On the availability and capacity requirements of shared backup path-protected mesh networks

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Abstract
The shared backup path protection (SBPP) approach to Optical Internet survivability uses GMPLS and other data-centric control principles for on-demand establishment of protected lightpath services. SBPP uses pre-determined backup routes on which spare capacity is shared with other failure-disjoint working paths. It is therefore of interest to consider how the service availability in SBPP depends on the total capacity and the amount of sharing allowed in establishing the protection arrangements. We provide methods for the analysis of the dual-failure restorability and related availability considerations in SBPP as well as methods to optimize SBPP capacity requirements with explicit limits on the number of primary service paths that are allowed to share the same backup link. We also set the SBPP results in some context relative to other recent work by providing comparative results on the dual-failure restorability of SBPP and span restoration on the same test cases. In considering SBPP from a general standpoint of availability considerations we also provide a comparative discussion that helps clarify and refine some of the current perhaps over-simplified general notions about protection versus restoration schemes in general.

1 Introduction
The necessity of capacity design, provisioning, and re-routing mechanisms for network survivability is widely recognized today. In recent years two issues of this magazine have been devoted to the topic, recognizing survivability considerations as being a fundamental aspect of optical network design [1,2]. Other research over the past decade has considered a variety of approaches including rings, span- and path-restorable networks, and more recently p-cycles [3-12]. Another popular and practical recent idea is that of shared backup path protection (SBPP) [13,14]. SBPP is like path restoration without stub release and with a single pre-planned backup route for each working path. Conversely it can be thought of as arranging a set of 1 + 1 diverse protection paths but keeping the spare links on the backup paths unconnected and shared with other 1 + 1 setups, with connection occurring as needed upon failure. SBPP has the desirable properties of being an end-to-end path-replacement scheme, and by forgoing re-use of surviving stub capacity, fault detection and switchover
are simplified. In addition the scheme is quite amenable to GMPLS-type path provisioning with survivability arrangements made at provisioning time in the service layer itself. The SBPP paradigm has been studied extensively in the optical networking literature in the past few years. To our knowledge, however, one aspect of SBPP that is not so well known yet is how high its service availability is, and in particular how it compares to other schemes in terms of resilience against dual failures, the predominant source of unavailability in a survivable network design [4,19]. As a protection-type scheme, its backup route is fixed. In addition as a path-oriented scheme, its backup routes are relatively long. Both of these characteristics suggest that it may provide lower dual-failure resilience (and hence availability) than span restoration which acts more locally in response to each failure and which is capable of both a pre-planned response to a single failure and an automatic adaptive response if needed to a dual-failure scenario [19,20]. It would therefore be useful to provide methods to analyze the dual failure restorability of SBPP. That is the primary contribution of the paper but the paper also provides a comparison of SBPP to span restoration in terms of dual failure restorability and explores the capacity-availability trade-off for SBPP if explicit limits on the sharing of spare capacity are introduced to enhance the dual-failure recovery levels.

1.1 Outline

Section 2 provides needed background to both motivate the conduct of this work and provide technical background on the SBPP scheme and the process of dual-failure restorability. This section includes a hopefully clarifying discussion about how notions of protection and restoration need to be extended or refined somewhat to fully reason about SBPP and span restoration characteristics from a speed and availability standpoint. It is not as simple as believing that a “protection” scheme is automatically faster and hence higher availability than a “restoration” scheme. Section 3 is then devoted to a capacity placement formulation for the optimal design of the SBPP networks that are tested in this work. Section 4 presents the theoretical and experimental approaches of our method of analyzing the impact of dual failures in these SBPP-protected networks. Sections 5 and 6 provide the experimental results obtained for optimal design of three families of test networks and their comparison to span-restorable network designs. Section 7 proposes a modification to the capacity design of SBPP networks to minimize the impact of dual failures by control of the maximum shareability of spare capacity and examines the trade-off between the total capacity requirements and the containment of dual-failure effects. Section 8 concludes the study with a brief discussion of findings.

