Design of Fault-Tolerant Logical Topologies in Wavelength-Routed Optical IP Networks

A. Nucci[1], B. Sansò[2], T.G. Crainic[3], E. Leonardi[1], M. Ajmone Marsan[1]
[1] – Dipartimento di Elettronica - Politecnico di Torino
[2] – Departement of Electrical and Software Engineering - École Polytechnique de Montréal
[3] – Centre de Recherche sur les Transports (CRT) - École Polytechnique de Montréal
email: nucci@mail.tlc.polito.it, bruni@crt.umontreal.ca,
theo@crt.umontreal.ca,leonardi@mail.tlc.polito.it,ajmone@mail.tlc.polito.it

Abstract—

In this paper we illustrate a new methodology for the design of fault-tolerant logical topologies in wavelength-routed optical networks exploiting wavelength division multiplexing, and supporting both unicast and multicast IP datagram flows.

Our approach to protection and restoration generalizes the "design protection" concepts, and relies on the dynamic capabilities of IP routing to re-route IP datagrams when faults occur, thus leading to high-performance cost-effective fault-tolerant logical topologies.

Our approach to protection and restoration for the first time considers the resilience properties of the topology during the logical topology optimization process, thus extending the optimization of the network resilience performance also on the space of the logical topologies.

Numerical results clearly show that our approach outperforms the previous ones, and is able to obtain very good logical topologies with limited complexity.

Keywords— **WDM Networks; Logical Topology Design; Survivability; Fault-Tolerance; Multicast**

I. Introduction

For the short-term implementation of a high-capacity IP infrastructure, network designers are considering the use of optical networks exploiting Wavelength Division Multiplexing (WDM) and Wavelength Routing (WR). Indeed, such networks permit the exploitation of the huge fiber capacity, with no need for complex processing functionalities in the optical domain.

In WR IP networks, nodes comprise an optical section, and an electronic section; the former is an optical cross-connect (OXC), while the latter is a high-capacity IP router. Nodes are connected by optical fibers over which a WDM scheme is implemented. At each node, incoming WDM channels can either be transparently connected to outgoing channels through the OXC, possibly after wavelength convertion (but with no processing of in-transit information), or converted to the electronic domain, so that packets can be passed to the IP router, processed, and possibly retransmitted after IP routing.

This setup allows the definion within the optical domain of semi-permanent optical pipes called "lightpaths" that may extend over several physical links. Thus, lightpaths can be seen as chains of physical channels through which packets are moved from a router to another toward their destinations. OXCs transparently connect the incoming WDM cannels corresponding to in-transit lightpaths, and convert to the electronic domain the incoming WDM channels corresponding to terminating lightpaths.

The set of lightpaths and routers defines a logical topology, overlayed to the physical topology made of optical fibers and OXCs.

In order to best exploit the capacity of a WDM infrastructure, a crucial task thus is the identification of the best feasible logical topology for the transport of a given traffic pattern.

In recent years, the Logical Topology Design (LTD) problem in WDM networks was extensively studied, considering a number of different setups. It was shown that the identification of the optimal logical topology is computationally intractable for large size networks [1], [2], and several heuristic approaches were proposed for the identification of suboptimal solutions in several different conditions [3], [4], [5].

The search for good solutions of the LTD problem can consider different objectives; in this paper we concentrate on an important characteristics of the logical topology that is produced by the LTD algorithm: its resistance to physical faults. Note that, since several lightpaths may traverse the same fiber on different wavelengths, the fault of a single physical link may cause the disruption of a number of lightpaths.

Many physical level protection and/or restoration schemes were proposed for WR networks (see [6], [7] for a survey). Such schemes always rely on the presence of spare resources in the network, that are used to restore disrupted lightpaths. In general, two disjoint physical paths p_1 and p_2 are associated with each existing lightpath l. In normal conditions, only path p_1 is used to support lightpath l; however, enough capacity is reserved on p_2 to be able to re-route lightpath l when one of the physical links belonging to p_1 fails. Protection and/or restoration schemes normally guarantee the resilience to the failure of a single physical link; thus, the capacity to be reserved in the network must be sufficient to successfully re-route all the lightpaths disrupted by a link failure.

The main advantage of physical protection and/or restoration schemes, is that they entail no complex management procedure, and thus guarantee fast restorations to link failures. Their main drawback is that a large amount of network resources, in terms of both processing and bandwidth is devoted to restoration. As a consequence, physical protection and/or restoration schemes, in many situations, are not cost-effective.

