A Practical Perspective in Designing Mesh Networks Based on $1:N$ Self-Healing Wavelength Division Multiplexing Rings

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Technical Report UTD/EE-03-99

May 1999

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Abstract

A fundamental task of the optical layer in modern telecommunication systems consists of providing a fast protection mechanism against possible faults in the network. A particularly attractive protection technique in the optical layer is the so called shared line protection, in which network lines are protected using shared resources. A previous work of the authors formally describes the problem of minimizing the total wavelength mileage necessary in a Wavelength Routing mesh network to provide shared line protection. However, two practical issues remain to be addressed: the solution feasibility in presence of design constraints and the problem complexity in large size networks.

This paper presents an approach to addressing the above two issues based on: 1) an algorithm that identifies a feasible solution with the minimal, possibly null, violation of the design constraints, 2) an intelligent pruning technique of the search space that reduces the complexity of the optimization problem. Using the proposed approach, a study on the total wavelength mileage is carried out for the European network (19 nodes) and the PanAmerican network (79 nodes) to assess the influence that some design constraints have on this cost function.

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[*] Part of this work is supported by contract # DASG60-97-C-0050 from US Army Space and Strategic Defense Command.

1 Introduction

The optical layer, as defined by the International Telecommunications Union (ITU), can provide a number of network functionalities today available only in the higher (electronic) layers. Protection against faults is a well known example. Protection in the optical layer is becoming a reality due to the commercial availability of optical crossconnects (OXC) and optical add-drop multiplexers (OADM) that make it possible to address the network survivability issue directly where the fault may occur, i.e., in the optical layer. In addition, fault restoration in the optical layer yields optical transparency and fast and easy reconfiguration of the network [1, 2, 3]. Using the optical layer to provide protection has the advantage to offer a resilient layer that is independent from the higher layers and protocols, e.g., SONET/SDH, ATM, and IP. Another fundamental advantage is the capability of the optical layer to protect large amounts of traffic directly in optics, thus avoiding the relatively slow electronic processing required in the higher layers. For example, if Wavelength Division Multiplexing (WDM) is used to obtain parallel channels on the same fiber [4, 5], the optical protection of the fiber appears to be a better solution than the distinct protection of every individual wavelength (channel) in some other higher layer.

Among the possible WDM protection techniques, rerouting mechanisms in Self-Healing WDM Ring (SHR/WDM) have been successfully demonstrated in field trials [6]. The SHR/WDM makes use of a counter-rotating ring to reroute the traffic that can no longer be supported by a faulty line. As opposed to techniques in which distinct protection resources are dedicated to protect each traffic demand, such as the $1+1$ path protection [7], the lines of a SHR/WDM are protected by means of shared spare resources, thus achieving the so called efficient $1 : N$ line protection [7]. Another advantage of using SHR/WDM is that in case of line failure only the two nodes connected to the faulty line need to reroute the traffic demands that are disrupted by the fault. The required network management and node hardware are therefore simple, due also to the easy restoration technique provided by the protection wavelengths in the counter-rotating ring. The restoration time is proportional to the size of the ring, thus a bound on the ring size allows to achieve the satisfactory restoration time the different applications and protocols, sharing the optical medium, require. This is an important feature of the SHR/WDM, as it offers the possibility to arbitrarily control the restoration time of the optical layer, and make it totally transparent to the higher layers.

The SHR/WDM mechanism can be used to protect mesh network. Protection is achieved by covering the mesh with a number of rings sufficient to protect every mesh line carrying some traffic demands. This approach offers a solution that is scalable in the network size, i.e., the network size can grow while the maximum size of the cover rings allowed in the mesh is limited by the designer to maintain the desired restoration time.

One of the factors that determine the cost of the SHR/WDM mechanism when applied to protect a generic WDM mesh is the total wavelength mileage (or λ-mileage) of both working lightpaths and protection wavelengths. A *working lightpath* is a path of light established between a source-destination pair to transmit information all-optically [5]. A *protection wavelength* is a spare channel reserved on the counter-rotating ring of a

SHR/WDM.

The feasibility of the SHR/WDM based protection mechanism and the total λ-mileage necessary in a mesh topology to support a set of traffic demands[1] depend on three factors:

- The target maximum ring size - although limiting the maximum size of the ring (in terms of number of nodes or lines) helps maintain the restoration time below satisfactory values, it may increase the λ-mileage of the protection wavelengths. This is caused by the larger number of rings required on average to protect a working lightpath. In addition to that, if the imposed maximum ring size is too stringent it may so happen that not all the mesh lines carrying traffic can be protected.

- The node hardware constraints - to limit the node hardware cost and management complexity, it may be necessary to limit the maximum number of rings a mesh node can be associated with and the maximum number of rings that can share a mesh line. While limiting the cost of the node realization, these constraints may also limit the number of rings in the system, thus limiting the number of alternative solutions available to protect the traffic. In turn, this may increase the total λ-mileage.

- The size of the mesh - the problem of minimum wavelength mileage has complexity that grows exponentially with the size of the network and the number of traffic demands. As a result, for large networks the exact formulation of the problem may lead to a *best found solution* that is not sufficiently good, or even worse, that cannot be found at all in a realistic time period. From a practical point of view, this is a limiting factor in the design of the SHR/WDM based mesh. This factor must be taken into account while evaluating the feasibility and final cost of the protection mechanism.

The paper analyses both issues of solution feasibility and problem complexity that arise in the design of SHR/WDM based mesh network. The analysis is based on the Integer Linear Programming (ILP) formulation of the following optimization problem [3]: minimize the total λ-mileage in the system by optimally choosing both the routing for the traffic demands (working lightpaths) and the protection rings (protection wavelengths). In this work two features are added to the formulation given in [3] that enhance the designer's capability to deal with the issues of solution feasibility and problem complexity:

1. an algorithm to guarantee that when the allowed maximum ring size does not yield a 100% protection of the mesh lines, a minimal number of rings exceeding the maximum size is added to yield full protection;

2. an algorithm to provide various degrees of intelligent pruning of the search space for the ILP solver.