2 Background

2.1 Setting the stage: clarifying protection and restoration, speed, and availability

Let us first appreciate some of the differences between protection and restoration schemes, and refine the popular classifications a bit. The term protection derives originally from automatic protection switching (APS) systems. Originally the notion of protection was that provided by a 1 + 1 APS system, in which the switching actions to make use of the protection system are completely pre-defined and the protection system itself is also fully connected and in a pre-tested, ready-to-use state. The working system is said to be protected, as opposed to restorable, in these circumstances. If a 1:1 APS is involved, then signalling is required to request the head-end bridge and to bump any “extra traffic” off of the spare-span. In addition the received signal on the protection system has to be tested in real time for correct transmission of the bridged signal. Here, the protection route is completely pre-defined but capacity seizure and a head-end bridge connection is needed in real time to access the protection signal path. In this regard UPSR rings are similar to 1 + 1 DP APS and BLSR rings correspond to 1:1 DP APS. The term protection is now generally used for both these schemes and schemes where the protection route is known ahead of time, but multiple hops of capacity seizure and cross-connection remain to be accomplished in real time, such as in SBPP. The main difference in (pure) restoration is that the replacement paths to re-route the payload signals are both found and cross-connected in real time when the failure occurs. Thus, we would say that in a pure protection scheme, the backup paths are completely dedicated and ready to use immediately and in a pure restoration scheme all redundant resources are held in a shared pool until configured on demand for restoration against a specific failure that arises.

For several reasons, including competitive positioning, the classification of actual schemes as either protection or restoration seems, however, have become rather over-emphasized and over-simplified. Part-and-parcel with this trend towards simple classification seems to be an almost axiomatic assertion, which warrants challenging, that protection schemes are automatically fast and restoration schemes are automatically slow. This is a far too simplified view from at least two important standpoints. First, if service availability is what matters to customers, it is not the switching time in response to single failures that matters as much as the ability to recover from dual failures that is most important. This is easily seen with a simple application of the well-known expression $A = \text{MTTF}/(\text{MTTF} + \text{MTTR})$: Using typical mean time to failures (MTTF), set the restoral time as the mean time to repair (MTTR) and compare (1-A) in seconds per year for 50 ms versus, say, 2 seconds. The difference in unavailability is completely insignificant. On the other hand, the impact on availability if MTTR is, instead of just the switching time, half of the physical repair time of
a cable, arising from the inability to protect against dual failures, then the impact is severe. These are issues that have been developed in more depth in [19,20]. The upshot is that the recovery levels against dual failures are far more important to availability that the immediate speed of response to single failures.

Secondly, even though the speed of switching is not actually important to the service availability (across any likely range of argument from 50 ms to 2 s), it is an impact measure of concern in its own right. But in this regard the somewhat axiomatic assertion that restoration is necessarily slower than protection does not hold up in light of the always-present relationship between a restoration scheme and a corresponding pre-planned protection scheme, which is derivable from it, and constantly updated, through distributed pre-planning (DPP). Under DPP a distributed restoration mechanism (or strictly even a centralized computation system) is used to repeatedly and autonomously pre-plan fast protection reactions to any single failure. These pre-plans record the simplest possible local information of what spare links each node needs to cross-connect, as fast as possible, in response to a simple flooding advertisement of the failure notification. Even if path-finding is slow, it is of little concern because distributed pre-planning does this before failure and can create (and frequently update) the protection plans. Thus the speed of path-finding is completely decoupled from the real time speed of reaction. The concept is described more fully in [15,16]. Its main significance is that, like SBPP, it provides for a fast pre-planned protection reaction to any single failure. Unlike SBPP, however, it has the added advantage that the option to fall back to on-demand use of the adaptive distributed restoration process is always there, on-call, if needed to maximize the restorability in the face of dual-failures, or in any situation where the pre-planned response did not yield the desired recovery level. This permits a very robust integrated strategy of first-failure: (pre-planned) protection, second-failure: (adaptive) restoration. In contrast, with SBPP, if a prior failure or a certain maintenance action on another span thwart the access to the one pre-planned backup, there is no automatic secondary response that can recover adaptively in under a second or so. There may be some sort of slower secondary response, for instance an applications layer path re-establishment process, but a severe impact on services is sustained if the predetermined backup path is not immediately available for the planned protection action.

In this regard DPP-based pre-planned span protection responses to single failures are categorically the same as SBPP in that (i) protection routes are fully known ahead of failure, but (ii) capacity remains to be seized and cross-connected on multiple hops in real time. Span restoration with DPP and SBPP are thus actually in the same category of scheme when it comes to single failures. And neither is a pure protection scheme or a pure restoration scheme, so as to be confidently predicted to be either automatically fast or slow. We think they are more properly recognized as an important intermediate category of scheme where routes are known, but multi-hop capacity-seizure and cross-connection remains to be done in real time. Thus, while a generalization that pure protection can always be faster than pure restoration, no such generalization is warranted for the intermediate schemes relative to either of the pure categories.