In [8], [9], [10], a different fault-tolerance methodology called *design protection* was presented. In this case, restoration is obtained by exploiting the dynamic capabilities of IP routing. When a physical link fails in the optical network, the IP routing algorithm is able to update its tables, and restore disrupted paths, if the set of non-disrupted lightpaths still forms a connected topology. In order to achieve a good degree of fault resilience, it is fundamental *to map* (i.e., to route) the lightpaths onto the physical topology in such a way that, given any single physical link failure, the set of non-disrupted lightpaths still forms a connected network. Thus, an optimization of the physical mapping of lightpaths is necessary [9], [10].

In this paper we generalize the *design protection* approach, providing a powerful framework for the design of logical topologies with a good degree of fault resilience. Our approach differs from the approach proposed in [8], [9], [10], since it considers the resilience properties of the topology directly during the LTD optimization process, thus extending the optimization of the network resilience properties also to the space of the logical topologies. In addition, we further extend the *design protection* approach, also considering multicast traffic.

Note that, according to the *design protection* approach, restoration requires the execution of signalling and management procedures, and thus entails significant restoration times; however, *design protection* is much more cost-effective with respect to physical protection schemes. Thus, *design protection* should not be considered as an alternative to physical protection, but as a complementary technique that may be successfully employed in order to reduce the level of physical protection required to achieve a desired level of fault-tolerance.

II. Problem Statement

The Survivable Logical Topology Design Problem (SLTDP) under a given unicast and multicast traffic pattern can be stated as follows:

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i) an existing physical topology (which must be at least biconnected), comprising nodes equipped with a limited integer number of tunable transmitters and receivers, connected by optical fibers that support a limited number of wavelengths;

ii) a description of the average traffic exchanged by sources and sets of destinations;

iii) a multi-hop routing strategy, defined both for unicast and multicast flows;

iiii) a failure scenario;

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a logical topology and a "mapping" that optimize (i.e. maximize or minimize) an objective function.

The objective function must be carefully selected, in order to obtain the best trade-off between network performance in normal condititions and resilience properties. Since the network performance depends on the network failure state, the objective functions must combine the network performance levels under different network failure states. Therefore, it is necessary to introduce the concept of "failure state probability", which represents the probability for the network to be in a given failure state, as will be better explained in the next sub-sections, where we report a formulation of the SLTDP.

Finally, for what concerns the multi-hop routing strategy adopted on the logical topology, we selected shortest path routing for unicast traffic, and the SCTF algorithm proposed in [11] for multicast traffic.

A. Problem Formulation:

A.1 Notation

We adopt the notational typology for multi-layered networks presented in [12]. The supra-index indicates the layer, starting by the lowest layer, zero, that represents the physical network. Let $G^0 = (V, E^0)$ be the unidirectional graph representing the physical topology. It is composed by OXC nodes V interconnected by optical fibers E^0. Let $|V| = N$ be the cardinality of set V and $|E^0| = M$ that of the set E^0. Let R_i and T_i be the number of receivers and transmitters at physical node $i \in V$, W_v be the maximum number of wavelengths allowed within optical fiber $v \in E^0$. Let S_v be the network state, where S_0 represents the no-failure state, while S_v for $v \geq 1$ is the state in which the optical fiber $v \in E^0$ is broken. Let $G^1_l(S_0) = (V, E^1_l(S_0))$ be the directed graph representing the l^{th} logical topology in the no failure state. It is composed by IP routers V interconnected by lightpaths $E^1_l(S_0)$. Let $\mathcal{G}$ be the set of all possible logical topologies in the no failure state, while $\mathcal{E} = \bigcup_l E^1_l(S_0)$ be the set of all possibles lightpaths that can take place in any logical topology. Let $G^1_l(S_v) = (V, E^1_l(S_v))$ denote the l^{th} logical topology in the network state S_v, obtained from $G^1_l(S_0)$ by dropping all the lightpaths $u \in E^1_l(S_0)$ crossing over the optical fiber $v \in E^0$. Let $\Lambda = (\lambda^{oD})$ indicate the average traffic matrix where each entry λ^{oD} represents the average traffic flow between the source node o and the destination set D. Note that the unicast traffic is a particular case of the multicast traffic in which $|D| = 1$. Let $\tau^{oD}_l(S_v)$ be the routing tree for the traffic relation between o and D over the l^{th} logical topology in the network state S_v, determined by the global routing algorithm for unicast or multicast. The routing tree $\tau^{oD}_l(S_v)$ is composed of a subset of lightpaths of set $E^1_l(S_v)$. If $\tau^{oD}_l(S_v) = \emptyset$ no routing for the connection between o and D is possible for the l^{th} logical topology in the state S_v. Let $f^{oD}_{ul}(S_v) \in \{0, 1\}$ be an auxiliary variable that is equal to 1 if $u \in \tau^{oD}_l(S_v)$ and 0 otherwise. Finally we use the variable $t^{oD}_l(S_v) \in \{0, 1\}$ to determine whether the connection oD is lost in network state S_v for the l^{th} logical topology; in fact $t^{oD}_l(S_v)$ is equal to 1 if $\tau^{oD}_l(S_v) = \emptyset$ and 0 otherwise.

