

# Fault Tolerant Design of Wavelength-Routed Optical Networks

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## Abstract

This paper considers optical networks which employ wavelength-routing switches that enable the establishment of wavelength-division-multiplexed (WDM) channels, called lightpaths, between node-pairs. In such networks, the failure of a single link may cause the failure of several optical channels. Given a set of lightpaths, that may comprise of a *virtual topology*, and fixed alternate routing tables at each node, this paper examines the following problem: how to allocate capacity in an optimal fashion and assign routes and wavelengths to each lightpath such that upon any link failure lightpaths that are affected by the failure, can be reestablished without any blocking. A simple approach, called *one-on-one protection*, protects against link failures by reserving a link-disjoint *backup* lightpath for every working lightpath. In this paper, we examine an Integer Programming (IP) approach, called *multiplexed spare capacity protection*, that multiplexes the spare capacity among all lightpaths in an optimal fashion. This paper examines the performance of this approach on representative network topologies, and shows that this approach is superior to one-on-one protection.

# 1 Introduction

Wavelength division-multiplexing (WDM) [1] divides the tremendous bandwidth of a fiber (potentially a few tens of terabits per second) into many nonoverlapping wavelengths (WDM channels). Each channel can be operated asynchronously and in parallel at any desirable speed, e.g., peak electronic speed of a few Gbps. An access node (or access station) may transmit signals on different wavelengths, which are coupled into the fiber using wavelength multiplexers. An optical signal passing through an optical switch may be routed from an input fiber to an output fiber without undergoing optoelectronic conversion. Figure 1 illustrates a wavelength-routed optical network consisting of 6 access stations (labeled A through F) and 6 switches (labeled 1 through 6).

A connection request is setup by establishing a *lightpath* from the source node to the destination node. A lightpath is an all-optical channel which may span multiple fiber links, to provide a circuit-switched interconnection between two nodes. In the absence of wavelength converters, a lightpath would occupy the same wavelength on all fiber links that it traverses. This is called the *wavelength-continuity* constraint. Two lightpaths on a fiber link must also be on different wavelength channels to prevent the corruption of the optical signals. Figure 1 shows the following wavelength continuous lightpaths: (a) between nodes 10 and 6 on  $\lambda_1$ , and (b) between nodes 15 and 9 on  $\lambda_2$ .

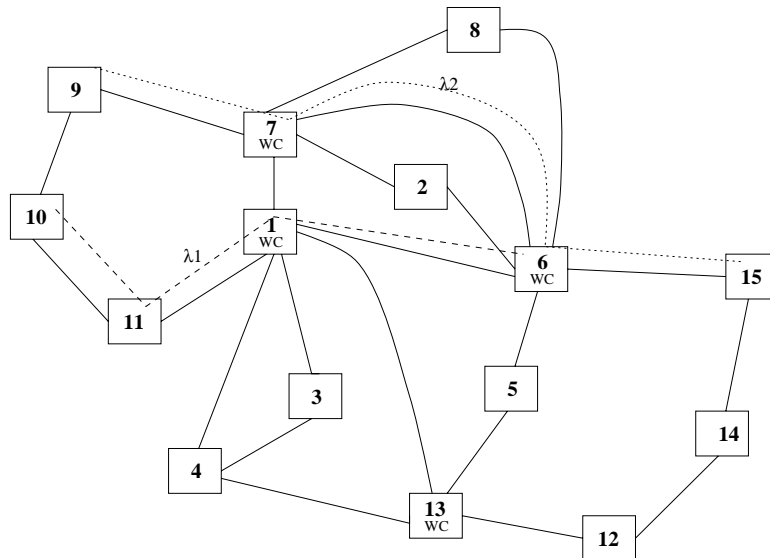


Figure 1: An wavelength-routed optical network, with two lightpaths illustrated.

