On the Efficacy of GMPLS Auto-Reprovisioning as a Mesh-Network Restoration Mechanism

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Abstract—GMPLS provides standardized protocols through which nodes can request and establish (or release) lightpaths on demand between themselves and peer nodes. The primary intent is to support automated provisioning for dynamic demand environments. But an apparently tempting assumption is that GMPLS therefore also provides a mechanism for physical layer network restoration, wherein all affected node pairs “simply re-dial their connections”—simultaneously. We argue from basic considerations and illustrate with experimental results, that this is an oversimplified view. It assumes that the problem of replacing a failed path is the same when the path fails in isolation and when numerous paths fail together from a cable cut. Without some form of preplanning or overall coordination of the multiple simultaneous reprovisioning attempts in the latter case, no guarantees are possible about the overall extent or pattern of recovery level. Capacity over-provisioning can mitigate the risk but may involve almost as much overprovisioning as would suffice for simple 1+1 signal duplication in the first place, which defeats one of the main aims (efficiency) of a mesh-oriented scheme.

Index Terms—Generalized multiprotocol label switching (GMPLS), mutual capacity, mesh restoration, transport networks, reconfiguration, network planning and optimization.

I. INTRODUCTION

W ith the advent of GMPLS [1], which can mechanize the process of path provisioning, and hence also path replacement upon failure, we have encountered a surprising number of colleagues in industry and academia, who assume that GMPLS therefore also offers a response to the problem of network restoration following, say, a cable cut [2,3]. To paraphrase, the notion is typically stated: “Restoration? – All you do is let everyone redial their path.” In this paper we hope to provide a timely clarification that this is a seriously oversimplified view. We do this by revisiting some basic concepts about multi-commodity flow problems and illustrate the issue in related simulations of the “mass simultaneous redial” approach. Our basic message is that while functionally mass GMPLS auto-reprovisioning will provide a form of restoration response, there is no assurance about the overall recovery level or pattern of recovery that will arise. This is a fundamental difference from prior proposals for protection or restoration, such as shared-backup path protection (SBPP), for example, which can provide explicit assurances of 100% restorability. Depending on who one talks with, a converse misunderstanding is also apparently common: that is the mistaken assumption that all forms of restoration are similarly unassured. When encountered, this view seems to be based on a simple assumption that any restoration scheme must be equivalent to a mass of individual blind re-attempts. There is, however, abundant literature on restoration schemes that achieve assured levels of restoration within a correspondingly planned environment of spare capacity, so we do not address that misunderstanding further here.

Let us start by considering the isolated failure of a single working path in a GMPLS-based network. Assuming a WDM network, the path end nodes recognize the failure by Loss of Signal alarms or by AIS inserted on the failed path by other nodes (nearer the failure) along the path [4,5,6]. In the shared backup path protection (SBPP) scheme, a pre-defined backup route (with corresponding capacity allocation) exists to replace the path whether it fails individually or as a result of a cable-cut, because the sharing of spare capacity on the backup route is coordinated with respect to the common-cause physical failures. Using GMPLS re-dial only, there is no such pre-planned backup route or spare capacity, only a belief that sufficient unused capacity will generally be available for a re-dial under a trunk-group like analogy to telephone calling. Most of the time, in most networks, it will be quite likely that a re-provisioning attempt can find a replacement path on-demand for a single failed path. The network as a whole is still essentially stable and intact and GMPLS can then reliably replace the single failed path with the next-shortest path through the graph of unused capacity. So everything is fine for a single isolated path failure and this, we think, is the real value of GMPLS re-dial as a restoration mechanism—to cope with single isolated path failures such as may arise from a single interface card failure.

The issue arises when this single-path replacement idea is extrapolated to be the basis of a network’s entire response to a cable cut. When a cable is cut (and this is the most frequent form of physical layer failure), an arbitrarily large number of service paths, involving a large fraction of all end-node pairs, fail simultaneously. In this case there are two sources of uncertainty about the overall outcome if every affected node-pair then pursues an independent GMPLS path re-provisioning attempt for each path failure that affects it:

(a) Message-handling behavior of nodes and protocols under the mass onset of concurrent, semi-synchronized, distributed, path re-establishment attempts occurring at the
same time that OSPF-TE type of link-state update information is being disseminated about the failure.

