Capacity Efficiency and Restorability of Path Protection and Rerouting in WDM Networks Subject to Dual Failures

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Abstract

Resilient optical networks are predominately designed to protect against single failures of fiber links. But in larger networks, operators also see dual failures. As the capacity was planned for single failures, disconnections can occur by dual failures even if enough topological connectivity is provided.

In our approach the design of the network minimizes the average loss caused by dual failures, while single failures are still fully survived. High dual failure restorability is the primary aim, capacity is optimized in a second step.

For WDM networks with full wavelength conversion, we formulate mixed integer linear programming models for dedicated path protection, shared (backup) path protection, and path rerouting with and without stub-release. For larger problem instances in path rerouting, we propose two heuristics.

Computational results indicate that the connectivity is of much more importance for high restorability values than the overall protection capacity. Shared protection has similar restorability levels as dedicated protection while the capacity is comparable to rerouting. Rerouting surpasses the protection mechanisms in restorability and comes close to 100% dual failure survivability. Compared to single failure planning, both shared path protection and rerouting need significantly more capacity in dual failure planning.

Keywords: Multiple Failures, Path Protection, Rerouting, Path Restoration, WDM Networks.

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1 Introduction

Optical networks are subject to many kinds of disruptions, especially environmental disruptions and those caused by hardware failures and operational errors. The most important failure type is regarded as the fiber cut, e.g., caused by a backhoe. As such a cut typically breaks all fibers of a fiber link, the end-nodes which were previously neighbors become disconnected. In order to re-establish the connectivity of disrupted paths, appropriate protection and restoration mechanisms are deployed in the network. Often these networks are designed to protect against single failures of such fiber links at a time.

But for larger and more connected networks dual failures—though much less probable than single failures—should be taken into account [1, 2]. This can be made plausible by the following calculation. Consider a network with fiber links of equal length l, with $[l] = \text{km}$. Then a fiber link has the availability of:

$$a = \left(\frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \right)^l$$

where MTBF is the mean time between failures and MTTR is the mean time to repair of one link-kilometer. For a network with m fiber links we calculate the probability for two simultaneous link failures as:

$$p_2 = \binom{m}{2} (1-a)^2 a^{m-2}$$

Assume a MTBF value of 300 years per kilometer and a MTTR value of 8 hours. The mean time of dual failures in a network with 25 fiber links of 500 km length is then almost 6 hours per year. Thus, even for this medium size network, just dual fiber link failures can already account for critical connection outage times.

One mean to counteract the disconnection impact caused by double failures is to include these failure states when planning the capacity and routes of the network. For path protection and path rerouting, we investigate how the average loss of connections during double fiber link failures can be minimized. We use mixed integer linear programming methods to get the best achievable values for the investigated network instances.

In taking this extreme view of high restorability design, we are interested in the additional expenses and improvements in restorability compared with a single failure design. This gives us an insight of what can be gained at most by following this approach, and whether high restorability improvements can at all be achieved (for an acceptable cost) or not. This is particularly relevant for path rerouting which is capable to offer 100% dual failure restorability (given sufficient connectivity and capacity).

The more network users benefit from having higher restorability, the less disconcertment will arise after dual failures. But even if high dual failure survivability is guaranteed only for some network users, we may get a notion of what dual failure design is able to achieve for these users.

We consider WDM networks with full wavelength conversion. Although many findings hold also for other network technologies, we focus on WDM networks, in particular with respect to the recovery methods and network scenarios. Because of wavelength-conflict effects and longer paths to resolve these, we expect higher capacity requirements and/or lower restorability for WDM networks with partial or no wavelength conversion.

The structure of this article is as follows. The reminder of this section presents related work and gives some definitions and the failure scenarios employed in this article. Section 2 describes the investigated recovery mechanisms. For these recovery mechanisms, a consolidated structure of optimization models showing the details for dual failures and building the basis for the following evaluations is developed in Section 3. Section 4 proposes two solving heuristics for one of the optimization models. Section 5 contains a performance evaluation based on different network instances. Finally, Section 6 concludes this article.

1.1 Related Work

To the best of our knowledge, this is the first contribution on the design of path-level protected networks, taking dual failure states into account. References [1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] deal with dual failures in networks with link restoration where the adjacent nodes restore a failed link, while we consider end-to-end path recovery. References [1, 2, 4, 10] point out the significance of multiple failures and develop frameworks to classify recovery of multiple failures. Capacity and availability performance in presence of dual failures are also investigated in [13] for 1+1 protection, link restoration, and path restoration. The case study networks are not dimensioned under direct consideration of dual failures. For path rerouting, link overprovisioning is suggested to alleviate dual failure loss. The restorability of dedicated and shared path protection is also part of the study in [4], where the primary path and the protection path are found by an algorithm which reduces capacity costs, whereas we use mixed integer linear programming methods with inclusion of costs and dual failures.

1.2 Definitions and Failure Scenarios

The physical level is described by a graph with nodes and edges. The network's n nodes are interconnected by m fiber links which are the *edges*, i.e., an edge comprises all fibers between adjacent physical nodes, and will therefore be the entity which is subject to failure. A transmission channel link, or briefly *link*, denotes an individual transmission wavelength-channel between two adjacent nodes on an edge. In the networks, a *path* is a sequence of edges, while a *connection*, following a path, is described as a sequence of links. A *demand-unit* between two nodes is a request to carry a bidirectional client wavelength-channel over the network. Depending on the protection mechanism, a single demand-unit needs one or more connections within the network. The total number of demand-units between two nodes is called *demand*. Edges, links, connections, and paths are undirected to model bidirectional communications. The *degree* of a node is the number of its incident edges. A network is *two-edge-connected (two-node-connected)*, if two edge-disjoint (node-disjoint) paths between any node pair in the network exist.

We assume that edges fail independently, i.e., the edges are mutually disjoint (enough) such that a single failure intrusion does not affect multiple edges. Since the recovery time of protection and rerouting is much shorter than the mean time between failures, we also assume that the second failure does not occur when the first failure (with recovery time t_{rec}) has not yet been recovered. Thereby, double failures are treated as ordered events (f,g), which means a failure of edge f at some time t_1 and failure of edge g at some time t_2 with $t_2 \geq t_1 + t_{rec}$ and $f \neq g$.

2 Considered Path-based Recovery Mechanisms

We fix our attention to dedicated path protection, shared (backup) path protection, and path rerouting. The reason for this focus is that the first recovery mechanism is widely employed today, and the latter two become attractive as the need for efficient recovery strategies emerges. Path rerouting is also an important candidate for networks requiring high multiple failure survivability.

For comparability of the mechanisms, we make a set of assumptions:

- One type of recovery mechanism is used in the network and all connections are protected by this method.
- The paths are chosen based on a (central) global view on the network, such that optimal solutions can be found. In this way we can make comparisons for the best-case performance of the mechanisms.
- The networks are two-node-connected.

2.1 Dedicated Path Protection

Using dedicated path protection, two disjoint paths are selected for a demand-unit in the network. Dedicated path protection can be classified in 1+1 protection and 1:1 protection.

In 1+1 protection the capacity on both paths is reserved exclusively for the corresponding demand-unit. See Figure 1(a) for two dedicated protection demands, one between A-F, and one between C-D. The sender sends the signal and a copy of the signal on the two paths, respectively. The receiver selects one of the paths which is called the working path (solid line) in the failureless case, and switches to the other path, the protection path (dotted line) if a failure occurs on the working path.

1:1 protection is similar to 1+1 protection, except that the protection path does not transport a copy of the signal. Instead, upon a failure on the working path, sender and receiver switch to the protection path, which then carries the traffic. When no failure is present on one of the paths, the protection path can carry "low-priority" traffic, i.e., traffic that will be pre-empted if a failure on the working path occurs.