This paper considers backbone WDM optical networks. The architecture of a wavelength-routed optical network, shown in Fig. 1, consists of Wavelength Routing Switches (WRSs) interconnected by fiber links. Each link consists of a pair of unidirectional fibres. Technological constraints dictate that the number of

WDM channels that can be supported in a fiber be limited to  $W$  (whose value is a few tens today, but is expected to improve with time and technological breakthroughs).

A *virtual topology* consists of a set of lightpaths set up to exploit the relative strengths of both optics and electronics - viz., packets of information are carried by the virtual topology “as far as possible” in the optical domain using optical switching, but packet forwarding from lightpath to lightpath is performed via electronic packet switching, whenever required. A virtual topology can be utilized as an IP network backbone, by having IP routers perform the packet forwarding between lightpaths.

In a backbone optical network, the failure of a component such as a fiber-link can lead to the failure of all the lightpaths that traverse on the failed link. We assume in this paper that a link is unidirectional, and therefore, a link failure is a unidirectional link failure. More than one simultaneous physical link failure is not considered in this paper.

Higher protocol layers such as IP can recover from such (possibly multiple link) failures, by rerouting data packets around such failures. However, the recovery time for higher layers (such as IP) is still significantly large (of the order of seconds). Since lightpaths are expected to carry data at data rates of the order of a few gigabits per second, the failure of a lightpath can potentially lead to large data losses.

*Physical protection* [5] is a potential approach to recover from failures. In physical protection, hardware components are duplicated to provide redundancy at the physical level. Upon a failure, the redundant hardware is activated automatically, without the higher layers of software being aware of the failure. Physical protection is however expensive because of the hardware duplication that is necessary.

Another approach to protecting against link failures, called *one-on-one*, or *design* protection [5], is to reserve a backup lightpath for every lightpath that needs to be protected against link failures. The backup lightpaths are designed such that they do not share any links with their corresponding working lightpaths. When a protected lightpath fails because of a link failure, its backup lightpath is activated. The reservation of the backup lightpath involves reserving wavelength channels on the links of the backup lightpath route.

We consider an approach to protecting against link failures called *multiplexed spare-capacity*. In our approach, we do not reserve a backup lightpath for every lightpath. Given a set of lightpaths to be protected against link failures, we reserve wavelength channels in the links of the network in a clever way. Our approach ensures that upon any link failure, all lightpaths that traverse the failed link can be rerouted around the failed link, without blocking any of them, and at the same time also minimizes the number of wavelength channels that need to be reserved in the links of the network.

We illustrate the above approaches in an example. Consider the network illustrated in Fig. 1. Assume that the two lightpaths in the network, need to be protected against link failures: (a) the first lightpath from Node 10 to Node 6 and (b) the second lightpath from Node 15 to Node 9. The routes and wavelengths of

working and backup lightpaths in one-on-one protection are illustrated in Table 1.

	<i>WorkingLightpath</i>	<i>BackupLightpath</i>
10 → 6	(10,11,1,6) on $\lambda_1$	(10,9,7,6) on $\lambda_1$
15 → 9	(15,6,7,9) on $\lambda_1$	(15,14,12,13,1,11,10,9) on $\lambda_2$

Table 1: The routing and wavelengths of primary and backup lightpaths with one-on-one protection.

In the following discussion, a wavelength-link is wavelength on a link. A total of 16 wavelength-links are reserved on the links of the network, 6 wavelength-links for the working lightpaths and 10 wavelength-links for the backup lightpaths. We note that, the two working lightpaths, (10,11,1,6), and (15,6,7,9) are link disjoint. As a result, upon any link failure, at most one of the two lightpaths can fail, i.e., both lightpaths cannot fail simultaneously upon a link failure. Therefore, the backup lightpaths can share wavelengths since they will not be activated simultaneously. This observation leads to the routes and wavelength assignments for the working and backup lightpaths illustrated in Fig. 2. We note that a total of 15 wavelength-links are reserved in this case, a reduction of 1 wavelength-link from the one-on-one protection case.

