On Survivability in IP Networks
M. Goyal and K.K. Ramakrishnan

Abstract—In this paper, we examine different aspects of the survivability in IP networks by experimentation on several current IP backbone network topologies. Maintaining service continuity even under failures requires redundancy in terms of connectivity and capacity. We analyze the cost of survivability for protection against single node failures for traditional OSPF based recovery as well as current MPLS based schemes using local or end-to-end recovery. We examine how link weight adjustments and careful introduction of a small number of new links in the network can significantly reduce the cost of network operation for survivability. The traffic matrix in the network can change significantly over time. However, our simulation results indicate that the benefits of weight adjustments and new link additions are robust to variations in the traffic matrix. We also investigate the relationship between load balancing and the cost of survivability and show that gaining a better degree of load balance in the network through the link weight adjustments may involve sacrificing the savings in the cost of operating the network and vice versa.

Index Terms—Simulations

I. INTRODUCTION
Survivability has been defined as “the capability of a network to maintain service continuity in the presence of faults” [1]. Since the Internet has become a key for communications and commerce in the world today, network survivability has assumed great importance. Networks need to be designed so that connectivity is maintained in the face of failures in the network. Links have to be provisioned so that there is sufficient capacity to carry the additional network traffic coming their way in the event of failures. Protecting the service quality (minimally assuring availability of capacity) in the face of network failures requires redundant resources (over what is required for failure free operation) which increases the cost of network operation. In this paper, we focus on the evaluation of this “extra” cost of survivability and the investigation of mechanisms that help reduce the cost of network operation for survivability.

This paper begins with an evaluation of “cost of survivability” (defined as the ratio of the costs of network operation with and without survivability requirements) for several network topologies belonging to both commercial and educational ISPs. This evaluation is performed for traditional OSPF recovery (based on calculating new shortest paths from a node to all the destinations in the changed topology) as well as MPLS explicit routing based local recovery (based on local re-tunneling of the affected traffic around the failed node) and end-to-end (E2E) recovery (based on switching the affected traffic to a different end-to-end backup path which is node disjoint with the original path). Similar to the findings of several other studies [2], [3], [4], [5], [6], [7], [8], we observed that the cost of survivability associated with MPLS local recovery can be significantly higher than that of MPLS E2E recovery. In addition, our experiments revealed that those MPLS E2E recovery schemes that are based on “shortest path routing” do not necessarily result in a lower cost of survivability than OSPF recovery. The most significant revelation in our evaluation was the observation that the cost of survivability is essentially determined by the topological characteristics and is not significantly influenced by the variations in the traffic matrix.

Next, we investigate the ways to reduce the cost of network operation for survivability. Since the cost is determined by the required link capacities which in turn are determined by the traffic routes, the cost of network operation for survivability can be significantly reduced by adjusting the traffic routes in an intelligent manner. Traditional OSPF routing as well as shortest path based explicit routing schemes depend directly or indirectly on “static” link weights to make routing decisions. Adjusting link weights provides a natural handle to reduce the cost of network operation. Often, owing to sparse connectivity in the network, there are only a few choices for possible routes, and in such scenarios weight adjustments may not offer significant savings. In our analysis of network topologies and link loads, we observed that typically there are certain node pairs that act as transit points for large fractions of total network traffic and are connected via multiple long distance hops. Hence, careful addition of new links in the topology, to enable such node pairs to be directly connected, can reduce the capacity requirements at other links significantly. In this paper, we examine the effectiveness of link additions and weight adjustments in terms of reducing the cost of network operation for survivability. We also show that the benefits of link weight adjustments and link additions persist even if there is a significant change in the network
Finally, we investigate the relationship between the cost of network operation for survivability and the load balancing. Traffic engineering has traditionally been associated with load balancing i.e., adjusting the routes so that traffic loads move from highly utilized links to links with lower utilization. Recently, the link weight adjustments have been identified as the practical and effective means of achieving better balance in link utilizations [9], [10], [11], [12]. However, we observed that the route changes performed during load balancing operations can significantly increase the cost of network operation for survivability. Moreover, a previously failure-resistant network might become susceptible to failures as a result of route changes done to achieve a better balance among link loads. Similarly, the route changes designed to reduce the cost of network operation for survivability can significantly deteriorate the load balance. We illustrate the non-complementary nature of the load balancing and the cost reducing route adjustments.