(b) Fundamental “mutual-capacity” allocation issues that affect the maximum restoration level that can be achieved even if there were no signaling issues and every O-D pair took an independent isolated attempt in to establish a shortest-surviving replacement path.

Point (a) is, in its own right, a significant issue that can greatly extend the restoration time and degrade the overall recovery success. The complete dynamics of the mass concurrent onset of all the relevant protocol instances, and the message handling and buffering ability of nodes coping with the suddenly huge messaging onset is fundamentally difficult to model. Constituent protocol instances of GMPLS, primarily OSPF-TE for state update and CR-LDP for path resource seizure will be running on the network simultaneously in large numbers. Opportunities for deleterious interaction between simultaneous CR-LDP instances seem particularly worrisome: one instance has reserved a wavelength on a span and is propagating back to complete its path, but it fails in back-propagation due to other instances of the CR-LDP being initiated. Meanwhile another path attempt may fail elsewhere because of the reservation on the first resource mentioned, which is then freed. Such failed CR-LDP attempts result in re-attempted connections between the host nodes, compounding the dynamic deadlocks, fall backs, and re-attempts. Signaling aggregation [7] could mitigate the effects but the overall dynamics remain very unpredictable in their worst case because temporary seizure, release, and network state update processes all operate concurrently, indirectly affecting each other in ways that these protocols were not designed to encompass. The exact sequence of dynamic signaling actions that occurs will depend on the precise time-delays between failure onsets and responses at each end node, exact message handling and queuing logic in each node, and the exact topology, distances, delays and failure that occurred.

On the other hand the considerations of capacity allocation, point (b), can be studied and alone can suffice to illustrate a fundamental problem with “mass redial.” These are fundamental limits to the recovery level that can be achieved if the effective sequence of path replacement attempts is not coordinated in any way. Thus, what follows is in a sense a study of the best-case limits to the performance associated with GMPLS “mass-redial.” The restoration performance that we will observe is based fundamentally on only the sequence-dependence of individual shortest-path attempt sequences within a finite amount of capacity. Actual performance could only further be reduced further by signaling congestion and contention expected in such a mass redial event.

To avoid confusion, we also need to separate the use of GMPLS as it may be employed to establish SBPP protection arrangements [7] and its direct use in real time to try to find the next-shortest replacement path for each failed working path. The concern is with the latter real-time use of GMPLS for mass simultaneous restoration path deployment, not with its use as a basic path-identifying utility at service provisioning time. Using OSPF-TE and CR-LDP constituents of GMPLS to arrange backup path protection in advance inherently does lead to a capacity-aware and failure-coordinated arrangement for sharing spare capacity upon failure. But this is significantly different than the direct reliance on OSPF-TE/CR-LDP in real time to attempt simultaneous re-establishment of all failed paths with no pre-planned reservation or sharing arrangements for capacity.

Section II provides background on the concept of multic commodity max-flow, which is an inherent issue in any mass simultaneous end-to-end path provisioning process. Section III details an experimental approach designed to simulate the possible outcomes of GMPLS auto-reprovisioning for restoration. Section IV applies the methods to three test networks of varying nodal degree and discusses the results. Unpredictable and often severe fluctuation in the overall and individual Origin-Destination (O-D) pair restorability is one of the major findings. This section also looks at the extent to which over-provisioning capacity could “buy one’s way out of the problem.” Section V concludes.

