Comparison of Protection Cost at IP or WDM Layer

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***Abstract*— We consider wavelength routed networks used to overlay a logical topology over a WDM optical infrastructure. We evaluate the additional capacity required to manage single fiber fault. In particular, we consider both optical protection mechanism in which additional wavelengths are reserved to face faults (WDM protection), and IP restoration mechanisms, in which additional link capacity is deployed to assure no traffic is lost after re-routing of traffic flows affected by the fiber fault.**

By considering simple yet common scenarios in which bidirectional rings are used as physical topology while regular topologies are designed at the logical layer, we are able to obtain analytical results to compare the two fault management schemes. Results show that optical protection in general requires fewer additional capacity resources. When considering large number of nodes, however, the advantage of WDM protection tends to become less attractive.

I. INTRODUCTION

Wavelength Routed (WR) networks [1] are considered the best candidate for the short-term implementation of a high-capacity IP infrastructure, since they permit the exploitation of the huge fiber bandwidth, but do not require complex processing functionalities in the optical domain.

In WR networks, remote high-capacity (electronic) routers are connected through IP-tunnels. IP tunnels are implemented by optical pipes called *lightpaths* that may extend over several physical links. Lightpaths are routed in the optical layer through the physical topology using a single wavelength (we assume not to exploit wavelength conversion); at intermediate nodes, incoming wavelengths belonging to in-transit lightpaths are switched to outgoing fibers through an optical cross-connect that does not process in-transit information. At the IP layer, lightpaths are seen as data-link channels through which packets are moved from a router to another router toward their destinations following the classic IP forwarding procedure. Therefore, in a WR network, an *IP layer topology* (also called logical topology), whose vertexes are IP routers and whose edges are lightpaths, is overlayed to the *physical topology*, made of optical fibers and optical cross-connects (OXC).

Lightpaths can either be semi-permanent [2], or be allocated in on-demand fashion [3]. In the first case a static topology is seen at the IP layer, while in the second case more adaptivity can be gained at the cost of additional complexity both at the optical layer and the IP layer. In this paper we consider semi-permanent WR networks in which the IP layer topology is known.

In classic WR networks, the Routing and Wavelength Assignment (RWA) problem must be faced. Indeed, for each IP logical link, a route across the physical topology must be found, and a wavelength must be selected with the constraints that i) two (or more) lightpaths sharing the same fiber must be identified by two (or more) different wavelengths (also called “wavelength integrity constraint”) and ii) a lightpath must be identified by the same wavelength on all the physical fibers along the path (also called “wavelength continuity constraint”). This second constraints may be relaxed when considering OXCs with wavelength converters capability. The goal of the RWA is to minimize the number of wavelengths required to overlay the logical topology over the physical topology. This problem is known to be NP-complete, and several heuristic approaches have been proposed in the literature [4].

Once the logical topology has been setup, IP routers, which are the nodes of the logical topology, can start sending IP packets using the logical links. At the IP layer, routers adopt traditional routing protocols and algorithms to find routes across the logical topology, such as link state based protocols, i.e, OSPF [5] or IS-IS [6].

The failure of a network component such as a fiber link leads to the failure of all the lightpaths that traverse the failed fiber. Since each lightpath is expected to operate at a rate of several Gbit/s, a failure can lead to a severe data loss. Therefore, fault management mechanisms must be implemented to recover from faults, at either the WDM layer, or at the IP layer. In the first case, the WDM layer implements mechanisms to recover from faults, so that the failed lightpaths are automatically recovered on backup paths. Therefore, no modification of the logical topology is perceived at the IP layer and IP routers do not face any failures [7]. In the case no fault management scheme is adopted at the WDM layer, it is possible to relay on the recovery mechanisms implemented at the IP layer. In this case, the failure of an optical fiber leads to the disruption of several logical links, so that traffic must be rerouted on the survived portion of the logical topology. Therefore, an overprovision of lightpath capacity must be considered, so that the network, after the rerouting of disrupted traffic, is still able to carry the traffic it was carrying before the fiber failure. The analysis of single fiber failure is particularly interesting in this context, and the additional costs in terms of bandwidth can be taken as comparison index.

When considering fault management schemes, either *protection* or *restoration* mechanisms can be deployed. Protection schemes are based on the reservation of spare capacity during

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lightpath setup, while restoration schemes use spare capacity to dynamically reroute disrupted lightpaths; generally they more efficiently use spare resources.