II. CONNECTIVITY AND COST OF SURVIVABILITY

Survivability against failures requires redundancy in the network in terms of connectivity and capacity. It is necessary that the network be well-connected so that the failure of a part of the network does not lead to a partitioning of the network. Similarly, the links in the network should have sufficient capacity so that they can accommodate the additional traffic load coming their way after a failure in the network. In this section, we attempt to understand the connectivity and capacity requirements associated with protection against single node failures.

The link and node failures constitute the two main types of network failures that are typically observed in a service provider network [13]. The link failures can be caused by either the interface failures in a router or cable/fiber cuts. The node failures can be associated with either the failure of a single router or a complete PoP depending on the level of granularity associated with the topology. Router failures may occur when they are brought down for maintenance. In a large network, this could be quite frequent. Routers can also fail due to hardware and software problems, or due to a power failure. A complete PoP may fail due to power failures, weather and terror-strikes and other disasters. Most of the previous work regarding

1 the group of access and core routers located in the same facility such as the same room or the same building.
survivability has focused on providing protection against single link failures. However, recently, protection against single node failures (including facility failures that may impact a complete PoP) has become particularly relevant, given the potentially catastrophic impact of such failures on the network services. Also relevant is the increased concerns that a physical facility where a PoP is located could be brought down due to a disaster. Moreover, protection against single node failures also provides protection against single link failures.

A. Improved Connectivity to Improve Survivability

The survivability analysis presented in this paper is based on the examination of 28 real network topologies used as the IP backbones by commercial and educational ISPs [14]. Most of these topologies are at the PoP level. That is, a node in our representation of the network topology is often a PoP. Figure 1 illustrates the characteristics of these topologies in terms of the number of nodes and links in the topology. Figure 2 shows the degree of connectivity in the topology i.e., the average number of directly connected neighbors for a node, calculated as the ratio of the number of unidirectional links to the number of nodes. We observed these topologies to have very poor survivability characteristics. A remarkably high percentage of the nodes have only one directly connected neighbor (Figure 3). If this neighbor fails, the network will be partitioned. Clearly, there is a need to improve the connectivity in these topologies if survivability against single node failures is desired.

A simple strategy will be to introduce new links in the topology so that each node is directly connected to at least two other nodes. Accordingly, we connected each node with connectivity 1 to the closest node which is not already connected to it. The distance between the nodes was calculated using the latitude and longitude information about the node locations. Figure 4 illustrates, the percentage of fatal single node failures for each topology with OSPF/MPLS local recovery, i.e., the single node failures that will lead to a network partition (where a node is not reachable from at least one other node in the network), before and after making each node at least doubly connected. Note that increasing the minimum node connectivity to 2 decreases the percentage of fatal failures, but does not eliminate them. Figure 4 illustrates only OSPF/MPLS local recovery results. The situation is much worse for MPLS end-to-end recovery. Without any connectivity improvement, only 2 out of 28 topologies were connected enough to provide node-disjoint primary and backup path for all the flows in the network. Increasing the minimum node connectivity to 2 made only one additional topology connected enough to provide node-disjoint primary and backup paths for all the flows.

In order to make the topologies single node failure proof, we adapted an alternative strategy. We enhanced the inter-connectivity among the nodes to such a level that the topology could survive any single node failure. For MPLS end-to-end recovery, we added randomly selected links to the topology so that all the flows could be assigned node-disjoint primary and backup paths. After the link addition step, we removed those newly added links that were no longer required to provide node-disjoint primary and backup paths to all the flows.

We use the term “flow” to refer to the traffic flowing between a source node and a destination node in the network.