	<i>WorkingLightpath</i>	<i>BackupLightpath</i>
10 → 6	(10,11,1,6) on $\lambda_1$	(10,9,7,6) on $\lambda_1$
15 → 9	(15,6,7,9) on $\lambda_1$	(15,14,12,13,1,11,10,9) on $\lambda_1$

Table 2: The routing and wavelengths of primary and backup lightpaths with multiplexed spare-capacity protection.

We note that one-on-one protection is *static* in the sense that the switches are configured at setup-time for the working and the backup lightpaths. Multiplexed spare-capacity protection is *dynamic* in the sense that the switches need to be configured appropriately upon a failure to establish the backup lightpaths, and the decision on which switches need to be configured depends on the link that fails. As a result, the protocols that perform multiplexed spare-capacity protection, may be more complex than those that perform one-on-one protection. The multiplexed spare-capacity approach trades-off the economy of spare-capacity allocation with the protocol complexity to establish backup lightpaths upon a link failure.

## 1.1 Previous work

Fault tolerant design of virtual topologies has been studied in [5]. In [5], the authors propose physical protection schemes and one-on-one design protection for the lightpaths in the virtual topology. Optimal spare-capacity design has been studied extensively in circuit-switched networks [6, 6].

Our work is the first to consider multiplexed spare-capacity for protection against link failure in WDM optical networks.

## 1.2 Outline of remaining sections

In Section 2, we present the Integer Programming (IP) formulation of the problem. Bounds on the performance and the computational complexity of the problem is considered in Section 3. In Section 4, we elaborate on the approach to solve the Integer Programs. In Section 5 we present results for a representative network topology. Section 7 concludes the paper with a discussion of the main contributions of this work and related problems for further research.

# 2 Problem Formulation

In this section, we develop a general Integer Programming (IP) formulation of the multiplexed spare-capacity design problem.

## 2.1 Routing

We assume that each access node in the network contains a routing table. The routing table at a source node contains a ordered list of routes for each destination node. When a connection request arrives at the source node, routes are tried in sequence from the routing table, until an available wavelength continuous route is found. If no available route is found from the list of alternate routes, then the connection request is blocked and lost. We assume that routing tables are statically specified at each node. Fixed alternate routing provides benefits that includes the following: (a) simplicity of control needed to setup and teardown lightpaths, and (b) fault tolerance upon link failures [4, 2].

For the networks we consider in this paper, the routing tables at nodes are ordered by the hop distance to the destination. Therefore, the shortest hop path to the destination is the first route in the routing table. When there are ties in the hop distance between different routes, the ordering among them in the routing table is random.

<i>Destination</i>	<i>Route1</i>	<i>Route2</i>
2	1 6 2	1 7 2
3	1 3	1 4 3
4	1 13 4	1 3 4
5	1 13 5	1 6 5
6	1 6	1 7 6
7	1 7	1 6 7
8	1 7 8	1 6 8
9	1 7 9	1 11 10 9
10	1 11 10	1 7 9 10
11	1 11	1 7 9 10 11
12	1 13 12	1 6 15 14 12
13	1 13	1 6 5 13
14	1 6 15 14	1 13 12 14
15	1 6 15	1 13 12 14 15

Table 3: The routing table at node 1 for the network in Fig. 1, with two alternate routes to each destination.

## 2.2 Problem Formulation

We are given a network represented as a directed graph  $G$ , and a demand matrix, i.e., the number of lightpath requests between node-pairs, and we are also given the alternate routing tables at nodes.

Given:

- $N$  Nodes in the network, numbered 1 through  $N$ .
- Node pairs are numbered 1 through  $N(N-1)$ .
- $E$  Links in the network, numbered 1 through  $E$ .
- $W$  Total number of wavelengths on a link.
- $R^i$  Set of alternate routes for node-pair  $i$ .
- $M^i = |R^i|$  Number of alternate routes between node-pair  $i$ .
- $R_j^i$  Set of eligible alternate routes between node pair  $i$  after link  $j$  fails.
- $d_i$  Demand for node-pair  $i$ , in terms of number of lightpath requests.