Note that the connection is lost if there is one failure on the working path and at the same time one failure on the protection path. In mesh networks with a noticeable level of dual failure probability, 1+1 protection or 1:1 protection can thereby attain less availability than, e.g., restoration [1]. It is obvious that any chronological order of a double failure leads to the same result, i.e., failure events (f, g) and (g, f) have the same loss value.

2.2 Shared Path Protection

For shared (backup) path protection a working path is provided, and additionally a backup path which is disjoint from the working path. The backup path can be shared with other connections, as long as the working paths are disjoint, e.g., see Figure 1(b) where the longer paths are shared. After a failure on the working path, the reserved protection path has to be configured (cross-connected) in the passed nodes before traffic can be carried along the protection path.

It claims attention that a connection can be lost, even if a failure pair does not simultaneously hit the working path and the protection path. This is caused, e.g., in situations where the (shared) protection capacity is optimized for single failures only. Figure 2 depicts an example network with four connections which should be provided by dedicated and shared path protection. Dedicated path protection in Figure 2(a) needs most capacity, but is able to survive any dual failure, except for those which hit both disjoint connections simultaneously. Shared path protection as in Figure 2(b) requires less capacity. However, as the capacity is planned for single failures, it cannot survive a double failure, e.g., on edges A-B and C-D, since the shared diagonal edge has not sufficient reversed capacity. If more capacity is reserved on that edge, see Figure 2(c), this dual failure can be survived. Compared to dedicated path protection, the shared path protection optimized for dual failures still needs less capacity.

Unlike dedicated path protection, the order of a dual failure cannot be ignored. For example, the network in Figure 3 carries three working connections (solid lines), which are protected by protection paths (dotted lines). Assume at most one connection can be carried by all edges except for edge E-H which can carry two. Then a failure (A-B, H-E) effects a loss for two demand-units (F-H and D-H), whereas a failure (H-E, A-B) causes a loss for one demand-unit (A-B) only.

For dual failures, a stub-release mechanism is conceivable in shared path protection. After the first failure, active backup paths can be disrupted by a second failure. These backup paths can be torn-down so that, afterwards, other backup paths can access the freed capacity. As this stub-release mechanism adds signaling complexity and is only needed for dual failures, we do not expect it to be implemented in the networks, and disregard stub-release for shared path protection in this article. Note that for path rerouting (Section 2.3) the same stub-release mechanism works for both single and dual failures.

2.3 Path Rerouting

Using path rerouting, demand-units are served by single connections. If a failure disrupts a connection, it will be re-setup after the failure has been signaled to the end-nodes. Figure 4 shows an example of five connections between nodes A and D, which are disrupted by a failure. The subsequent re-setup restores the connection on two different paths.

To allow the re-setup of affected connections, spare capacity is needed in the network. For the ease of comparison to path protection, we denote this additional capacity also as "protection capacity." For rerouting featuring stub-release, affected paths are torn down before re-setup to make the used resources available again. Without stub-release, the paths maintain the reserved capacity. The former option allows for better capacity sharing, the latter offers faster restoration, and simple path reversion after failure repair.

In a similar fashion, if enough capacity is available, any double failure can be survived, except if the network becomes disconnected, e.g., by failures around nodes with degree two.

The order of dual failure events is important to determine the paths after failure rerouting. Figure 5 exemplifies this with a network having one capacity unit per edge and routed connections between A-F, B-E, and C-D (solid lines). If edge B-E fails, the B-E connection can be rerouted over B-F-E. If then edge A-F fails, the A-F connection cannot be rerouted, since edge B-F is unavailable. Hence, using B-F-E as rerouting path, a failure (B-E, A-F) yields a lost connection, but a failure (A-F, B-E) has no loss, since rerouting paths A-B-F and B-D-E can be taken for A-F and B-E, respectively. Obviously, if we use for failure (B-E, A-F) path B-D-E as rerouting path of the first failure, this blocking could have been avoided. However, by symmetry, it will lead to a loss for the dual failure (B-E, C-D), since edge B-D is not available for the rerouting path C-B-D.

3 Optimization Models Including Dual Failure States

For the three recovery mechanisms we formulate mixed integer linear programming models taking double failures into account. Given connection-demands $\delta_{s,t}$ from nodes s to nodes t have to be fully provided and protected against single edge failures. We assume homogeneous transmission systems with λ wavelengths. An edge e carries ϕ_e fibers. A used link on edge e has a cost ψ_e.

If not mentioned otherwise, the primary objective will be to minimize the average double failure loss of connections. The average is taken over all double edge failure occurrences. This planning objective puts an emphasis on highly available network designs. With secondary priority we aim to minimize the total cost.

The optimization models are composed of given indexing sets, given parameters, solution variables, the objective, and constraints. First, we describe a simple provisioning model without protection in Figure 6. This model is also a basis for the models in the following three subsections, since we just point out which different or additional formulations to the provisioning model are needed.

The optimization procedure works with the set $\mathbf{D}$, the set of node pairs which have a demand relation, and the set of edges $\mathbf{E}$. For every $d \in \mathbf{D}$, a set of paths is precomputed, where each path p (of a total of π_d paths) is described by the set of edges $\mathbf{T}_{d,p}$. The variable $P_{d,p}$ counts how many connections go over path p. We introduce the auxiliary variable E_e for the number of required links on edge e. Constraints (4) ensure the demand is carried by the connections over the paths. For the edges, Equations (5) calculate the number of links, for which the capacity Constraints (6) apply.

3.1 Dedicated Path Protection Model

In contrast to the unprotected provisioning model with one connection per demand-unit, in dedicated path protection two disjoint connections have to be set up for every demand unit. See the model in Figure 7 which relates to the provisioning model in Figure 6.

We generate a set $\mathbf{P}_d$ which stores for every demand pair d the pairs of disjoint paths. Hence, for a path combination (p, q), one of p and q in $\mathbf{P}_d$ is working path, and the other protection path. In the evaluation (Section 5), we interpret the shorter path as working path, the longer as protection path.

We introduce variables $P'_{d,p,q}$ which count for each demand pair d the number of connections taking path pair (p, q). The variables $L_{d,f,g}$ are the number of lost demand-units of pair d, when the dual failure of edges f and g occurs.

Objective (7) minimizes first of all the sum of the demands lost by all the dual failures (first sum). This objective also minimizes the *average* double failure loss of connections, since the average is just the sum scaled by the constant $\frac{1}{m(m-1)}$, the reciprocal of the number of dual failures. The constant κ ensures that this objective is the primary objective and does not interfere with the by-objective (second sum) which minimizes the total cost. In other words, among the solutions with least average lost demands, we take the minimal-cost solution.

Constraints (4) of the provisioning model are substituted by Equations (8), since connection pairs are required. Constraints (9) determine the number of connections on path p. Per failure (f, g) and per pair d, Constraints (10) determine the number of lost demand-units $L_{d,f,g}$ by adding the traffic of those path-pairs (p, q) which are simultaneously affected by the failure. As the chronological order of the dual failure events does not matter in dedicated path protection, Equations (11) can be introduced, to allow for substitutions of variables (e.g., in a presolving step) and thus, to make the computation faster.

3.2 Shared Path Protection Model

The shared path protection model, as depicted in Figure 8, relates to the provisioning model in Figure 6 and the dedicated path protection model in Figure 7. We generate a set $\mathbf{P}_d^+$ which stores for every demand pair d the pairs of disjoint paths. Hence, the path variation (w, b) assigns the path w in $\mathbf{P}_d^+$ to the working path, and path b to the protection path which can be shared. As a path p can have the role of a working path or a shared protection path, the set $\mathbf{P}_d^+$ has twice as much entries as the path pair set in dedicated protection. From the capacity and survivability point-of-view, the distinction between working and protection path is not necessary in dedicated protection. (Therefore, we deal with path variations here, rather than with path combinations.)