Together, these features permit to find a feasible solution to the minimal wavelength mileage problem. In addition, the latter feature allows us to vary the complexity of the

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[1] In this work traffic demands are expressed as the number of lightpaths requested between each node pair.

problem formulation and find the one that yields the best found solution for the considered network size, traffic demands and design constraints.

The analysis, made possible by the two added algorithms, shows that, by varying the target maximum ring size, the node hardware constraints and the complexity of the problem formulation, significant differences in the total λ-mileage (up to 20%) can be observed in real world networks, such as the European and the PanAmerican networks.

2 Protection of Mesh Network Using WDM Self-Healing Rings

To understand how a mesh network can be protected against faults using WDM self-healing rings, it is first necessary to describe the protection mechanism of a single ring. The SHR/WDM protection mechanism is then generalized to design resilient WDM mesh network.

A bidirectional shared line protection SHR/WDM consists of 4 fibers: two working fibers and two protection fibers. For each direction of signal propagation, there is one working fiber and one protection fiber. Working fibers carry working lightpaths. Protection fiber carry protection wavelengths. We assume that full wavelength conversion [8] is available at the nodes of the ring.

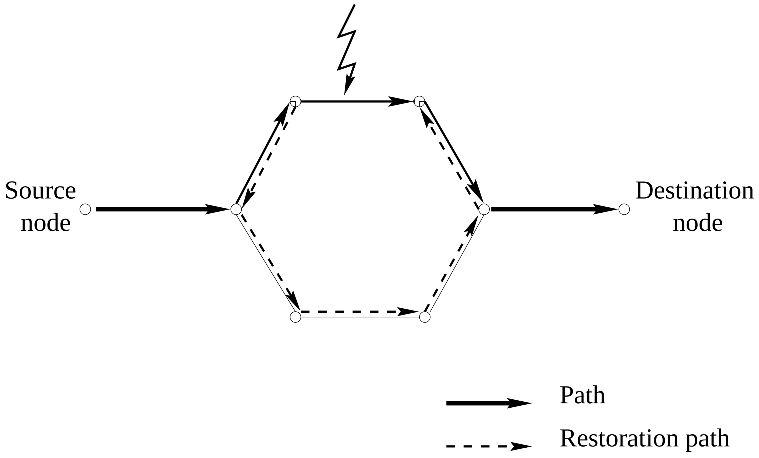

Figure 1: Line protection in a ring

The restoration mechanism in a SHR/WDM is shown in Figure 1. Upon line failure, every working lightpath relying on the faulty line is rerouted using one protection wavelength of the counter rotating fiber with respect to the lightpath direction of propagation. The protection wavelength is used to establish an alternative path between the nodes adjacent to the faulty line as shown in the figure. Wavelength conversion between the lightpath wavelength and the protection wavelength may be necessary in these two nodes, to guarantee all-optical transmission in the ring also in presence of a line fault.

The same set of protection wavelengths is used throughout the protection fiber. The set of protection wavelengths is shared to protect the ring from a single fault occurring in any line, thus the name of shared $1:N$ line protection scheme [8, 3, 9]. The number of protection wavelengths in each protection fiber is determined by the largest number of working lightpaths (or load) flowing in any line with opposite direction to the protection fiber.

The total λ-mileage in the SHR/WDM depends on the routing of the working lightpaths. Similarly to the SONET/SDH BLSR [12], the minimum λ-mileage is achieved when the traffic is optimally balanced, i.e., when the maximum line load is minimized. For example, in Figure 2, $1:N$ protection of the working lightpaths is achieved using 8 wavelengths, as opposed to the 11 wavelengths required by the $1+1$ dedicated path protection scheme [8].

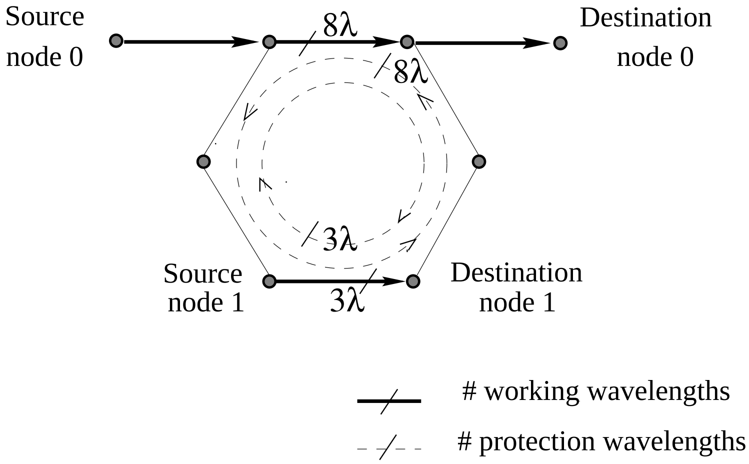

Figure 2: Capacity assignment inside the ring

The restoration time in the SHR/WDM is proportional to the number of nodes in the ring, i.e., the *ring size*. Thus, the restoration time in the ring can be bounded by introducing a *maximum ring size*.

The protection technique offered by SHR/WDM can be ported to mesh network by superimposing a number of rings onto the mesh topology with at least one ring covering each mesh line carrying some traffic demands. This is possible when the mesh topology is two-connected[2], as this property ensures that every node can be associated with at least one ring.

The same restoration mechanism described for a stand alone ring is used in presence of multiple rings covering the mesh network, with the additional constraints that:

- a working lightpath carried on a line covered by two or more rings must be protected by only one ring,
- rings can share fibers but cannot share protection wavelengths.