Variables that are to be “solved” by the IP

- $s_j$  Minimum number of “spare” wavelengths on link  $j$ , integer.
- $w_j$  Number are the “working” channels on link  $j$ .

- $g^{i,r}$  The number of “working” wavelengths used on route  $r$  to satisfy the demand between node-pair  $i$ , before any link failures.
- $\gamma_w^{i,r}$  takes the value of 1 if the  $r^{th}$  route between node-pair  $i$  utilizes wavelength  $w$  before any link failures, 0 otherwise.
- $f_j^{i,r}$  The number of “spare” wavelengths used on the  $r^{th}$  route between node-pair  $i$ , after link  $j$  fails.
- $\delta_{i,r}^{w,j}$  takes the value 1 if the  $r^{th}$  route for node-pair  $i$  uses “spare” wavelength  $w$  after link  $j$  fails, 0 otherwise.

## 2.3 IP Formulation

### 2.3.1 Introduction

We will formulate three Integer Programs.

- IP1: IP1 is an IP formulation of the Routing and Wavelength Assignment problem for a given set of lightpaths without any failure protection.
- IP2: IP2 is an IP formulation of the one-on-one protection design problem. This IP determines the RWA of working and backup lightpaths.
- IP3: IP3 is an IP formulation of the multiplexed spare-capacity design problem. This IP determines the RWA of working lightpaths and the assignment of spare-capacity, and the determination of rerouting and wavelength assignment of restoration lightpaths upon a link failure.

### 2.3.2 IP1 – RWA without failure protection

$$(1) \quad \text{Minimize } \sum_{j=1}^E w_j$$

$$(2) \quad w_j \leq W \quad 1 \leq j \leq E$$

The demand between a node-pair  $i$  is satisfied.

$$(3) \quad d^i = \sum_{r=1}^{M_i} \sum_{w=1}^W \gamma_w^{i,r} \quad 1 \leq i \leq N(N-1)$$

The “working” channels used on a link.

$$(4) \quad w_j = \sum_{i=1}^{N(N-1)} \sum_{r \in R^i, j \in r} \sum_{w=1}^W \gamma_w^{i,r} \quad 1 \leq j \leq E$$

Wavelength continuity, only one “working” route can use wavelength  $w$  on link  $j$ .

$$(5) \quad \sum_{i=1}^{N(N-1)} \sum_{r \in R^i, j \in r} \gamma_w^{i,r} \leq 1 \quad 1 \leq w \leq W, 1 \leq j \leq E$$

### 2.3.3 IP2 – RWA with one-on-one failure protection

$$(6) \quad \text{Minimize} \sum_{j=1}^E w_j$$

$$(7) \quad w_j \leq W \quad 1 \leq j \leq E$$

The demand between a node-pair  $i$  is satisfied. Each “working” lightpath has a backup lightpath.

$$(8) \quad 2 * d^i = \sum_{r=1}^{M_i} \sum_{w=1}^W \gamma_w^{i,r} \quad 1 \leq i \leq N(N-1)$$

The “working” channels used on a link.

$$(9) \quad w_j = \sum_{i=1}^{N(N-1)} \sum_{r \in R^i, j \in r} \sum_{w=1}^W \gamma_w^{i,r} \quad 1 \leq j \leq E$$

Wavelength continuity, only one “working” route can use wavelength  $w$  on link  $j$ .

$$(10) \quad \sum_{i=1}^{N(N-1)} \sum_{r \in R^i, j \in r} \gamma_w^{i,r} \leq 1 \quad 1 \leq w \leq W, 1 \leq j \leq E$$

When a link fails, demands between all node-pairs can still be satisfied.

$$(11) \quad \sum_{r \in R_j^i} \sum_{w=1}^W \gamma_w^{i,r} \geq d^i \quad 1 \leq j \leq E, 1 \leq i \leq N(N-1)$$

### 2.3.4 IP3 – RWA with multiplexed spare-capacity protection

$$(12) \quad \text{Minimize} \sum_{j=1}^E (w_j + s_j)$$

$$(13) \quad w_j + s_j \leq W \quad 1 \leq j \leq E$$

### 2.3.5 Before Fault

The demand between a node-pair  $i$  is satisfied.

