Design of Reliable Communication Networks (DRCN) 2003, Banff, Alberta, Canada, October 19-22, 2003

Availability models for protection techniques in WDM networks

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***Abstract*— This paper deals with the most common protection schemes in WDM optical networks, providing for each of them an algebraic formulation of availability analysis. We consider single or multiple link failure scenarios, being a link failure a fault that affects all the optical connections routed on the involved link. Availability models are applied to some numerical examples that allow us to compare the different availability degrees granted by each protection technique. When an approximation is introduced in the presented formulas, Monte-Carlo-approach simulation results are given to verify the accuracy of the theoretical analysis. The paper highlights some important availability relations between path-protection schemes and most relevant network parameters.**

***Index Terms*— Protection techniques, WDM networks, link failure, system availability.**

I. Introduction

Recent advances in photonic technologies paved the road for the large-scale deployment of WDM networks able to transmit at very high aggregated bit rate on each single fiber. In such networks protection techniques have become extremely important for operators to win the competition for broadband traffic transport. While methods aimed to plan survivable networks have been extensively studied in the last decade, giving origin to various protection approaches, the related topic of how these affect availability is of growing interest today. In this paper we focus our attention on *path protection*, a common strategy for WDM networks which consists of associating backup capacity to each *working lightpath* (WL) on an end-to-end basis [1]. The basic requirement is that any connection can be recovered from a single link failure, regardless of the failure location. For this reason the *protection lightpath* (PL) of each connection must be always link-disjoint from the working lightpath. Spare lightpaths can use exclusively allocated resources (*dedicated path protection*) or can share some WDM channels with protection lightpaths of other connections (*shared path protection*). To satisfy the above basic requirement, sharing in this latter case can occur only among connections having link-disjoint WLs.

Clearly any protection technique requires additional network costs to deploy spare resources, payed off by the network operator's capability of guaranteeing agreed levels of Availability and Reliability (A&R) to customers. A&R analysis is a fundamental tool for the operators to understand the relations between the protection mechanisms they install and the performance of connection integrity of their network. The final goal is to optimize the trade-off between extra deployment costs and higher revenues from more advantageous service level agreements. Modelling of the network and of the optical connections in terms of availability or reliability is the first step of the application of A&R analysis to WDM networks. Once modelling has been carried out, A&R theory offers rules and methods to combine various functional-block parameters according to each particular system configuration and protection layout. In this paper we wish to concentrate on A&R evaluation methods more than modelling operations.

The majority of publications on A&R analysis focused on the evaluation of connection availability in WDM ring networks [2], [3]. WDM mesh networks, that allow us to implement a richer set of protection strategies, have been considered in a recent body of research papers, investigating availability-efficient routing methods [4], [5], the effect of availability on network capacity [6], and functional modelling description of WDM networks [7]. This work, too, is dedicated to WDM mesh networks. The aim of this paper, in particular, is to analyze and compare the availability performance of any possible end-to-end protection technique: each dedicated and shared configurations will be analyzed by a combinatorial approach, providing at the end a closed-form algebraic equation (sometimes by introducing approximations). These simple back-of-the-envelope equations are however sufficient to discover interesting properties of end-to-end protection, presented later on. This work is intended also to prepare an analytical tool that, comprising a set of equations solvable with limited computational complexity, can be usefully adopted in a full network-design environment. The development of our own WDM-network availability-constrained design and optimization tool is a work currently in progress.

The rest of the paper is organized as follows: in Sec. II we illustrate assumptions and basic principles on which our analytical model is based; in Sec. III we present the derivation of the algebraic relations that evaluate the availability performances of the dedicated and shared N:M end-to-end protection schemes. In Sec. IV we report some numerical examples to compare the availability degree provided by the different

Work partially supported by MIUR, Italy, under FIRB Project ADONIS.

protection techniques and highlight interesting dependencies of A & R on some network parameters. In Sec. V some tests based on the Monte Carlo approach are carried out to validate our analytical equations that are based on approximations.

II. Assumptions and Fundamentals of the WDM-Network Availability Model

Our analysis is developed according to the following classical scheme: a) system identification and decomposition in functional elements; b) characterization of each element in terms of its A&R parameters; c) development of an A&R mathematical model taking into account the relations among the elements within each subsystem and among the subsystems within the system; d) A&R evaluation of each subsystem and of the whole system.

Since this paper is aimed to the comparison of different end-to-end protection mechanisms, the system that we are going to study for each case of protection is the set of optical connections that may be involved by common protection actions. We call this set of connections a *protection group* (PG). We will see that, according to their various implementations, the protection mechanisms can create interdependency between connections having the same source and destination (M:N case) or even connections among different couples of nodes of a network (mesh shared-protection). We will assume that routing and wavelength assignment have already been solved for the working and protection lightpaths of all the connections of the PG under study. This means that a WDM channel has been reserved and is in use for every WDM link of the network crossed by a WL of the PG. On the other hand, a WDM channel has been assigned for every WDM link of the network on which a PL of the PG will be routed in case of failure. Note that we assume that spare resources are preplanned (protection mechanisms do not require the knowledge of failure location) and that protection is achieved by a standby redundancy strategy. In order to better focus on protection comparison, the WDM network systems we are going to analyze will be reduced to comprise only one PG at the time: all the other possible connections not belonging to the PG and physical resources (WDM channels) assigned to them will be neglected.