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[2] A graph is *2-connected* if it cannot be disconnected by omitting less than 2 edges.

An additional advantage offered by the mesh network is its capability to be resilient in presence of multiple faults as long as those take place on lines covered (protected) by distinct rings. Furthermore, optical crossconnects are required in the rings only at the nodes where working lightpaths are switched from one protection ring to another, while the remaining nodes need only optical add/drop multiplexers.

Clearly, the number of protection wavelengths in a multi-ring network depends on how working lightpaths are routed and how they are assigned to rings. In addition, the selection of the rings designated to cover a mesh network considerably affects the efficiency of the protection mechanism.

3 Problem Definition

Let $G(V, E)$ be a 2-connected unidirectional graph representing the mesh network, with V the set of nodes (vertex of the graph) and E the set of weighted lines (edges of the graph). The line weight represents the length of the corresponding line in the mesh.

The problem of minimizing the λ-mileage in a resilient mesh network based on the SHR/WDM consists of two subproblems: one is to select the protection rings that will cover the graph to provide restoration in case of line failure, the other is to determine the routing for the lightpath demands. (In this paper, a traffic demand between a source and a destination consists of an integer set of distinct wavelength connections, or working lightpaths.) As the routing for each working lightpath must rely on one or more protection rings, the two subproblems affect each other and the optimal solution can only be found by solving both of the subproblems at once. The exact joint formulation of the two subproblems in the form of ILP is given in [3]. The formulation makes use of the following input sets: the set of rings in G, R_i, whose size does not exceed the maximum ring size allowed by the designer, and for each source-destination pair, $(s, d) \in V$, the set of possible paths in G, P_{sd}. The output of the ILP solver consists of the set of rings selected for the covering, $R_o \subseteq R_i$, and for each working lightpath, the path selected from the source to the destination. From the solution returned by the ILP solver it is possible to compute the λ-mileage of both working lightpaths and protection wavelengths in the rings [3].

3.1 Proposed Solution

Two algorithms are added to enhance the ILP formulation of the λ-mileage problem given in [3]. The first algorithm guarantees that when the maximum ring size defined by the designer does not allow us to protect every line in the graph, a minimal number of rings exceeding the maximum size is added to set R_i to yield protection of all lines. The second algorithm reduces the complexity of the ILP by limiting the number of paths in every set P_{sd}.

3.1.1 Derivation of Set R_i

Define the ring weight as the summation of the weights of the ring lines. Define S_r as the number of nodes connected to ring r, i.e., the ring size. Given a node pair, $(s, d) \in V$, the shortest ring with respect to that pair, r_{sd}, is defined as the ring connecting both nodes that has the minimum weight. Define the set of shortest rings in graph G whose size does not exceed the designer's maximum ring size, N_r, as $R_s = \{r_{sd}, \forall(s, d) \in V \ |S_{r_{sd}} \leq N_r\}$.

Setting $R_i = R_s$ seems to be a reasonable approach to building the set of protection rings with the aim to minimize the total wavelength mileage of every working lightpath and corresponding protection wavelength. However, in a sparse graph, it may happen that the maximum ring size, N_r, does not permit to cover all the nodes and/or lines in the graph, thus potentially leaving some working lightpaths unprotected. Under this circumstance the considered problem does not have a feasible solution unless additional rings, violating the size constraint N_r, are added to set R_i.

To identify a feasible solution to the problem set R_i is augmented by first adding the minimum weight rings that complete the covering of the nodes. After this step, lines with high weight may still not be covered by any ring in R_i. If so, set R_i is further augmented by adding the minimum weight rings that complete the covering of all lines.

A detailed description of the algorithm is given next.

```
begin
$R_i =$
$N = |V|$, number of nodes in the network
$N_{rmax} =$ initial maximum size of the ring
$N_{rmax} = N_r$
  for (each node pair)
      find the shortest ring covering the two nodes
      $S_r =$ size of found ring
      if ($S_r \leq N_{rmax}$)
          add ring to set $R_i$
      endif
  endfor
  while (some nodes are uncovered)
      $N_{rmax} = N_{rmax} + 1$
      for (each uncovered node $i$)
          find the shortest ring covering node $i$
          $S_r =$ size of found ring
          if ($S_r \leq N_{rmax}$)
              add ring to set $R_i$
      endfor
  endwhile
  $N_{rmax} = N_r$
  while (some lines are uncovered)
```

```
        $N_{rmax} = N_{rmax} + 1$
        if ($N_{rmax} > N$) goto label
        for (each uncovered line $(i, j)$)
            find shortest ring covering nodes $i$ and $j$
            $S_r$ = size of found ring
            if ($S_r \leq N_{rmax}$)
                add ring to set $R_i$
        endfor
    endwhile
    label
end
```

3.1.2 Derivation of Set P_{sd}

To limit the complexity of the minimum λ-mileage problem, the search space for the ILP solver is pruned by limiting the number of alternative paths in P_{sd}, for every pair $(s, d) \in V$.

The pruning is based on the conjecture that a good path must rely on the minimum number of rings. This conjecture is supported by two observations. First, since a crossconnect is necessary to switch a working lightpath between two adjiacent rings, the number of crossconnects visited by a good path must be minimum. In turns, this choice minimizes the overall number of crossconnect ports in the system. Second, although a good path may not necessarily follow the shortest path throughout the network, it must tend to rely on large portions of the visited rings. As a result, a balanced distribution of the working lighpaths is easier to achieve in the rings.

Set P_{sd} is constructed in two steps.