Finally, on the speed issue, the apparent conclusion that restoration must be a relatively slow process, seems to be based on thinking that one could only do restoration with OSPF-TE/GMPLS type explicit routing processes: processes that are high in the protocol stack and very software and database intensive. But that is not the only approach: In the 1990s it was well validated [15-17] that very simple logical-layer state-based signalling interactions between finite state machines in each node could self-organize efficient pathsets for restoration (or provisioning) without any database dependencies or any global topology information. SONET with GFP, or Digital Wrapper, or Optical Service Channel techniques all provide means to support the same kind of signalling on a per-lightwave channel basis now in optical networks. Such lower-level self-organizing interaction is based on nodal rules that require only tens of kilobytes of source code and spontaneously form maximal feasible pathsets in the spare capacity, in parallel, as a pattern-formation effect, in only hundreds of ms. Thus, while SBPP provides attractive, but software-intensive, options for those who only have access to the service-layer, operators of facilities-based networks and their equipment vendors may find attractive and availability-enhancing options with self-organizing span restoration in the logical channel layer, used for both pre-planned single-failure protection reactions and on-demand adaptive response to higher-order failures.

2.2 How SBPP works

SBPP can be thought of as an extension of 1 + 1 diversely routed automatic protection switching (1 + 1 APS) where the capacity used to form protection paths is shared over failure disjoint primary paths. Because of the sharing however, SBPP is much more capacity efficient than 1 + 1 APS while utilizing a protection mechanism nearly as simple to employ from the standpoint of an end-node in the service layer. The problem of finding efficient fully disjoint or span-disjoint backup routes for each primary route is treated extensively in [18]. Fig. 1 illustrates the concept of spare capacity sharing on pre-defined backup routes. In Fig. 1, O-D pairs AB, CD, EF, and GH use primary working paths that are mutually disjoint, and are therefore all allowed to have backup links in common (span XY), since (for single failures) no two of those O-D pairs will require those spare links at the same time. The SBPP restoration mechanism requires a signalling phase from each tail-end switch to confirm availability of
the backup route and to seize and cross-connect capacity to activate the backup path. SBPP can be considered to be failure-independent path protection because the route of the backup path is the same regardless of where a failure might arise on the corresponding primary service path. This simplifies the signalling requirements to activate the backup path. It has also been shown that since restoration is performed between the O-D pair nodes instead of between the failed span's end-nodes, SBPP is slightly more capacity efficient than span restoration restoration [7,8], although on very sparse topologies a technique of establishing express-route bypasses on chain subnetworks can make span restoration almost as efficient as SBPP [7,8].

### 2.3 Motivation for dual-failure considerations

In motivating this work, it is worth stressing that lest the interest in dual-failure situations seem rather arcane and unlikely to arise in the real world, there are two contexts in which we find industry colleagues generally very interested, concerned even, about dual-failure issues. One is that, depending on technical details, putting a span in a maintenance state can often amount to withdrawing its spare capacity from the network or may even require mesh-like re-routing of its working capacity around the maintenance span. Maintenance for in-service upgrades etc., can be fairly frequent and is functionally similar to a first failure in a theoretical dual-failure situation [22,23]. The other ongoing concern is of a hidden or unknown shared-risk link group (SRLG) [24,25] the result of which is that a single physical failure can expand into two (or more) simultaneous failures in the logical architecture which were previously assumed to be statistically independent.

In addition customers are interested in the service availability they can expect and may even insist on a Service Level Agreement (SLA). And yet what is it that will determine availability once we have designed-in measures against all single failures? Obviously zero unavailability is not expected; it is dual-failure situations that will come up next to dominate availability in these circumstances. There is therefore abundant interest, both practical and theoretical in understanding the impact of dual-failure situations on survivable networking schemes, of which SBPP is the most prominent current technique.

The idea here is not, however, to design to withstand dual failures, as has been the goal in related work [21] that might seem to suggest that ambition here. Rather, our scope is only to continue to design for survival of services against all single failures, but to then analyze how the resulting network withstands all dual-span failure combinations given the investment in single-failure survivability. Later, however, we will consider a small change in the design method so as to enhance the dual failure restorability through sharing limits. These kinds of studies have recently been conducted in some depth for span restoration [19,20] with unexpected findings and it seems quite timely to apply some of the analogous questions to the even more popular SBPP scheme.