Each connection of the PG is a subsystem of our model. The functional elements should comprise all the transmission and switching equipment crossed by each lightpath. In this work we have however considered ideal WDM switching devices, i.e. perfectly reliable and free from any kind of failure (assumption not far from reality, according to Ref. [8]). This ideality assumption extends also to any device providing switching of the optical signals of a connection from working to protection paths in case of failure. Thus only *WDM channels* have to be taken into account as functional blocks. A WDM channel is part of a WDM link, composed of the fiber cable installed between two adjacent nodes and equipped by a set of line devices (e.g. optical amplifiers). The A&R parameters of a WDM channel can be obtained by suitably combining those of the line devices plus those of other possible devices such as transponders, transmitters, receivers, WDM multi-demultiplexers, etc. Such parameters are commonly specified by technology vendors. The details of the reliability description of a WDM channel (see for example Ref. [4]) are not of interest in this paper and will be omitted. We shall only say that the model is based on the usual approximation of considering a constant rate of failure $z(t) = \eta$, corresponding to a negative exponential reliability function $R(t) = e^{-\eta t}$. According to such approximation, the Mean Time To Failure (MTTF) of a WDM channel is independent on the components age. Moreover, the WDM channels of a given optical connection are mutually failure-independent [11], [12], [13], [14].

WDM links can be realistically considered reparable systems: we thus assume the MTTF of a WDM channel to be equal to its *Mean Time Between Failures* (MTBF); thus: $\text{MTBF} = 1/\eta$. The *Mean Time To Repair* (MTTR) of a WDM channel is also assumed to be constant in time. Eventually, for the purpose of this paper, we will assume each functional element of our system (i.e. each WDM channel assigned to any lightpath of the PG) characterized by a known average steady-state availability $A = \text{MTBF}/(\text{MTBF}+\text{MTTR})$ or by a known MTTF (the mean value of the reliability distribution).

All the components included in our model have been characterized in terms of their intrinsic availability. Externally-provoked failures are not considered[1]. Rigorously, the internal failure on a WDM channel does not coincide with a link failure. However, in the context of our model they are equivalent, since we do not include protection mechanisms able to locally reroute a failed WDM channel onto another WDM channel of the same link and thus a WDM channel failure activates exactly the same mechanisms as a link failure. In the examples reported in the following we will assume WDM channels assigned to PLs to have the same A&R parameters of those assigned to WLs. This implies the assumption of hot-standby protection mechanisms, which is quite appropriate for WDM networks: spare resources are in fact usually employed by low-priority connections that are preempted in case of failure; thus, protection WDM channels, though being standby resources of high-priority connections, are never really "off", as the working counterparts. It should also be considered that a common routing method is to route the WL on the first shortest path between source and destination and the PL on the second link-disjoint shortest path: the total A&R of the standby path can be even worse of that of the primary path, being the former usually longer than the latter. Finally, let us specify that in this work we are not considering for simplicity the presence of disjoint links belonging to the same shared risk-group (e.g. passing through the same conduit), nor protection or restoration errors.

Being our system composed of reparable elements, we will refer in the following only to availability as a measure of quality. This however does not mean that reliability is irrelevant (it

[1] Statistically modelling external failure agents is generally difficult: often, intrinsic availability only appears in system specifications.

may be even more important from the customer perspective for certain types of services). The model we propose, presented in terms of availability, can in any case be applied without major changes also to cases in which reliability is the major concern. The following basic notation, in fact, allows us to analyze reliability and availability in the same way. Be E_{xy} a generic event associated to a functional element, a subsystem or the whole system: if E_{xy} stands for "xy has never failed up to the time t", then $P\{E_{xy}\}$ is a reliability. Otherwise, if E_{xy} stands for "xy is operating at the time t, independently of what has previously occurred", then $P\{E_{xy})$ is an availability.

III. Availability of WDM path-protection schemes

In this section, for each possible implementation of path-protection we provide algebraic equations to evaluate the availability of the single optical connections (subsystems) and of the entire PG (system). Starting from the simplest scheme (dedicated 1:1), we will increase first the number of working lightpaths in the PG (1:N) and then the number of spare lightpaths (M:N), to pass to the mesh shared-cases. All these schemes may be of practical interest in WDM network planning. It should be noted however that, due to the fundamental requirement of path-protection (see Sec. I), at least all the WPs of a PG are link-disjoint. The increase of the number of mutually link-disjointness constraints in the same PG makes the most complex schemes applicable only in extremely highly-connected network topologies.