II. THE “MUTUAL CAPACITY” ISSUE

Any form of end-to-end path-oriented restoration inherently poses a form of a capacitated multi-commodity simultaneous flow problem [8]. In such a problem, flow requirements of different O-D pairs must be simultaneously satisfied within finite capacity on each edge of the graph. Any time capacity is efficiently allocated, this requires a set of carefully coordinated simultaneous route allocations. In a sense all the flows compete for the use of edge capacities in the network, especially for capacity on edges along their shortest paths. To assure an overall maximum flow (or in our case maximum restorability—where flow requirements are limited for each commodity), the decision about how much of each flow to route over each edge is coupled with that for every other commodity under the edge capacity constraints. This gives rise to what are called “mutual capacity constraints” in the formal model (to follow) for path restoration routing. This is the central issue that blind, independent, uncoordinated path re- attempt processes fundamentally cannot to take into account. If the capacity of one edge is allocated to the flow solution of one commodity, it changes the apparent network solution of the other max-flow sub-problems. From the standpoint of mutual capacity considerations the overall outcome of a mass-redial approach for restoration is thus the luck of the draw. The outcome will not be assured and will be completely dependent, in a very detailed way, on exactly which path attempt succeeds in seizing capacity on each network edge.

A. Path Restoration Routing (PRR)

Let us now look formally at the problem of path restoration routing. This not only develops the basic theoretical issue, but the model below is also used in our experimental work to validate that the test cases are theoretically capable of 100% restorability. We represent the network as G(N,E,s) where N is
the set of nodes, \( E \) is the set of spans, and \( s \) is the vector of spare capacities. The PRR problem given a failure scenario \( i \), is then defined in terms of \( D_i \), number of O-D pairs (lightpaths) that have lost one or more units of demand, \( P_i \), the set of all distinct routes between end node pair \( r \) excluding failure span \( i \), \( X_i \), the number of demand units affected on O-D pair \( r \), by failure \( i \). In addition \( \delta_{i,j}^{r,s} = 1 \), if the \( p \)th distinct route between node pair \( r \) after the failure of span \( i \) uses span \( j \), and 0 otherwise. Finally \( f_{i,j}^{r,s} \) is the restoration flow assigned to the \( p \)th distinct route between node pair \( r \), excluding the failure span \( i \).

\[
\text{PRR: Maximize} \left\{ \sum_{r \in D_i} \sum_{p \in P_i} f_{i,j}^{r,s} \right\} \quad (1)
\]

Subject to:

\[
\sum_{r \in D_i} f_{i,j}^{r,s} = X_i \quad \forall i \in E, \forall r \in D_j \quad (2)
\]

\[
\sum_{r \in D_i} \sum_{p \in P_i} \delta_{i,j}^{r,s} \cdot f_{i,j}^{r,s} \leq s_j \quad \forall (j) \in E \quad (3)
\]

The objective (1) maximizes the total of all restoration flow assignments to the different possible routes between each pair of affected nodes. It considers only flows for replacement of working paths that are affected in the failure scenario and it excludes any routes that include the failed span. Constraint (2) ensures that no O-D pair gets more restoration flow than it needs and (3) are the “mutual capacity” constraints which couple the flow assignment decisions for every O-D pair under the available capacity of each span in the network. All flows and capacities non-negative integers. Note that there is no requirement or implication that the restoration paths for any O-D pair would necessarily be the same as its shortest replacement path. Instead, the optimum routing model chooses a route for each restoration flow that permits the most efficient use of available capacity to obtain a maximum overall restoration level. A closely related model for minimum spare capacity allocation to support 100% path restoration [9]. The latter was also used here to create test cases that, for reference, are known to require the minimum total capacity under which 100% restoration is possible.

### III. EXPERIMENTAL METHOD

The basic performance measure in the experiments is the overall network restorability (\( R_n \)), and the restorability of individual failure scenarios (\( R_i \)). \( R_n \) is the average over all span failures of the fraction of failed working paths that were restored. The fraction of all affected paths that are restored, over all affected O-D node pairs, in failure scenario \( i \) is \( R_i \). For this study we also make the simplifying assumption that adequate wavelength conversion is available at the OXC nodes so that wavelength blocking is a negligible factor.

