Design of availability-guaranteed OTN

Massimo Tornatore, Guido Maier, Achille Pattavina

Abstract—A design technique for reliable optical transport networks is presented. The network is first dimensioned in order to carry a given set of static protected optical connections, each one routed maximizing its availability. The network can be further optimized by minimizing the number of fibers to be installed, while keeping a control on connection availability, which can remain the same or decrease by a prefixed margin factor. Design and optimization algorithms are provided for networks adopting dedicated and shared path-protection. The optimization approach is heuristic. Results obtained by applying the proposed technique to a case-study network are shown and discussed.

I. INTRODUCTION

Network availability and protection are among the most important issues concerning the transport of high-speed connections: interruption of an optical connection even for a short period (e.g. a second) could cause the loss of a huge quantity of data (e.g. 5 GByte for a 40 Gbit/s wavelength channel).

The guarantees of connection availability [1] is becoming a fundamental component of the service level agreement between an operator and its customers. Even if optical transmission systems and OTN switching nodes have reached high or at least acceptable technological quality, trying to satisfy customers’ requirements by relying only upon this aspect would be too expensive. Redundancy is the technique that is commonly exploited to meet availability requirements. In the context of OTN, redundancy is implemented by adopting optical protection techniques, which require redundant resources and thus an extra cost for the operator.

Many authors have proposed ad-hoc availability parameters to be employed to networking problems [1], [2], [3].

In this work we will consider planning of an OTN starting from a known set of static connection requests and from a green-field physical installation (with a fixed and given topology). Each connection has to be end-to-end protected, i.e. it is implemented by setting up a pair of lightpaths from the source to the destination node, one of which is used in working conditions and the other is for protection. Our approach consists in allocating resources (in terms of WDM channels) pursuing two optimization objectives: a) maximization of the availability level guaranteed to the users and b) minimization of the total number of fibers that must be installed to deploy the network.

Our design procedure, based on heuristic optimization, can be applied to two possible implementations of end-to-end OTN protection, which are: Dedicated Path Protection (DPP) and Shared Path Protection (SPP).

This paper has been organized as follows. In Sec. II some basic elements of availability theory are briefly reviewed. In Sec. III we illustrate the algorithms used by our optimization procedure, for dedicated and shared protection. In Sec. IV results on case study are shown and discussed.

II. AVAILABILITY ANALYSIS

Availability theory [4] gives the instruments to calculate the availability parameters of a complex system. In our case, the system is the optical connection, which comprises as functional blocks the WDM channels and the nodes on which it is routed. In this work we have however considered ideal OTN nodes (according to Ref. [2]), so that only WDM channels have to be taken into account as functional blocks.

A WDM channel is part of an OTN link, composed of the fiber cable installed between two adjacent nodes and equipped by a set of line devices (e.g. optical amplifiers). The details of the availability model adopted to evaluate a WDM channel availability are discussed in [5].

Availability corresponds to the probability that the system is able to perform its function at the time it is requested to do so. It can be shown [4] that for each functional block of the system the following relation holds: 

\[ A = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} \]

where MTTF and MTTR represent the Mean Time To Failure and the Mean Time To Repair of a WDM channel. The complement of A is the average unavailability \( U = 1 - A \).

Let us focus our attention on the evaluation of availability provided by DPP and SPP. Given that nodes have been assumed ideal, it is sufficient to enforce the link-disjoint routing condition for the working-protection (w/p) path pair.

This work was partially supported by MIUR, Italy, under FIRB Project ADONIS and by EU IST Network of Excellence e-Photon/One.

![Fig. 1. Availability scheme of a path-protected optical connection](image)

working lightpath is given by the following equation: 

\[ A_w = \prod_{i=1}^{n} A_i \]

where \( A_i \) indicates the \( i \)-th of the \( n \) WDM channels composing the working lightpath. For realistic systems, \( A_i \approx 1 \). The following useful approximate equation will then be employed to evaluate lightpath unavailability [3]: 

\[ U_w = 1 - A_w = 1 - \prod_{i=1}^{n} (1 - U_i) \approx \sum_{i=1}^{n} U_i \]

Similar equations apply to the protection lightpath in order to evaluate \( A_p \) (or \( U_p \)).

Availability of the DPP connection \( c \) is obtained by considering the parallel of working and protection lightpaths [2] according to the following simple equation: 

\[ U_c = U_w \cdot U_p \]
Analysis of connection availability gets more complicated in case of SPP. In order to assess availability of the connection with sufficient accuracy, combinations of multiple failure events should be taken into account: the list of such combinations becomes rapidly lengthy as the number of shared WDM channels and the number of sharing connections increase. We have however exploited in this work a simplified approach which has been presented in [5].