Generally, when considering WDM network fault management schemes, protection mechanisms are often preferred, since they guarantee better recovery time and reduced signaling requirement. Either shared or dedicated protection mechanisms are possible, in which backup resource are i) shared among possible different failures (i.e., 1:N mechanism), or ii) dedicated each to a single failure (i.e., 1:1 mechanisms). Similarly, both path protection or link protection may be considered. In the first case, for each lightpath, a working and a disjoint backup paths are computed. The backup path is activated in case of failure of any fiber along the working path. In the second case, each fiber is protected by finding an alternate set of fibers having the same source and destination nodes of the failed fiber. In case of failure of a fiber, then all the lightpaths using it will use the alternate path along the failure.

Considering on the contrary IP networks, restoration schemes have been traditionally implemented. After a failure is identified by a node, alternate routes are identified by means of signaling among nodes. Considering the intra-routing protocols, the solution adopted by the majority of the ISPs relies on link-state protocols such as OSPF or IS-IS. By broadcasting to all other nodes the status of outgoing links, each node builds an image of the topology and accordingly finds minimum cost paths for any destination. In case of link failure, the two nodes close the failing link will start a signaling phase to broadcast all other nodes the topology changes, so that each node can find alternates minimum cost paths on the survived topology.

In this paper we will consider IP logical topologies overlayed over a physical WDM network. We will then evaluate the cost, in terms of extra capacity, to provide either protection at the WDM layer, or restoration at the IP layer. We will consider ring physical topologies, and simple and regular logical topologies. This allows us to simplify the evaluation of the extra cost, thanks the symmetry of the considered scenarios. The aim of this paper is indeed to obtain simple guidelines to compare the two possible fault management schemes, comparing them among different network size and configurations.

In the remaining of the paper, Section II describes the modeling assumptions we used to obtain capacity requirement when either WDM protection is assumed (Section III) or IP restoration is assumed (Section IV). Results are compared in Section V for different networks. Finally, Section VI summarizes our findings.

II. ASSUMPTIONS AND DEFINITIONS OF THE SCENARIO

In order to simplify the analysis at the WDM layer and obtain some guidelines to compare the fault management bandwidth cost, we selected simple and regular topologies both for the physical layer, and for the IP layer. Indeed, both the Routing and Wavelength assignment problem and the Logical Topology Design problem are known to be NP-complete problems in their general formulation [1]. Therefore, to fairly compare the results, we restrict our analysis to simple cases in which the optimal solutions are known.

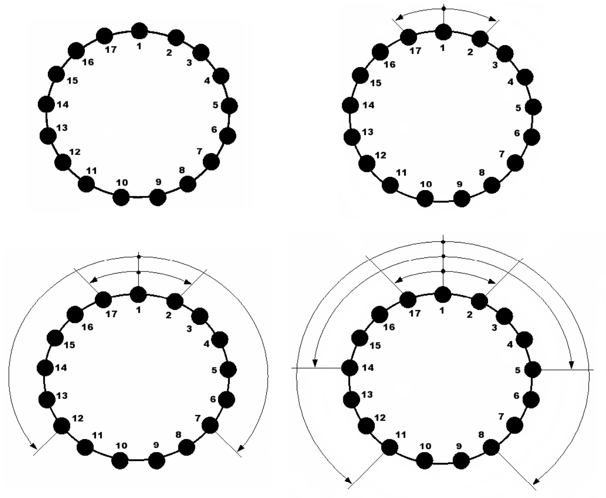

Fig. 1. Sample Physical Topology and Logical Topologies: 17 nodes bidirectional ring physical topology and 17 nodes logical topologies considering $\Delta = 2, 4, 6$. Only arcs from node 1 are shown.

In particular, at the physical layer, we consider bidirectional ring topologies of N node. All nodes are equipped with an even number Δ of transmitters/receivers. Nodes are numbered according to their position in the physical ring, following a clockwise order. All the nodes participate in the logical topology, and each node has $\Delta = 2 * k < N, \ k = 1, 2, \ldots$ outgoing/incoming lightpaths.

To further simplify the LTD problem, we consider the case in which the traffic demands between any source-destination pair are equal to 1 unit of capacity. Under these assumptions, there is a particular symmetry for both the LTD and RWA problems, so that all nodes are equivalent. Therefore, we consider simple regular logical topologies, in which each node i is connected to node $[(i-1) \bmod N]$ and $[(i+1) \bmod N]$. Eventual additional transmitters are used to setup logical links so that arcs are evenly distributed among remaining nodes. In particular, among $N-3$ remaining nodes, $\Delta-2$ links are setup every $(N-3+1)/(\Delta-2+1) = (N-2)/(\Delta-1)$ nodes. In order to build such regular topologies, N and Δ must be selected such that

$$(N - (\Delta + 1)) \bmod (\Delta - 1) = 0 \qquad (1)$$

Figure 1 reports for example the physical topology comprising $N = 17$ nodes on the top-left, and the resulting logical topologies when considering $\Delta = 2, 4, 6$. Only arcs from node 1 are shown, since all nodes have the same arc set.