To characterize the possible outcomes of a mass radial attempt we adopt the philosophy that ultimately any arbitrarily complex sequence of actual signaling and capacity seizure protocol interactions will be equivalent to the outcome of some specific sequence of individual shortest replacement path attempts. This seems reasonable to characterize the range of outcomes that could arise because following any actual failure, the response of all affected end-node pairs is essentially concurrent at the time-scale of a second or so, suggesting all individual attempts are essentially of equal priority. But at the time scale of milliseconds or microseconds on which the actual signaling processes and path establishment protocols will interact, the fate or progress of any one individual path creation attempt is essentially random. It depends in very minute detail on the exact sequence of event timings at the microsecond time scale, starting from when each end-node actually reacts, and depending on every propagation and queuing or processing delay at every intervening node. Thus, viewed at a planners perspective or from the viewpoint of any one customer, the overall outcome is essentially no more predictable than if each individual shortest-path attempt was executed in some random order over all the failed lightpaths to be replaced.

Accordingly, the way we study the possible outcomes is to enumerate all sequences of individual path replacement efforts. Where the permutations overwhelm the ability to enumerate all possible sequences, we will instead generate an unbiased statistical sample of the possible sequence space. The net effect is to observe the range and frequency of restoration outcomes arising from the purely capacity-related dependence on the effective sequence in which end pairs were allowed to individually (greedily) seize their shortest surviving replacement paths.

The three test networks shown in Figure 1 provide a range of network degree for the tests. Net-1 is a very sparse facility route topology based on Level3’s N. American network (www.level3.com). Net-2 is the European planning network, COST239 and Net-3 a random network with an intermediate nodal degree. In capacity design for the tests, the cost of each span is proportional to the distance on the plane between its end nodes, as drawn. Uniform random sets of demand intensities were generated between each node pair for each network as follows (minimum, maximum, average): Net-1 (9, 15, 3.4), Net-2 (1, 20, 10.4), Net-3 (2, 14, 8.4).

For the experiments these working demands were shortest path routed before any failures. In the initial test cases an efficient allocation of spare capacity was made so that 100% path-restorability was supported for all single span failures under optimal path restoration routing. After using PRR to validate that each test network was indeed 100% restorable to all span failures under routing that respects mutual capacity considerations, the test networks were then subjected to the same set of failure scenarios where for each failure, all possible sequences (or a sample thereof) of individual shortest-path replacement were effected.
For each span cut, we generate a large number of random orderings of the index numbers that identify each end-to-end path that is affected by the failure. Then we look at the purely capacity-constrained outcome when each node pair independently seeks a path on its shortest surviving route that has enough capacity. There is absolutely no a priori knowledge about what a preferred sequence of individual attempts would be. After each individual shortest path replacement attempt in each sequence, the available capacity is updated and the next node pair in the sequence gets its chance, and so on until all affected node pairs have had a chance to find a GMPLS-based replacement path. Some sequences of individual path seizing attempts may luck in to being almost perfect solutions, other may be disastrous in that a particular early attempt may seize the spare capacity that was crucial for many other O-D pairs. Only one attempt for the capacity reservation is permitted in the experiment for each demand before passing on to the next path in the sequence. (In reality, each attempt that fails may lead to reattempt(s) further confounding the capacity contention and signaling congestion.) Each replacement path-finding effort is individually a perfect shortest-path routing with complete global knowledge of the topology and available capacity at that stage in the experimental sequence.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

For each span cut, we generate a large number of random orderings of the index numbers that identify each end-to-end path that is affected by the failure. Then we look at the purely capacity-constrained outcome when each node pair independently seeks a path on its shortest surviving route that has enough capacity. There is absolutely no a priori knowledge about what a preferred sequence of individual attempts would be. After each individual shortest path replacement attempt in each sequence, the available capacity is updated and the next node pair in the sequence gets its chance, and so on until all affected node pairs have had a chance to find a GMPLS-based replacement path. Some sequences of individual path seizing attempts may luck in to being almost perfect solutions, other may be disastrous in that a particular early attempt may seize the spare capacity that was crucial for many other O-D pairs. Only one attempt for the capacity reservation is permitted in the experiment for each demand before passing on to the next path in the sequence. (In reality, each attempt that fails may lead to reattempt(s) further confounding the capacity contention and signaling congestion.) Each replacement path-finding effort is individually a perfect shortest-path routing with complete global knowledge of the topology and available capacity at that stage in the experimental sequence.