The following notation will be used, also in the figures. Events, negated events and availability are identified by E, $\overline{E}$ and A, respectively. These symbols always appear with a subscript, the first letter of which indicates what the symbol refers to: the whole PG system (s), a connection (k), a working (w) or a protection (p) lightpath, a working (λ) or a spare (π) WDM channel. Except for the whole PG, a second letter of the subscript identifies the particular element in the considered system: e.g. A_{w1} is the availability of the working lightpath number 1. Each connection obviously corresponds to one and one only WP. Therefore a connection has always the same identifier of its WL. The same does not apply to PLs when they are shared.

The equations are obtained by a combinatorial method [9], enumerating all the favorable cases and summing their probabilities. The well-known formulas of the availability of parallel and series systems [10] are often applied. For instance, a WL wi is a series of WDM channels. Thus its availability is the product of the availability of all the elements λj of the set Λ_{wi} of WDM channels assigned to it

$$A_{wi} = \prod_{\forall \lambda j \in \Lambda_{wi}} A_{\lambda j}$$

A. 1:1 dedicated protection

In the 1:1 technique (Fig. 1) the PG is simply composed of one connection (connection $k1$), which is coincident with the entire system and comprises a working ($w1$) and a link-disjoint protection lightpath ($p1$). The backup path, which is used when a failure occurs on the working lightpath, in this case is dedicated to one single connection. The system availability is given by the union of two disjoint events: the WL is available (E_{w1}); the WL is not available ($\overline{E_{w1}}$), but the PL is available and can be used (E_{p1})

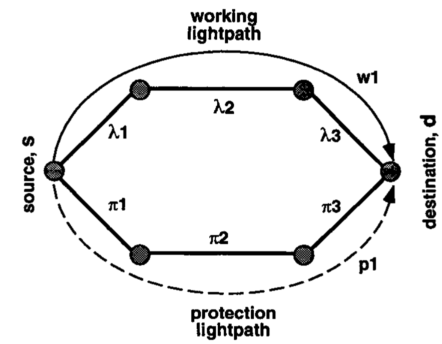

Fig. 1. Protection group of 1:1 dedicated protection

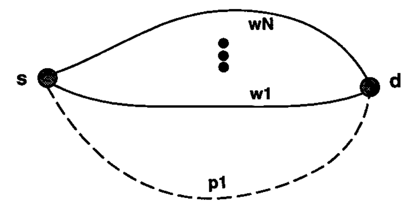

Fig. 2. Protection group of 1:N protection

$$P\{E_s\} = P\{E_{k1}\} = P\left\{E_{w1} \cup \left(\overline{E_{w1}} \cap E_{p1}\right)\right\}$$

The connection (and PG) availability is given by

$$A_s = A_{k1} = A_{w1} + A_{p1} - A_{w1}A_{p1} \tag{1}$$

B. 1:N protection

The PG is composed of N connections with the same source and destination, sharing a single PL (Fig. 2). Let us consider first the simplest case with $N = 2$. System availability is the union of three disjoint events:

$$P\{E_s\} = P\left\{(E_{w1} \cap E_{w2}) \cup \left(E_{w1} \cap \overline{E_{w2}} \cap E_{p1}\right) \cup \cup \left(\overline{E_{w1}} \cap E_{w2} \cap E_{p1}\right)\right\}$$

$$A_s = A_{w1}A_{w2} + A_{w1}A_{p1} + A_{w2}A_{p1} - 2A_{w1}A_{w2}A_{p1}$$

The availability of connection $k1$ (similarly to that of $k2$) is given by:

$$P\{E_{k1}\} = P\left\{E_{w1} \cup \left(\overline{E_{w1}} \cap E_{p1} \cap E_{w2}\right)\right\} \tag{2}$$

$$A_{k1} = A_{w1} + A_{p1}A_{w2} - A_{w1}A_{p1}A_{w2}$$

Now we we can extend the previous case to the general case of N connections (N WLs plus one PL, all mutually

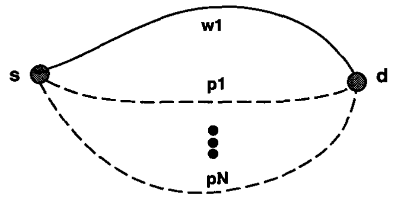

Fig. 3. Protection group of M:1 protection

link-disjoint). The system availability is expressed by:

$$P\{E_s\} = P\left\{\bigcap_{j=1}^{N} E_{wj} \bigcup_{h=1}^{N}\left[\overline{E_{wh}} \cap E_{p1} \cap \bigcap_{j=1}^{N} E_{w(j\neq h)}\right]\right\}$$

$$A_s = (1 - NA_{p1})\prod_{j=1}^{N} A_{wj} + \sum_{h=1}^{N}\left[A_{p1}\prod_{j=1}^{N} A_{w(j\neq h)}\right]$$