We introduce variables $P'_{d,w,b}$ which count for each demand pair d the number of demand-units which take the path-pair (w, b). Variables S_e represent the shared protection capacity on edge e. Variables $B_{d,b,f,g}$ denote the capacity of protection path b for demand-pair d, if the second failure g hits the working path and the protection mechanism has not been activated because of the first failure, i.e., f did not hit the working path. The variables $L_{d,f,g}$, as in dedicated path protection, are the number of lost demand-units of pair d if the failed edges are both on working and protection paths. For shared protection additionally the variables $L'_{d,b,f,g}$ are necessary, which denote the number of lost demand-units of pair d because of insufficient capacity on the shared protection path.

Objective (12) minimizes the demand lost by dual failures, which has a portion due to joint working and protection path hits, and a portion caused by insufficient capacity. Again, the by-objective minimizes the total cost.

The Constraints (8-10) from the dedicated path protection model apply also for shared path protection. We augment them by the capacity sharing constraints. In Constraints (13), we obtain the shared capacity S_e on edge e by amounts from single and dual failures. The first sum also accounts for backup paths which become disrupted by second failures g, since these paths are not stub-released (Section 2.2). Since S_e will be minimized using Constraints (14), which determine the required capacity on an edge e, and Objective (12), these constraints determine the actually required capacity (minimax-relation). For double failures, Constraints (15) equate the number of working connections which are affected by the second failure only and which do not have a failure on the corresponding protection connection, to the required number of protection connections for the second failure plus the number of lost connections due to insufficient capacity.

Shared path protection becomes coincident to path rerouting, since we can regard the former as a special case of the latter, where rerouted connections are restricted to take the same path for each failure. However, the corresponding model becomes more complex than the one in Figure 8.

3.3 Path Rerouting Model

The path rerouting model, again relating to the provisioning model in Figure 6, is shown in Figure 9. For the failureless state we find connections to serve the demands, as well as rerouting paths for all connections which are affected by single edge failures f and, where possible, by dual edge failures (f, g).

The parameter σ indicates if stub-release is employed. Variables $R_{f,d,p}$ measure the amount of capacity on path p for demand-pair d if edge f fails. Analogously $R'_{f,g,d,p}$ does this for the dual edge-failure (f, g). On edge e, W_e and S_e are working capacity and spare capacity, respectively. $L_{f,g,d}$ counts the number of lost demand-units of pair d because of dual failure (f, g).

Again with highest priority, Objective (16) minimizes the sum of the demands lost by all the dual failures, then it minimizes the total cost. By Equations (17), the total capacity on an edge is the sum of working and spare capacity. Equations (18) determine the working capacity. Constraints (19) and (20) calculate the minimum spare capacity on a link, needed to survive any single failure and dual failure, respectively. With stub-release ($\sigma = 1$), less spare capacity may be required than without sub-release ($\sigma = 0$), since paths passing the edge and being affected by the (single or dual) failure are torn down, and thus, free capacity. Equations (21) determine the reroute connections of a demand-pair for each single failure on basis of the affected connections. For any two-failure case, Constraints (22) equate the number connections which are affected by the second failure (right part) to the number of reroutable connections plus the number of lost connections (left part). The connections affected by the second failure are working connections and connections rerouted after the first failure. Equations (23) and (24) prohibit to take reroute paths which are subject to single failures and dual failures, respectively.

4 Solving Heuristics

As the path rerouting mixed integer linear programming (MILP) problem (Section 3.3) can become complex, we propose the two solving heuristics “decomposition” and “rounding.” As with any heuristic, we can tackle the problem computationally, but may not attain (globally) optimal solutions, or we might even obtain infeasible problems.

4.1 Decomposition

The first heuristic is the straightforward approach where we decompose the problem into three steps. In each step we solve a subpart of the overall MILP problem and fix variables obtained in the previous steps. In the first step, we minimize the working capacity for which the Constraints (19-24) of the model in Figure 9 are dropped. After fixing W_e and $P_{d,p}$, we compute in the second step the protection capacity needed to protect against single failures by adding Constraints (19), (21), and (23) to the model. Finally, based on the fixed variables W_e, $P_{d,p}$, and $R_{f,d,p}$ we solve the complete model in Figure 9.

In steps one and two we do not offer the entire capacity in the network (by modifying the right-hand side of Constraints (6)). For example, in Step 1 and 2 we allow 60% and 80% of the capacity, respectively, thereby allowing a capacity margin for the subsequent steps. The overall computation of the three steps is much faster than solving the problem in a whole.

4.2 Rounding

The second heuristic is based on linear programming (LP) relaxation. The path rerouting problem PRP is described as a MILP model, which works on the integer vector variable X. In the first step, the computation of its LP relaxation PRP' returns a continuous solution vector X', which may be infeasible for the MILP. In a subsequent rounding step we add the rounding constraints $\lfloor X' \rfloor \leq X \leq \lceil X' \rceil$ to the PRP MILP and solve it. Note that if an entry of X' is integer, these constraints will keep it integer. Compared to solving the PRP MILP, solving the LP and the more restricted MILP is faster.

5 Evaluation

In this section we evaluate the performance of the recovery methods using several study networks. Performance measures are capacity efficiency and double failure restorability:

- The capacity of the network is the sum of reserved links in all fibers in the network. For this we set in the optimization model $\psi_e = 1$ for all edges $e \in \mathbf{E}$.

- The restorability of a double failure (f, g) is defined in this article (similar to [1]) as the portion of all working paths on the edges f and g that are simultaneously affected by a double failure and survive this failure. The average dual failure restorability R_2 (or short restorability) is the average taken over all double failures in the network:

$$R_2 = \frac{1}{m(m-1)} \sum_{\substack{f,g \in \mathbf{E} \\ f \neq g}} \left(1 - \frac{L_{f,g}}{\omega(f,g)}\right) \quad (1)$$

  where $L_{f,g} = \sum_{d \in \mathbf{D}} L_{d,f,g}$ is the total loss in the network if f and g fail. We compute the number of working paths $\omega(f,g)$ on f and g in path protection by

$$\omega(f,g) = \sum_{\substack{d \in \mathbf{D}, \{(p,q) \in \mathbf{P}_d^{(+)}\} : \\ (f \in \mathbf{T}_{d,p}) \vee (g \in \mathbf{T}_{d,p})\}}} P'_{d,p,q} \quad (2)$$

  and in path rerouting by

$$\omega(f,g) = \sum_{\substack{d \in \mathbf{D}, \{p \in \{1,2,\ldots \pi_d\} : \\ (f \in \mathbf{T}_{d,p}) \vee (g \in \mathbf{T}_{d,p})\}}} P_{d,p} \quad (3)$$

Note that restorability could also be an objective for the optimization models in Section 3. However, by the definition of R_2, this results in non-linear mixed integer linear programming models.

5.1 Topology Generator

In order to investigate different network instances, we use a random topology generator (for $\mathbf{E}$) which tries to reflect the structure of optical networks. It is based on the the generator by Salama [14], which we enhanced to ensure two-node-connectivity and degree bounds, to come close to the optical networks' connectivity.

The generator takes the number of nodes n, a rectangle of size $X \times Y$, a distance parameter γ, and linking parameters α and β as input. In the first loop, points with coordinates x and y are generated at random. If, at an iteration, a point is not nearer than $\gamma\sqrt{\frac{XY}{\pi n}}$ to any present node, a new node is placed on this point. The loop finishes after n nodes are positioned. Then, links are generated with the intention that node-pairs having shorter distance will be connected with a higher probability than those having longer distance. Specifically, two nodes u and v are linked with probability $P_{u,v} = \beta \exp\left(\frac{-l(u,v)}{\alpha \times \max\limits_{u',v'} l(u',v')}\right)$, where $l(u,v)$ denotes the distance between nodes u and v. Using this connection rule, the generator in [14] generates two-edge-connected networks of arbitrary degree. We modified the generator by prohibiting nodes to become less connected than a minimum degree $\underline{\Delta}$ or more connected than a maximum degree $\overline{\Delta}$. Finally, we check if the topology output of the generator is two-node-connected. If it is not two-node-connected, the generator restarts for another randomized topology.