III. DESIGN AND OPTIMIZATION PROCEDURE

Let us now describe our availability-design method. As we have stated in Sec. I, network optimization is carried out in two phases according to two different cost functions: connection availability and fiber number. The first phase is called Maximum-Connection-Availability Design (MCAD). It solves the problem of allocating resources to each of the demanded connections in an unconstrained-capacity network. The second phase is named Availability-Constrained Physical-Resources Optimization (ACPRO).

A. MCAD - dedicated path protection

MCAD is solved with a heuristic technique by allocating resources for all the connection requests in sequence, starting from an empty network with oversized number of fibers on all the links, so that the amount of physical resources is never a constraint.

Allocating resources to a protected connection is equivalent to solving Routing and Fiber and Wavelength Assignment (RFWA) for its working and protection lightpath (under the link disjoint constraint). To solve this problem we have exploited a tool previously developed for WDM network design, the details of which have been published in [6], and will be omitted here for brevity. Availability-oriented design capability has been introduced as a new feature of the tool, by assigning each arc link a weight equal to the unavailability value of the corresponding WDM channel. In [5] it is reported how these values are obtained. Some changes have however to be made upon the algorithms, that are different for DPP and SPP.

We know that the unavailability of a DPP connection is $U_c = U_w \cdot U_p$. The most available assignment is the w/p pair that minimizes $U_c$. Such w/p pair could be found by non-linear programming, with a high computational complexity. We propose instead the following heuristic method. Two known algorithms can be applied to find a w/p on a weighted graph: the “One-step” (or Bhandari [7]), finds the link-disjoint pair of paths having the minimum total weight ($\min\{U_w + U_p\}$); the “Two-step” (or repeated Dijkstra), assigns as working the least-unavailability path ($\min\{U_w\}$) and as protection the second link-disjoint least-unavailability path ($\min\{U_p[U_p \cap U_w = \emptyset]\}$). Our method applies both the algorithms for each connection and keeps the solution found which gives the lowest unavailability. None of the two algorithms actually minimizes $U_c$, but the sub-optimal solutions they find are expected to be very close to the absolute optimum. It can be proved that when the two solutions are identical, they also coincide with the actual optimum [5].

Once all the connection requests have been satisfied, empty fibers are removed from the network.

B. MCAD - shared path protection

The heuristic method described for DPP cannot be applied in the case of SPP because the “One-step” (Bhandary) algorithm does not work in the shared scenario. We have therefore developed another heuristic algorithm which is divided in the following steps:

1) Start with the network idle and oversized
2) Take the first not-yet satisfied connection request $c$ of the sorted list of connection requests
3) Find RFWA of the working lightpath $w_c$ applying Dijkstra, using WDM-channel unavailability as weights
4) Build the list $Y(c)$ of already-allocated connections whose working path shares at least a link with $w_c$
5) Disable links crossed by $w_c$
6) Find RFWA of the protection lightpath $p_c$ applying Dijkstra on the remaining MLG, using WDM-channel unavailability as weights. An arc of the MLG can be allocated to $p_c$ only if it is not already allocated to a protection lightpath of a connection belonging to $Y(c)$
7) Set to a negligible cost $\epsilon$ all the weights of the arcs belonging to $p_c$. This operation induces future protection lightpaths to share WDM channels with $p_c$
8) Remove empty fibers and end if all the connection requests have been satisfied; else go to step 2.

C. ACPRO - dedicated and shared path protection

After the MCAD phase, ACPRO allows to decrease the number of installed fibers while keeping connection availability under control. ACPRO is transparent to the protection adopted and thus works the same with DPP and SPP.

A margin $M$ is fixed as an input to ACPRO: the optimization procedures guarantees that the final unavailability of each connection is less than $M$ times the unavailability reached for that connection after MCAD. ACPRO starts from the network with all the connections allocated as resulting from MCAD.

The optimization procedure is displayed in the flow-chart of Fig. 2. The following symbols are used in the chart:

- $K$ is a counter running from 0 to $W - 1$, where $W$ is the number of wavelengths per fiber
- a $K$-fiber is a fiber having $K$ used WDM channels
- $f$ is the index denoting the currently processed fiber
- $X(f)$ is the set of connections crossing fiber $f$
- $\Omega[X(f)]$ denotes a particular RFWA solution for the w/p pairs of all the connections of $X(f)$
- $U[\Omega[X(f)]]$ is the set of unavailability values of all the connections of $X(f)$ routed according to $\Omega[X(f)]$.

IV. CASE STUDY ANALYSIS

The design procedures explained in the previous sections have been applied to a realistic case-study network connecting the major cities of Italy (Fig. 3), conventionally named ITNet. It comprises 32 nodes and 72 links, 10 of which are submarine systems (dashed segments in Fig. 3). The set of
connection requests comprises 250 unidirectional asymmetric optical connection requests. Two sets of design and optimization experiments have been carried out, for DPP and SPP, respectively. In each of the two sets, the following set of values has been run three times (separately), adopting the following explanation:

- **average connection unavailability** \( U \)
- **total number of fibers** \( F \)
- **total number of used WDM channels** \( C \)

For each protection case, the network has been initially dimensioned by performing the MCAD. Then the ACPRO has been run three times (separately), adopting the following values for the margin \( M \): \( M = 1 \) (unchanged unavailability compared to MCAD), \( M = 10 \) and \( M = 100 \).