The availability of the generic connection ki is given by the union of two disjoint events: (a) the working path of wi is operating or (b) all the other working paths and the protection path $p1$ are available:

$$P\{E_{ki}\} = P\left\{E_{wi} \cup \left[E_{p1} \cap \overline{E_{wi}} \bigcap_{j=1}^{N} E_{w(j\neq i)}\right]\right\}$$

$$A_{ki} = A_{wi} + A_{p1}\,(1 - A_{w}\ )\prod_{j=1}^{N} A_{w(j\neq k)} \quad (3)$$

In ki availability evaluation we have considered as non-favorable the event in which more than one WL fail, but wi has failed first and has been recovered "grasping" $p1$. This could have been taken into account appending further availability terms (e.g. $(1/2)\ (1 - A_{w1})A_p(1 - A_{w2})$ in the 1:2 case), which are however negligible, as confirmed in Sec. V. Similar approximations are introduced also for M:N connection availability, neglecting multiple WL failures that however result in connection recovery.

C. M:1 protection

In this scheme the PG comprises one single connection $k1$ (Fig. 3). Its WL $w1$ is protected by multiple link-disjoint PLs $p1 \ldots pM$. pi is used when $w1$ and all the PLs from $p1$ to $p(i-1)$ are unavailable. Up to M failures can be recovered.

Let us start with the case 2:1. (4) and (5) refer to the system availability that coincides to the single connection availability.

$$P\{E_s\} = P\left\{E_{w1} \cup \left(\overline{E_{w1}} \cap E_{p1}\right) \cup \left(\overline{E_{w1}} \cap \overline{E_{p1}} \cap E_{p2}\right)\right\} \quad (4)$$

$$A_s = A_{w1} + (1 - A_{w1})\,A_{p1} + (1 - A_{w1})\,(1 - A_{p1})\,A_{p2} \quad (5)$$

(6) and (7) express system and connection availability in the general M:1 case.

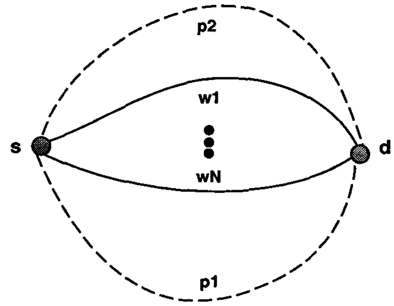

Fig. 4. Protection group of 2:N protection

$$P\{E_s\} = P\left\{E_{w1} \cup \bigcup_{h=1}^{M}\left[\overline{E_{w1}} \cap E_{ph} \bigcap_{j=1}^{h-1} \overline{E_{pj}}\right]\right\} \quad (6)$$

$$A_s = A_{w1} + (1 - A_{w1})\sum_{h=1}^{M} A_{ph}\prod_{j=1}^{h-1}(1 - A_{pj}) \quad (7)$$

D. M:N protection (2:N case)

The most general path-protection configuration involving connections between the same end nodes is obtained by combining 1:N and M:1 in the M:N case. Unfortunately, a general equation for the M:N availability can not be written in a closed form, since its algebraic form changes with M and N. Let us therefore develop the 2:N scheme with $N > 2$ (Fig. 4). Of the two link-disjoint PLs, $p2$ is used only when $p1$ is down. Availability is obtained by the disjoint union of $\binom{2+N}{N}$ events:

$$P\{E_s\} = P\{E_a \cup E_b \cup E_c \cup E_d\}$$

where

$$E_a = \bigcap_{h=1}^{N} E_{wh}$$

$$E_b = \bigcup_{h=1}^{N}\left[\overline{E_{wh}} \cap E_{p1} \bigcap_{j=1}^{N} E_{w(j\neq h)}\right]$$

$$E_c = \bigcup_{h=1}^{N}\left[\overline{E_{wh}} \cap \overline{E_{p1}} \cap E_{p2} \bigcap_{j=1}^{N} E_{w(j\neq h)}\right]$$

$$E_d = \bigcup_{h=2}^{N}\bigcup_{j=1}^{h-1}\left[\overline{E_{wh}} \cap \overline{E_{wj}} \cap E_{p1} \cap E_{p} \bigcap_{k=1}^{N} E_{w(k\neq j\neq h)}\right]$$

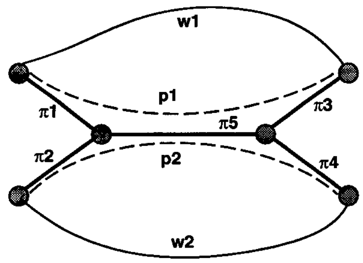

Fig. 5. PG of the 2×(1:1) mesh shared-protection

And thus

$$\begin{aligned}A_s = &\prod_{h=1}^{N} A_{wh}+\\ &+\sum_{h=1}^{N} (1-A_{wh})(A_{p1}+A_{p2}-A_{p1}A_{p2}) \prod_{j=1}^{N} A_{w(j\neq h)}+\\ &+\sum_{h=2}^{N}\sum_{j=1}^{h-1} (1-A_{wh})(1-A_{wj}) A_{p1}A_{p2} \prod_{k=1}^{N} A_{w(k\neq j\neq h)}\end{aligned}$$

The availability of a generic protected optical connection ki is not reported for brevity. The same analysis has been carried out in the 3:N case, and we will show only the numerical values in Sec. IV.