A.2 Decision Variables

Two types of binary variables are introduced into the formulation: X^l_u and Y^l_{uv} that correspond, respectively to logical topology and mapping variables. Logical topology variables $X^l_u \in \{0, 1\}$ describe the lightpaths used in the l^{th} logical topology $G^1_l(S_0)$:

$$X^l_u = \begin{cases} 1, & \text{if auxiliary lightpath } u \in \mathcal{E} \text{ is} \\ & \quad \text{used in logical topology } G^1_l(S_0) \\ 0, & \text{otherwise} \end{cases}$$

Then we can state that the used logical topology $G^1_l(S_0) = (V, E^1_l(S_0))$ has $E^1_l(S_0) = \{u : X^l_u = 1, \quad u \in \mathcal{E}\}$.

Mapping variables $Y^l_{uv} \in \{0, 1\}$ describe the routing for the lightpaths of the logical topology $G^1_l(S_0)$ over the physical topology G^0:

$$Y^l_{uv} = \begin{cases} 1, & \text{if lightpath } u \in E^1_l(S_0) \text{ crosses} \\ & \quad \text{over the optical fiber } v \in E^0 \\ 0, & \text{otherwise} \end{cases}$$

A.3 Mathematical model

Let $\Gamma^+(i)$ be the set of lightpaths outgoing from node $i \in V$ and $\Gamma^-(i)$ be the set of lightpaths ingoing to node $i \in V$. We can then write:

A.4 Constraints

- Connectivity:

$$\sum_{u \in \Gamma^+(i)} X^l_u \leq T_i \qquad \forall i \in V, l \in \mathcal{G} \tag{1}$$

$$\sum_{u \in \Gamma^-(j)} X^l_u \leq R_j \qquad \forall j \in V, l \in \mathcal{G} \tag{2}$$

- Mapping:

$$Y^l_{uv} \leq X^l_u \qquad \forall u \in E^1_l(S_0), v \in E^0, l \in \mathcal{G} \tag{3}$$

where:

(1) indicates that the number of lightpaths outgoing from each node of the network has to be smaller than the number of transmitters in the node, for each logical topology in the no failure state ($G^1_l(S_0)$);

(2) indicates that the number of lightpaths ingoing to each node of the network has to be smaller than the number of receivers in the node, for each logical topology in the no failure state ($G^1_l(S_0)$);

(3) ensures that a lightpath can be mapped only if it exists in the considered logical topology.

To extend the formulation to the case in which a limited number of wavelengths is available, it is necessary to introduce an additional constraint. Let W_v be the number of wavelengths supported on each fiber. The set of lightpaths $v \in E^1_l(S_0)$ must satisfy the following constraint:

- Mapping

$$\sum_{u \in E^1_l(S_0)} Y^l_{uv} \leq W_v \qquad \forall v \in E^0, l \in \mathcal{G} \tag{4}$$

where:

(4) indicates that the number of lightpaths that cross over each optical fiber has to be smaller than the maximum wavelength capability. The

set of lightpaths that does not satisfy (4) is the set of lightpaths that have not successfully mapped on the physical topology. Note that, in this case, $G_l^1(S_0)$ comprises only the lightpaths that has been successfully mapped on the physical topology.