Under these assumptions, the RWA problem can be solved to the optimum. Indeed, given again the symmetry of the physical and logical topologies, a Shortest Path-First Fit [4] algorithm guarantees to find a solution which minimizes the number of wavelengths used to solve the RWA problem. We omit the formal proof which is out-of-scope of this paper, and we only give the intuition of that in the next Section, since it is instrumental to the problem analysis.

Considering the fault management mechanisms, only shared path protection mechanisms at the WDM layer are taken into account to overcome to single fiber failure. The symmetry of the problem comes to help again in the problem definition and solution. Indeed, all fiber failures are identical, allowing therefore to consider just one fiber failure instead of every possible failures. We will consider single faults, distinguishing the case when only one fiber is failing between two nodes in the ring, i.e., monodirectional single link cut, and when both fibers between two nodes in the ring are failing, i.e., bidirectional single link cut.

Considering the IP layer routing on the logical topology, we assume that a link state protocol like OSPF is responsible of finding the minimum cost paths among every nodes. We assume all links have the same cost set to 1 for convenience, therefore paths will be *minimum hop* paths. In case more than one minimum hop paths are available, we assume that either one is picked at random, so that a *Single Path* routing is implemented, or that perfect load-balancing of traffic among all equal-cost paths is performed, so that a *Traffic Splitting* routing is implemented. In case of fault management mechanisms adopted at the WDM layer, we assume no modification of the logical topology is perceived at the IP layer. On the contrary, if faults have to be managed at the IP layer, we assume that the traffic routed on faulty lightpaths will be re-routed on alternate paths after a reconfiguration of the routing occurs. Transient periods will be ignored.

To compare the fault management costs, we will consider the following performance figures at the WDM and IP layers:

- $\lambda_{no}, \lambda_{mono}, \lambda_{bi}$: minimum number of wavelengths to solve the RWA problem with i) no fault, ii) a single fiber fault, i.e., monodirectional single link cut, iii) a 2-fiber fault, i.e., bidirectional single link cut respectively;
- C_{no}, C_{mono}, C_{bi}: the minimum aggregate capacity required to carry all traffic demands with i) no fault, ii) monodirectional single link cut, iii) bidirectional single link cut.

C_{mono}, C_{bi} can be evaluated considering fault management mechanisms at either at WDM or IP layer, so that we will distinguish among $C_{mono}^{WDM}, C_{mono}^{IP}$ and $C_{bi}^{WDM}, C_{bi}^{IP}$ when necessary. A similar notation will be used throughout the paper.

$$C_{no} = N * \Delta * c_{no}$$

holds in general, being c_{no} the IP capacity of a lightpath when no faults are present. c_{no} depends on the selected logical topology and on the IP routing algorithms. c_{no} will be evaluated has the maximum capacity among all lightpaths, so to consider the worst case.

When IP fault management mechanism is considered, $c_{mono}^{IP}, c_{bi}^{IP}$ will be the minimum IP layer capacity of a lightpath required to route all the traffic considering the re-routed traffic flows. When WDM fault management mechanism is considered, lightpath capacity will be not modified in presence of faults. Therefore $c_{no}^{WDM} = c_{mono}^{WDM} = c_{bi}^{WDM}$

Finally, to compare the costs, we define

$$\eta_{mono} = \frac{C_{mono}}{C_{no}} \qquad \eta_{bi} = \frac{C_{bi}}{C_{no}}$$

to gauge the incremental cost in dealing with monodirectional and bidirectional faults. η_{mono} and η_{bi} will allow us to evaluate the total bandwidth ratio increase due to rerouting of faulty traffic. Also in this case we will distinguish WDM and IP cases.

III. WDM PROTECTION RESULTS

We start by evaluating the minimum number of wavelengths required to solve the RWA problem considering N nodes with $\Delta = 2 * k$ lightpaths each. Recall that we consider a bidirectional ring at the physical topology. Referring to Fig. 1, we start by evaluating the number L of lightpaths routed over a fiber, e.g., the fiber from node 1 to node 2, since the symmetry of the problem makes each fiber equivalent to every other.

A. Analytical Results

Considering the logical topology, each node i is connected to nodes $[(i-1) \bmod N]$ and $[(i+1) \bmod N]$. Remaining $\Delta - 2$ links are setup every j nodes, where

$$j = \frac{N-2}{\Delta - 1}$$

Therefore, node 1 will use fiber from 1 to 2 to route $\Delta/2$ lightpaths, since the remaining $\Delta/2$ lightpaths will be routed over fiber from 1 to N. Considering node N, it will use fiber from 1 to 2 to route $\Delta/2 - 1$ lightpaths. Similarly, nodes $N-1, N-2, \ldots, N-j+1$ will use fiber from 1 to 2 to route $\Delta/2-1$ lightpaths, while nodes $N-j, N-j-1, \ldots, N-2j+1$ will route $\Delta/2 - 2$ lightpaths. Or, j nodes will have $\Delta/2 - 1$ lightpaths over fiber from 1 to 2, j nodes will have $\Delta/2 - 2$ lightpaths over fiber from 1 to 2, etc.