### 2.4 Defining the dual-failure restorability of survivable network designs

Not surprisingly making a network restorable to single span failures brings a considerable improvement to the availability of service paths [19]. The main improvement is due to the fact that single span failures no longer contribute to service unavailability. But rather surprisingly, we saw in [19,20], that at least in span-restorable networks, the availability benefit is also due to the fact that service paths are also protected against many multiple-span-failure scenarios as a side-effect of the single-failure restorable capacity design. In general, therefore, to evaluate the availability of service paths in a survivable network design one needs to analyze the way a given survivability mechanism will react to multiple failures. In practice, however, amongst multiple failures, dual span failures are the ones that contribute the most service outage, so studying this type of failure provides a good comparative estimate of the availability of service [19].

To quantify the reaction to a specific dual failure of span a and span b we define the dual-failure restorability of the affected service paths $R_2(a,b)$ as:

$$R_2(a,b) = 1 - \frac{N_{nr}(a,b)}{N_{aff}(a,b)}$$

where $N_{nr}(a,b)$ is the number of non-restorable service paths during the dual failure of span a and in the presence of failure on span b, and $N_{aff}(a,b)$ is the number of demands affected by dual failure of span a and span b.

If $R_2(a,b)$ is known for every dual span failure (a,b) then it is possible to determine the end-to-end availability of a given service path $p$:

$$A_p = 1 - \sum_{\text{all dual span failures } (a,b) \text{ affecting } p} p(\text{failure state } (a,b)) \cdot (1 - R_2(a,b))$$

$$= 1 - \sum_{\forall (a,b) \in p} U_a U_b \cdot (1 - R_2(a,b))$$
The unavailability of a span, $U_a$, and hence the probability of dual-failure restorability, is measured directly by the expression that the probability of finding a given path down (due to dual failures) is the likelihood that a dual span failure state exists in the first place, times the likelihood that if it does, that the particular path is not restorable, i.e., $1-R_{s}^{2}(a,b)$, under that scenario. The unavailability of a span, $U_a$, and hence the probability of a dual span failure state existing at any time depends on numerous network- and equipment-specific details such as span length, mean time between fiber cuts per unit length, mean time to repair fiber, etc. These are data that can change with every network context, however, and are best embodied in specific planning tools or assigned by network planners in their own companies. In other words, each $U_a$ value is always computable by standard means of transmission system availability engineering, without any dependence on overall network architecture of survivability schemes. What is fundamentally dependent on the basic choice of logical architecture and survivability scheme is the $R_{s}^{2}(a,b)$ values in Eq. (1). So for more lasting generality and insight about the networking strategy itself, it is actually the measure of dual failure restorability $R_{s}^{2}(a,b)$ that we characterize in the study. It can always be related to service availability through Eq. (2). Moreover, however, $R_{s}^{2}(a,b)$ itself has the direct practical interpretation of answering the question: “on the average (or on a specific) dual-failure combination, what fraction of affected demands will experience a service disruption?” In effect all that Eq. (2) adds are the implications due to consideration of the probability of occurrence and expected duration effects of the outage. But the number magnitude of the dual-failure impact is measured directly by $R_{s}^{2}(a,b)$. For more on the relationship between availability, unavailability, and $R_{s}^{2}(a,b)$, and to see how Eq. (2) is developed with more steps, see [19].

3 Design of Shared-Backup Path Protected Networks

Our SBPP network design method is based on Integer Linear Programming (ILP). This produces a minimum-capacity design result for a given demand matrix. We recognize the view that demands may arrive and depart randomly but our present purpose is to obtain insights about the basic properties of SBPP, so a practical way to proceed for research purposes is to employ optimal designs produced to suit static demand matrices. The assurance of near-optimality of the designs is important not because we argue it is necessary in practice but because in research this allows us to view networking phenomena or architectural truths with “clear glasses.” In practice it is usual to assume procedural heuristics can be used, although on many real networks repeated solution of the optimal update or incremental configuration change problem is actually quite feasible too. But in research, to know what is fundamentally true about various basic schemes, we need to remove all effects that might be due only to the heuristics used to design the test case alternatives. Designs using optimization methods give test cases having this assurance regarding any comparative conclusion that is drawn.