E. Mesh shared-protection

We call mesh shared-protection a 1:1 protection strategy, in which spare paths associated to disjoint working paths having different source and/or destination can share WDM channels. This strategy, peculiar of the mesh physical topology, allows a relevant saving of network capacity.

Let us consider the PG of Fig. 5, composed of only two connections (the 2×(1:1) case). The two WLs $w1$ and $w2$ are protected by two PLs ($p1$ and $p2$) which share the WDM channel $\pi 5$. The system availability is the probability that both connections are routed successfully and is obtained in (8) and (9) by the union of three disjoint events.

$$P\{E_s\} = P\{(E_{w1} \cap E_{w2}) \cup E_a \cup E_b\} \qquad (8)$$

where, keeping in mind that $E_{p2} = E_{2} \cap E_{\pi 5} \cap E_{\pi 4}$ ($A_{p1} = A_{1} A_{\pi 5}\ A_{\pi 3}$) and $E_{p1} = E_{1} \cap E_{\pi 5} \cap E_{\pi 3}$ ($A_{p1} = A_{\pi 2} A_{\pi 5} A_{\pi 4}$), we set

$$\begin{aligned}E_a &= E_{w1} \cap \overline{E_{w2}} \cap E_{p2}\\ E_b &= \overline{E_{w1}} \cap E_{w2} \cap E_{p2}\end{aligned}$$

Thus

$$\begin{aligned}A_s = &A_{w1}A_{w2} + A_{w1}(1-A_{w2})A_{p2}+\\ &+(1-A_{w1})A_{w2}A_{p1}\end{aligned} \qquad (9)$$

To evaluate the availability of a single connection, we have to distinguish different double-link failure scenarios. For instance, even though lightpath $w2$ and WDM channel $\pi 2$ fail, connection $k1$ can be routed successfully. So the first subsystem (protected connection $k1$) is characterized by the following availability:

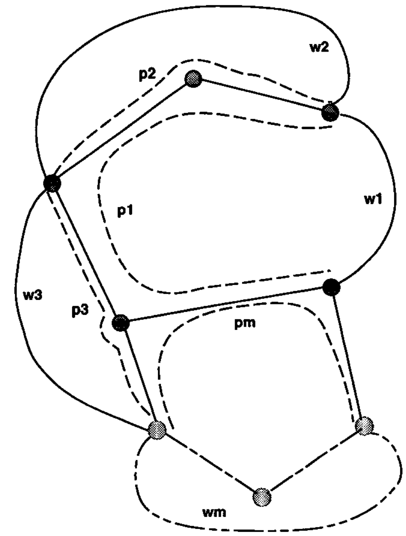

Fig. 6. PG of the m×(1:1) mesh shared-protection

$$P\{E_{k1}\} = P\{E_{w1} \cup E_\alpha \cup E_\beta \cup E_\gamma\}$$

where

$$\begin{aligned}E_\alpha &= \overline{E_{w1}} \cap E_{p1} \cap E_{w2}\\ E_\beta &= \overline{E_{w1}} \cap E_{p1} \cap \overline{E_{w2}} \cap \overline{E_{2}}\\ E_\gamma &= \overline{E_{w1}} \cap E_{p1} \cap \overline{E_{w2}} \cap E_{\pi 2} \cap \overline{E_{\pi 4}}\end{aligned}$$

Thus

$$\begin{aligned}A_{k1} = &A_{w1} + (1-A_{w1})A_{p1}A_{w2}+\\ &+(1-A_{w1})A_{p1}(1-A_{w2})(1-A_{2})+\\ &+(1-A_{w1})A_{p1}(1-A_{w2})A_{\pi 2}(1-A_{\pi 4})\end{aligned} \qquad (10)$$

The need to consider all the possible multiple-failure combinations makes the problem intractable for larger PGs. We introduce an approximation by neglecting multiple failure scenarios. This is equivalent to consider only terms in which $(1-A)$ appears at the first order, neglecting higher-order terms. It can be proven that the second order terms are always absent even without the approximation, except when the spare path is totally shared (but this case coincides with the 1:N case). In the next section we will show by numerical examples that the approximated formula converges to the real availability values for highly available components (rare-event approximation). The approximated availability of connection $k1$ is calculated in (11) and (12).