Fig. 4a refers to DPP. It displays the average connection unavailability \( U \) plotted as a function of \( W \). Resource utilization, the other objective function of the design process, is dealt by Figs. 4b and 4c, which plot the two output parameters \( C \) and \( F \) as functions of \( W \).

In the three graphs, results of MCAD have not been represented, since in the DPP case they are coincident with those of ACPRO with \( M = 1 \). By comparison, we have reported on the graph also the results of optimization performed without considering any constraint on availability and adopting a new routing criterion, instead of an availability metric: the objective is to minimize the number of fibers recurring to shortest-path-based algorithm [6], and we refer to this strategy as SP.

It should be noted that the minimum average unavailability obtained by MCAD is fully independent of \( W \) (Fig. 4a). This is a consequence of a capacity-unbounded problem and of the fact that availability weights, in our model, are completely independent on the number of wavelengths per fiber.

When the margin \( M \) is relaxed to 10 and 100, ACPRO is able to reduce the number of deployed fibers, as it appears in Fig. 4b, where the results for SP and for ACPRO with \( M \) equal to 10 and 100 are almost overlapped. The number of occupied channels \( C \) is shown in Fig. 4c and it increases when the constraint on availability is relaxed. The reason of this increasing trend is that the ACPRO algorithm essentially reroutes connections on longer lightpaths in order to free and remove fibers. This is allowed by the relaxation of the bound on the unavailability for all the connections. There is, however, just a small increase of the average unavailability value (less than a factor 2, far less than the margin), indicating that only few connections undergo rerouting. Rerouting on longer cycles, besides being effective in freeing some partially-used fibers, has also the opposite consequence of increasing the total number of consumed channels: resource optimization results from a trade-off between these two trends (Fig. 4c).

As far as the total channel number is concerned, it is apparent that ACPRO with margins 10 and 100 converges almost perfectly to the SP solution.

Let us now switch to SPP. Results obtained are displayed in Figs. 5. The curves are quite different from the dedicated case. Resource-sharing implies a general unavailability increase of about one order of magnitude. On the other hand, the number of occupied channels \( C \) decreases of about 300 (roughly from 20 to 30%), while the number of installed fibers decreases by 20% for \( W = 2 \) and by a small percentage for \( W = 32 \).

The MCAD curve \( U \) is no longer flat, but it has a minimum around \( W = 16 \). Availability decreases compared to DPP due to sharing. As the MCAD SPP curve Fig.5c confirms, for the value \( W = 16 \) at which unavailability is minimum, channel occupation has a maximum, indicating a low sharing degree.

The ACPRO curve with \( M = 1 \) does not coincide with MCAD any more. Surprisingly at a first sight, ACPRO with \( M = 1 \) reaches lower unavailability values than MCAD. The explanation is that in the attempt of minimizing resources, ACPRO, by rerouting, forces many connections to return from sharing to dedicated path protection. This is proved also by the fact that ACPRO with \( M = 1 \) occupies more channels than MCAD and is successful in reducing the number of fibers (Fig. 5b).

The difference in terms of unavailability between the results of ACPRO with \( M = 10 \) and \( M = 100 \) is more relevant than in the dedicated case. The increments compared to MCAD and ACPRO with \( M = 1 \) indicate an increased use of sharing. Unavailability of some connections rapidly increases as their
sharing groups get populated. The chance of sharing are increased by the relaxation of the availability constraint that allows to route connections along longer cycles. The average unavailability remains however well below the threshold set by the margin even in this SPP case. In fact the values of $F$ and $C$ obtained by ACPRO with margins 10 and 100 are again very close to the corresponding values of the shortest-path optimization. This indicates that even with SPP, relaxing availability constraints beyond a certain level does not help in further reducing physical resources.

V. CONCLUSIONS

In this paper we have presented a heuristic method to design and optimize an optical transport network according to a given set of static protected connections, so that two objectives are pursued: obtaining high availability of the connections and minimizing the network deployment cost. Case-study analysis has been carried out by solving some examples of optimization, starting from realistic availability data, network topologies and traffic.

Good network resource minimization can result from a our heuristic optimization phase, without severely compromising connection availability. By exploiting this procedure the network can be designed with a total amount of fibers not far from the theoretical lower bound for the given traffic. Sharing of preplanned protection resources proved to be a good technique to reduce the network cost while achieving an acceptable reliability performance.

REFERENCES