Multilayer network survivability models and application

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This abstract is submitted in support of the INFORMS Telecommunications Dissertation Award [1].

Internet backbone networks are evolving to a layered architecture where IP with Multi-Protocol Label Switching (MPLS) network is on top of Wavelength Division Multiplexing (WDM) optical networks. Providing survivability in such networks presents several challenging problems.

The requirements for rapid restoration and the conflicts between the distributed routing in MPLS and cost-driven centralized network management have suggested to pre-calculate backup paths and spare capacity before failure happens [2]. This decision is also driven by the increasing requests for bandwidth-on-demand services. These requests have fostered an open market to trade network capacity. How to improve the cost performance ratio of spare resource has recently become one of research focuses and many algorithms have been proposed [3], [4], [5], [6], [7], [8], [9], [10].

There are two similarities among these algorithms. Firstly, they utilize shortest path algorithm to preplan backup paths. By finding backup paths for each flow, the original spare capacity allocation problem, as a multi-commodity flow problem, is partitioned into multiple smaller and easier ones. Secondly, these algorithms share link spare capacity protecting different failure cases. The spare capacity sharing happens at the overlapped segments on backup paths of two or more traffic demands whose working paths are disjoint from any failure case (not affected by the same failure case simultaneously).

One of the benefits of using the shortest path algorithm is to be implemented in distributed routing protocols. The spare capacity sharing scheme reduces network redundancy significantly but its requirement of saving per-flow state information becomes a bottleneck. Resource aggregation for Fault Tolerance (RAFT) uses only hop count [3] to route backup paths. Sharing with partial information (SPI) algorithm avoids this bottleneck by using link metrics calculated on an estimation of the spare capacity sharing information [4], [5].

Recent works show that only a small amount of aggregated state information is needed for spare capacity sharing. The minimum link spare capacity is equal to the maximum of link spare capacities for different failure cases. Such a link to failure relationship was captured for span (link) restoration in [11]. For path restoration, it was used in building link metrics for a heuristic "LOCAL" algorithm in [12]. The results show that LOCAL does not find very close results to the better column generation algorithm. Recently we formulate this relationship in a *spare provision matrix* (SPM) with size of the number of links times the number of failure cases [6], [9]. It models arbitrary failure cases in addition to link failures in the earlier works. An algorithm, termed successive survivable routing (SSR), calculates additional link spare capacities as link metrics to route backup paths. Numerical results show that the SSR results are very close to the optimal solutions found by branch and bound (BB) and much better than those of RAFT and SPI. Similar spare capacity sharing structures have also been used for link metrics in [7]. The redundancy found is not close to the integer programming solution, with more than 10% difference. One of the drawback of using the complete spare capacity sharing information is the size of the spare provision matrix. A study in [10] on reducing this complexity shows that this reduction produces worse results than SSR but better ones than SPI.

Nederlof et al [13] reported a framework to evaluate network survivability. A new term, *Escalation*, is defined for the interworking between restoration mechanisms in different network layers or subnetworks. Doverspike [14], under the prospect of the large amount of bandwidth-on-demand network services, introduced a layered network architecture in the backbone networks and discussed its failure management issues. Demeester et al [15] introduced the results from Protection Across Network Layers (PANEL) project. Contention between restoration schemes in different layers and sharing spare capacity across layers were the main topics of this work. A new concept, *common pool survivability*, was introduced to reduce redundancy by sharing spare capacity between network layers. A numerical study [16] have shown that an integrated protection cooperating all layers achieves lower

Supported by NSF ANIR9980516 and DARPA F30602-97-1-0257

cost than that in a single layer. These works focused mainly on concepts and restoration schemes for multilayer networks. Optimization of spare capacity allocatoin and network topology layout are mentioned but their formulation and solution are still open.

One of the major problems in multilayer network survivability is called "failure propagation". It is a scenario when multiple upper-layer links are torn down simultaneously due to the failure at lower-layer. Corchat et al [17] provided a heuristic algorithm to design higher layer logical topology on a physical WDM optical network to avoid the impact of failure propagation. Modiano and Narula-Tam [18] provided an integer programming model for the 2-connected logical topology layout problem. This model guarantees that the logical topology can tolerant any single lower layer link failure by proving a theorem extended from Menger's theorem. However, it is an NP-hard problem and the approach will not scale to larger networks. The above topology layout problems are also be called topology mapping or embedding in [19].

In this paper, we extends the spare provision matrix (SPM) method and successive survivable routing (SSR) to formulate two problems on multi-layer network survivability. First issue is the survivable virtual topology layout problem. we give a matrix-based model based on Modiano and Narula-Tam's recent work [18]. A layout information matrix captures the logical topology layout over its lower layer network. Then the model to minimum cost of building a fault tolerant upper layer topology on top of a lower layer physical network is given. This upper layer topology is fault tolerant of both upper and lower layer failure scenarios in addition to single link failures.

The second major issue is the spare capacity allocation problem. Based on the SPM method for the single layer network [6], [8], [9], several models are provided for the restoration schemes on different layers. The SSR algorithm is also modified for these models. One of the applications of these models is to assign spare capacity on fault tolerant virtual private network (VPN) where numerical results from both SSR and BB are given. In addition, several cases using failure dependent path restoration schemes versus failure independent; and node failure protection versus link failures are compared.

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