$$(14) \quad d^i = \sum_{r=1}^{M_i} g^{i,r} \quad 1 \leq i \leq N(N-1)$$

The “working” channels used on a link.

$$(15) \quad w_j = \sum_{i=1}^{N(N-1)} \sum_{r \in R^i, j \in r} \sum_{w=1}^W \gamma_w^{i,r} \quad 1 \leq j \leq E$$

Wavelength continuity, only one “working” route can use wavelength  $w$  on link  $j$ .

$$(16) \quad \sum_{i=1}^{N(N-1)} \sum_{r \in R^i, j \in r} \gamma_w^{i,r} \leq 1 \quad 1 \leq w \leq W, 1 \leq j \leq E$$

### 2.3.6 After Fault

The total rerouted lightpaths between node-pair  $i$  when link  $j$  fails equals the number of “broken” lightpaths between node-pair  $i$  when link  $j$  fails.

$$(17) \quad \sum_{r \in R_j^i} \sum_{w=1}^W \delta_{w,j}^{i,r} = \sum_{r \in R^i, j \in r} \sum_{w=1}^W \gamma_w^{i,r} \quad 1 \leq i \leq N(N-1), 1 \leq r \leq M_i, 1 \leq j \leq E$$

Wavelength continuity of “restoration” lightpaths, i.e., only one “restoration” route can use “spare” wavelength  $w$  on link  $k$ .

$$(18) \quad \sum_{i=1}^{N(N-1)} \sum_{r \in R_j^i, k \in r} \delta_{w,j}^{i,r} \leq 1 \quad 1 \leq w \leq W, 1 \leq j, k \leq E$$

Spare capacity on a link  $k$  meets “restoration” demands on the link  $k$ , after all lightpaths that are “broken” because of the failure of link  $j$  are released.

$$(19) \quad \sum_{i=1}^{N(N-1)} \sum_{r \in R_j^i, k \in r} \sum_{w=1}^W \delta_{w,j}^{i,r} \leq s_k + \sum_{i=1}^{N(N-1)} \sum_{r \in R^i, j, k \in r} \sum_{w=1}^W \gamma_w^{i,r} \quad 1 \leq j, k \leq E$$

### 2.3.7 Extensions

The above integer programs can be modified in a straightforward fashion to the following problem scenarios.

- Node failures.

- Multiple failures of nodes and/or links.
- Wavelength conversion, sparse and full.
- Preconfigured spare-capacity.

### 3 Complexity

We expect that the multiplexed spare capacity design problem is NP-complete.

#### 3.0.8 Performance Bounds

Let  $M_i$  be the number of link-disjoint alternate routes between node-pair  $i$ . Let  $\alpha = \text{Min}M_i, 1 \leq i \leq N(N-1)$ . Let  $s = \text{Min}s_j, 1 \leq j \leq E$ .

$$(20) \quad \frac{W}{\alpha} \leq s \leq \frac{W}{2}$$

## 4 Solution Approach

### 4.1 LpSolve

We have used a free LP/IP solver lpSolve [1].

### 4.2 Heuristics

## 5 Results and Discussion

### 5.1 Network Topologies

We consider two networks for all our studies: (a) a network of interconnected rings illustrated in Fig. 1, and (b) the European optical network illustrated in Fig. 2 [3]. The interconnected rings network topology was provided to us by Pacific Bell as being representative of their SONET network.

### 5.2 Results

Figure 3, and Table 4 illustrate the performance of different protection schemes, for the interconnected rings network for random virtual topologies with number of links ranging from 5 through 20. We note that significant savings are obtained in the number of channels used in the multiplexed spare-capacity approach.