The SBPP model follows the approach to capacity allocation used by Herzberg et al [5] for the optimal spare capacity design of span-restorable networks. The basic approach views the problem as one of assigning restoration flows to distinct eligible routes over the network graph. In practice this approach is desirable so that backup route properties can be under engineering control for length, loss, or any other eligibility criteria. In these designs we assume primary service paths have already been routed via shortest paths. In a small number of cases where no disjoint backup route was feasible after routing the primary on its shortest path, a change was made to the primary route to resolve the infeasibility, equivalent to finding the shortest cycle containing both end nodes. Once primaries are routed and a set of possible backup routes identified for each, the optimization goal is to choose one specific backup route for every primary service path so as to minimize the total cost of spare capacity on the network. The design model is:

\[
\text{SBPP: Minimize } \sum_{j \in S} s_j \cdot C_{j} \cdot L_{j} \tag{3}
\]

Subject to:

\[
\sum_{b \in R_{j}} x_{j}^{b} = 1 \quad \forall r \in D \tag{4}
\]

\[
\sum_{r \in D} \sum_{b \in R_{j}} x_{j}^{b} \cdot d' \leq s_{j} \quad \forall (i,j) \in S \times S : i \neq j \tag{5}
\]

\[
0 \leq x_{j}^{b} \leq 1 \quad 0 \leq s_{j} \quad x_{j}^{b}, s_{j} \text{ integer} \tag{6}
\]

Here, $s_{j}$ is the number of spare links or wavelength channels required on span $j$. $C_{j}$ is the unit-length cost per wavelength placed on span $j$, $L_{j}$ is the length of span $j$, and $S$ is the set of all spans in the network. Constraint set (4) asserts that only one backup route $b$ per demand pair $r$ is allowed. $s_{j}$ is a 1/0 decision variable taking the value of 1 if backup route $b$ for demand pair $r$ is used, and 0 otherwise. $R_{j}$ is the set of eligible disjoint backup routes for demand pair $r$, and $D$ is the set of all O-D pairs exchanging some amount of working demand. Constraint set (5) assigns sufficient spare capacity on each span to accommodate all backup paths simultaneously crossing the span for failure of any other span, $D$, is the set of O-D pairs affected by failure of span $i$, $R_{j}$ is the set of backup routes for demand pair $r$, and $d'$ is the number of wavelengths of traffic exchanged between O-D pair $r$.

A technical challenge with the above formulation is that if one enumerates all possible backup routes for each primary, exact solution of the problem can become impractical because of the large number of $1/0 \cdot x_{j}^{b}$ decision
variables. This is addressed in practice by budgeting a reasonable number of eligible backup routes per working path, typically 5 to 20 say of the next-shortest disjoint routes as backup route options for each primary. Extensive testing varying the number of eligible routes and trials to compare against results for small cases where completely optimal designs are found gives considerable confidence that the resulting designs are within a few percent of optimal.

Another aspect of the SBPP design model above is that in the context of an optical lightpath-managed network it is a capacity-only or virtual wavelength path (VWP) design model which assumes that wavelength conversion is available to facilitate access to needed capacity on each span. This is based on many other studies, such as [26] and [27], with findings indicating that allowing wavelength conversion in a few selected nodes, or, having a small pool of wavelength converters at each node effectively removes the issue of wavelength “color clash.” Secondarily, it can also be appreciated that as the number of wavelengths supported by DWDM technology increases, any remaining differences in capacity and routing between WP and VWP designs tend to vanish (because unresolvable colour clash type blocking situations become insignificantly small in the pure WP case). In other words, if a large enough number of wavelengths are available to choose from, we can always construct a WP design that is equivalent to VWP. These considerations allow capacity design without having to consider explicit wavelength assignment.

4 Analyzing the Impact of Dual Failures on SBPP

In this section we identify the different scenarios that can lead a given service path protected by SBPP to experience outage. We limit this to considering the most likely scenarios or single and dual span failures.

<table>
<thead>
<tr>
<th>Failure Category of Failed Span 1</th>
<th>Location of Failed Span 2</th>
<th>Outage for SBPP</th>
<th>Outage for 1 + 1 APS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 P1 P1</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>2 P1 P2</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>3 P1 Elsewhere</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>4 P2 P1</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>5 P2 P2</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>6 P2 Elsewhere</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>7 Elsewhere P1</td>
<td>Case dependent</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>8 Elsewhere P2</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>9 Elsewhere Elsewhere</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Different dual-failure types from the point of view of a specific service path.
detailed inspection of all the paths affected by the first failure, and of the capacity that their backup paths are subsequently consuming, is needed to conclude whether a primary service path affected by the second span failure is left exposed to outage or not. Thus a computer-experimental approach has been developed to accurately determine the impact of dual span failures on networks protected by SBPP and follows in Section 4.2. Note in passing that, based on the simple observations in Table 1, the availability of service paths with $1 + 1$ APS is an upper bound on the availability of paths with SBPP.