Depending on the output of the topology generator and the permitted simulation time, a different amount of solvable instances was produced for the investigations in the following subsections. For instance, a random instance for which the capacity is insufficient to ensure the minimal requirement of single failure survivability is excluded from the results. The number of feasible instances per investigation is indicated in the captions of Figures 10 to 13.

5.2 Common Parameters

For topology generation, we set the parameters $\gamma = 0.5$, $\alpha = 0.15$, $\beta = 2.2$, $\underline{\Delta} = 3$, and $\overline{\Delta} = 5$. The number of nodes is equal to 12 and the number of edges ranges from 20 to 26, yielding average nodal degrees between 3.3 to 4.3. Note that only few random instances with 20 edges exist. We therefore have some deviations of the mean values at this value (see, e.g., Figure 10 b). Per edge $e \in \mathbf{E}$ we deploy $\phi_e = 1$ fiber and $\lambda = 32$ wavelengths. A random and equally distributed demand of 120 connections is offered to the network. As path set we compute for each demand-pair all paths within a number of hops h. For a demand-pair, we start with $h = 2$ and increment h until at least four paths are available and until all paths do not traverse a common edge or a common (intermediate) node. By this, the average number of paths for a demand-pair increases approximately linearly from 5.7 for networks with 20 edges to 6.9 for networks with 26 edges. Note that enough paths should be available for optimization; in [15] we used fewer paths (where the average ranged from 3.4 to 6.2) which made the optimization instances too restrictive.

5.3 Comparison of Recovery Mechanisms

Figure 10 depicts the results for the considered recovery mechanisms. The average computation times are 2 seconds for dedicated path protection, 21 minutes for shared path protection, and (using the rounding heuristic in Section 4) 24 minutes and 58 minutes for path rerouting without and with stub-release, respectively.

The restorability in Figure 10(a) becomes higher for all mechanisms as the number of edges increases, since the network becomes more connected. Rerouting (using stub-release) outperforms the other protection alternatives by approximately 10-15% and reaches very high values of more than 98%. Therefore, rerouting proves to be the best mechanism for high restorability.

Due to the inflexible path assignment, shared path protection and dedicated path protection achieve 91% restorability at best. Shared path protection often has shorter protection paths (because of the sharing) than dedicated path protection. Therefore, the restorability is slightly higher, because less edges are needed for a connection and thus, less dual failure events affect the connection.

The total capacity consumption (for 21 and more edges) in Figure 10(b) decreases for all recovery mechanisms as the network becomes more connected, since paths can become shorter. Also, for shared path protection and rerouting, as shorter working paths are available, less protection capacity is needed. Each recovery mechanism requires about the same working capacity. The protection capacity for dedicated path protection is on average 1.5 as much as the working capacity. Using shared path protection, the protection capacity drops to an average of 75% of the working capacity. The entire capacity for rerouting is slightly higher than the capacity for shared path protection, since more failures are protected yielding in better restorability (see Figure 10(a)).

For path rerouting, an interesting detail-question is if capacity can control restorability (R_2). In our investigations more capacity does not take direct influence on R_2, but high R_2-levels are reached anyway. Different topologies having a capacity range of 400 to 500 yield similar R_2-values (in the range of 99.1% to 99.8%). In other words, one topology can have approximately the same R_2-performance as another one, but needs 25% more capacity. Therefore, the topology rules the R_2 outcome much more than the deployed capacity (Figure 10(a)). Similar results have also been found for several link-restoration mechanisms in [1].

The gain of stub-release effects approximately 6% better capacity efficiency for rerouting, as depicted in Figure 11. On average, the working capacity is slightly higher with stub release than without, since longer working paths help to reduce the (shared) protection capacity. With a growing number of edges, the total capacity decreases, because less protection capacity is needed, while the restorability increases. The restorability of rerouting with and without stub-release (not depicted) is comparable. We attribute this to the phenomenon that again, the additional capacity offered by stub-release cannot be exploited for better restorability.

5.4 Double Failures in Networks Planned for Single Failures

Figures 12-13 compare capacity and restorability of networks planned for double failures with those planned for single failures. Planning for single failures means that the (primary) aim, which is to reduce the sum of lost paths over all possible dual failure scenarios, is not included in the optimal paths selection (i.e., $\kappa = 0$).

Consequently, the restorability of shared path protection in Figure 12(a) drops from an average value of 91% in dual failure planning to an average of 65% in single failure planning. The capacity limitations imposed by single failure planning, as described in Section 2.2, cause high loss in the average dual failure case. While the working capacity in Figure 12(b) turns out to be the same, dual failure planning requires approximately 2.2 times more protection capacity than single failure planning. Surprisingly, although shared path protection has just two path alternatives, more capacity has a remarkable impact on restorability. And still, shared path protection is much more capacity efficient than dedicated path protection (Figure 10) with comparable restorability performance.

We obtain a similar picture for path rerouting with stub-release. The restorability in Figure 13(a) achieves a mean of 72% only. In comparison, the restorability of networks planned for dual failures is close to 100%. This result underlines the expectation that a network with path rerouting and planned for single failures has a reasonable but not optimal performance in dual failure survivability. The achieved restorability range (61%-79%) for *path* rerouting is comparable to the one found for networks with *link* restoration in [1].

The provisioning of near-100% restorability needs on average 44% more capacity in the network than the provisioning of the 72%-levels. As depicted in Figure 13(b), the main contributor to this capacity augmentation comes from the protection capacity. For single failure planning the average protection capacity is 29% of the working capacity, whereas for dual failure planning 76% is required. This higher value is produced by the protection paths which account for double failures. Compared to shared path protection, rerouting needs even more capacity. Because of its flexible and failure-dependent path selection, more failure scenarios are protected, requiring more capacity. In contrast to [13], where 10-20% overprovisioning of the protection capacity achieved significant improvements in the expected loss of traffic due to double failures, the results suggest that for rerouting, much more overprovisioning of the single failure protection capacity is expedient.

5.5 Comparison of Heuristics

For path rerouting the decomposition and rounding heuristics are deployed in the dual failure planning case. For the sake of capacity and restorability comparison, the suboptimality of the heuristics has no consequence. Since rerouting outperforms the dedicated and shared path protection well, the heuristics' deviation from the real optimal values is negligible.

On average, the decomposition heuristic computes 10% more capacity than the rounding heuristic, while the restorability is about equal. However, the decomposition heuristic calculates in some tens of seconds and the rounding heuristic takes two orders of magnitude more time. Because of the better capacity values we used the rounding heuristic in the previous path rerouting results.

6 Conclusions

We investigated the working and protection capacity efficiency and the dual failure restorability for protected WDM networks with full wavelength conversion. Our focus was on dedicated path protection, shared (backup) path protection, and path rerouting with and without stub-release. We reviewed these recovery mechanisms with special attention to their dual failure behavior.

In order to find out what can be achieved at best, we formulated mixed integer linear programming models to compute optimal paths for the three mechanisms. The objective minimized the average loss caused by dual failures. From the minimal-loss solutions we took the configuration which had minimum required capacity in the network. For the path rerouting computation we proposed a decomposition heuristic and a rounding heuristic.

In a case study for mid-sized random optical networks, we obtained the following results with respect to capacity and dual failure restorability:

- The connectivity is of particular importance for high restorability, rather than the overall capacity. Rerouting surpasses dedicated and shared path protection by 10-15% more restorability.

- As the networks become more connected, the restorability improves while the capacity requirements drop. This suggests for network upgrade (and in view of high dual failure restorability) that, instead of looking only at augmenting capacity in the existing topology, adding new fiber links to an existing topology is an interesting option.