A.5 Objective functions

As objective functions we selected four possible expressions:

$$TL^l_{Max} = \max_k \sum_{o,D} t_l^{oD}(S_k)\lambda^{oD} \tag{5}$$

$$C^l_{Max} = \max_k \max_{u\in E_l^1(S_k)} \sum_{o,D} f_{ul}^{oD}(S_k)\lambda^{oD} \tag{6}$$

$$TL^l_{Mean} = \sum_{k=1}^{M} P_r(S_k)\sum_{o,D} t_l^{oD}(S_k)\lambda^{oD} + P_r(S_0)\sum_{o,D} t_l^{oD}(S_0)\lambda^{oD} \tag{7}$$

$$C^l_{Mean} = \sum_{k=1}^{M} P_r(S_k)\max_{u\in E_l^1(S_k)}\sum_{o,D} f_{ul}^{oD}(S_k)\lambda^{oD} + P_r(S_0)\max_{u\in E_l^1(S_0)}\sum_{o,D} f_{ul}^{oD}(S_0)\lambda^{oD} \tag{8}$$

where:

- $P_r(S_k)$: represents the "state probability", i.e., the probability that the system is in the state S_k;
- (5) and (6): represent respectively the maximum amount of traffic that cannot be routed (lost traffic) and the maximum congestion level over all the network states S_k for the l^{th} logical topology. Note that traffic λ^{oD} is considered lost only when the set of working lightpaths does not provide a path from o to all the destinations in D, (i.e., we do not consider losses due to lightpaths congestion).
- (7) and (8): represent respectively the mean lost traffic and the mean congestion level over all the network failure states S_k for the l^{th} logical topology.

Note that, in general, the evaluation of each objective function would require the computation of some network performance index under all the 2^M possible failure states; however, since we are mainly interested in single failure resilience properties, we restrict the evaluation of the above objective functions to the states S_k associated with the normal operational conditions and with single link failure states.

Note that, if the inequalities (3) and (4) are relaxed, and $P_r(S_0) = 1$, i.e., if we assume that there will never be a failure, the SLTD problem reduces to the traditional LTD problem.

Unfortunately, the SLTDP is NP-hard, since it is a generalization of the traditional LTD problem that was proved NP-hard, thus in the next section we present a heuristic methodology for the solution of the SLTDP, based on the application of Tabu-Search.

III. Mapping Between Physical and Logical Topology: HDAP

The definition of algorithms that optimally map the lightpaths on the physical topology is an important sub-problem of the SLTDP. This problem is related to inequalities (3) and (4) in Section II. The mapping problem is solved by an algorithm that, given a logical topology, finds a routing for each lightpath of the logical topology onto the physical topology, such that a single optical link failure leaves the virtual network connected.

In [8] this problem was found NP-complete, and Tabu search was proposed to find a sub-optimal solution. However, since the mapping problem is only a part of SLTDP, the utilization of Tabu search to solve the mapping problem could have a disruptive impact on the CPU time necessary for the solution of SLTDP.

Thus, for the solution of the mapping problem in this section we present a simple greedy algorithm, the Heuristic Disjoint Alternate Path (HDAP), whose computational complexity is small. A brief description of the HDAP algorithm follows.

$HDAP$ algorithm

Let $OR(i)$ and $IR(i)$ be the sets of already routed lightpaths, respectively outgoing and ingoing from and to node i, and let $ON(i)$ and $IN(i)$ be the sets of outgoing and ingoing lightpaths not yet routed. Let V_{ij} be the lightpath belonging to the logical topology, with endpoints i and j. Let $\mathcal{O}$ denote a set of nodes. Initialize $\mathcal{O}$ to the set of all nodes in the network:

Step 0: route all lightpaths V_{ij} whose endpoints are adjacent in the logical topology. Insert V_{ij} in $(OR(i), IR(j))$ and extract V_{ij} from $(ON(i), IN(j))$;
Step 1: if $\mathcal{O} = \emptyset$ STOP, otherwise select $i \in \mathcal{O}$ and extract i from $\mathcal{O}$;
Step 2: if $ON(i) = \emptyset$ GOTO Step3, otherwise select each $V_{ik} \in ON(i)$ and try to find a route for V_{ik} which is physically disjoint from the routes on which the $V_{ij} \in OR(i)$ and the $V_{jk} \in IR(k)$ have already been routed. If a physically disjoint route for V_{ik} has not been found, V_{ik} is routed on the shortest path. If also the shortest path is not available, due to the lack of free wavelengths, lightpath V_{ij} is not mapped.
Step 3: if $IN(i) = \emptyset$ GOTO Step1, select each $V_{ki} \in IN(i)$ and try to find a route for V_{ki} which is physically disjoint from the routes on which the $V_{ji} \in IR(i)$ and the $V_{kj} \in OR(k)$ have already been routed. If a physically disjoint route for V_{ki} has not been found, V_{ki} is routed on the shortest path. If also the shortest path is not available, due to the lack of free wavelengths, lightpath V_{ji} is not mapped.

