y_{kl}) c_{kl}, \qquad (8)$$

where α is the weight on the working path while β should be set to a smaller value to have the right side of the sum dominating.

3 The Proposed Algorithm

In this section, first, three commonly used heuristic methods are shortly described to solve the problem. Since all these methods have significant drawbacks, we propose a new algorithm that solves the problem very efficiently in a reasonable amount of time.

Linear Relaxation. In this case the integer condition of the ILP formulation is relaxed, i.e., a linear program is solved. It has shorter (polynomial) running time but real numbers should be interpreted and rounded to integers.

Two Shortest Path Algorithms (TSPA). This method uses Dijkstra's (or one of the other) shortest path algorithms twice. After finding the working path using Dijkstra's algorithm, it deletes all upper layer links temporarily that use the same physical span(s) as the working paths (this can be decided on the basis of the mapping). Finally, run the shortest path algorithm again on this stamped graph. Although this method is very fast, it does not yield solution in many cases (even if there exists one) when the routing of the first path blocks the routing of the second one.

Suurballe's Algorithm. To find two disjoint paths with minimal total cost, Suurballe's algorithm [21] can be used. However, to run this in the upper layer, there arises the problem that it can not consider the mapping and the lower layer. On the other hand, applying the algorithm in the lower layer may lead to paths that are not valid in the upper layer [16].

3.1 Algorithm for the *Disjoint or Blocking* Approach

In this Subsection we describe the proposed heuristic algorithm based on Dijkstra's shortest path algorithm solving the problem efficiently in polynomial time. First, for each edge $e \in E$ set length l_e to the number of links that belong to the same SRLG (i.e., physically not disjoint) and run Dijkstra's algorithm with these lengths. In this way, the number of critical edges in the second step is minimized. If the second path is blocked by the first one then the first path is changed so that the blocking in the second step will be avoided as far as possible. Accordingly, running the shortest path algorithm the second time will succeed with a higher probability. If it does not succeed increase the length of all links used by the path by one and iterate this procedure until a threshold TR (e.g., 1, 5, 10 or 20) is overrun. We summarize the algorithm:

1. For each $e \in E$ set length l_e to the number of links belonging to the same SRLG as link e; and set iteration counter $c := 0$.

2. Run the shortest path algorithm to find the working path; and $c = c + 1$.

3. Delete all links temporarily that use the same physical span(s) as the working path.

4. Run the shortest path algorithm. If a protection path is found then exit with SUCCESS, if $c > TR$ then exit with NO SUCCESS, otherwise proceed to step 5.

5. Restore all deleted links and increase the length of these links by 1. Goto Step 2.

3.2 Algorithm for the *Disjoint or Joint* Approach

In this case Steps 1 and 2 are the same as in the previous Subsection, Step 5 can be omitted since the second shortest path algorithm always succeeds, while Steps 3 and 4 are modified as follows:

3. Add temporarily an infinite number (a number greater than the number of links multiplied by the maximum link cost) to the length of each link that uses the same physical span(s) as the working path.

4. Run shortest path algorithm to find the protection path. Exit with SUCCESS.

3.3 High Priority Traffic

For high priority traffic a certain level of guaranteed availability can be assigned to each connection. The availability of a connection in a multilayer network can be calculated by projecting all equipment and paths into the lower layer and by executing the calculations on one layer by formulating series and parallel configurations [16].

An obvious algorithm is as follows. First we define only a working path for the demand ($n = 1$); if the aimed availability is not achieved then n is increased by 1 and we find two paths; and so on we find one more path until the system of n paths reaches the aimed level of availability. This raises the question how to define three or more disjoint paths; or alternatively, three or more paths with minimum number of common spans. The ILP formulations are extended as follows: We define flow indicators y^i_{kl} and add Constraints (3) for each protection path. Furthermore, $(x_{kl} + \sum_{i=1..n} y^i_{kl})$ stands instead of $(x_{kl} + y_{kl})$ and $(x_{kl} + \sum_{i=1..n} \alpha^i y^i_{kl})$ instead of $(\alpha x_{kl} + y_{kl})$ and Constraints (4) and (7) should be extended for every n-tuple of the link set. In the proposed method, ED, Steps 3 and 4 are to be run for each protection path.

4 Performance of the Algorithms

We have investigated four networks N5, N15, N25 and N35 also studied in [1, 16, 17] consisting of 5, 15, 25 and 35 WDM nodes respectively. The WDM layer of these networks were optimally designed and configured by a method developed earlier [2]. The IP layer of N5 consists of three more links compared to the WDM layer, N15 has a centralized IP network, while in N25 and N35 some nodes have been deleted and some links added randomly. An IP layer demand is defined for each node-pair and routed one-by-one. Some additional details of the networks are shown in Table 1.

We have investigated the *Disjoint or Blocking* approach with the Two Shortest Path Algorithms (TSPA), our proposed method (ED(*TR*) where *TR* is the maximum number of iterations) and ILP for each test network. *Disjoint or Joint* (minimum number of common spans) approach is solved with Suurballe's algorithm (Suurb), our proposed algorithm (ED) and ILP.

The methods are compared according to 8 criteria:

- Computational time [Time]
- Success rate [SRate]
- Average and minimum availability[1] (indicating the minimum and average of all connection availabilities) [AvA, MinA]
- Average and maximum number of common spans [AvCS, MaxCS]
- Average length of working and protection paths [LW, LP]

The tests were carried out on a standard (500MHz Intel PentiumIII) PC, for ILP tasks ILOG's CPLEX 6.6.0 has been used. The results are summarized in Table 2.