$$P\{E_{k1}\} \approx P\{E_{w1} \cup [\overline{E_{w1}} \cap E_{p1} \cap E_{w2}]\} \qquad (11)$$

$$A_{k1} \approx A_{w1} + (1-A_{w1})A_{p1}A_{w2} \qquad (12)$$

We extend now our analysis to a PG comprising the m protected working connections whose protection lightpaths share some optical channels (m×(1:1) scheme, Fig. 6). The system availability formulas (13) and (14) are obtained neglecting multiple-failure cases.

$$P\{E_s\} \approx P\left\{\bigcap_{j=1}^{m} E_{wj} \bigcup_{h=1}^{m}\left[\overline{E_{wh}} \cap E_{ph}3 \bigcap_{k=1}^{m} E_{w(k\neq h)}\right]\right\} \quad (13)$$

$$A_s \approx \prod_{j=1}^{m} A_{wj} + \sum_{h=1}^{m}(1-A_{wh})\,A_{ph}\prod_{k=1}^{m} A_{w(k\neq h)} \quad (14)$$

Also in (15) and (16) we use the single failure approximation. When evaluating approximated connection availability, in mesh shared-protection only $m_{ki} \leq m$ WLs belonging to PG_{ki} are relevant. PG_{ki} is the subset of PG comprising only connections sharing spare WDM channels with the PL of connection ki. In Fig. 6, for example, PG_{km} contains $k1$ and $k3$, but not $k2$.

$$P\{E_{ki}\} \approx P\left\{E_{wi} \cup \left[\overline{E_{wi}} \cap E_{pi} \bigcap_{\forall h \in \mathrm{PG}_{ki}} E_{w(h\neq i)}\right]\right\} \quad (15)$$

$$A_{ki} \approx A_{wi} + (1-A_{wi})\,A_{pi} \prod_{\forall h \in \mathrm{PG}_{ki}} A_{w(h\neq i)} \quad (16)$$

Thanks to the approximation, the previous two formulas express the availability of a connection ki as a function of the availability of wi and of all the other working paths of PG_{ki}. So A_{ki} is influenced by the length of its spare path, but not by the number of actually shared spare WDM channels. In other words, if a spare path px has a length L_{px} of 5 hops and it shares channels with other 3 spare paths (associated to disjoint WLs), A_{ki} is fixed by (16) and we are not interested on the number of effectively shared channels, that can vary from 1 to 5.

IV. Numerical Examples

In this section we analyze the protection techniques through numerical examples. We assume each working lightpaths wi is composed of a single hop (channel) with availability $A_{wi} = 1 - U$. Each protection lightpath px has length $L_{px} = 3$, being the availability of each of its 3 WDM channels $A_{\pi j} = 1 - U$). The total spare path availability is $A_{px} = (1-U)^3$. The reported numerical values refer to the availability of a single protected connection.

A. M:N protection

For all the results in this section: $U = 10^{-4}$. The connection unavailability values of 1:N, 2:N and 3:N are plotted in Fig. 7 as a function of N.

Fig. 7a plots (1) and (3) showing that unavailability grows for increasing values of N with a linear slope of about 10^{-8} per $\Delta N = 1$. By comparing these values to those of Fig. 7b, we can observe that a connection protected by the 2:N technique is always more available for any value of N. This is simply because dedicated protection recovers any single failure while the 2:N protection recovers any single and double failures. The same consideration can be drawn

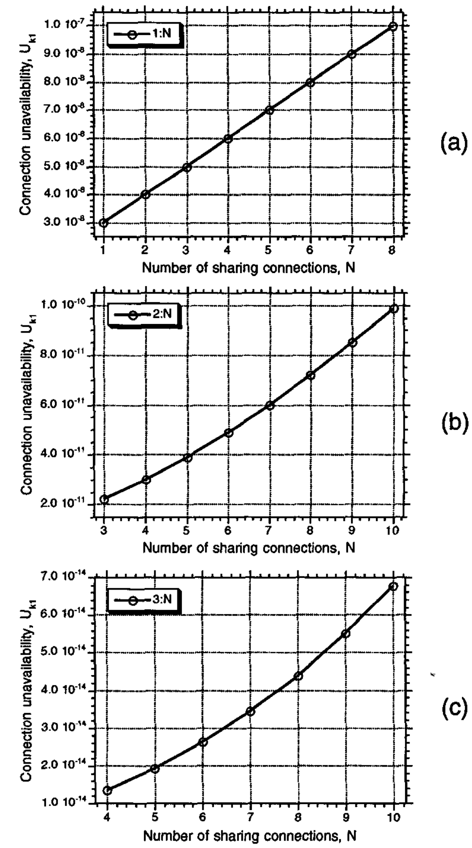

Fig. 7. Connection unavailability of protection schemes 1:N (a), 2:N (b) and 3:N (c)

TABLE I

CONNECTION UNAVAILABILITY IN M:1 PROTECTION

Protection technique	Unavailability $U_{k1} = 1 - A_{k1}$
2 : 1	8.99825×10^{-12}
3 : 1	2.77556×10^{-15}
4 : 1	1.11022×10^{-16}

for the 3:N case. For 2:N and 3:N techniques connection unavailability increases more than linearly with N: the slope of function $U_{ki}(N)$, which is constant when single failures are recoverable, tends to increase more and more rapidly as the number of recoverable failures increases. The values of Table I are obtained applying (7): unavailability decrease of orders of magnitude by adding protection lightpaths, since a higher number of connection failures can be recovered.