- The working capacity of all recovery mechanisms is about equal. The protection capacity for dedicated path protection is 1.5 as high as the working capacity. For shared protection and rerouting, the protection capacity is comparable, requiring 3/4 of the working capacity. Path rerouting with stub-release has less than 10% better capacity efficiency than without, while the restorability is about the same.

- In shared path protection, single failure planning produces a gap in restorability of 25% to dual failure planning. To protect against dual failures, a doubling of the single-failure protection capacity has to be invested. But the total capacity still stays significantly below the capacity for dedicated protection.

- For path rerouting, near-100%-values for the restorability can be attained, if the network is planned for dual failures. The restorability drops by 1/4 for single failure planning. Networks planned for dual failures require at least 40% more capacity than those planned for single failures.

- In a comparison of a decomposition heuristic (which assigns capacity per failure level) with a variables-rounding heuristic for the path rerouting problem, we found that the latter produces slightly better network performance values than the former, but requires much more computation time.

Our primary objective, which was the minimization of the average double failure loss of connections, dominates our secondary objective, being the minimization of the total cost. Since minimizing the average dual failure loss can be very capacity expensive, another approach would be to pursue a mixture of these objectives. For instance, the capacity could be optimized such that a certain dual failure loss is ensured.

The authors would like to acknowledge the suggestions of A. Autenrieth.

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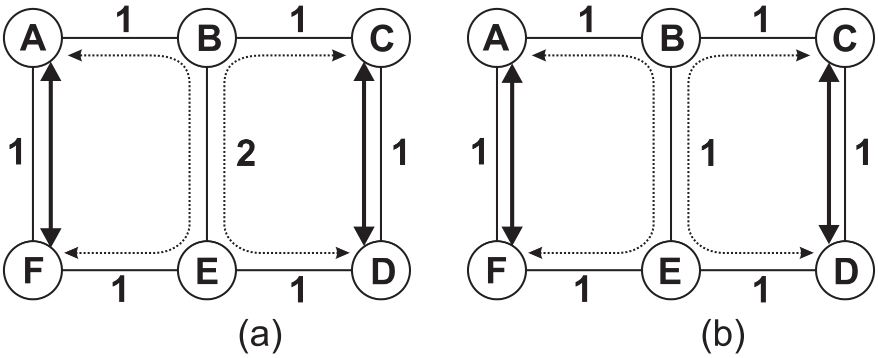


Figure 1: Dedicated path protection (a) and shared path protection (b) for connections between A-F and C-D. The numbers indicate the capacities on the edges.

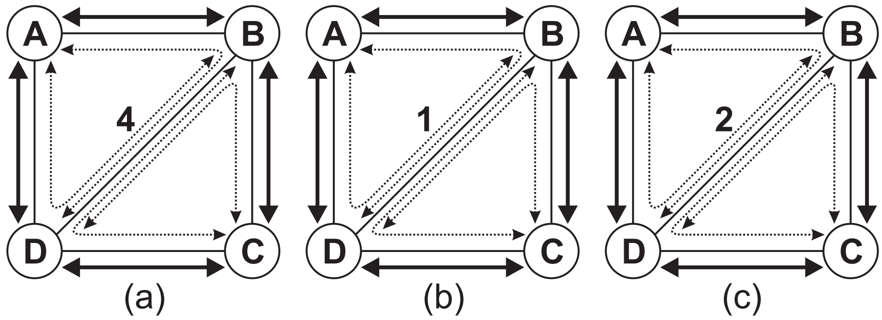


Figure 2: Comparative example for dedicated path protection (a), shared path protection optimized for single failures (b) and for double (c) failures. Demands are between A-B, B-C, C-D, and D-A. The numbers indicate the capacities on the edges.

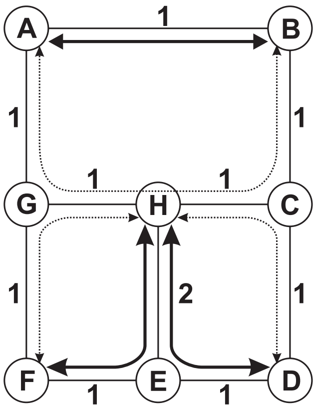


Figure 3: Example network with three working connections and their shared backup connections to illustrate the dependence on the event order of dual failures. The numbers indicate the capacities on the edges.

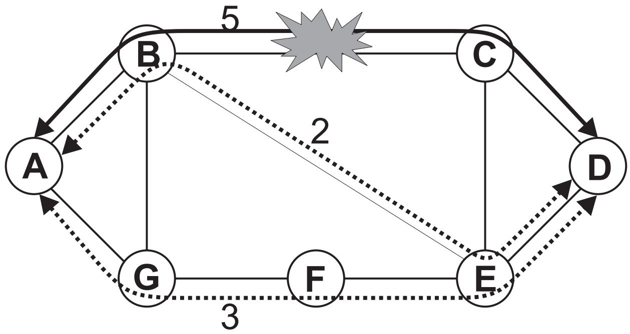


Figure 4: Path rerouting of five disrupted connections (solid line) over two different paths (dotted lines).

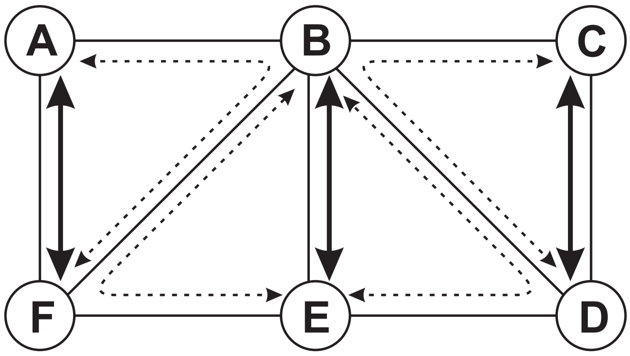


Figure 5: Example network with three connections and their possible reroute paths to illustrate the dependence on the event order of dual failures.

PROVISIONING MODEL

Sets:

$\mathbf{D}$		Node pairs with demand relation
$\mathbf{E}$		Edges in the physical topology
$\mathbf{T}_{d,p} \subset \mathbf{E}$	$\forall d \in \mathbf{D}$, $\forall p \in \{1, 2, \ldots \pi_d\}$	Edges of path p connecting pair d

Parameters:

$\lambda \in \mathbb{N} \backslash \{0\}$		Number of wavelengths
$\phi_e \in \mathbb{N}$	$\forall e \in \mathbf{E}$	Number of fibers in edge e
$\delta_d \in \mathbb{N}$	$\forall d \in \mathbf{D}$	Demand of pair d
$\psi_e \in \mathbb{R}_+$	$\forall e \in \mathbf{E}$	Cost of edge e
$\pi_d \in \mathbb{N}$	$\forall d \in \mathbf{D}$	Number of given paths for demand-pair d

Variables:

$P_{d,p} \in \mathbb{N}$	$\forall d \in \mathbf{D}$, $\forall p \in \{1, 2, \ldots \pi_d\}$	Number of connections which take path p for demand-pair d
$E_e \in \mathbb{R}_+$	$\forall e \in \mathbf{E}$	Number of links (i.e., required capacity) on e

Constraints:

$$\sum_{p \in \{1,2,\ldots \pi_d\}} P_{d,p} = \delta_d \qquad \forall d \in \mathbf{D} \tag{4}$$

$$E_e = \sum_{\substack{\{d \in \mathbf{D}, \\ p \in \{1,2,\ldots \pi_d\} : \\ e \in \mathbf{T}_{d,p}\}}} P_{d,p} \qquad \forall e \in \mathbf{E} \tag{5}$$

$$E_e \leq \phi_e \times \lambda \qquad \forall e \in \mathbf{E} \tag{6}$$

Figure 6: Provisioning model without resilience.