4.2 Experimental method

The experimental approach for the analysis of the impact of dual span failures assumes there is no priority for the order in which individual demands are restored in cases where it is not possible to restore all affected demands. So when restorability levels are analyzed, we restore affected demands in a random order. In the case of an initial span failure, this usually makes no difference since all service paths are guaranteed availability of their backup path. For the secondary span-failure however, the order in which service paths are considered can influence which of these are restored and which are not. Here the results average over an assumed single priority class of service. This is an easily changed detail in the computer method if specific priority scheme assumptions were to be applied in actual planning studies.

The dual-failure restorability calculations take as input the set of demands, a description of the routes for primary and backup paths used for each demand, and total spare capacity on each span (arising from the SBPP design model). Fig. 2 gives the algorithm for the analysis of the restorability of demands to dual span failures. The two failures are denoted $a$ and $b$. The first step checks the restorability of service paths to the failure of the first failed span. For each service path the algorithm verifies that enough spare capacity is available along the corresponding backup path (as defined in the SBPP design) and seizes the required spare capacity. This is repeated until all affected service paths have been considered. The first step thus serves as a validator of single-failure restorability of the initial design and more importantly forms the single-failure restored network contexts within which a second failure’s effects are to be considered. Step 2 considers the second failure, span $b$, and determines if any of the demands (from Step 1) that are currently on their backup routes are hit by the second failure. If so, these demands are marked as failed. Step 3 then considers whether the backup paths for new demands affected by failure $b$ can access their backup paths given the existing spare capacity usage from step 1. The process is actually identical to the first step but occurs in the presence of the removal of spans $a$ and $b$ from the graph and the removal of spare capacity used in step 1.

5 Experimental Results

The SBPP capacity design model in Section 3 (and the modified method to be introduced in Section 7) were implemented in AMPL and solved with the Parallel CPLEX 7.1 MIP Solver on a 4-processor Ultrasparc Sun Server at 450 MHz with 4 GB of RAM running the Sun Solaris 8 Operating Environment. The results are based on a full CPLEX termination with a MIPGAP under 0.01 (i.e., solutions are provably within 1% of optimal). A number of other aspects were common to all designs and their solutions. All working and spare capacity allocations were integer, corresponding to capacity design and restoration mechanisms at the wavelength channel level. Lengths of spans are taken as the Euclidean distance between each span’s end-nodes within the plane of the graph. In other words relative span distances are as they
appear in the figures that follow. All costs are assumed to be proportional to the length of the span and the number of links or wavelengths placed on the span. For comparative studies we avoid any modularity assumptions which could obscure the general underlying comparison of methods that is intended, although the models can easily be converted to a modular formulation as in [28].

Tests were conducted using three test network families, each family consisting of a master network and a series of progressively sparser networks derived from the master as in [7]. The network families were produced by starting with a master network and incrementally removing one span at a time (by random selection), subject to retaining bi-connectivity. Family-A networks are based on a 20-node 40-span master network, Family-B networks are based on a 25-node 50-span master, and Family-C networks are based on a 30-node 60-span master, all shown in Fig. 3. Conducting tests on such families of networks allows us to investigate how our phenomenon of interest relates to a network's connectivity while avoiding complications in comparison between networks with very different topologies. We use three different families to validate our findings and show their consistency through a variety of topology configurations. The master networks are all of average nodal degree 4.0 and provide sample networks down to about degree 2.6. Real networks are known ranging from at most about 4.7 down to 2.3, so most of this range is covered. A specific network from one of these families is denoted by its family letter and the number of spans it contains. For instance C-50 is the 50-span member of the family of successively sparser networks derived from the C master network of 30-nodes and 60-spans.

All networks were tested with a full-mesh configuration of demands (i.e., every node-pair exchanged traffic), with each demand drawn from a discrete uniform random distribution from 1 to 10 (inclusive) lightpath requirements. Demands were generated once for each master network and the same demands for each O-D pair were reused for the other members of each set. The SBPP capacity designs were also formulated with the set of five shortest distinct eligible route choices (by span-length) for possible backups on each O-D pair. Out of the 45 test case networks studied, only one network (C-46) exhibited disjoint path infeasibilities, for three O-D pairs. For these three O-D pairs only, we modified the shortest path algorithm to choose the shortest route for which at least one disjoint backup route exists, effectively repairing the infeasibility.