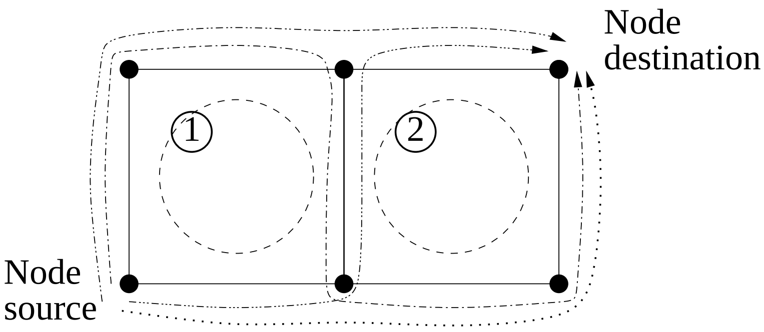

Figure 3: Alternative paths

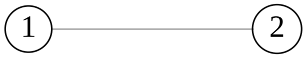

Figure 4: Auxiliary graph

Consider the auxiliary graph $G'(V', E')$, where V', the set of vertices, contains one vertex for each ring in R_i, and E', the set of edges, contains edge (i, j) $i, j \in V'$ if ring i and ring j share at least one vertex in G. Figure 4 shows the auxiliary graph G' build from graph G shown in Figure 3.

The set of shortest paths, in terms of number of hops, between each node pair is derived in the auxiliary graph. The nodes along a shortest path in G' represent the sequence of rings that are visited by a set of paths in G from s to d. More specifically, each ring visited by the shortest path in G' identifies two alternative paths in G, one per direction of propagation in the ring. Finally, for each identified sequence of rings in G', all possible alternative paths in G from s to d, that rely on only but all the rings in the sequence, are included in P_{sd}. Figure 4 shows an example of a ring sequence in the auxiliary graph. Figure 3 shows the corresponding paths in G idetified by the ring sequence.

The number of paths in P_{sd} after this first step can be fairly large and can be shown to be at least 2^p for each ring sequence found, where p is the number of rings in the sequence. In the second step of the algorithm the size of P_{sd} is, therefore, artificially reduced to k paths, where k is a varying parameter used by the designer to control the complexity of the ILP formulation. Paths in P_{sd} are sorted first by increasing number of nodes in G, then by increasing length. Only the first k paths are kept in set P_{sd}, the others are droped. The above choice is motivated observing that the paths remaining in P_{sd} cross the minimum number of add/drop multiplexers, and at the same time have the minimum end-to-end power loss.

3.2 Results

In this section the two proposed algorithms, together with the ILP formulation in [3], are applied to study two worldwide network topologies: the European network with 19 nodes (Figure 5) and the PanAmerican network with 79 nodes (Figure 6). The former network is more connected than the latter. In the European network the line lengths and the (non-uniform and symmetric) traffic demands are given in the Appendix A.1. The traffic demands for the PanAmerican (see Appendix A.1) are sparse and connect 162 node pairs among the possible 3081.

Two sets of experiments are carried out, depending whether or not the complexity of the node optical hardware is bounded. In the former set, we assume some design restrictions on the set of rings that can be superimposed on the mesh, i.e., a maximum of 2 rings per line and a maximum of 4 rings per node (Figures 8, 9 and 11). This case is referred to as the *constrained design.* In the latter set no constraints are imposed on the set of rings associated with the nodes and the lines (Figures 7, 10, and 11). This case is referred to as the *unconstrained design.*

The ILP optimization problem is solved using the *lp_solve* package [11], stopping each instance after 5 hours if still running. Due to the problem complexity most of the results are best found values.

In each experiment, various values for the target maximum ring size, N_r, are used ranging from 3 to 16 nodes. For the PanAmerican network, results for $N_r = 3, 4, 5$ are

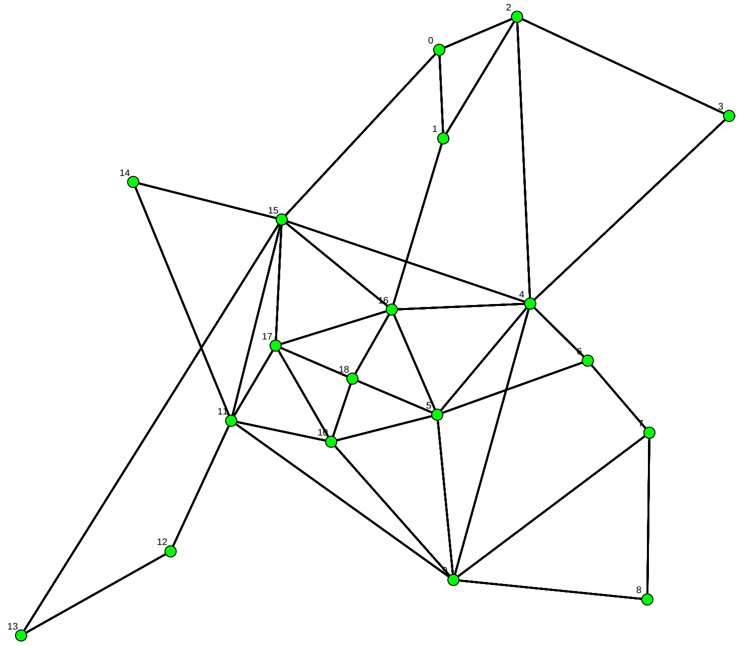

Figure 5: European Network

not shown as they yield the same result obtained by $N_r = 6$. This is due to the sparse nature of the network that requires rings of at least 6 nodes. (Recall that when necessary, rings exceeding the maximum size are used to yield full protection of the mesh network as described in section 3.1.1.)

3.3 Problem Complexity vs. Wavelength Mileage

We first address the problem complexity. Recall that the number of candidate paths in set P_{sd}, k, determines the search space explored by the solver. The solution space is also proportional to the number of rings in set R_i, that is proportional to N_r. ¿From a theoretical standpoint, at any value of N_r, the optimal solution found with k is better than or at least equivalent to the solution found with $k' < k$. With $k = all$, the optimal solution found with N_r is better than or at least equivalent to the solution found with $N_r' < N_r$.