Fig. 2. Sample data showing sequence-dependent variation in restorability.

The complete set of such raw data can be reduced to a histogram form such as in Fig. 3. This shows the statistical distribution of the sequence-dependent restorability outcome for two different span failures in Net-3. In the case shown one span is at least 85% restorable over all sequences. For the other span failure shown, the restorability is distributed as shown down to 70% even though the capacity is present to make 100% restorability possible. To an individual affected customer this means a 30% chance of remaining disconnected. But the outcome can often be worse than in Figure 3. Table 1 summarizes the complete series of experimental trials in terms of the probabilities, taken over all failure scenarios and all sampled sequences, of the restorability being as low as 30% or 50%.

<table>
<thead>
<tr>
<th>X, Ri over all trials</th>
<th>NET-1</th>
<th>NET-2</th>
<th>NET-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 30%</td>
<td>10%</td>
<td>31%</td>
<td>18%</td>
</tr>
<tr>
<td>&lt; 50%</td>
<td>14.3%</td>
<td>39%</td>
<td>26%</td>
</tr>
</tbody>
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Table 1 Experimental probabilities that failure scenarios have less than X % restorability under independent mass redial.

Fig.4 (a)-(c) shows the variation of average node-pair restorability for single failure cases across all the ordered sequences of the demands for the three test networks. The average restorability is seen to be quite unpredictable. These results are based on sampling of the sequence-space, but are exhaustive for all span failures. Sample numbers and variance considerations indicate 95% confidence intervals are all under 6.3% in estimating the average restorability level.

A. Effect of Excess Capacity

Of course provisioning excess spare capacity should tend to mitigate the unpredictability and worst-case outcomes of the independent mass re-dial process. So the trials were repeated with varying factors of excess capacity relative to the minimum required. Fig. 5. is a plot of the average network restorability against the excess capacity factor. This indicates a high price in terms of overprovisioning to be able to rely solely on a mass redial approach. With Net-2, if 175% of the theoretical minimum spare capacity is provided on each span, average restorability of 90% is reached, but some individual O-D pairs in some orderings still receive near zero recovery
levels. And for Net-1 and Net-3 to achieve 100% restoration levels, spare capacity in the range of 150% of theoretical minimum spare capacity has to be provided.

These over-provisioning levels approach or even exceed the capacity where a dedicated 1+1 APS arrangement could have been established for every O-D pair in the first place.

**B. Effect of Nodal Degree**

Figure 5 suggests that the performance of mass auto-reprovisioning is poorer in the highly connected networks. The sequence dependent restorability level of the sparse Net-1 is higher because, with sparseness, spare capacity efficiency is in the first place not as high as in highly meshed topologies. A sparse network tends to have less extensive shariability and hence also less dependence on precise mutual capacity coordination in the access to spare capacity. In the limit of sparseness, a ring is reached for which mutual capacity coordination is not possible in any failure state—there is simply one route choice for each affected node-pair and the spare capacity must meet the sum of all affected flows for both optimal and GMPLS re-dial restoration.

**V. CONCLUDING COMMENTS**

The main issue with GMPLS auto-reprovisioning as a restoration mechanism is that one cannot give any precise or repeatable performance assurance unless capacity is greatly over-provisioned. Many colleagues are well-aware of this. But we increasingly hear the view from others that GMPLS re-dial is itself a restoration mechanism—motivating this attempt to illustrate what the concern is with that view. For anything beyond an isolated path failure, GMPLS mass redial is a weak solution. Individual node-pair recovery levels can be only statistically characterized at best. Customers have no individual assurance of avoiding disconnection in the event of a cable cut if their service provider relies on mass redial for restoration. The trials here dealt only with the capacity-related issues of such a blind scheme. The outcome in practice could be even worse when the implications mass concurrent signaling for path seizure and state update is considered. Given several other reliable alternatives available for survivability, we see little need to rely on GMPLS for physical-layer restoration. 1+1 dedicated APS can require less capacity if a restorability guarantee is required.

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**REFERENCES**