6 Comparison of Dual-Failure Restorability in SBPP and Span-Restoration

In Fig. 4 to Fig. 6, we compare results of dual-failure scenario analysis for the SBPP designs and with a span-restorable design. For space, the design of the span-restorable reference networks is referred entirely out to sources where this is already documented in detail such as [5-8]. However, the span-restorable designs serve the identical demand patterns, have working paths shortest-path routed, and use the set of eligible routes for restoration of each span failure up to five hops long. The dual-failure restorability of the span-restorable designs is logically the same as here for SBPP but with differences corresponding to the span restoration mechanism as opposed to the end-to-end switchover to a backup path. Specifically, we assume the partly adaptive model for restoration behaviour that is described in [19,20]. Basically the second failure response is adaptive to the spare capacity usage of the first but if the second failure hits restoration paths of the first failure they are not re-restored. In the fully adaptive model for span restoration $R_2(a,b)$ is even higher, but the partly adaptive model seems like the fairest comparison to make against SBPP.

Fig. 4 shows the average dual-failure restorability $R_2(a,b)$ for both restoration schemes for all the test case network families plotted against the corresponding average nodal degree. Two main observations can be made. First, we have the finding that for SBPP on average about 70-80% of all service paths would withstand a dual failure
that affected them, over almost the whole range of network average nodal degree. Secondly, the restorability of dual span failures is significantly (approximately 20%) lower for SBPP than for span restoration. We can also see a modest but clear trend that as the connectivity increases the dual-failure restorability improves for both schemes. We think the surprisingly constant nature of these curves is due to the two counteracting factors. One is the shortening of the working routes. With more spans in the network, there is a decrease of the number of service paths crossing each span and each path is exposed to fewer spans, so the average number of affected service paths for dual failures decreases. This by itself should tend to improve the average $R_2(a, b)$. However, the second factor is the diminution of the spare capacity as nodal degree increases and both forms of mesh-restorable network become increasingly efficient. This by itself will tend to decrease the dual-failure restorability $R_2(a, b)$. Evidently, the opposition between the two factors seems to nearly balance, but the first effect (shortening of primary routes) seems to win out slightly overall. Note that these curves present the average dual-failure restorability over all possible combinations of span pairs.

In contrast Fig. 5 and Fig. 6 let us see sample distributions of the individual dual-failure restorability outcomes. The Family-B networks with 37 spans (network
B-37) and 50 spans (network B-50) are chosen for these exhibits. These are the most sparse and most richly connected Family-B networks, respectively. The distributions are, however, quite representative of all the other test networks studied. Both distributions show that most individual dual-failure scenarios have a very low or often (80% of the time in B-37) no impact at all under span restoration. The only cases where \( R_2(a, b) = 0 \) correspond (in both SBPP and span restoration) to dual failures isolating a degree-2 node. In contrast a dual span failure is more likely to cause a loss of demand in SBPP. To relate things together, the mean values of the distribution plots of type Fig. 5 and Fig. 6 are the data points of Fig. 4.

7 SBPP Design with Controlled Maximum Sharing

As seen in Section 6, the impact of dual span failures on service paths protected by SBPP is significantly higher than average with span restoration. In Section 4 we explained that one of the factors that contribute to the unavailability of paths protected by SBPP is the fact that (unlike with 1 + 1 APS) spare capacity can be shared between several service paths. Based on this observation, we now investigate the possibility of reducing the impact of multiple failures on the availability of service paths in SBPP networks and examine the trade-off between resilience to dual failures and spare capacity requirements.

7.1 Designing to limit the sharing of spare capacity

The formulation in Section 3 does not include any particular constraint concerning the number of service paths that are allowed to be assigned to the same unit capacity of spare capacity. The only underlying consideration even affecting sharing is that spare capacity cannot be assigned to the restoration of two paths that have a span in common in their working paths. Therefore it is possible that some spare wavelength channel could be shared by say 10 or more service paths, provided all of these service paths are routed through mutually disjoint primary paths.

From Section 4, one significant class of outage-causing failures is when a service path affected by a fiber cut cannot be restored because part of the spare capacity along its backup path has already been used for the first-failure protection of another service path. In this light it appears that it would be desirable to restrict the amount of sharing an individual link may tolerate. Allowing fewer service paths to share the same spare capacity should reduce the probability of a situation such as the one described above, albeit possibly at the expense of capacity depending on how much we restrict the sharing. Thus we propose adding the following constraint to the SBPP formulation:

\[
\sum_{d' \in D} \sum_{j \in R_j} x_{j, d'} \leq s_j F_j \quad \forall j \in S
\]

This ensures that the sum of all backup routes crossing span \( j \) must be no more than the number of spare wavelength channels on the span multiplied by \( F_j \), the maximum shareability factor for that span. For instance, say in total, there are 10 spare channels on span \( j \) who we wish individually to be shared by at most two different primary paths. If there are no more than 20 backup routes which cross that span in the entire design, then the capacity to “bookings” ratio will be 2, (or less) as intended.
7.2 Experimental results with sharing limits