It holds

$$L = \frac{\Delta}{2} + j \sum_{i=1}^{\frac{\Delta}{2}} \left(\frac{\Delta}{2} - i \right) = \frac{\Delta}{2} + j \sum_{i=1}^{\frac{\Delta}{2}-1} i = \frac{\Delta}{2} \left(1 + j \frac{\Delta - 2}{2} \right) \tag{2}$$

Considering now the particular symmetry of the logical topology, it is possible to prove that the wavelength assignment problem can be solved by considering exactly L wavelengths[1]. Therefore it holds

$$\lambda_{no} = L \tag{3}$$

Given this result, it is straightforward to evaluate λ_{mono}, since a single monodirectional single link cut will break L lightpaths, and at least L additional more wavelengths must be present to reroute faulty lightpaths on their (unique) backup path. Therefore

$$\lambda_{mono} = 2\lambda_{no} \tag{4}$$

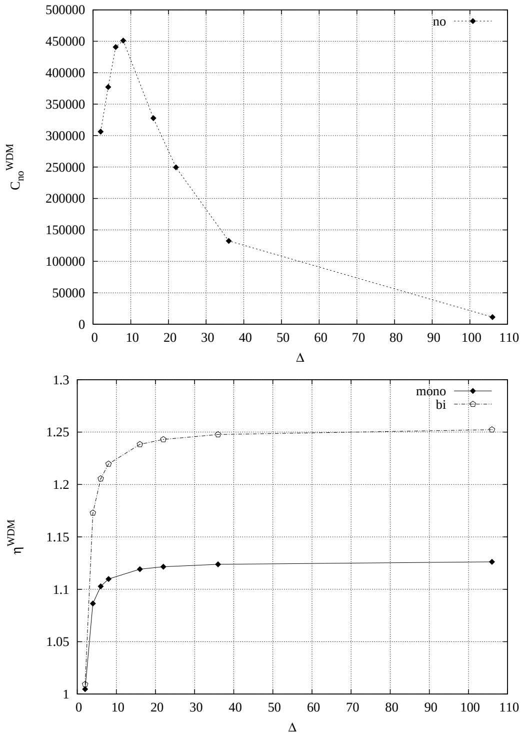

Fig. 2. Total network capacity versus Δ considering a topology with $N = 107$ nodes. Absolute total capacity at the WDM layer C_{no}^{WDM} required to route all traffic on the top, and incremental costs $\eta_{mono}^{WDM}, \eta_{bi}^{WDM}$ on the bottom.

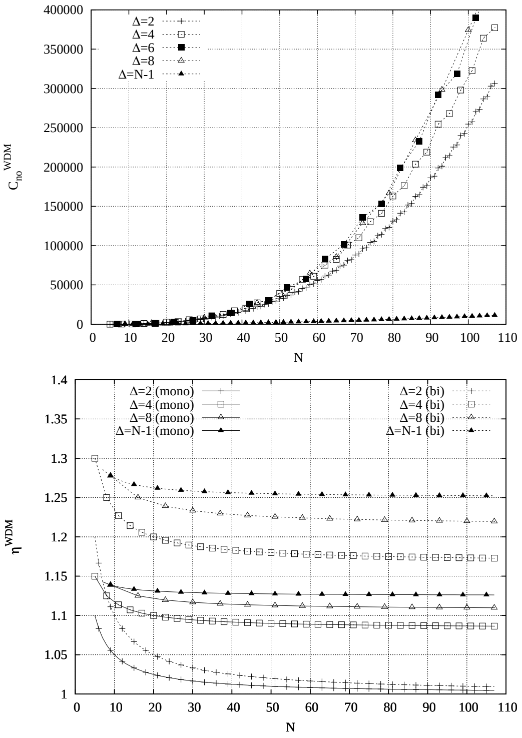

Fig. 3. Total network capacity versus number of nodes N for different connectivity degree Δ. Absolute total capacity at the WDM layer C_{no}^{WDM} required to route all traffic on the top, and incremental costs $\eta_{mono}^{WDM}, \eta_{bi}^{WDM}$ on the bottom.

Similarly, considering a bidirectional single link cut, we have

$$\lambda_{bi} = \lambda_{mono} = 2\lambda_{no} \tag{5}$$

since lightpaths will be rerouted on the counter-rotating physical ring, and therefore on different fibers.