However, due to the complexity of the problem and the size of the considered networks, a trade-off is found between the size of the search space and the optimality of the solution reached by the solver in 5 hours (see curves with k=all). As a matter of fact, for some network configurations, a solution may not be found at all (see Figure 9).

For example, the curves in the Figure 8 show a nearly theoretical behaviour: by increasing N_r or/and k the total λ-mileage decreases. However, when $k = all$ or when both values of k and N_r are large, the curves do not follow the predictable course, due to the increasing complexity of the problem. Similarly, in the PanAmerican network (Figures 9 and 10), case $N_r = 16$ yields high λ-mileage due to the difficulty to select the

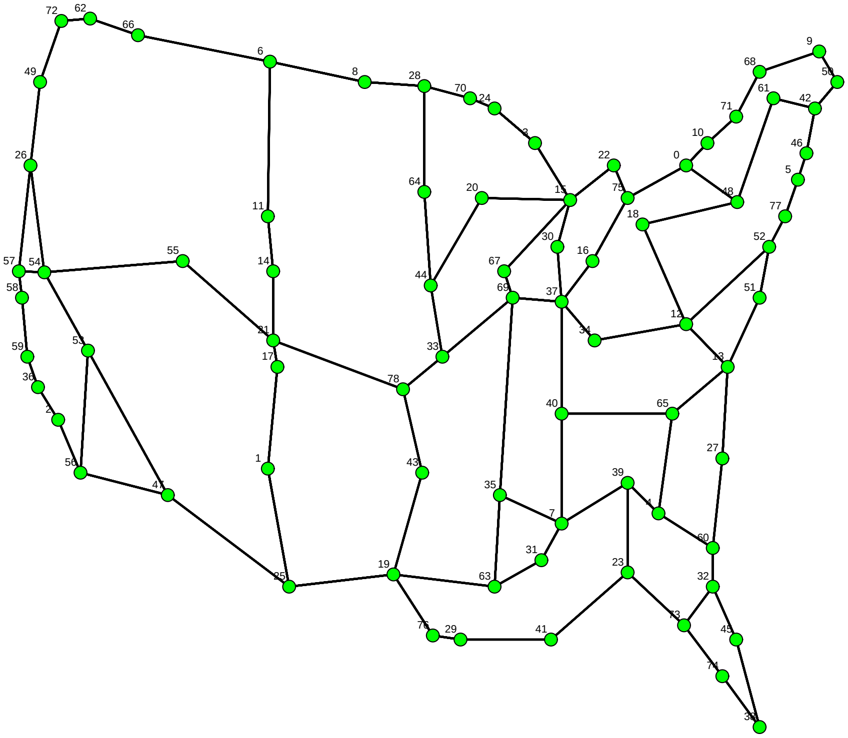

Figure 6: PanAmerican Network

best cover rings from the large number of available rings in set R_i.

The complexity of the problem can be minimized by setting $k = 1$, i.e., the working lightpaths are routed first by the algorithm in section 3.1.2. then the rings and protection wavelengths are selected for the working lightpaths by the ILP solver. In this case the working mileage is minimized, but the overall mileage (working and protection) suffers considerable penalty when compared to solutions with $k > 1$. Depending on the value of N_r, this penalty can grow up to 20% in the European network and up to 10% in the PanAmerican network.

An interesting conclusion can be drawn from Figure 11, which shows the total working λ-miles in the PanAmerican network obtained using the unconstrained design. As k decreases, the total working λ-miles decreases while the total λ-mileage increases as shown in Figure 10. This result clearly shows the trade-off between the minimization of the working lightpath miles and the minimization of the protection wavelength miles.

3.4 Varying N_r

Increasing N_r can only yield solutions with decreasing λ-mileage; however, from a practical point of view, the maximum size of the ring has a tangible effect on the total λ-mileage only for a relatively small values of N_r. For example, in the European network the reduction of λ mileage becomes marginal for values of $N_r > 6$ (see Figures 8 and 7).

This can be explained observing the results in Table 1) that show the average size of

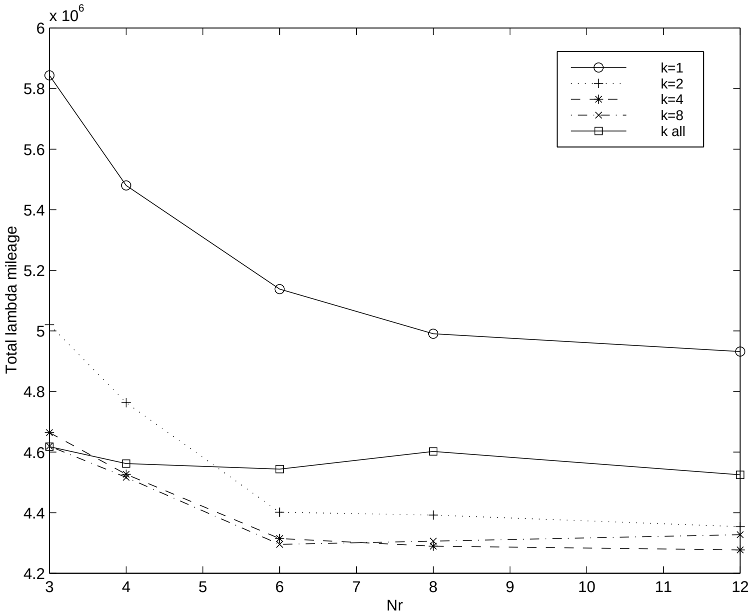

Figure 7: European Network: total λ-miles under unconstrained design

the cover rings found by the solver in a number of experiments. The average size of the ring does not grow proportionally with N_r, especially in the constrained design.