2We used simple shortest path routing to calculate the primary path. The backup path was calculated after removing all the nodes on the primary path, except the source and destination, and re-running the shortest path algorithm.
OSPF and MPLS based local recovery, the link additions to achieve single node failure protection followed the following procedure:

```plaintext
for each node in the topology
    fail the node;
    calculate the number of "disconnected" node pairs;
    while there are "disconnected" node pairs;
        add a link between randomly selected neighbors of the node;
        calculate the number of "disconnected" node pairs;
        retain the new link if "disconnected" node pairs reduce in number;
    for each newly added link
        remove the link if it does not cause any node pair to become "disconnected";
for each newly added link to the topology
    remove the link if it is not necessary to avoid "disconnected" node pairs for any single node failure;
```

Figure 5 compares the resulting average connectivity of the topologies with the original average connectivity values and Figure 6 shows the actual number of links in the original and modified topologies. It can be seen from the Figure 5 that the topologies with low average connectivity required a substantial number of new links to achieve protection against single node failures. Note that OSPF and MPLS based local recovery can use the same set of new links for protection against single node failures, whereas a different set is required for the MPLS based end-to-end recovery mechanism. Further, the average connectivity levels required for single node failure protection in OSPF and MPLS local recovery are comparable to those required for MPLS end-to-end recovery.

**B. Cost of Survivability**

Having achieved survivability against single node failures, we proceed to estimate the cost of survivability in terms of the extra capacity requirements. The cost of network operation is influenced by a number of parameters including the initial investment required in establishing nodes/links (capex or capital expenditure) and the continuing expenditures involved in maintaining the network (opex or operational expenditures). Since most of the capital expenditure has already been incurred in existing IP backbone networks, this study is focussed on reducing the operational expenditure of the networks taking in consideration the survivability requirements. In the absence of a generally applicable and yet sophisticated opex model, we employ a simple model, described next, for operational expenditures incurred in a network.

In this model, we assume that the continuing cost of network operation primarily consists of the cost of operating the links, i.e., the cost of leasing capacity for the backbone links over underlying fiber networks. While calculating the cost of network operation, it is important to consider both the capacity required on a link to accommodate all the traffic coming its way for all possible failure scenarios as well as the characteristics of the link such as the distance spanned by the link. For example, a trans-continental link between Los Angeles and New York City is potentially more expensive than a much shorter link of the same capacity between Washington DC and New York City. A number of such considerations may determine the actual cost of the capacity required on a link. In our model, we use the distance spanned by the link as the scaling factor for the cost of the link, i.e.

\[
\text{link cost} = \text{link capacity} \times \text{link distance} \quad (1)
\]

While the actual distance traversed by a link depends on the underlying fiber network, a rough estimate can be obtained by calculating the geographical distance between the end nodes using their latitude and longitude values. We have assumed that the required capacity on a link in a given scenario is simply the sum of the average traffic load of all the “flows” (i.e., traffic belonging to a particular source-destination pair) passing through the link.\(^4\) Therefore, the required capacity on a link for protection against all single node failures is the maximum of the capacities required on the link for different failure scenarios as well as for failure free operation.

The overall cost of network operation is calculated as

\(^4\)We verified with packet level simulations that, when the number of flows passing through a link is large enough (about 20 or more), statistical multiplexing ensures that a link capacity equal to the sum of average traffic loads of all the flows is sufficient to accommodate the variations in the traffic load of individual flows even for very bursty traffic load distributions.
2) No conclusion can be drawn regarding the comparison of cost of survivability for OSPF based recovery and MPLS E2E recovery mechanism.

3) The cost of survivability depends essentially on the network topology and the link cost model. The actual traffic loads between source-destination pairs have relatively minor impact on the cost of survivability.

Let us examine these results in more detail. As expected, MPLS based local recovery is more expensive than any other protection mechanisms we studied here. OSPF splits traffic among multiple shortest paths and hence the cost of network operation for no failure protection may not be exactly equal for both the OSPF and MPLS based approaches. However, in our experiments, we found this difference to be very small.

The actual traffic loads between source-destination pairs have relatively minor impact on the cost of survivability.

Let us examine these results in more detail. As expected, MPLS based local recovery is more expensive than any other protection mechanisms we studied here. OSPF splits traffic among multiple shortest paths and hence the cost of network operation for no failure protection may not be exactly equal for both the OSPF and MPLS based approaches. However, in our experiments, we found this difference to be very small.

The actual traffic loads between source-destination pairs have relatively minor impact on the cost of survivability.

Let us examine these results in more detail. As expected, MPLS based local recovery is more expensive than any other protection mechanisms we studied here. OSPF splits traffic among multiple shortest paths and hence the cost of network operation for no failure protection may not be exactly equal for both the OSPF and MPLS based approaches. However, in our experiments, we found this difference to be very small.