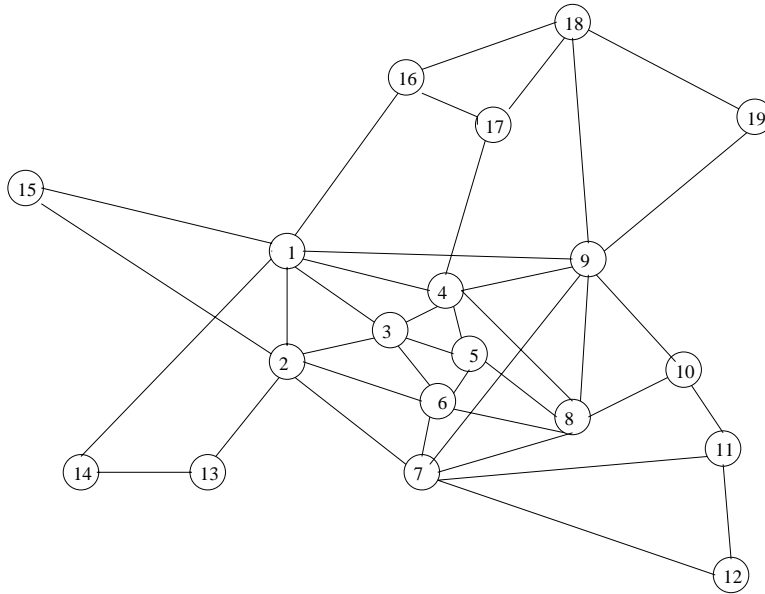


Figure 2: Topology of the European optical network.

Figure 5 illustrates the performance of different protection schemes, for the interconnected rings network, enhanced with two added rings, shown in Fig. 4, The results are illustrated for random virtual topologies with number of links ranging from 5 through 15.

Figure 6, Table 6 illustrate the performance of different protection schemes, for the European optical network for random virtual topologies with number of links ranging from 5 through 20.

## 6 Implementation

### 6.0.1 One-on-One Protection

A central manager can compute the wavelength channel requirements and reserve them at the time of lightpath setup. Switches are configured for the working as well as the backup lightpaths at setup time.

### 6.0.2 Multiplexed spare-capacity

In multiplexed spare-capacity, working and spare channels are reserved at setup time. However, switches are configured after the link failure.

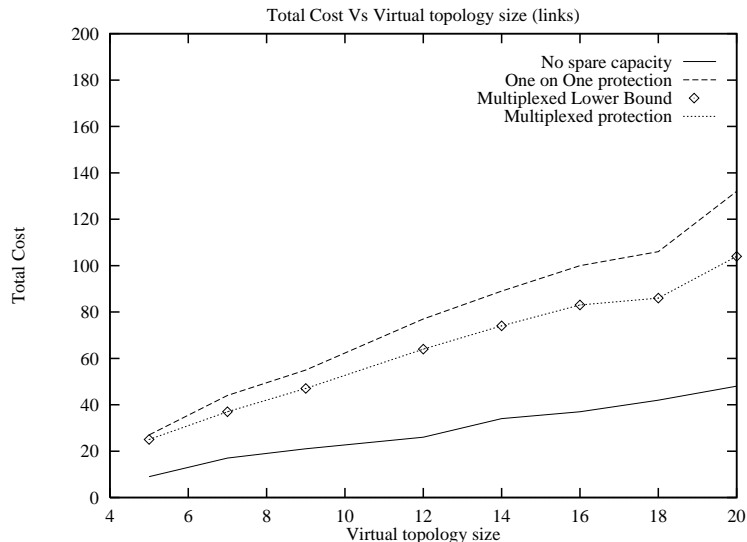


Figure 3: Performance of different protection schemes for the interconnected rings network.

## 7 Conclusion

Photonic backbone networks based on WDM technology can potentially transfer several gigabits of data on each fiber link in the network. However, the high bandwidths carried by links have the drawback that a link failure can potentially lead to loss of large amounts of data.

One-on-One protection is a technique that protects lightpaths from link failures by reserving a backup lightpath that is link-disjoint from the lightpath that needs to be protected. One-on-one protection has the benefit of being a static scheme. However, one-on-one protection is not optimal with respect to the use of the network wavelength resources.