Considering the capacity, since λ_{no} lightpaths will always affected by any single fiber cut, we have

$$C_{mono}^{WDM} = C_{no} + \lambda_{no} * c_{no} \tag{6}$$

$$C_{bi}^{WDM} = C_{no} + 2\lambda_{no} * c_{no} \tag{7}$$

Finally, considering fault management additional cost, we have

$$\eta_{mono} = 1 + \frac{1 + \frac{(N-2)(\Delta-2)}{4(\Delta-1)}}{2N} \tag{8}$$

$$\eta_{bi} = 1 + 2\frac{1 + \frac{(N-2)(\Delta-2)}{4(\Delta-1)}}{2N} \tag{9}$$

Note that, for large values of N, we have

$$\lim_{N\to\infty} \eta_{mono} = 1 + \frac{(\Delta-2)}{4(\Delta-1)} \tag{10}$$

$$\lim_{N\to\infty} \eta_{bi} = 1 + \frac{(\Delta-2)}{2(\Delta-1)} \tag{11}$$

η_{mono} and η_{bi} are both increasing with Δ; considering fully connected logical topologies ($\Delta = N-1$), we have

$$\eta_{mono} \simeq 1 + \frac{1}{8} \qquad \eta_{bi} \simeq 1 + \frac{1}{4} \tag{12}$$

B. Performance Analysis

In this section we plot the previous expressions to give some insights about the extra-capacity cost induced by protection mechanisms at the optical layer.

Figures 2 plot on the top C_{no}^{WDM} versus the connectivity degree Δ when considering $N = 107$. Bottom plot reports η_{mono} and η_{bi} for the same topologies. We selected a large values of N, since only values of Δ that satisfy Eq. 1 are valid. c_{no} has been considered to be obtained after routing IP traffic by selecting one single path among eventual equal cost paths (simulations results have been averaged over 50 different runs). Considering C_{no}^{WDM} in the top plot of Fig.2, we observe that, for small values of Δ, C_{no}^{WDM} grows almost linearly with Δ, but for larger values of Δ, C_{no}^{WDM} decreases with Δ. This is due to c_{no} which decreases more than linearly with Δ, being it related to the average distance among node in the IP topology. In particular, for $\Delta = N-1$, we have $c_{no} = 1$ since there is always one direct link for every source/destination pair, so that $C_{no}^{WDM} = N\Delta = N(N-1) = 107 \cdot 106$ in this case.

Looking at bottom plot of Fig.2, we observe the additional protection costs when considering monodirectional (solid line) and bidirectional (dotted line) single link cut versus Δ. As expected, η_{mono}, η_{bi} increases with Δ up to the asymptotic

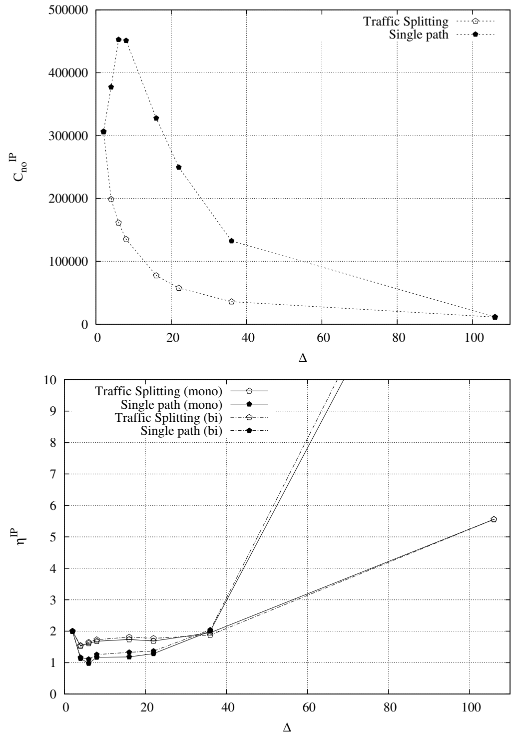

Fig. 4. Total network capacity versus Δ considering a topology with $N = 107$ nodes. Absolute total capacity at the IP layer C_{no}^{IP} required to route all traffic on the top, and incremental costs $\eta_{mono}^{IP}, \eta_{bi}^{IP}$ on the bottom. Both Single Path and Traffic Splitting routing of traffic are reported.