Let us examine these results in more detail. As expected, MPLS based local recovery is more expensive than any other protection mechanisms we studied here. OSPF splits traffic among multiple shortest paths and hence the cost of network operation for no failure protection may not be exactly equal for both the OSPF and MPLS based approaches. However, in our experiments, we found this difference to be very small.
With MPLS based local recovery, the nodes in the neighborhood of the failed node tunnel the affected traffic around the failed node. These tunnels are typically the shortest paths between the neighbors of the failed node. However, the effective end-to-end backup path taken by a flow in MPLS local recovery may turn out to be much longer than the backup paths used in either OSPF based recovery or MPLS E2E recovery schemes. Now we discuss the comparative cost of survivability for OSPF based recovery and MPLS E2E recovery. In OSPF based recovery, there is no need for each flow to have capacity reserved along both a primary path and a node-disjoint backup path. The new path(s) followed by a flow after the failure is (are) the new shortest path(s) between the source-destination node pair in the topology after the failure. Thus, in OSPF, some of the links (and hence the capacity) belonging to the flow’s path before the failure can be reused after the failure. This should help in reducing the capacity requirements for survivability in OSPF based recovery when compared to MPLS E2E recovery. However, in many cases the need for capacity reservation along two paths in MPLS E2E recovery may not be that expensive, especially if the same backup capacity can be shared across multiple flows that do not fail simultaneously. Moreover, MPLS E2E recovery can manipulate the link weights to improve the sharing of backup capacity among flows in the network, thereby reducing the capacity requirements for survivability. The experimental results regarding the comparative cost of survivability for OSPF based recovery and MPLS E2E recovery did not indicate a clear trend. In 20 out of 28 topologies, OSPF based recovery had a higher surv cost value than MPLS E2E recovery. A deeper analysis of the experimental results showed that, for all but two of the largest 11 topologies, MPLS E2E recovery resulted in 5% to 13% savings in the surv cost value over OSPF based recovery. However, for smaller topologies, MPLS E2E recovery can result in as much as 16% higher surv cost value than OSPF based recovery. Since the particular backup path calculation scheme [16] we have used in MPLS E2E recovery may not be universally applicable, we repeated the MPLS E2E recovery experiments with backup paths calculated without any adjustments to the link weights. When compared with this scheme, OSPF based recovery had a lower surv cost value in 17 out of 28 topologies. Also, we observed that the surv cost value for MPLS E2E recovery with this simple backup path calculation scheme could vary between 92% to 122% of the surv cost value with OSPF based recovery. Though the results are inconclusive, it is clear that MPLS E2E recovery is not a clear winner over OSPF based recovery as far as the cost of survivability is concerned. This issue has to be considered when making a choice between traditional OSPF based IP routing infrastructure and new MPLS based explicit routing.

C. Evaluating The Impact of Traffic Matrix Variations on the Cost of Survivability

The most remarkable result observed in the experiments reported in this section is the insensitivity of the surv cost value to the variations in the flow-level traffic loads. Figure 8 illustrates MPLS E2E recovery surv cost values for different topologies for traffic loads. Figure 8 shows that the cost of survivability (the surv cost value) seems to be largely not influenced by the traffic matrix. This result can be explained on the basis of the nature of the surv cost expression as analyzed next.

Let distance be the distance spanned by the link i. Assuming that the average flow-level traffic loads belong to a particular probability distribution, let cnload be the average traffic load for the jth flow and let x be a random variable with same probability distribution as the average traffic loads. Let loadj be the traffic load on link i due to flow j during failure free operation, i.e., loadj = cnloadj if flow j passes through link i during failure free operation else loadj = 0. Similarly, let loadj be the traffic load on link i due to “extra” flow j passing through the link i during the failure scenario max cap scenario that results in the maximum traffic load on link i, i.e., if flow j passes through the link i during failure free operation then loadj = 0 otherwise if flow j passes through the link i during the failure scenario max cap scenario then loadj = cnloadj.