3.5 Effects of Design Constraints

Bounding the maximum number of rings per line and per node (constrained design) influences the selection of the cover rings and indirectly the total λ-mileage.

In the unconstrained design the total λ-mileage in the system can be reduced by a factor up to 10% (see Figure 7) when compared to the constrained design (see Figure 8). However, nearly a double number of rings is required in the unconstrained case (see Table 1), significantly complicating the network management.

If the design constraints are too stringent the problem may not have a feasible solution even if the rings in R_i cover all the mesh lines. This may happen when the number of paths in in set P_{sd} is not large enough to provide the necessary degree of flexibility to select the paths for the working lightpaths in order to accommodate the enforced design constraints (see Figure 7, cases $N_r = 3$ and $k \leq 4$).

Table 1 shows the influence of the design constraints on the number of cover rings and number of nodes per rings in the solutions found for the European network. Under constrained design, the number of rings is almost the same in every solution, independently of the maximum ring size. The average size of the cover rings increases marginally in comparison to the growth of the average ring size in set R_i. Under unconstrained design, a large number of rings is selected to cover the mesh. As N_r increases, the average size of the cover rings grows faster than in the constrained design.

In conclusion, when compared to the constrained design, the unconstrained design

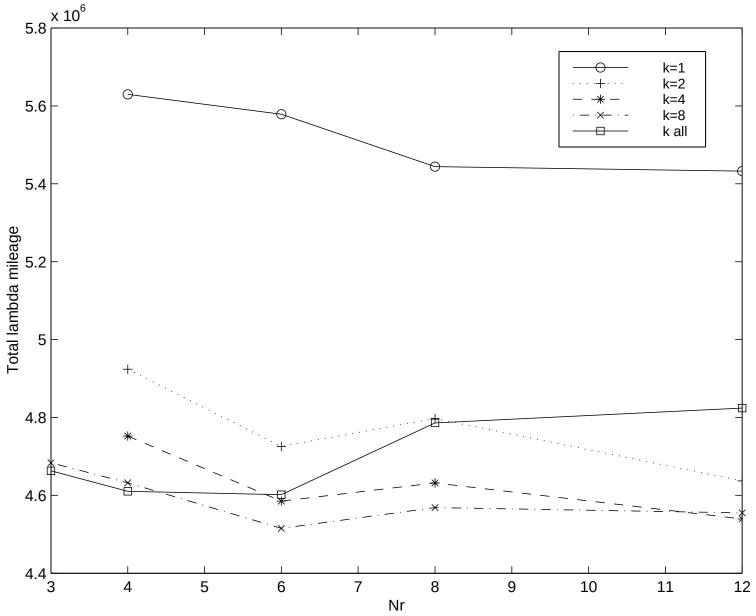

Figure 8: European Network: total λ-miles under constrained design, i.e., when at most 2 rings per line and 4 rings per node are allowed

yields reduced λ-mileage, but, on the other hand, requires more complex node hardware and network management, and increases the average ring size, i.e., the average restoration time in the system.

4 Conclusions

With the advent of optical add/drop multiplexers and crossconnects protection mechanisms against line faults can be provided directly in the optical layer. This paper analyzed the influence that some practical design criteria have on the total wavelength mileage required in mesh network to realize the shared line protection mechanism of Self-Healing WDM Rings (SHR/WDM). The study was carried out using the ILP formulation presented in [3] to minimize the mesh wavelength mileage by optimally selecting both the (protection) rings that cover the network and the paths for the traffic demands. Two algorithms were introduced in the paper. The first guarantees protection of all the mesh lines carrying traffic, while minimizing the number of rings that exceed the designer's target maximum ring size. The second algorithm makes it possible to vary the complexity of the problem formulation by intelligently pruning the search space, thus providing a timely solution even in large size networks, e.g., the 78 node PanAmerican network.

The study showed that the target maximum ring size and the number of rings selected to cover the network significantly affect the total wavelength mileage. For example, increasing the maximum ring size helps reduce the wavelength mileage (2-10%), but practically speaking this advantage is limited to relatively small sizes (e.g., up to 6 nodes in the

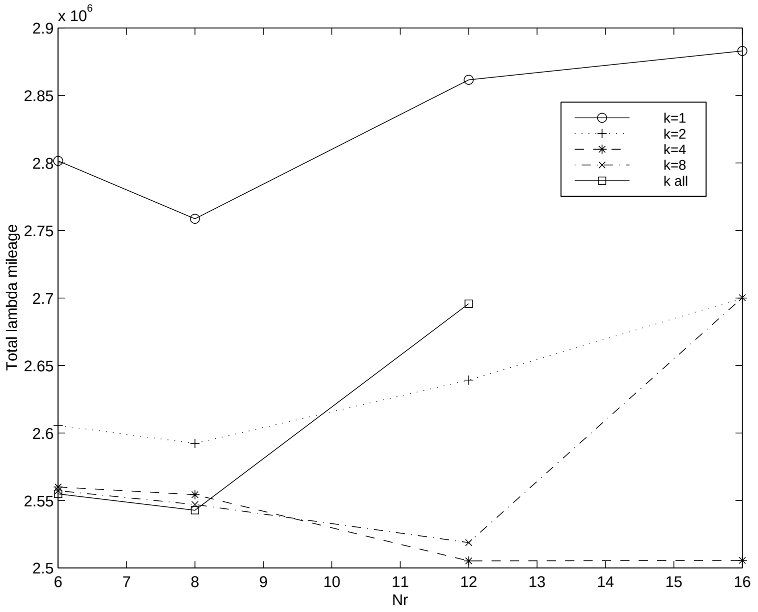

Figure 9: PanAmerican Network: total λ-miles under costrained desiegn, i.e., when at most 2 rings per line and 4 lines per node

European network and up to 12 nodes in the PanAmerican network). Any further increase of the maximum ring size does not yield any significant mileage reduction, while on the contrary it increases the system restoration latency and the computational complexity of the optimization. Increasing the number of rings in the network leads up to 5% mileage reduction, but it requires more complex node architectures and management. Finally, the importance of jointly optimizing the selection of the rings and the paths for the traffic demands was demonstrated showing that up to 20% mileage reduction is possible when compared to a predefined (e.g., shortest path obtained with $k = 1$) wavelength routing.