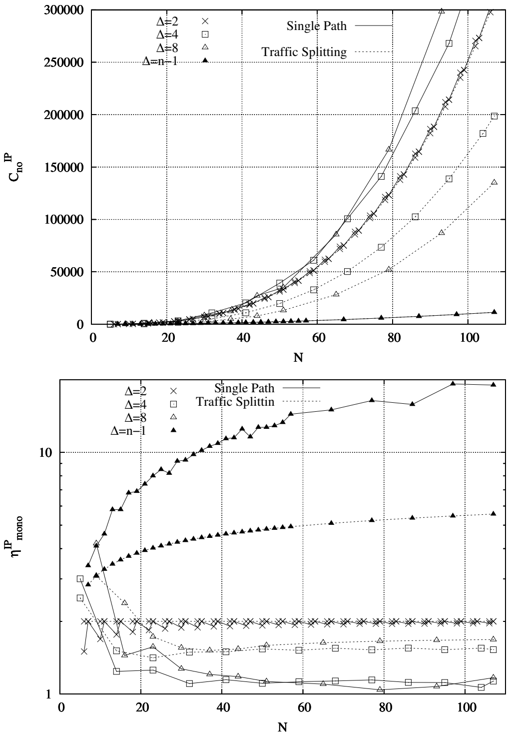

Fig. 5. Total network capacity versus number of nodes N for different connectivity degree Δ. Absolute total capacity at the IP layer C_{no}^{IP} required to route all traffic on the top, and incremental costs $\eta_{mono}^{IP}, \eta_{bi}^{IP}$ on the bottom. Both Single Path and Traffic Splitting routing of traffic are reported.

limit (Eq. 12) for $\Delta = N - 1$ (fully connected logical topology): the protection cost is upper bounded by 1.125 and 1.25 respectively, and for values of $\Delta > 20$ the upper bound is already close.

Figure 3 reports on top plot C_{no}^{WDM} versus N when considering different values of Δ, while bottom plot reports the additional protection costs when considering monodirectional (solid line) and bidirectional (dotted line) single link cut versus N. Considering C_{no}^{WDM}, it increases more than linearly with N. Considering η_{mono} and η_{bi}, it is possible to observe that both decrease with N, and both tend to the limit reported in Eq. 10 and Eq. 11. Also in this case it is possible to notice that η_{mono} and η_{bi} increase for increasing values of Δ. Finally, it is possible to observe that the additional protection costs are upper-bounded and never exceed the values of 1.3.

IV. IP RESTORATION RESULTS

In this section we evaluate the IP restoration additional cost. In this case, given the complexity of the IP routing algorithms on the logical topology, it is not possible to derive analytical results for any values of Δ and N, but for the i) fully connected topology, i.e., $\Delta = N - 1$ and ii) for a bidirectional ring topology, i.e., $\Delta = 2$. In all other cases, we present results obtained via simulations. Given the graph that describe the logical topology (either considering all links, or considering only the survived links after a fiber cut), it is possible to find minimum-cost paths, and evaluate the capacity of links after that all traffic has been routed either considering Traffic Splitting, or Single Path routing. Each lightpath will be then assigned a capacity equal to the traffic flowing through it, and the total network capacity can be then evaluated as the sum of all lightpath capacities. If Single Path Routing is adopted, different runs can give different results (since ties among equal cost paths are randomly broken); we will consider the average over 50 runs to obtain good averages.

A. Fully Connected Logical Topology

When $\Delta = N - 1$, there exists always a link in the logical topology between every source/destination pairs. Therefore, the minimum hop routing is unique, and traffic flowing from node s to node d will be routed on the direct link from node s to node d. Therefore

$$C_{no}^{IP} = N(N-1) \tag{13}$$

A link cut at the physical layer will affect several lightpaths at the logical layer. Eq. 2 gives the number of lightpaths crossing a fiber, and therefore it gives also the number of broken lightpaths due a single fiber cut. After a transient, traffic routed on faulty lightpaths will be re-routed on minimum-cost paths on the residual topology. Considering monodirectional single link cut, if traffic splitting is allowed, we have

$$C_{mono}^{IP} = N(N-1)\left(1 + \sum_{i=1}^{\lfloor \frac{N}{2} \rfloor} \frac{1}{i}\right) \tag{14}$$

since $\lfloor \frac{\Delta}{2} \rfloor$ nodes will be affected by the fiber cut. Node close to the fault will have $\lfloor \frac{\Delta}{2} \rfloor$ traffic flows that must be re-routed on backup minimum-cost paths, and the number of such paths varies from 1 to $\lfloor \frac{\Delta}{2} \rfloor$, so that traffic will be equally split among those links. Similarly, the node at distance 2 from the fault will have $\lfloor \frac{\Delta}{2} \rfloor - 1$ links affected by the faults, whose traffic must be carried by backup minimum-cost paths, etc.

Considering bidirectional single link cut, we have

$$C_{bi}^{IP} = C_{mono}^{IP} \tag{15}$$

since the fault on the backward fiber affects links and traffic that is not affected by the fault on the forward fiber, i.e., the faults are "independent".