The Cost of Survivability with different traffic matrices

Fig. 8. The cost of survivability does not change significantly as the zipf traffic matrix is replaced with uniformly distributed traffic matrix (MPLS E2E Recovery).
otherwise \( \text{load}_{f_i} = 0 \). Hence, the total traffic loads on link \( i \) during the failure free operation and during failure scenario \( \text{max}_{\text{scenario}} \) are \( \sum_{ij} \text{load}_{nf_{ij}} \) and \( \sum_{ij} (\text{load}_{nf_{ij}} + \text{load}_{f_{ij}}) \) respectively. Accordingly, the expression for \( \text{surv} \text{cost} \) can be expanded as follows:

\[
\text{surv} \text{cost} = \frac{\text{cost}_{\text{protection}}}{\text{cost}_{\text{no-protection}}}
= \frac{\sum_{ij} (\text{distance}_i \times \sum_{ij} (\text{load}_{nf_{ij}} + \text{load}_{f_{ij}}))}{\sum_{ij} (\text{distance}_i \times \sum_{ij} \text{load}_{nf_{ij}})}
= 1 + \frac{\sum_{ij} (\text{distance}_i \times \sum_{ij} \text{load}_{f_{ij}})}{\sum_{ij} (\text{distance}_i \times \sum_{ij} \text{load}_{nf_{ij}})}
\approx 1 + \frac{\sum_{j=1}^{m} x_k}{\sum_{j=1}^{n} x_k}
= 1 + \frac{X}{Y}
\]

where \( m \) and \( n \) depend on the distance of each link and the number of flows passing through each link during the failure-free operation and during the failure scenario that causes the maximum traffic load on the link. Since \( X (Y) \) is the sum of \( m \) (\( n \)) independent random variables from a particular probability distribution with mean \( \mu \) and variance \( \sigma^2 \), by central limit theorem, for large values of \( m \) (\( n \)), the sum \( X (Y) \) tends to be normally distributed with mean \( m \mu \) (\( n \mu \)) and variance \( m \sigma^2 \) (\( n \sigma^2 \)).

Figure 9 shows how the CDF curve for \( X \) changes as the variance of \( X \) increases. In this figure, both \( X \) and \( Y \) are normally distributed and share the same mean(=1) and variance. Clearly, \( X \) will vary in a small range around value \( \frac{m}{n} \) if the variance for the \( X \) and \( Y \) distributions is not very large. The variance of \( X \) and \( Y \) distributions is not significant if the traffic loads come from a uniform distribution. If the traffic loads follow a zipf distribution then, depending on \( \alpha \), the variance of \( X \) and \( Y \) distributions could be significant for relatively small values of \( m \) and \( n \). However, as the values of \( m \) and \( n \) increase, the variation in \( X \) and \( Y \) values decreases. This is illustrated in Figure 10 where we compare the CDF curves for \( X \) as the number of zipf distributed random variables comprising the sums \( X \) and \( Y \) increases from 50 to 500. This happens because most of the values, determined according to a particular zipf distribution, are small and similar while only a small number of values are large. Hence as the number of variables in the sum increases, the variation in the values of the sum decreases. Since the \( m \) and \( n \) values will typically be large enough, we can expect the \( \text{surv} \text{cost} \) value to be close to \( 1 + \frac{m}{n} \) even if the traffic matrix varies significantly. Accordingly, the topological structure (inter-connectivity among nodes and the link weights) and the link cost model (in our case, the link distances), being the determinant factors for the \( m \) and \( n \) values, primarily determine the \( \text{surv} \text{cost} \) value for a network topology.

### III. Reducing the Cost of Network Operation for Survivability

The cost of network operation for survivability \( \text{cost}_{\text{protection}} \), defined in Equation 2, can be reduced by controlling the traffic routes so that less traffic flows over high cost links. This can be achieved either via link weight adjustments or by adding new links to the topology. Link weight adjustments can be used to make low cost (i.e. short distance) links more attractive to the traffic than high cost (i.e. long distance) links. However, because the topology may be sparsely connected, often long and circuitous routes are the only possible choices. In such scenarios, link weight adjustments may not be useful. Careful introduction of a few new links to the topology providing direct connections between key transit points can significantly reduce the overall cost of network operation. Changes to the traffic routes can possibly alter the survivability properties of the topology,
i.e., a hitherto failure-proof topology might become susceptible to failures. The weight adjustment and link addition processes should take precautions against such a possibility.