This paper considers a multiplexed spare-capacity approach to providing protection from link failures. Multiplexed spare capacity significantly reduces the resources required to protect against failures. However, it is a dynamic scheme.

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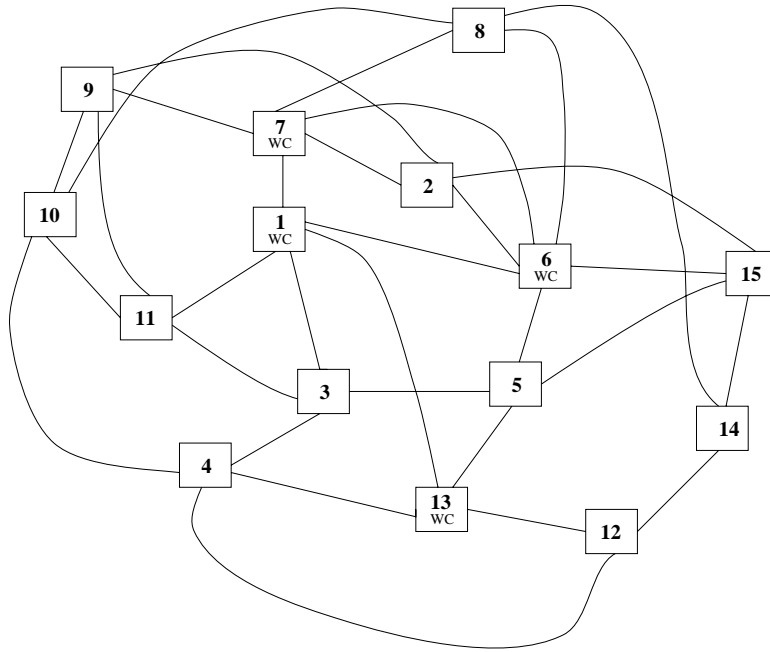


Figure 4: The interconnected rings network in Fig. 1 with two added rings.

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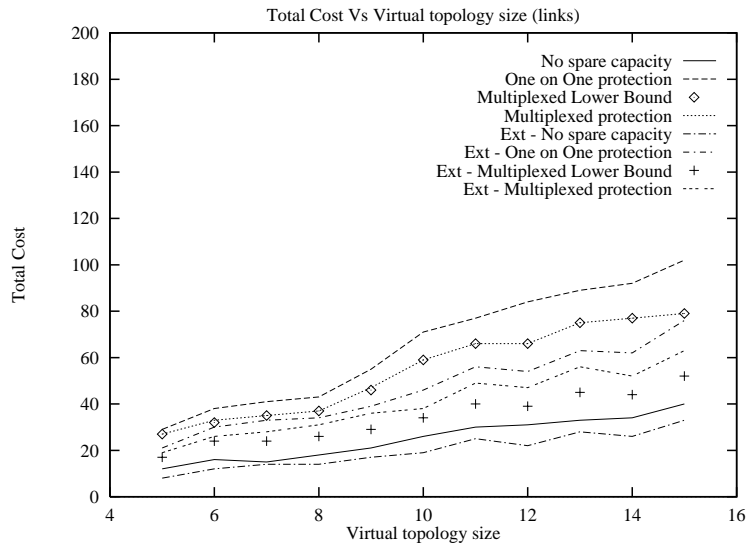


Figure 5: Performance of different protection schemes for the interconnected rings network.