IV. Tabu Search for the SLTDP: TabuSLTDP

A. General description of Tabu Search metaheuristic

The heuristic we propose to use in the solution of SLTDP relies on the application of the Tabu Search (TS) methodology. The TS algorithm can be seen as an evolution of the classical local optimum solution search algorithm called Steepest Descent (SD); however, thanks to the TS mechanism that allows worsening solutions to be also accepted, contrary to SD, TS is not subject to local minima entrapments. TS is based on a partial exploration of the space of admissible solutions, finalized to the discovery of a good solution. The exploration starts from an initial solution that is generally obtained with a greedy algorithm, and when a stop criterion is satisfied, the algorithm returns the best visited solution. For each admissible solution, a class of neighbor solutions is defined. A neighbor solution is defined as a solution that can be obtained from the current solution by applying an appropriate transformation, and is also called a *move*. The set of all the admissible moves uniquely defines the *neighborhood* of each solution.

At each iteration of the TS algorithm, all solutions in the neighborhood of the current one are evaluated, and the best is selected as the new current solution. Note that, in order to efficiently explore the solution space, the definition of neighborhood may change during the solution space exploration; in this way it is possible to achieve an *intensification* or a *diversification* of the search in different solution regions.

A special rule, the *Tabu list*, is introduced in order to prevent the algorithm to deterministically cycle among already visited solutions. The Tabu list stores the last accepted moves; until a move is stored in the Tabu list, it cannot be used to generate a new move. The choice of the Tabu list size is very important in the optimization procedure: too small a size could cause the cyclic repetition of the same solutions, while too large a size can severely limit the number of applicable moves, thus preventing a good exploration of the solution space.

B. Fundamental aspects of TabuSLTDP

Four fundamental aspects that must be defined in TS concern:
- the choice of an initial solution
- the definition of the topology perturbation that generates the neighborhood
- the evaluation of the visited solutions
- the stop criterion

As initial solution we select the result of the $R\&R$ heuristic, proposed in [13]. This heuristic initially considers a fully-connected logical topology, and iteratively removes the least-loaded lightpaths from the logical topology, until the degree constraints are satisfied.

The perturbation is defined according to the following algorithm:
- within the current solution, $2L^r$ nodes, $n_1, n_2, \ldots n_{2L^r}$, are selected, such that lightpaths $n_{2i-1} \rightarrow n_{2i},\ i = 1, 2, ..., L^r$ exist;
- in the perturbed solution, lightpaths $n_{2i-1} \rightarrow n_{2i}$ are replaced with lightpaths $n_{2i+1} \rightarrow n_{2i},\ i = 1, 2, \ldots, L^r - 1$, and $n_1 \rightarrow n_{L^r}$.

This is equivalent to identifying a cycle of $2L^r$ lightpaths, L^r of which are present in the topology, while the other L^r are missing; in the identified cycle, a present lightpath if followed by a missing one, as shown in Figure 1. To obtain the neighbor topology, we have to follow the lightpaths in the reverse direction, and remove the existing lightpaths while adding the new ones. If $L^r = 2$, the resulting perturbation is equivalent to a well known "branch exchange" operation.

This perturbation guarantees that degree constraints are not violated, thus generating a valid move. Note that with this perturbation it is very easy and fast to implement a *diversification* and/or *intensification* criterion; we can carefully explore a region of the solution space with small cycles, and move to another region of the solution space with large cycles.

The evaluation of solutions is performed by routing the traffic on the topology for all the single link failure states S_k, and computing TL^l_{Max} or TL^l_{Mean}. Ties are broken considering the values of C^l_{Max} or C^l_{Mean}, respectively. When the optimization is performed using (TL^l_{Max},C^l_{Max}) as performance indices, we say that the objective function F_{Max} is applied; instead, when the optimization is performed using (TL^l_{Mean},C^l_{Mean}) as performance indices, we say that F_{Mean} is applied.

Finally, the Tabu Search process is stopped after a fixed number of iterations.

V. Complexity

We now discuss the complexity of the proposed heuristics. Let F be the number of multicast flows that must be transported in the network. Let $\Delta = T_i = R_i \quad \forall i \in V$ denote the same in/out degree for each node in the logical topology. For each logical topology analyzed, we route i) its lightpaths over the physical topology with the HDAP algorithm, and ii) the unicast and multicast traffic over the logical topology.