Then, from Eq. 13 and Eq. 14 we have:

$$\eta_{mono}^{IP} = \eta_{bi}^{IP} = 1 + \sum_{i=1}^{\lfloor \frac{N}{2} \rfloor} \frac{1}{i} \tag{16}$$

from which we have

$$\lim_{N\to\infty} \eta_{mono}^{IP} = \lim_{N\to\infty} \eta_{bi}^{IP} = 1 + \ln \left\lfloor \frac{N}{2} \right\rfloor \tag{17}$$

If Single Path routing is considered, only simulation results are available.

B. Bidirectional Ring Logical Topology

When $\Delta = 2$, lightpaths form a bidirectional ring at the logical topology which is identical to the physical topology. Similarly to Eq. 2, it is then straightforward to evaluated

$$C_{no}^{IP} = 2N \sum_{i=1}^{\lfloor \frac{N}{2} \rfloor} i = 2N \left\lfloor \frac{N}{2} \right\rfloor \left(\left\lfloor \frac{N}{2} \right\rfloor + 1 \right) \tag{18}$$

since the number of traffic flows routed over a lightpath is $\sum_{i=1}^{\lfloor \frac{N}{2} \rfloor} i$ and only one minimum-cost path exists. Note that when Traffic Splitting is implemented, there are 2 minimum hop paths when N is odd. Therefore, we have

$$C_{no}^{IP} = 2N \left(\sum_{i=1}^{\frac{N}{2}-1} i + \frac{N}{4} \right) \quad \text{for odd N} \tag{19}$$

When one fiber fails, only the corresponding lightpath will fail as well. Traffic will then be rerouted over the counter-rotating logical rings, and the additional capacity costs become, since only one backup path always exists:

$$C_{bi}^{IP} = C_{mono}^{IP} = 2C_{no}^{IP} \tag{20}$$

Finally, from Eq. 18 and Eq. 20, it is possible to evaluate $\eta_{mono}^{IP}, \eta_{bi}^{IP}$.

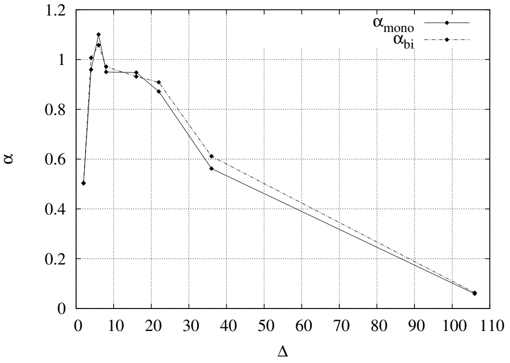

Fig. 6. Fault management bandwidth cost ratio α versus Δ considering a topology with $N = 107$ nodes. Both monodirectional and bidirectional single link cut are reported.

C. Performance Analysis

In this section we plot the previous expressions to give some insights about the extra-capacity cost induced by restoration mechanisms at the IP layer.

Figures 4 plot on the top C_{no}^{IP} versus the connectivity degree Δ when considering $N = 107$. Bottom plot report η_{mono} and η_{bi} for the same scenarios. Impact of traffic routing is reported by using solid black dots when Single Path routing is considered, while empty dots identify Traffic Splitting routing. Considering C_{no}^{IP} (top plot) we observe the effect of using traffic splitting, that allows us to reduce the total capacity by applying load balancing among equal cost path. When faults are present, the additional capacity required to guarantee that no traffic is dropped on backup paths grows quickly versus Δ, in particular when no traffic splitting is allowed. For small values of Δ the additional capacity cost ranges between 1 and 2, and is almost independent from Δ.

More complex is the figure when considering networks with different number of nodes N. Figure 5 reports on the top plot C_{no}^{IP} and on bottom plot C_{mono}^{IP} versus N for different values of Δ. Also in this case Traffic Splitting and Single Path routing are reported. Considering the total network capacity required to transport all the traffic when no fault is present (top plot), C_{no}^{IP} grows more than linearly with N, while it decreases with larger values of Δ, as expected. When faults are present, bottom plot show that the additional capacity required to re-route traffic affected by fault is in general smaller that 2 for small values of Δ, while it increases up to 20 when a fully connected topology is considered.