DEDICATED PATH PROTECTION MODEL

Additions to the provisioning model (Figure 6) without Constraints (4):

Parameters:

$\mathbf{P}_d = \{(p,q) : p,q \in \{1,2,\ldots\pi_d\}, p < q \wedge \mathbf{T}_{d,p} \cap \mathbf{T}_{d,q} = \emptyset\}$	$\forall d \in \mathbf{D}$	Combinations of disjoint paths for demand pair d
$\kappa > \sum_{e\in\mathbf{E}} \psi_e \phi_e \lambda$		Large constant

Variables:

$P'_{d,p,q} \in \mathbb{N}$	$\forall d \in \mathbf{D}$, $\forall p,q \in \{1,2,\ldots\pi_d\}$	Number of connections which take the path-pair (p,q)
$L_{d,f,g} \in \mathbb{R}_+$	$\forall d \in \mathbf{D}$, $\forall f,g \in \mathbf{E}$: $f \neq g$	Number of lost demand-units of pair d if edges f and g fail

Objective:

$$Z_{min} = \kappa \sum_{\substack{d \in \mathbf{D} \\ f,g \in \mathbf{E} \\ g \neq f}} L_{d,f,g} + \sum_{e\in\mathbf{E}} \psi_e E_e \tag{7}$$

Constraints:

$$\sum_{(p,q)\in\mathbf{P}_d} P'_{d,p,q} = \delta_d \qquad \forall d \in \mathbf{D} \tag{8}$$

$$\sum_{(p,q)\in\mathbf{P}_d} P'_{d,p,q} + \sum_{(q,p)\in\mathbf{P}_d} P'_{d,q,p} = P_{d,p} \qquad \forall d \in \mathbf{D}, p \in \{1,2,\ldots\pi_d\} \tag{9}$$

$$L_{d,f,g} = \sum_{\substack{\{(p,q) \in \mathbf{P}_d\} : \\ (f \in \mathbf{T}_{d,p}) \wedge (g \in \mathbf{T}_{d,q}) \vee \\ (f \in \mathbf{T}_{d,q}) \wedge (g \in \mathbf{T}_{d,p})\}}} P'_{d,p,q} \qquad \forall d \in \mathbf{D}, \forall f,g \in \mathbf{E} : f \neq g \tag{10}$$

$$L_{d,f,g} = L_{d,g,f} \qquad \forall d \in \mathbf{D}, \forall f,g \in \mathbf{E} : f \neq g \tag{11}$$

Figure 7: The dedicated path protection model taking dual failures into account.

SHARED PATH PROTECTION MODEL

Additions to the provisioning model (Figure 6) without Constraints (4) and (5):

Sets:

$\mathbf{P}_d^+ = \{(w,b) : w, b \in \{1, 2, \ldots \pi_d\}, \mathbf{T}_{d,w} \cap \mathbf{T}_{d,b} = \emptyset\}$	$\forall d \in \mathbf{D}$	Variations of disjoint paths for demand pair d
$\kappa > \sum_{e\in\mathbf{E}} \psi_e \phi_e \lambda$		Large constant

Parameters: Same as for dedicated path protection (Figure 7).

Variables:

$P'_{d,w,b} \in \mathbb{N}$	$\forall d \in \mathbf{D}, \forall (w,b) \in \mathbf{P}_d^+$	Number of demand-units which take the path-pair (w,b)
$S_e \in \mathbb{R}_+$	$\forall e \in \mathbf{E}$	Shared protection capacity on edge e
$B_{d,b,f,g} \in \mathbb{N}$	$\forall d \in \mathbf{D}$, $\forall b \in \{1, 2, \ldots \pi_d\}$, $\forall f, g \in \mathbf{E}$: $f \neq g$	Capacity of protection path b for demand-pair d if the second failure g disrupts the working path, while the first failure f does not
$L_{d,f,g} \in \mathbb{R}_+$	$\forall d \in \mathbf{D}$, $\forall f, g \in \mathbf{E}$: $f \neq g$	Number of lost demand-units of pair d if the failed edges are both on working and protection path
$L'_{d,b,f,g} \in \mathbb{R}_+$	$\forall d \in \mathbf{D}$, $\forall b \in \{1, 2, \ldots \pi_d\}$, $\forall f, g \in \mathbf{E}$: $f \neq g$	Number of lost demand-units of pair d if the failed edges are both on different working paths and the shared protection capacity is not sufficient

Objective:

$$Z_{min} = \kappa \sum_{\substack{\{d \in \mathbf{D}, \\ f,g \in \mathbf{E}: \\ g \neq f\}}} (L_{d,f,g} + \sum_{b \in \{1,2,\ldots \pi_d\}} L'_{d,b,f,g}) + \sum_{e\in\mathbf{E}} \psi_e E_e \tag{12}$$

Constraints:

Constraints (8-10) from the dedicated path protection model (Figure 7) using $\mathbf{P}_d^+$ instead of $\mathbf{P}_d$.

$$\sum_{\substack{\{d \in \mathbf{D}, \\ (w,b) \in \mathbf{P}_d^+: \\ (f \in \mathbf{T}_{d,w}) \wedge (e \in \mathbf{T}_{d,b})\}}} P'_{d,w,b} + \sum_{\substack{\{d \in \mathbf{D}, \\ b \in \{1,2,\ldots \pi_d\}: \\ e \in \mathbf{T}_{d,b}\}}} B_{d,b,f,g} \leq S_e \qquad \forall e, f, g \in \mathbf{E}: f \neq g \neq e \neq f \tag{13}$$

$$S_e + \sum_{\substack{\{d \in \mathbf{D}, \\ (w,b) \in \mathbf{P}_d^+: \\ e \in \mathbf{T}_{d,w}\}}} P'_{d,w,b} = E_e \qquad \forall e \in \mathbf{E} \tag{14}$$

$$L'_{d,b,f,g} + B_{d,b,f,g} = \sum_{\substack{\{(w,b) \in \mathbf{P}_d^+: \\ (f \notin \mathbf{T}_{d,w}) \wedge \\ (g \in \mathbf{T}_{d,w})\}}} P'_{d,w,b} \qquad \forall d \in \mathbf{D}, \forall f, g \in \mathbf{E}, \forall b \in \{1, 2, \ldots \pi_d\}: f \neq g, f \notin \mathbf{T}_{d,b}, g \notin \mathbf{T}_{d,b} \tag{15}$$

Figure 8: The shared path protection model taking dual failures into account.

PATH REROUTING MODEL

Additions to the provisioning model (Figure 6) without Constraints (5):

Parameters:

$\sigma \in \{0,1\}$	Set to 1 for stub-release, 0 otherwise
$\kappa > \sum_{e \in \mathbf{E}} \psi_e \phi_e \lambda$	Large constant

Variables:

$R_{f,d,p} \in \mathbb{N}$	$\forall f \in \mathbf{E}, \forall d \in \mathbf{D}, \forall p \in \{1, 2, \ldots \pi_d\}$	Capacity on path p for demand-pair d if edge f fails
$R'_{f,g,d,p} \in \mathbb{N}$	$\forall f, g \in \mathbf{E}, \forall d \in \mathbf{D}$, $\forall p \in \{1, 2, \ldots \pi_d\}$: $f \neq g$	Capacity on path p for demand-pair d if edge g fails after edge f
$W_e \in \mathbb{R}_+$	$\forall e \in \mathbf{E}$	Working capacity on edge e
$S_e \in \mathbb{R}_+$	$\forall e \in \mathbf{E}$	Spare capacity on edge e
$L_{f,g,d} \in \mathbb{R}_+$	$\forall f, g \in \mathbf{E}, \forall d \in \mathbf{D}$: $f \neq g$	Number of lost demand-units of pair d because of dual failure (f, g)