The HDAP algorithm has complexity $O(N\Delta(M + \Delta N log(\Delta N)))$, since at most $O(N\Delta)$ iterations are executed, while at each iteration at most $O(M + \Delta N log(\Delta N))$ operations are required; $O(M)$ operations, indeed, are necessary to update the cost of the links of the physical topology and $O(N log(\Delta N))$ operations are necessary to run the Dijkstra algorithm. Since $M \leq N^2$, the HDAP complexity is upper bounded by $O(N^3\Delta)$.

To evaluate solutions, it is necessary to route the unicast and multicast traffic. The unicast routing algorithm requires $O(N^2 log(N\Delta))$ operations (Dijkstra algorithm). For the multicast traffic routing, once shortest paths are known, the computation of each Steiner Tree according to algorithm $SCTF$ requires $O(N^2k)$ operations, where k is an internal parameter of the $SCTF$ algorithm that we set to 5. In conclusion, the computation of the unicast and multicast routing requires $O(N^2(log(N\Delta) + Fk))$ operations.

The $R\&R$ heuristic to evaluate the initial solution has complexity $O(N^3(log(\Delta N) + Fk) + N^4)$, since at most $O(N)$ iterations are needed to complete the algorithm, and at each iteration it is necessary to route traffic and execute a MWM (Maximum Weight Matching) algorithm.

Let us now focus on the complexity of the TS algorithm. At each iteration, the evaluation of all solutions in the neighborhood is necessary; this requires $O(\Delta^2N^2(N^3\Delta + N^2(log(N\Delta) + Fk) + MN^2(log(N\Delta) + Fk)))$ operations, since $O(\Delta^2N^2)$ neighbors are evaluated (assuming to generate perturbations using cycles of length 4), and the evaluation of each solution requires the execution of the HDAP algorithm and the execution of the routing algorithms for each failure state (i.e., $M + 1$ times). If the number of iterations is I, the resulting complexity is $O(I\Delta^2N^2(N^3\Delta + N^2(log(N\Delta) + Fk) + MN^2(log(N\Delta) + Fk)))$. Thus, the computational complexity of TS is upper-bounded by $O(I\Delta^2N^6(log(\Delta N) + Fk))$.

VI. Numerical Results

In this section we present numerical results obtained with the proposed approach (called joint optimization), and compare them against those obtained by performing a conventional optimization of the logical topology, and then mapping the lightpaths on the physical topology with the HDAP algorithm (this approach is called disjoint optimization). All the reported results refer to the ARPANET physical topology plotted in Figure 2, where weights associated with arcs represent the lengths of links.

We consider traffic patterns comprising $F = 3$ multicast connections, for each of which, both the source and the destinations are randomly selected among all nodes in the network. The average number of destinations of each multicast connection is fixed to 7. Each (unicast or multicast) traffic flow requires a bandwidth whose value is randomly extracted from an exponential distribution with mean $\mu = 1$.

The Tabu parameters used in our experiments, after an initial calibration were set as follows:
- $TabuList$: a Tabu list of fixed size equal to 12 is used;
- $Cycles\ size$: during the exploration of the solution space, cycles of length 4 are used. In some cases, however, different perturbation rules are used to implement the $diversification\ criterion$. In particular, to ease the exit from local minima regions, after 10 iterations without improvement a cycle of size 6 is used;
- $Stop\ Criterion$: the procedure is stopped after a fixed number of iterations. The number of iterations is set to 60, since this value seems to provide a good trade-off between the conflicting requirements of limiting the CPU time and obtaining good results.

In Tables I, II and III we report results obtained with the disjoint and the joint optimization techniques, for different network configurations. All the reported values were obtained by averaging the performance indices of the optimization procedure outcomes over 10 traffic instances.

We considered two different disjoint optimization processes. In the first, the logical topology is obtained by applying the greedy heuristic (R&R), while in the second a TS metaheuristic is applied. Five important network performance indexes are reported for the obtained solutions: the congestion level in the no failure state ($C(S_0)$), the mean and peak values of the lost traffic (TL_{Mean} and TL_{Max}) and the mean and peak values of the congestion level (C_{Mean} and C_{Max}). All the values are expressed as percentage of the total offered traffic. We report results for different values of the nodal connectivity degree (Δ), and maximum number of wavelengths on a fiber ($\mathcal{W}$).

In Tables I, II and III, respectively, we report results for three different values of connectivity degree, when $\mathcal{W} = \infty$. Note that, since $\mathcal{W} = \infty$, all lightpaths are mapped over the physical topology. The failure probability of each physical link is proportional to the link length. Moreover, the failure probability of the longest physical link in the topology has been set to 0.01.