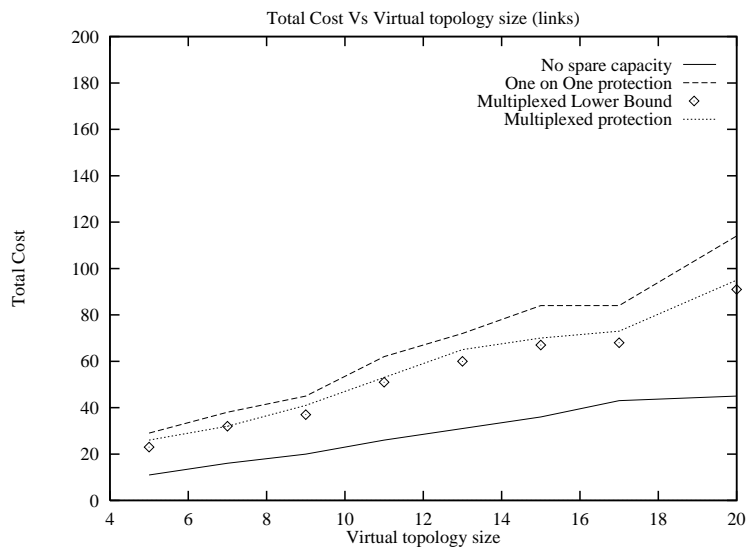


Figure 6: Performance of different protection schemes for the European optical network.

<i>Links</i>	<i>No Protection</i>	<i>One-on-One (lb,val,congestion)</i>	<i>Multiplexed (lb,val,congestion)</i>	<i>Gain</i>
5	12	30,30,2	26,26,2	4
	9	27,27,4	25,25,3	2
6	10	32,32,3	27,27,2	5
	12	43,43,3	37,37,2	6
7	17	47,47,3	41,41,2	6
	17	44,44,3	37,37,2	7
8	19	49,49,3	42,43,3	6
	18	57,57,4	48,48,2	9
9	21	55,55,3	47,47,2	8
	26	63,63,5	54,55,4	8
10	26	69,69,4	63,63,4	6
	27	67,67,4	55,55,3	12
11	31	80,80,5	71,71,5	9
	22	65,65,4	55,55,3	10
12	27	77,77,5	66,66,5	11
	26	77,77,6	64,64,4	13
13	29	88,88,5	74,74,4	14
	28	88,88,6	74,74,4	14
14	41	102,102,7	91,92,7	10
	34	89,89,7	74,74,4	15
15	37	93,93,5	79,79,3	14
	31	91,91,7	71,71,4	20
16	37	100,100,8	83,83,5	17
	43	116,116,7	97,97,6	19
17	43	119,119,7	99,99,6	20
	46	113,113,6	93,93,5	20
18	44	114,114,7	92,92,4	22
	42	106,106,7	86,86,4	20
19	44	125,125,7	99,99,5	26
	42	122,122,7	101,101,6	21
20	41	117,117,7	86,87,6	30
	48	132,132,7	104,104,5	28

Table 4: Results for the interconnected rings network

<i>Links</i>	<i>No Protection</i>	<i>One-on-One (lb, val, congestion)</i>	<i>Multiplexed (lb, val, congestion)</i>	<i>Gain</i>
5	11	29,29,2	23,26,2	3
	14	32,32,2	27,29,2	3
6	14	35,35,3	30,31,2	4
	18	41,41,3	36,37,2	4
7	21	46,46,4	37,43,3	3
	16	38,38,3	32,32,2	6
8	21	51,51,3	43,45,3	6
	19	44,44,3	37,41,2	3
9	20	45,45,2	37,41,2	4
	24	52,52,3	46,48,3	4
10	22	53,53,2	46,48,2	5
	23	52,52,4	44,47,3	5
11	28	67,67,4	59,64,3	3
	26	62,62,4	51,53,3	9
12	30	63,63,3	49,59,2	4
	24	58,58,3	50,54,2	4
13	31	72,72,3	60,65,3	7
	26	62,62,3	51,53,3	9
14	33	78,78,5	63,67,3	12
15	36	84,84,5	67,70,3	14
	31	80,80,4	67,69,4	11
16	39	92,92,4	75,81,3	11
	33	76,76,4	60,63,3	13
17	33	84,84,4	68,73,3	11
	43	100,100,4	81,85,3	15
18	36	91,91,4	71,79,4	12
	36	83,84,5	69,72,5	12
19	45	105,106,5	81,95,4	11
20	45	114,114,4	91,95,3	19
	47	101,101,4	76,88,4	13

Table 5: Results for the european optical network