A. The Methodology for Weight Adjustments and Link Additions

The adjustment of link weights in order to reduce the cost of network operation is performed using a heuristic based local search. The heuristic used in the search is to increment the weight of the costliest link so as to make it less attractive for use in either primary or backup paths. In this regard, the cost of a link is calculated using Equation 1. In each iteration of the local search, we identify the link with the maximum cost and increase its weight by a unit amount. The weight adjustment is made permanent if it results in lowering the cost\textsubscript{protection} value. Otherwise, the link weight adjustment is undone and the link is “marked” so that we do not attempt to modify its weight in a future iteration. The search process ends when all the links in the topology have been “marked”. It is possible that increasing the weight of a “marked” link in a future iteration may further reduce the cost\textsubscript{protection} value. However, avoiding such links in the search process helps avoid loops where the same sequence of link weight adjustments is tried over and over again.

In addition to incrementing the weight of the costliest links, we tried several other heuristics such as increasing the weight of the costliest link by more than a unit, increasing the weights of multiple high cost links simultaneously, decrementing the weights of one or more low cost links so as to make them more attractive and adjusting the weights such that a high (low) cost link and a low (high) cost path connecting the ends of the high (low) cost link have the same weight. Many other similar heuristics are possible. We observed that none of these heuristics results in a better performance than incrementing the weight of the costliest link. In general, the heuristics involving the weight adjustment of multiple links or significant change in the weight of a link were not very useful. This is because more than a small change in the link weight distribution can significantly alter the traffic distribution on the links in very complex ways. Hence the simple heuristics involving only a small change at a time perform better than others.

The process of adding new links to the topology begins with identifying a pool of “potential” new links and temporarily adding them to the topology. The potential new links are identified using an iterative process where in each iteration we select the link whose addition will lead to maximum reduction in the current cost\textsubscript{protection} value. Once all the potential new links have been identified and added to the topology, we eliminate the least useful among them one by one till only the desired number of new links remain in the topology. While a good size for the pool of potential links and the optimal number of new links to be added depends on the topology, the following discussion is based on the improvements to the cost\textsubscript{protection} obtained from the addition of 10% more new links to a topology with the size of the pool of potential new links being the original number of links in the topology.

B. Benefits of Weight Adjustments and Link Additions

Figure 11 shows the savings in values of the cost\textsubscript{protection} values for OSPF based recovery, after the weight adjustments and link additions mentioned above, over the cost\textsubscript{protection} values with the original single node failure protected topologies with unit weights. The figure shows three curves: savings achieved solely with weight adjustments, solely with 10% new link additions to the topology and cost savings with 10% new link additions followed by weight adjustments. It is clear from these figures that the weight adjustments and link additions can significantly reduce the cost\textsubscript{protection} for OSPF recovery. Similar results were obtained for other
Fig. 13. Weight adjustments lead to increased weights for long distance links (Topology 28, OSPF recovery, Zipf traffic loads)

Fig. 14. New links (solid lines) connect nodes that are otherwise connected by multiple hops of links. Dashed lines indicate the previous shortest paths connecting these nodes. (Topology 28, OSPF recovery, zipf traffic loads)

Fig. 15. Reductions in required link capacities for single node failure protection as we add new links to topology 28 (OSPF recovery, Zipf traffic loads)

Fig. 16. Savings in the cost of network operation for survivability with weight adjustments and link additions (OSPF recovery and Zipf traffic loads) for the cost model where link cost equals required link capacity.

protection methods as well. The savings are particularly significant when both weight adjustments and link additions are applied together. When only one approach is used, it appears that new link additions are more effective in reducing the cost\textsubscript{protection} compared to the weight adjustments. As illustrated in Figure 12, the weight adjustments are successful in shifting capacity requirements from long links to the short links, thereby decreasing the cost\textsubscript{protection} value. It appears that the net effect of weight adjustments is to cause the weights of high cost (long distance) links to increase while most of the links continue to have same (unit) weight as before (Figure 13). It is interesting to note that the adjusted weights typically lie in a small range of values (usually 1 to 5).