First, consider the *Disjoint or Blocking* approach, for which there are no commonly used spans while availability values are quite similar. The running time of our proposed method is within a factor of 2-3 compared to TSPA (except for Net35 with higher number of iterations) and it is in all cases about one order of magnitude better than ILP. The success rate [SRate] is very promising: ED was able to find a solution for 35% more node-pairs than the often used TSPA, and approached the optimal solution in the worst case by 2.2% (in case of N25 it is even the same, while its running time is more than 10 times shorter, see boldface in Table 2). ED has been run with 1, 5, 10 and 20 iterations. When increasing the number of iterations the quality improves but the running time is slightly longer.

Considering *Disjoint or Joint* case, the running time of ED is within factor of 1.4 longer compared to TSPA while it is about two orders of magnitude shorter compared to ILP. The success rate is obviously always 100%. Important objectives are to maximize availability and to minimize the number of commonly used physical spans. From this aspect, the often used Suurballe's method yields

[1] The values of availabilities are shown just from the fifth digit in order to avoid redundant 9-digits. For example 9600 means 0.99999600.

quite poor results (e.g., average number of common spans is quite high, 1.42 for Net25, see boldface in Table 2), while the proposed method, ED (with 0.39), approaches the quality of the optimal ILP (0.17).

5 Conclusions

The problem has been investigated how to find physically disjoint or minimally joint path-pairs in the upper layer of a survivable multilayer network. We have shown that both problems can be solved in a reasonable time by Integer Linear Programming (ILP). However, in dynamic environment, where the running time is of critical importance, we propose to use the extension of Dijkstra's shortest path algorithm (ED), which proved to be very fast while it yields either the optimum or a solution close to it. In the *Disjoint or Blocking* case it was able to protect up to 35% more node pairs than TSPA in the test networks, while in the *Disjoint or Joint* case it achieved much better availability than Suurballe's algorithm. With the spreading of intelligent multilayer networks like GMPLS and ASON the role of such fast and efficient algorithms will be even more important.

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Networks	No. of WDM nodes	No. of WDM links	No. of IP nodes	No. of IP links	No. of IP demands
N5	5	5	5	8	10
N15	15	15	14	26	91
N25	25	31	20	40	190
N35	35	51	30	59	435

Table 1: The 4 examined networks: Number of nodes, links and IP demands

Net5		Time	SRate	AvA	MinA	AvCS	MaxCS	LW	LP
	TSPA	0.013	100	9600	9600	-	-	1.2	2.5
Disjoint	ED(1)	0.013	100	9600	9600	-	-	1.2	2.5
or	ED(5)	0.013	100	9600	9600	-	-	1.2	2.5
Blocking	ED(10)	0.013	100	9600	9600	-	-	1.2	2.5
	ED(20)	0.013	100	9600	9600	-	-	1.2	2.5
	ILP	0.134	100	9600	9600	-	-	1.2	2.5
Disjoint	Suurb	0.013	100	9520	9400	0.4	1	1.2	2.1
or	ED	0.013	100	9600	9600	0	0	1.2	2.5
Joint	ILP	0.144	100	9600	9600	0	0	1.2	2.5
Net15		Time	SRate	AvA	MinA	AvCS	MaxCS	LW	LP
	TSPA	0.866	72.53	9600	9600	-	-	1.62	5.97
Disjoint	ED(1)	1.002	86.81	9600	9600	-	-	2.01	5.61
or	ED(5)	1.118	94.51	9600	9600	-	-	2.17	5.57
Blocking	ED(10)	1.235	95.6	9600	9600	-	-	2.14	5.63
	ED(20)	1.466	97.8	9600	9600	-	-	2.17	5.57
	ILP	18.271	100	9600	9600	-	-	2.2	5.34
Disjoint	Suurb	0.824	100	8745	6800	2.53	8	1.98	3.09
or	ED	0.976	100	9402	8200	0.59	4	1.73	5.18
Joint	ILP	24.913	100	9600	9600	0	0	2.21	5.33
Net25		Time	SRate	AvA	MinA	AvCS	MaxCS	LW	LP
	TSPA	5.193	**68.95**	9595	9400	-	-	1.98	3.58
Disjoint	ED(1)	6.021	**77.89**	9599	9400	-	-	2.18	3.76
or	ED(5)	8.355	**83.16**	9595	9400	-	-	2.24	3.77
Blocking	ED(10)	10.475	**85.79**	9596	9400	-	-	2.29	3.87
	ED(20)	14.061	**86.32**	9596	9400	-	-	2.3	3.85
	ILP	154.82	**86.32**	9600	9600	-	-	2.27	3.72
Disjoint	Suurb	4.518	100	9120	7000	**1.42**	7	2.28	3.14
or	ED	5.36	100	9426	8400	**0.39**	3	2.18	3.83
Joint	ILP	193.862	100	9540	8800	**0.17**	3	2.38	3.79
Net35		Time	SRate	AvA	MinA	AvCS	MaxCS	LW	LP
	TSPA	25.315	52.87	9563	9200	-	-	2.38	4.23
Disjoint	ED(1)	36.279	58.62	9563	9200	-	-	2.59	4.33
or	ED(5)	71.408	61.84	9562	9200	-	-	2.64	4.39
Blocking	ED(10)	111.95	62.07	9564	9200	-	-	2.65	4.42
	ED(20)	194.112	62.53	9559	9200	-	-	2.68	4.42
	ILP	1184.973	62.99	9540	9200	-	-	2.66	4.18
Disjoint	Suurb	22.106	100	8472	3400	2.85	16	2.68	3.75
or	ED	30.155	100	9073	6400	1.2	8	2.63	4.49
Joint	ILP	1613.412	100	9056	6600	1.2	7	2.9	4.39

Table 2: Nummerical results for the four test networks (see explanations in Section 4)