There are two expected effects to adding constraint set (7) to the SBPP formulation. We expect that dual span failures will have a reduced negative impact on path availability (a desirable result), and that capacity requirements may increase as a consequence. Fig. 7 to Fig. 9 confirm, but also quantify, both effects. On the left each figure shows the average dual-failure restorability $R_2$ versus design sharing limit. On the right each figure shows that the percentage of all network demands that suffer outage (i.e., are unrestorable) averaged over all dual span failures versus the sharing limit for selected test networks. As expected, when sharing limits are very restrictive, it is less likely that a service path affected by a dual failure will be unrestorable. However, as we “loosen the reins” on allowable sharing, more and more demands will be unrestorable to dual-failure scenarios, indicating that it’s more likely that backup routes employed to restore an initial failure will make use of shared capacity needed to provide backup routes for a second failure. The right hand plots have to be correctly understood. These are not just a flipped and blown up view of the left-hand plots. These curves show the average fraction of all demand in the

![Figure 7: SBPP dual-failure impacts versus sharing relationship limits curves for optimally designed Family-A networks at various nodal degrees.](image)

![Figure 8: SBPP dual-failure impacts versus sharing relationship limits curves for optimally designed Family-B networks at various nodal degrees.](image)
network that is lost due to a dual-failure scenario. An interesting finding is that when sharing limits are set higher than 5, the curves become effectively flat in the networks tested, meaning that sharing restrictions must be quite strict before any resiliency-related benefit is produced. In other words, we must use sharing limits of 3 or less (in most cases) for any real benefits in dual-failure restorability. Also notice that clearly, the minimum value we can set for sharing limits is 1 which correspond exactly to $1 + 1$ APS design where all backups consist of dedicated spare capacity. Note that even with sharing limits of 1 ($1 + 1$ APS), the dual failure restorability does not reach 100% because all dual failure combinations that hit one span on the primary and one span on the backup are still outage-causing even without sharing.

Fig. 10 to Fig. 12 confirm the second expected effect, that putting restrictions on the maximum amount of spare capacity sharing will increase capacity requirements. These figures show capacity costs versus sharing limits for the specified network. Capacity is the distance-weighted number of spare wavelength-channels including both primaries and backups. Over the three test network families, the cost of designing the networks with no sharing at all (sharing limits of 1) was on average 85% greater than the
design cost if we allowed just two primaries to share the same backup capacity. This is a strong indicator of the efficiency benefit of SBPP relative to 1 + 1 APS, even if only two primaries can share. Going from a sharing limit of 2 to a sharing limit of 3 reduced the design cost an additional 23% on average. Interestingly, allowing more than three times sharing provides only a very small further improvement (5% on average). This suggests that network designers could limit spare capacity sharing to three or four O-D pairs per spare wavelength and with minimal capacity cost penalty.

Finally, Fig. 13 to Fig. 15 illustrate the overall trade-off between network capacity requirements and the dual-failure restorability under varying sharing limits. These curves are parametric plots of capacity versus the complement of $R_2$ (the unrestorability) generated as the sharing limit increases. Starting at the right end of a curve (representing a design with no sharing allowed) and moving left, we see the decreased capacity requirements result in increased unrestorability. The “elbow” effect that is evident in virtually every curve, corresponding to a take-off in outage at sharing limits of 2 or 3, suggests that a network designer might choose to restrict sharing to one of those two values to get a most cost-effective trade-off between capacity consumption and containment of outage due to dual-failure effects.

8 Concluding Remarks
We have developed a method of assessing the resilience of shared backup path protected networks with respect to dual span failures. Results show that the resilience of an
Figure 13: SBPP dual-failure un-restorability versus total capacity for selected Family-A networks.

Figure 14: SBPP dual-failure un-restorability versus total capacity for selected Family-B networks.

Figure 15: SBPP dual-failure un-restorability versus total capacity for selected Family-C networks.
SBPP network is significantly lower than that of a corresponding span restorable network. A modification to the SBPP design methods, to limit maximum sharing relationships, can improve the dual-failure restorability at a cost in capacity to serve the same demands. When we combine the effects of backup capacity sharing and capacity costs in the form of trade-off curves we obtain a guideline that suggests limiting SBPP shareability to at most 2 or 3 primary paths per spare channel. This results in most of the enhancement of dual failure restorability, and hence average service path availability, without causing a significant take-off in capacity requirements.

9 References


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