Objective:

$$Z_{min} = \kappa \sum_{\substack{d \in \mathbf{D} \\ f,g \in \mathbf{E}, g \neq f}} L_{d,f,g} + \sum_{e \in \mathbf{E}} \psi_e E_e \tag{16}$$

Constraints:

$$S_e + W_e = E_e \qquad \forall e \in \mathbf{E} \tag{17}$$

$$\sum_{\substack{\{d \in \mathbf{D}, \\ p \in \{1,2,\ldots \pi_d\} : \\ e \in \mathbf{T}_{d,p}\}}} P_{d,p} = W_e \qquad \forall e \in \mathbf{E} \tag{18}$$

$$\sum_{\substack{\{d \in \mathbf{D}, \\ p \in \{1,2,\ldots \pi_d\} : \\ e \in \mathbf{T}_{d,p}\}}} R_{f,d,p} \leq S_e + \sigma \times \sum_{\substack{\{d \in \mathbf{D}, p \in \{1,2,\ldots \pi_d\} : \\ (e \in \mathbf{T}_{d,p}) \wedge (f \in \mathbf{T}_{d,p})\}}} P_{d,p} \qquad \forall f, e \in \mathbf{E} : f \neq e \tag{19}$$

$$\sum_{\substack{\{d \in \mathbf{D}, \\ p \in \{1,2,\ldots \pi_d\} : \\ e \in \mathbf{T}_{d,p}\}}} (R_{f,d,p} + R'_{f,g,d,p}) \leq S_e + \sigma \times \sum_{\substack{\{d \in \mathbf{D}, \\ p \in \{1,2,\ldots \pi_d\} : \\ e \in \mathbf{T}_{d,p} \wedge (f \in \mathbf{T}_{d,p} \vee g \in \mathbf{T}_{d,p})\}}} (P_{d,p} + R_{f,d,p}) \qquad \begin{array}{c} \forall f, g, e \in \mathbf{E} : \\ f \neq g \neq e \neq f \end{array} \tag{20}$$

$$\sum_{p \in \{1,2,\ldots \pi_d\}} R_{f,d,p} = \sum_{\substack{\{p \in \{1,2,\ldots \pi_d\}: \\ f \in \mathbf{T}_{d,p}\}}} P_{d,p} \qquad \forall f \in \mathbf{E}, \forall d \in \mathbf{D} \tag{21}$$

$$L_{f,g,d} + \sum_{p \in \{1,2,\ldots \pi_d\}} R'_{f,g,d,p} = \sum_{\substack{\{p \in \{1,2,\ldots \pi_d\} : \\ (g \in \mathbf{T}_{d,p}) \wedge (f \notin \mathbf{T}_{d,p})\}}} (P_{d,p} + R_{f,d,p}) \qquad \forall f, g \in \mathbf{E}, \forall d \in \mathbf{D} \tag{22}$$

$$R_{f,d,p} = 0 \qquad \begin{array}{r} \forall f \in \mathbf{E}, \forall d \in \mathbf{D}, \\ \forall p \in \{1,2,\ldots \pi_d\} : f \in \mathbf{T}_{d,p} \end{array} \tag{23}$$

$$R'_{f,g,d,p} = 0 \qquad \begin{array}{r} \forall f, g \in \mathbf{E}, \forall d \in \mathbf{D}, \\ \forall p \in \{1,2,\ldots \pi_d\} : f, g \in \mathbf{T}_{d,p} \end{array} \tag{24}$$

Figure 9: The path rerouting model taking dual failures into account.

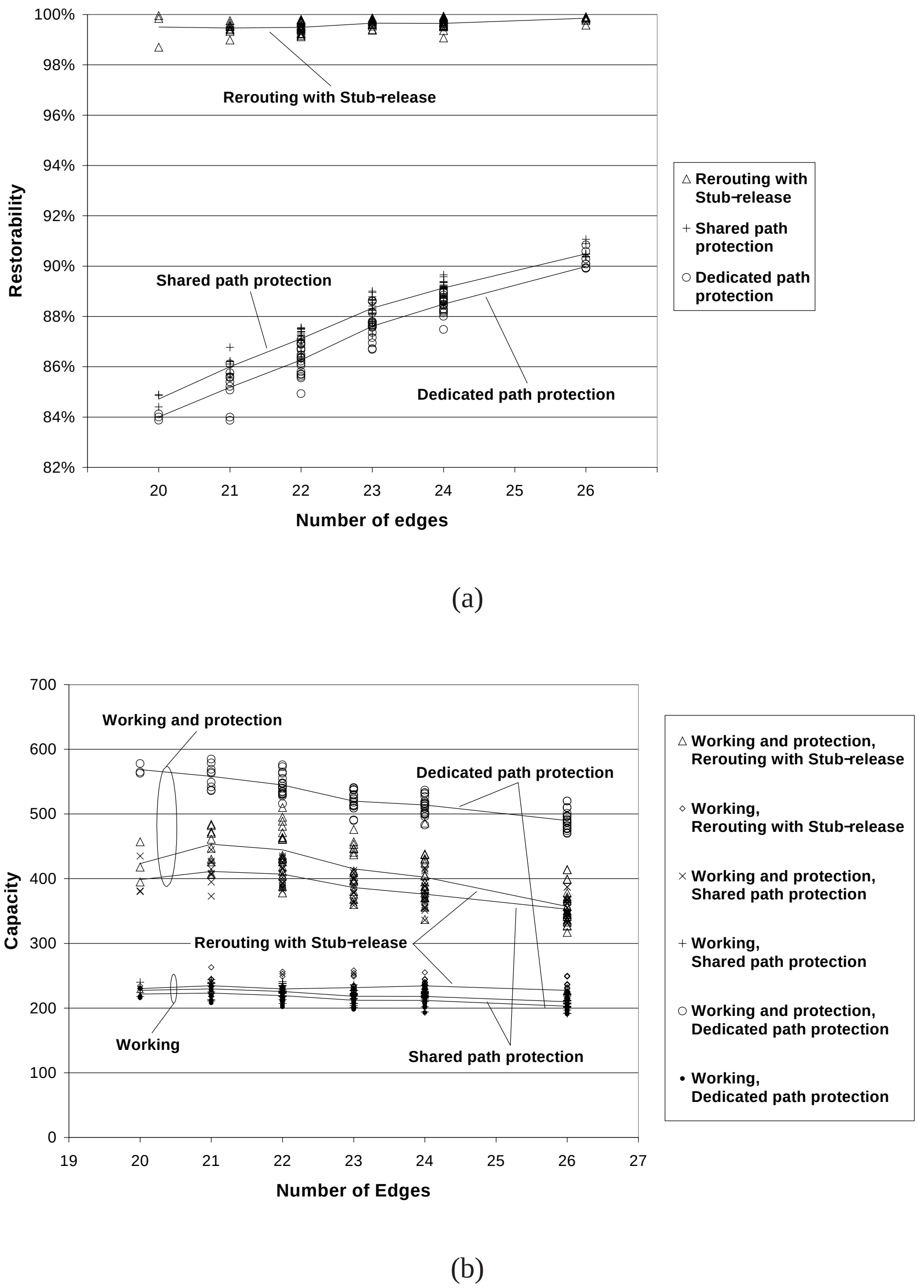


Figure 10: Double failure restorability (a) and capacity (b) of random networks with 20-26 edges, planned for rerouting with stub-release, shared path protection, and dedicated path protection. The points of each recovery mechanism are the results of 92 random instances and the curves connect the mean values.