We had observed in Figure 11 that the link additions are much more effective in reducing the cost\textsubscript{protection} than mere weight adjustments. Unlike weight adjustments which reduce the cost\textsubscript{protection} primarily by shifting traffic from high cost links to low cost links, the new link additions are able to not only shift the traffic from high cost links to low cost links but also reduce the capacity requirements for the links. In order to understand how newly added links help in reducing
the \( \text{cost}_{	ext{protection}} \), we examined the nature of the newly added links. Figure 14 illustrates the way in which 10 new links added to topology 28 reduce the \( \text{cost}_{	ext{protection}} \) for OSPF based recovery. For the two end nodes of each newly added link (the solid line), the figure shows the nodes and links (the dashed lines) that previously constituted the minimum hop paths between these nodes. The link lengths depicted in the figure are roughly proportional to the actual geographical distances between the end nodes of the links. It can be seen from this figure that the newly added links connect nodes that were otherwise connected by multiple hops of long distance links. The new links are typically added between nodes that act as transit points for significant amounts of traffic. Thus, the new links provide direct paths for the large fractions of traffic that would have otherwise traveled through multiple hops of long distance links. In this manner, the newly added links can significantly reduce the link capacity requirements and hence the \( \text{cost}_{	ext{protection}} \). Figure 15 illustrates how the link capacity requirements decrease for topology 28 as new links are added to the topology. In this figure, the links are sorted in the increasing order of their capacity requirements with original single node failure proof topology.

To verify that the benefits of weight adjustments and link additions are not limited to the particular cost model we use (where link distance serves as the link cost factor), we performed the weight adjustments and the link additions on all the topologies assuming a different cost model. We let the link cost be simply the required capacity on the link for single node failure protection, i.e., link cost = link capacity. Figure 16 shows the resulting savings for OSPF recovery and zipf traffic loads. Similar results were obtained for other protection methods and traffic loads as well. It is clear from this figure that the benefits of weight adjustments and link additions are not restricted to a particular cost model. We examined the nature of adjusted weights and newly added links for the simpler cost model. As can be expected, under the new cost model, the adjusted weights did not show a strong correlation to the link distance. The nature of newly added links is somewhat similar to the links added under the old cost model (defined in Equation 1), i.e., the newly added links connect the nodes that are otherwise connected by several hops. As before, the newly added links shift significant amounts of traffic away from the original paths that comprised multiple hops. As the new cost model does not take into account the link distances, the sole emphasis of link additions lies in reducing the number of hops. Hence, in a few cases, the new cost model leads to the addition of links that are almost as long as the combined length of the multiple hop path that previously constituted the shortest path connecting the nodes in question. We conclude that for a given network cost model, the weight adjustment and link addition processes described above can identify the appropriate link weight adjustments and new link additions that can significantly reduce the \( \text{cost}_{	ext{protection}} \).

Finally, we return to the question: how many new links should be added to the topology? Figure 17 shows the decrease in the \( \text{cost}_{	ext{protection}} \) values for the three largest topologies under consideration for MPLS E2E recovery as more and more new links are added to the topologies. In these experiments, the pool size of potential new links was limited to original number of links in the topology. Similar results were obtained for other protection methods. It can be seen from this figure that addition of new links to the topologies ultimately reaches a point of diminishing returns. The optimal number of new links clearly depends on the topology in question. The “knee” in the \( \text{cost}_{	ext{protection}} \) versus number of new links curve is some times very prominent, as in case of Topology 27 with MPLS E2E recovery (Figure 17), giving a clear answer to the “optimal number of new links” question. In other cases, the optimal number of new links may not be very clear. As mentioned earlier, in addition to the savings in the \( \text{cost}_{	ext{protection}} \) value, there will be several other factors that will ultimately decide how many new links can actually be added to a topology. Further, it should be noted that arbitrarily adding new links to the network may not reduce the cost of network operation for survivability. In fact, in our experiments, we observed that arbitrarily adding new links to the topologies can actually increase the \( \text{cost}_{	ext{protection}} \) value for the network significantly.
C. Evaluating The Impact of Traffic Matrix Variations On The Efficacy of Weight Adjustments and Link Additions