It can be observed that the joint optimization approach in these cases outperforms disjoint optimization specially for what concerns the max-

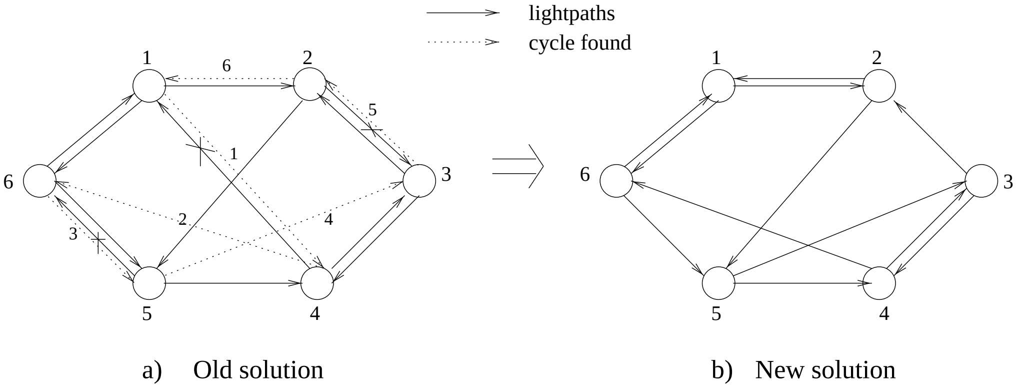

Fig. 1. Building of the new solution utilizing a cycle $C(1,6)$.

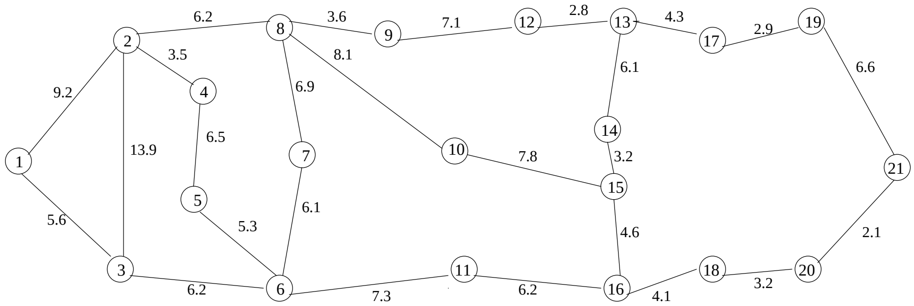

Fig. 2. Physical Topology ARPANET - 21 nodes 26 links

imum congestion level and maximum lost traffic in the network. In Table I we see that with disjoint optimization the maximum lost traffic is about the 10% of the offered traffic while with both F_{Mean} and F_{Max} this value is zero. Increasing the connectivity degree, this difference decreases, since the logical topology obtained with the dijoint optimization naturally exhibits an improved robustness to failures, being stronger connected. Note, finally, that the average performance for all systems is close to the performance in state S_0, since the probability of being in state S_0 approaches 1.

The difference between the two optimization procedures increases when only a small number of wavelengths is available on each fiber in the physical topology. When the number of wavelengths per fiber is small, some lightpaths may not be mapped over the physical topology, thus causing a further degradation of the network performance. As a consequence, a procedure that does not consider the effect of the mapping during the logical topology optimization leads to poor performance.

These effects can be easily observed in Tables IV, V and VI, where $\mathcal{W}$ is equal to the minimum number of wavelegths for which it exists a logical topology with the assigned degree that can be completely mapped onto the physical topology. The gain achieved with joint optimization is now very large, in terms of both lost traffic and maximum congestion level. Moreover, the gain now does not vanish when the connectivity degree increases.

VII. CONCLUSIONS

In this paper we proposed a new methodology for the design of fault-tolerant logical topologies in wavelength-routed WDM networks supporting unicast and multicast IP datagram flows.

Our approach to protection and restoration, generalizes the concepts first proposed in [8], [9], [10], and relies on the exploitation of the intrinsic dynamic capabilities of IP routing, thus leading to cost-effective fault-tolerant logical topologies.

Our approach differs from those proposed in [8], [9], [10], since it considers the resilience properties of the topology during the logical topology optimization process, thus extending the optimization of the network resilience performance also on the space of the logical topologies.

Numerical results clearly show that our approach largely outperforms the previous ones, and is able to obtain very good logical topologies with fault-tolerance properties at a limited cost.