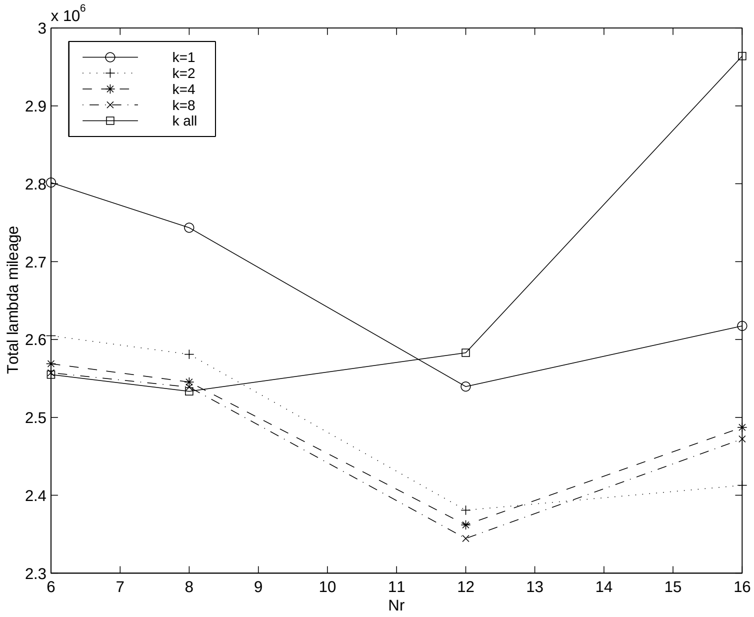

Figure 10: PanAmerican Network: total λ-miles under unconstrained design

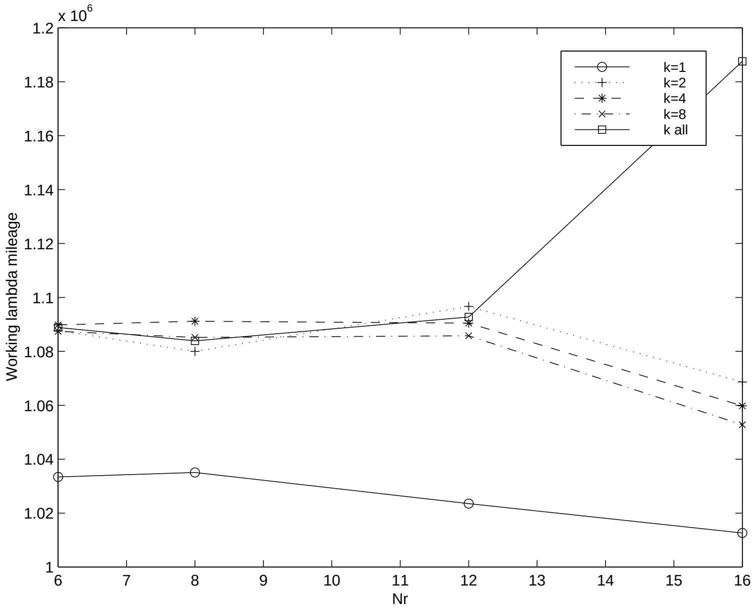

Figure 11: PanAmerican Network: total working λ-miles under unconstrained design

N_r	# rings			Average # nodes per ring of		
	R_i	R_o with constr.	R_o without constr.	R_i	R_o with constr.	R_o without constr.
3	19	13.5	17.4	3.21	3.3	3.22
4	30	13.8	17.8	3.5	3.43	3.53
6	63	13.6	25.2	4.56	3.69	4.26
8	93	13.2	25.4	5.46	3.64	4.36
12	112	13.8	24.6	6.19	3.66	4.47

Table 1: European Network: from left to right, maximum ring size, number of rings in the input set to the solver, average (over k) number of cover rings under constrained design, average (over k) number of cover rings under unconstrained design, average size of rings in the input set, average (over k) size of the cover rings under constrained design, average (over k) size of the cover rings under unconstrained design

Name		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Oslo	**0**	-	1	3	1	5	2	1	1	6	1	16	7	1	3	1	2	9	15	1
Copenhagen	**1**	500	-	1	4	1	6	1	1	1	10	12	7	1	1	1	9	1	11	5
Stockholm	**2**	560	560	-	1	1	1	1	3	5	16	13	2	4	1	1	1	5	1	1
Moscow	**3**	∞	∞	1300	-	1	1	9	3	1	5	1	11	1	16	1	12	8	1	1
Berlin	**4**	∞	∞	875	1650	-	1	4	1	1	4	4	16	1	14	2	4	1	1	1
Prague	**5**	∞	∞	∞	∞	280	-	9	1	3	1	4	1	10	1	5	1	16	1	1
Vienna	**6**	∞	∞	∞	∞	500	280	-	1	1	1	1	1	1	3	1	5	1	7	1
Zagreb	**7**	∞	∞	∞	∞	∞	∞	250	-	1	9	1	11	1	16	1	8	4	1	14
Athens	**8**	∞	∞	∞	∞	∞	∞	∞	1100	-	1	2	1	5	1	7	1	3	1	5
Milan	**9**	∞	∞	∞	∞	690	660	∞	530	1500	-	4	4	1	2	1	16	13	11	1
Zurich	**10**	∞	∞	∞	∞	∞	530	∞	∞	∞	220	-	7	3	8	1	3	3	3	3
Paris	**11**	∞	∞	∞	∞	∞	∞	∞	∞	∞	660	500	-	1	1	11	4	16	1	3
Madrid	**12**	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	1070	-	1	3	1	1	7	9
Lissa	**13**	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	500	-	4	5	1	1	1
Dublin	**14**	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	690	∞	∞	-	1	10	2	1
London	**15**	1190	∞	∞	∞	1000	∞	∞	∞	∞	∞	∞	500	∞	1600	500	-	9	1	1
Amsterdam	**16**	∞	600	∞	∞	600	750	∞	∞	∞	∞	∞	∞	∞	∞	∞	375	-	3	1
Brussels	**17**	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	470	280	∞	∞	∞	340	250	-	1
Luxemburg	**18**	∞	∞	∞	∞	∞	560	∞	∞	∞	∞	160	∞	∞	∞	∞	∞	340	220	-