We can conclude that availability in M:N protection is primarily determined by M, corresponding to the number of simultaneously recoverable failures. The number N of working paths sharing the backup paths has instead a marginal effect compared to M. The ratio M/N is not a significant parameter to compare the availability degree of different protection strategies: M is much more significant. For example, from Table I and from Fig. 7c we see that 2:1 unavailability is

TABLE II

UNAVAILABILITY OF CONNECTION $k1$ IN THE PG OF FIG. 5

U	U_{k1} exact	U_{k1} approx	% Error
10^{-1}	3.30049×10^{-2}	3.439×10^{-2}	4.2
10^{-4}	3.9992×10^{-8}	3.9994×10^{-4}	5×10^{-3}

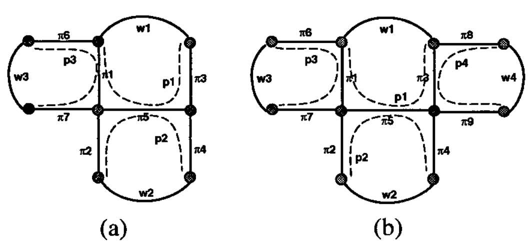

Fig. 8. (a) 3×(1:1) and (b) 4×(1:1) mesh shared-protection PGs

$\approx 9 \times 10^{-12}$ with $M/N = 2$, while in 3:4 case unavailability is $\approx 1.2 \times 10^{-14}$ with $M/N = 0.75$. Actually, 3:4 provides protection against any three link failure, achieving a higher level of availability.

B. Mesh shared-protection

In Sec. III-E we have obtained the single connection availability using either the exact (10) and the approximated (12). Table II shows the accuracy of our approximations considering the network of Fig. 5. In the first row ($U = 0.1$) unavailability is selected on purpose with values unrealistic for optical networks. We can observe that even in this extreme conditions the percentage error of the approximated result is quite small, while it is almost negligible with realistic unavailability ($U = 10^{-4}$). Note that in the approximated 2×(1:1) case connection unavailability results to be exactly equal to that of 1:2 protection shown in Fig. 7b.

To confirm the validity of the approximations, we propose two other topologies shown in Fig. 8; these are examples of m×(1:1) shared protection, with $m = 3$ and $m = 4$, respectively. In both cases we calculated the unavailability of the protected connection $k1$. Also in these cases testing has been carried out with $U = 0.1$ and $U = 01^{-4}$ ($A_{wi} = A_{\pi j} = 1 - U$, $L_{pi} = 3$). These results are shown in Table III and confirm the previous conclusions.

The values in Fig. 9 refer to the general m×(1:1) protection. The graph displays the unavailability of a generic connection ki given by (16). We consider that its spare path has length $L_{pi} = 5$ (straight line) and $L_{pi} = 7$ (dotted line). The number m_{ki} of connections sharing backup channels with $p1$ varies from 2 to 6. As already observed for 1:N (single

TABLE III

UNAVAILABILITY OF CONNECTION $k1$ IN FIGS. 8A AND 8B

Topology	U	U_{k1} exact	U_{k1} approx	% Error
Fig. 8.a	10^{-1}	1.50654×10^{-1}	1.66009×10^{-1}	10.2
Fig. 8.b	10^{-4}	4.9986×10^{-8}	4.999×10^{-8}	8×10^{-3}
Fig. 8.a	10^{-1}	1.77069×10^{-1}	1.94462×10^{-1}	9.8
Fig. 8.b	10^{-4}	5.9979×10^{-8}	5.9985×10^{-8}	10^{-2}

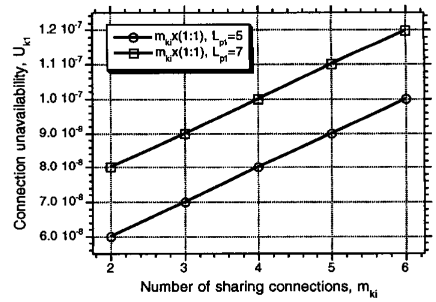

Fig. 9. Connection unavailability of m×(1:1) mesh shared-protection

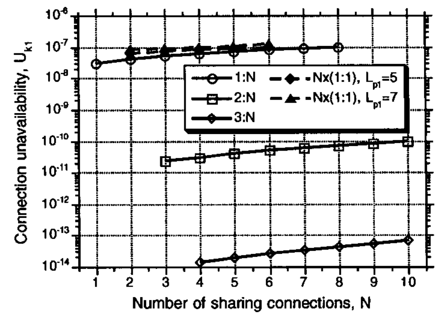

Fig. 10. Connection-unavailability comparison of various protection schemes

fault recovery), Fig. 9 shows a linear increase of connection unavailability, associated to the increase of m_{ki}. It can also be seen that, in terms of availability performance, increasing the length L_{p1} of the protection lightpath by x hops is exactly equivalent to increasing the number of sharing connections m_{ki} by x.