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Parameters	Disjoint-Opt (LTDP+HDAP)		Joint-Opt (SLTDP)	
	$R\&R + HDAP$	$TS + HDAP$	F_{Mean}	F_{Max}
$C(S_0)$ [%]	6.14	3.79	4.09	4.84
TL_{Mean} [%]	0.12	0.18	0.00	0.00
TL_{Max} [%]	7.93	10.74	0.00	0.00
C_{Mean} [%]	6.66	4.34	4.56	4.98
C_{Max} [%]	19.83	20.14	14.21	10.43

TABLE I
COMPARISON BETWEEN THE TWO METRICS FOR SLTDP AND THE DISJOINT OPTIMIZATION OF LTDP AND MP WITH $\Delta = 2$, AND $\mathcal{W} = \infty$.

Parameters	Disjoint-Opt (LTDP+HDAP)		Joint-Opt (SLTDP)	
	$R\&R + HDAP$	$TS + HDAP$	F_{Mean}	F_{Max}
$C(S_0)$ [%]	3.02	1.97	2.12	2.23
TL_{Mean} [%]	0.04	0.03	0.00	0.00
TL_{Max} [%]	6.06	5.28	0.00	0.00
C_{Mean} [%]	3.18	2.15	2.21	3.13
C_{Max} [%]	8.42	5.90	5.98	4.53

TABLE II
COMPARISON BETWEEN THE TWO METRICS FOR SLTDP AND THE DISJOINT OPTIMIZATION OF LTDP AND MP WITH $\Delta = 3$, AND $\mathcal{W} = \infty$.

Parameters	Disjoint-Opt (LTDP+HDAP)		Joint-Opt (SLTDP)	
	$R\&R + HDAP$	$TS + HDAP$	F_{Mean}	F_{Max}
$C(S_0)$ [%]	2.21	1.46	1.61	1.73
TL_{Mean} [%]	0.09	0.02	0.00	0.00
TL_{Max} [%]	7.68	2.68	0.00	0.00
C_{Mean} [%]	2.29	1.61	2.07	2.82
C_{Max} [%]	4.94	6.64	4.92	3.25

TABLE III
COMPARISON BETWEEN THE TWO METRICS FOR SLTDP AND THE DISJOINT OPTIMIZATION OF LTDP AND MP WITH $\Delta = 4$, AND $\mathcal{W} = \infty$.

Parameters	Disjoint-Opt (LTDP+HDAP)		Joint-Opt (SLTDP)	
	$R\&R + HDAP$	$TS + HDAP$	F_{Mean}	F_{Max}
$C(S_0)$ [%]	6.37	4.53	4.88	5.31
TL_{Mean} [%]	25.94	22.73	0.00	0.00
TL_{Max} [%]	34.97	33.54	0.00	0.00
C_{Mean} [%]	7.31	5.64	5.26	5.67
C_{Max} [%]	11.61	10.21	8.43	6.33

TABLE IV
COMPARISON BETWEEN THE TWO METRICS FOR SLTDP AND THE DISJOINT OPTIMIZATION OF LTDP AND MP WITH $\Delta = 2$, AND $\mathcal{W} = 5$.

Parameters	Disjoint-Opt (LTDP+HDAP)		Joint-Opt (SLTDP)	
	$R\&R + HDAP$	$TS + HDAP$	F_{Mean}	F_{Max}
$C(S_0)$ [%]	6.38	4.18	3.79	4.05
TL_{Mean} [%]	19.94	19.67	0.00	0.00
TL_{Max} [%]	33.28	28.34	0.00	0.00
C_{Mean} [%]	5.73	4.61	4.01	4.59
C_{Max} [%]	9.62	8.43	7.31	5.52

TABLE V
COMPARISON BETWEEN THE TWO METRICS FOR SLTDP AND THE DISJOINT OPTIMIZATION OF LTDP AND MP WITH $\Delta = 3$, AND $\mathcal{W} = 6$.

Parameters	Disjoint-Opt (LTDP+HDAP)		Joint-Opt (SLTDP)	
	$R\&R + HDAP$	$TS + HDAP$	F_{Mean}	F_{Max}
$C(S_0)$ [%]	4.88	3.94	2.91	3.12
TL_{Mean} [%]	19.32	10.93	0.00	0.00
TL_{Max} [%]	32.03	25.48	0.00	0.00
C_{Mean} [%]	5.32	4.46	3.11	3.98
C_{Max} [%]	8.89	8.14	5.95	4.21

TABLE VI
COMPARISON BETWEEN THE TWO METRICS FOR SLTDP AND THE DISJOINT OPTIMIZATION OF LTDP AND MP WITH $\Delta = 4$, AND $\mathcal{W} = 7$.