Table 2: European Network: non-uniform traffic matrix (upper right), distance matrix (lower left)

A Appendix

A.1 Distance and Traffic Matrix for the European and PanAmerican network

Table 2 presents the distance (lower left) and the traffic demands(upper right) for the European network. Table 3 shows the line distance in the PanAmerican network. Table 4 shows the traffic demands used to study the PanAmerican network.

Node	**Node**	Distance	**Node**	**Node**	**Distance**	**Node**	**Node**	**Distance**	**Node**	**Node**	**Distance**
0	10	189	0	48	70	0	75	172	1	17	313
1	25	237	2	36	75	2	56	83	3	15	256
3	24	164	4	39	168	4	60	200	4	65	91
5	46	112	5	77	98	6	8	420	6	11	275
6	66	571	7	31	200	7	35	372	7	39	133
7	40	185	8	28	207	9	50	61	9	68	79
10	71	145	11	14	150	12	13	249	12	18	156
12	34	153	12	52	212	13	27	156	13	51	170
13	65	162	14	21	159	15	20	230	15	22	300
15	30	200	15	67	172	16	37	145	16	75	136
17	21	50	18	48	158	19	25	550	19	43	240
19	63	290	19	76	134	20	44	200	21	55	453
21	78	432	22	75	80	23	39	93	23	41	333
23	73	188	24	70	102	25	47	390	26	49	120
26	54	373	26	57	350	27	60	102	28	64	260
28	70	260	29	41	359	29	76	120	30	37	200
31	63	200	32	45	154	32	60	189	32	73	121
33	44	154	33	69	189	33	78	121	34	37	133
35	63	200	35	69	240	36	59	78	37	40	138
37	69	294	38	45	143	38	74	168	40	65	238
42	46	81	42	50	147	42	61	89	43	78	222
44	64	214	47	53	450	47	56	383	48	61	210
49	72	161	51	52	145	52	77	82	53	54	415
53	56	124	54	55	529	54	57	123	57	58	47
58	59	272	62	66	231	62	72	45	67	69	92
68	71	184	73	74	212						

Table 3: PanAmerican Network: distance matrix

Node	**Node**	Demand	**Node**	**Node**	**Demand**	**Node**	**Node**	**Demand**	**Node**	**Node**	**Demand**
1	19	2	1	21	2	1	47	1	2	36	9
2	56	4	2	58	4	4	7	1	4	15	9
4	19	8	4	27	1	4	31	1	4	32	3
4	36	6	4	38	2	4	39	2	4	40	2
4	41	3	4	42	9	4	45	2	4	51	2
4	58	4	4	62	2	4	69	4	4	77	4
5	9	2	5	42	10	9	10	1	9	15	4
9	19	2	9	22	4	9	42	8	9	48	2
9	50	1	9	58	3	9	61	2	9	62	4
9	67	3	9	69	4	9	77	5	11	21	1
14	21	1	15	16	3	15	19	5	15	20	1
15	21	3	15	22	6	15	30	2	15	33	4
15	36	3	15	41	2	15	42	14	15	58	8
15	62	3	15	67	2	15	69	4	15	70	2
15	77	7	17	19	3	17	33	2	19	21	5
19	25	3	19	29	5	19	33	7	19	35	2
19	36	5	19	41	4	19	42	5	19	43	2
19	47	2	19	55	3	19	56	5	19	57	4
19	62	3	19	69	3	19	78	3	20	33	1
21	25	2	21	33	7	21	36	5	21	42	3
21	47	3	21	49	2	21	55	2	21	56	4
21	57	4	21	58	3	21	62	2	21	69	4
25	33	1	25	47	1	26	57	1	26	58	1
26	62	2	33	36	4	33	43	2	33	44	1
33	56	3	33	57	4	33	58	5	33	64	1
33	69	4	33	70	1	34	69	1	35	69	1
36	42	4	36	47	2	36	49	2	36	53	7
36	54	2	36	55	2	36	56	7	36	57	11
36	58	9	36	59	2	36	62	3	36	66	2
36	69	3	37	69	2	38	42	4	40	69	1
41	69	3	42	46	7	42	58	6	42	62	4
42	77	11	44	69	2	47	56	2	47	57	1
47	58	1	47	62	1	49	56	1	49	57	3
49	58	3	49	62	5	53	56	3	53	57	5
53	58	5	54	56	2	54	57	4	54	58	4
55	57	3	55	58	2	55	62	2	56	57	4
56	58	2	56	62	1	56	66	1	56	72	1
57	58	12	57	59	2	57	62	6	57	69	4
57	72	2	58	59	1	58	62	4	58	69	3
58	72	3	62	66	3	62	69	2	62	72	5
67	69	2	69	70	1						

Table 4: PanAmerican Network: non-uniform symmetric traffic matrix

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