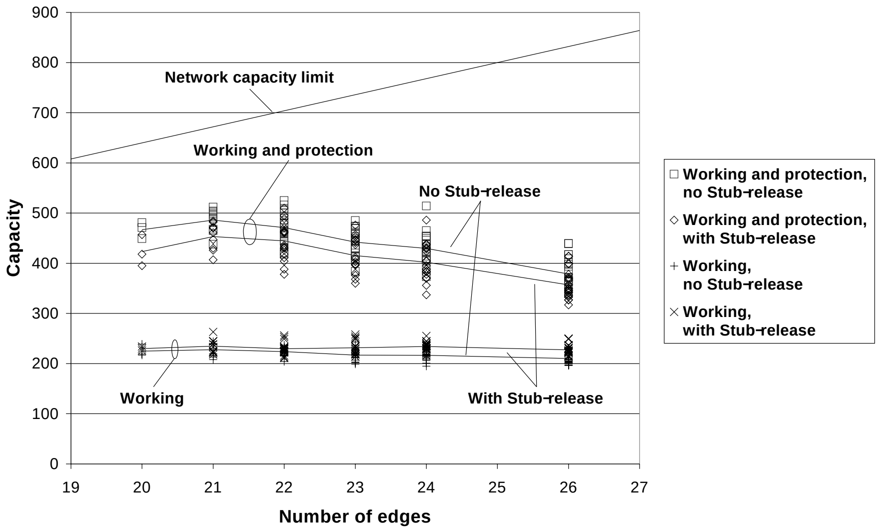
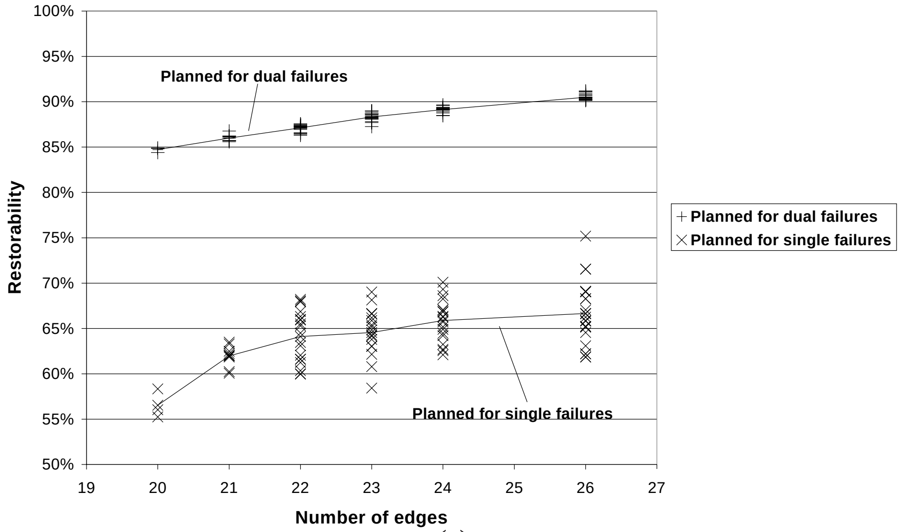
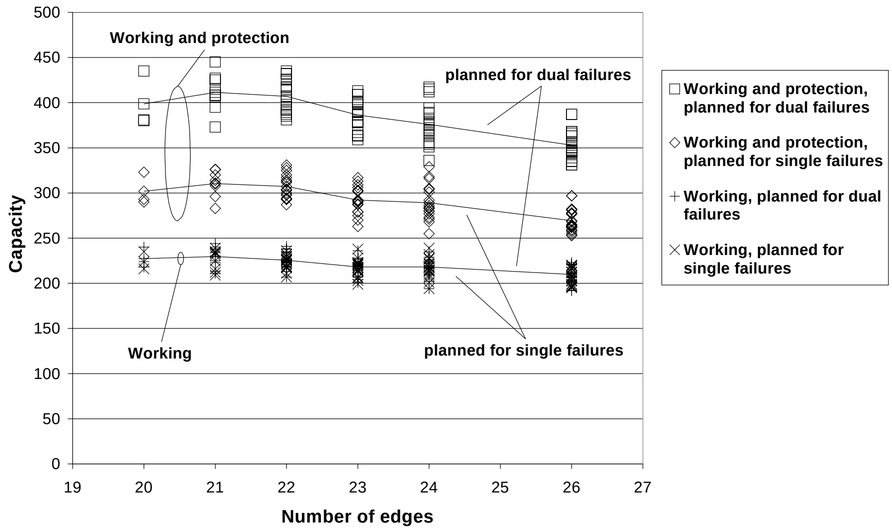


Figure 11: Capacity of random networks with 20-26 edges using rerouting with and without stub-release. The points of each planning scenario are the results of 92 random instances and the curves connect the mean values.

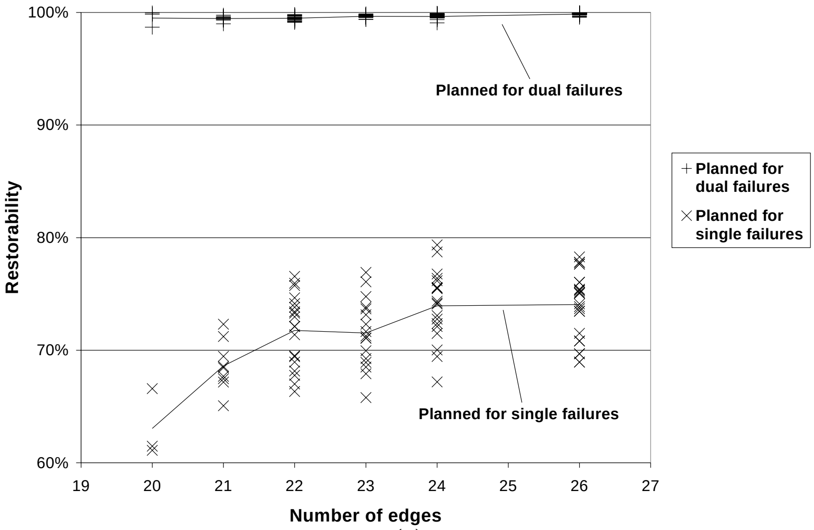


(a)

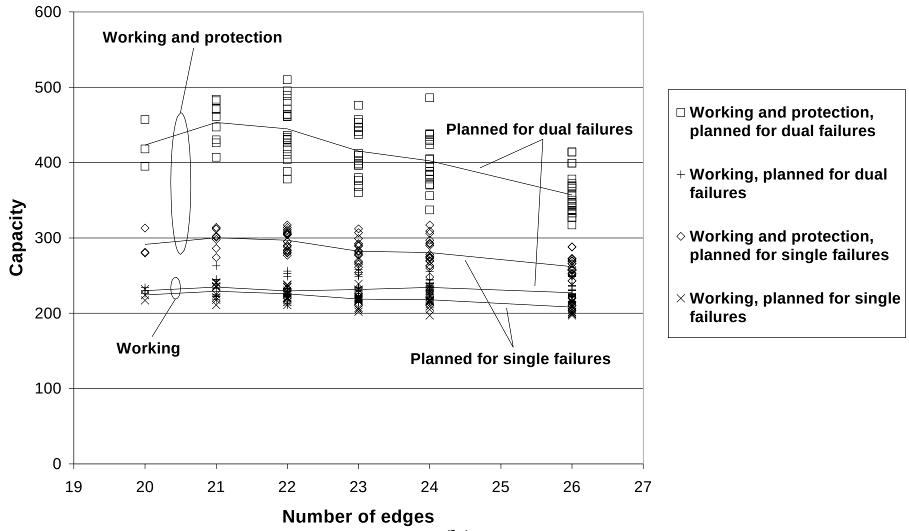


(b)

Figure 12: Shared path protection: Double failure restorability (a) and capacity (b) of random networks with 20-26 edges, planned for single and double failures. The points of each planning scenario are the results of 92 random instances and the curves connect the mean values.



(a)



(b)

Figure 13: Rerouting (with stub-release): Double failure restorability (a) and capacity (b) of random networks with 20-26 edges, planned for single and double failures. The points of each planning scenario are the results of 92 random instances and the curves connect the mean values.