C. Final comparison

In the previous sections we have separately studied the different protection approaches. Now we can jointly compare the performances of the various approaches (Fig. 10).

As already explained, unavailability improves sensibly when the protection scheme is able recover multiple failures: this behavior is apparent in Fig. 10. Mesh shared-protection and 1:N, recovering single failures, give similar unavailability results. The availability advantages of survivability to multiple failures should be compared keeping the cost of the resource-consuming protection techniques into account. Further work will be dedicated to the investigation of the capacity versus availability trade-off.

V. MONTE CARLO SIMULATIONS

We have developed a simple Monte-Carlo (MC) approach simulator to verify some aspects of our theoretical analysis. The equations we introduced in Sec. III are obtained by considering a constant failure rate $z(t) = \eta$. As previously said, our analysis is time independent and approximated by neglecting some sequences of events. For example, in 1:2 protection in case of failures affecting both the working lightpaths,

TABLE IV
NUMERICAL COMPARISON BETWEEN MONTE CARLO APPROACH AND ANALYTICAL METHOD

Topology	MC	Analysis	% error
Fig. 11.a, w_1	0.9813	0.9729	0.865
Fig. 11.b, w_1	0.99693	0.99477	0.217
Fig. 11.c, w_1	0.99899	0.999	0.0012
Fig. 11.d, w_1	0.97399	0.96715	0.707
Fig. 11.d, w_2	0.97351	0.96634	0.742

according to (2), both the connections are considered blocked, even though the protection path is available and thus one at least could be recovered (see Sec. III-B). By means of MC we attempt to solve this problem introducing a random failure sequence that allows us to better represent events and simulate the recovery of one of the failed connections.

The procedure to evaluate the connections unavailability by means of MC method is the following. A given network topology is decomposed in separated subnetworks each one representing a connection, with its working and spare paths (possibly more than one). Links that are shared by many backup lightpaths appear replicated in the subnetworks corresponding to all the sharing connections. The unavailability of each link is simulated exploiting the generation of random numbers uniformly distributed in the range $[0, 1]$. If the number returned by random generator is lower than A_i, we assign the value *one* to the link. Viceversa, if the number is above the threshold, the value assigned to the link is *zero*, indicating it is not available. At each simulation iteration the state of all the links is randomly and independently set as described above. Then the connections are scanned in a sequential order which varies randomly at each iteration. Each connection is available if the working path is available (all its links have state one). Else, all the associated spare paths are scanned (with a priority sequence dependent on the protection technique). The first "all-one" free path to the destination found is used for recovery. The links crossed by such a path are assigned to the connection. If no free "all-one" path is found, the connection fails. All the subsequent connections can use only unassigned "one" links for a possible backup. At the end of the simulation all the favorable events, i.e. connections which could be established successfully are counted. MC simulation is particularly useful when many connections compete for the shared protection resources. While the analytical method of Sec. III assumed all these cases as unfavorable, they are instead adequately measured and counted by the MC simulation.

Table IV compares analysis and MC simulation results concerning the PGs represented in Fig. 11. Availability is 0.9 for all the links and 50 million iterations are generated to gather MC statistics. The table proves a good convergence of analysis to simulation even for high values of link unavailability.

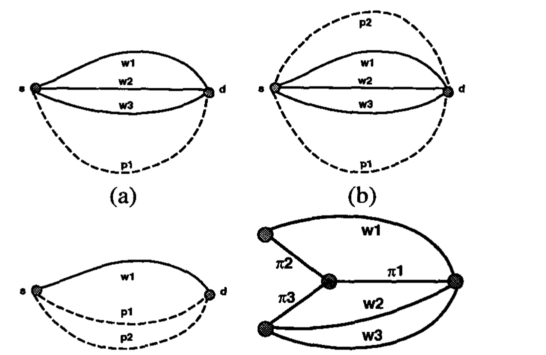

Fig. 11. Topologies used for the Monte Carlo simulations

VI. CONCLUSION

In this paper a rigorous methodology is proposed which can be used to quantify the connection availability under several protection schemes. Different protection strategies provide a different availability degree in a set of simple topologies. The proposed method is capable of estimating both connection and system availability of many protection techniques. In treating shared protection we have introduced an approximation that allows us to analyze complex topologies.

Our analysis led us to the following interesting findings: in M:N protection the number of shared protection paths is more important than the number of sharing connections; in mesh shared-protection the two most relevant parameters are the number of sharing connections and the protection-lightpath length (not the number of shared WDM channels); in general, the number of simultaneous failures a protection scheme can recover sets the order of magnitude to the availability of its protected connections.

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