V. PERFORMANCE COMPARISON

In this section we compare the additional cost required to face the same fault via optical protection or via IP restoration. We define the following performance indexes to directly compare the additional fault management costs:

$$\alpha_{mono} = \frac{C_{mono}^{WDM}}{C_{mono}^{IP}} \qquad \alpha_{bi} = \frac{C_{bi}^{WDM}}{C_{bi}^{IP}} \tag{21}$$

Values of α_{mono} or α_{bi} smaller than one state that WDM protection is more efficient than IP restoration. By combining

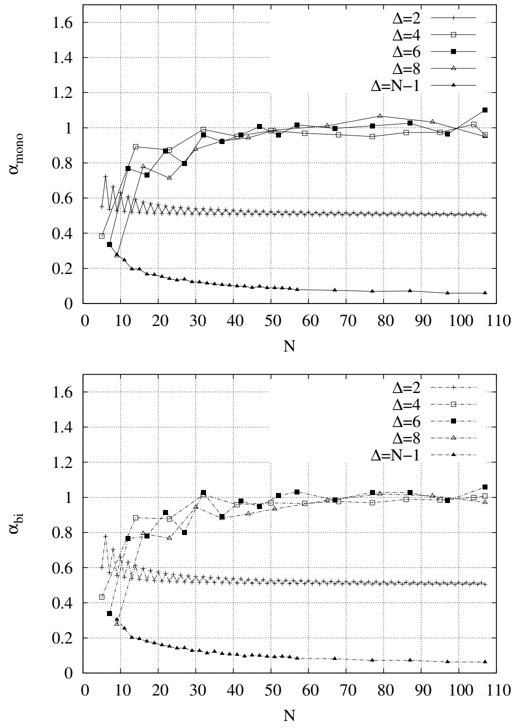

Fig. 7. Fault management bandwidth cost ratio α versus number of nodes N for different connectivity degree Δ. Monodirectional single link cut ratio α_{mono} on the top, and bidirectional single link cut ratio α_{bi} on the bottom.

the results obtained in the previous section, we have are able to obtain analytical results only for the fully connected or bidirectional ring logical topologies. In all other cases we are forced to rely on simulation results. We report again results considering different connectivity degree Δ for a network of $N = 107$ nodes (Figure 6, or by considering different network size N for a given values of Δ (Figure 7). Only Single Path traffic results are considered, since Traffic Splitting routing are very similar.

Considering α versus Δ, Fig. 6 shows that for all values of Δ except for $\Delta = 6$, optical protection requires fewer additional capacity to reroute lightpath affected by faults. Single and bidirectional fiber cut exhibits the same results, given that backup paths do not share any physical resource (involving counter-rotating rings and fibers). The higher is the connectivity degree, the smaller is α, showing that rerouting of traffic at the IP layer is much more expensive for logical topologies with many links. This is due to the increasing number of lightpaths involved by a fiber cut, since C^{IP}_{mono} and C^{IP}_{bi} grows much larger than the corresponding C^{WDM}_{mono} and C^{WDM}_{bi}.

When considering the impact of the number of nodes N over α, Figure 7 shows that in general optical protection requires fewer additional capacity to manage faults compared to IP restoration. This holds true considering both monodirectional single fiber cut (top plot) and bidirectional single fiber cut (bottom plot). Only when the number of nodes grows larger than 30 and for values of $\Delta \neq 2, N-1$, α tends to 1, showing that for large networks the amount of additional capacity required to face faults is almost the same when WDM or IP fault management techniques are considered. This is due to the fact that the impact of a fiber cut tends to become negligible for increasing network sizes, since the amount of traffic not affected by the fault increases.

Considering on the contrary $\Delta = 2$, we notice that α tends to 0.5, underlining that WDM protection requires half additional capacity compared to IP protection. This is due to the fact that wavelengths are *shared* among different faults, i.e., only additional $\lambda_{mono} - \lambda_{no} = \lambda_{no}$ wavelengths are used to reroute lightpaths for any faults. On the contrary, $C^{IP}_{mono} - C^{IP}_{no} \simeq 3C^{IP}_{no}$, since *all* lightpaths have to support rerouted traffic, but only part of that capacity is actually used when a particular fault is considered.

Finally, considering $\Delta = N-1$, we observe that WDM protection is much more efficient than IP restoration. Indeed, recalling that Eq. 10 and Eq. 11 shows that $\eta^{WDM}_{mono}, \eta^{WDM}_{bi}$ tend to a constant values for large values of N, while Eq. 17 grows as $\ln N$, we have that

$$\lim_{N\to\infty} \alpha_{mono} = \lim_{N\to\infty} \alpha_{bi} = 0 \qquad (22)$$

VI. CONCLUSIONS AND FUTURE WORK

In this paper we have evaluated the fault management cost of providing either WDM protection or IP restoration mechanisms. By considering simple yet common scenarios in which bidirectional rings are used as physical topology while regular topologies are embedded at the logical layer, we present analytical results to compare the two schemes. If no analytical results are possible due to the complexity of the scenarios, simulation results were reported. By considering a wide set of possibilities, we have shown that WDM protection generally tends to require additional capacity resources to manage lightpaths rerouting compared to IP traffic rerouting. For topologies with large number of nodes, however, the two mechanisms show no significant differences. We are currently extending the methodology to consider more generic scenarios.

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