Given the varying nature of network traffic matrix, it is important that the weight adjustments and new link additions, determined on the basis of a particular traffic matrix, maintain their beneficial impact on the cost of network operation even if there is a large scale change in the traffic matrix. In order to understand the impact of the traffic matrix variations on the utility of the weight adjustments/link additions, we performed weight adjustments and link additions on the topologies using the following traffic matrices: 1) a unit traffic matrix where the traffic load between each source-destination pair is assumed to be a unit value and 2) a uniformly distributed traffic matrix where the traffic load between source-destination pairs is determined according to a uniform distribution. This was followed by calculating the cost of protection with zipf traffic matrix on the modified topologies. We then calculated the savings thus obtained in the cost of protection value over the cost of protection value on the original single node failure proof topologies (with unit weights) with the zipf traffic matrix. We compared the cost savings thus calculated with cost savings obtained when the weight adjustments and the link additions are performed assuming the zipf matrix itself. The comparison results for MPLS E2E recovery are shown in Figure 18. Similar results were observed for other protection methods as well. It is clear that the weight adjustments/link additions done assuming unit or uniformly distributed traffic matrices result in very similar cost savings for the zipf traffic matrix as the weight adjustments/link additions done using the zipf traffic matrix itself. The reasons behind this significant observation become clear when we examine the curves showing the link costs (i.e., link capacity/length, normalized with respect to average link cost) on one of the original single node failure proof topology for different traffic matrices (Figure 19a). Notice that the normalized link costs are remarkably similar for very different traffic matrices. This observation can be explained using an argument similar to the one presented in Section II-C to explain the insensitivity of survival cost value towards traffic matrix variations. The implication of this observation is that the weight adjustment/link addition processes for different traffic matrices have similar starting points and hence result in weight adjust-
ments/link additions that are beneficial even for other traffic matrices. Additionally, we have seen earlier that the adjusted link weights have a strong correlation with the link distances and the newly added links directly connect nodes that are otherwise connected via multiple hop paths. Thus, it is intuitive to expect such topological modifications to have a beneficial impact on the cost protection regardless of the traffic matrix. We verified that the observed insensitivity of benefits of weight adjustments/link additions to the traffic matrix variations is not restricted to the particular cost model we have employed. Even if we assume a different cost model (link cost = link capacity), where link distance does not play any part in calculating the cost of operating a link, we observed very similar results. This happens because, even for the new cost model, the normalized link costs for different traffic matrices on the original single node failure proof topologies look remarkably similar (Figure 19b).

IV. LOAD BALANCING AND THE COST OF NETWORK OPERATIONS FOR SURVIVABILITY

Load balancing in IP networks has traditionally been associated with achieving efficient utilization of network resources by adjusting the route traffic takes so that traffic loads move from high utilization (or congested) links to low utilization links. For a given topology and traffic matrix, a straightforward metric for measuring the degree of load balance is the standard deviation among link utilization values. The smaller the standard deviation among link utilizations, the better is the degree of load balance in the network. From a quality of service point of view, it is important that link utilization values do not become very high, so that the link can easily accommodate transient increase in the traffic load. However, when we combine the problem of load balancing with the problem of reducing cost protection, we encounter a dilemma. The solutions to both these problems involve traffic route adjustments which can work in a conflicting manner. That is, the route adjustments designed to reduce the standard deviation among link utilizations may increase the cost protection (or worse - make the hitherto failure-proof network susceptible to link/node failures) and vice versa.

We can modify the iterative weight adjustment process described in Section III-A so that the objective is reducing the imbalance in link utilization values, rather than reducing the cost of survivability. Here, the link utilization is measured as the ratio of the traffic load on the link during failure-free operation to the required link capacity for single node failure protection. The modification consists of incrementing the weight of the most heavily utilized link (rather than the costliest link). The weight adjustment will alter the traffic routes, thereby causing the required link capacities for single node failure protection and the load on the links during failure-free operation to change. The new link utilization values as well as the new value of standard deviation among link utilizations are calculated. The weight adjustment is accepted if it does not make the network susceptible to single node failures and the new value of standard deviation among link utilizations is less than the old value.

The non-complimentary nature of the weight adjustments done with different objectives is illustrated in Figures 20 and 21. Figure 20 compares the standard deviation in the link utilizations for different topologies in the following four cases: 1) unit weights 2) weights adjusted to reduce cost of network operation 3) weights adjusted to improve link load balance 4) weights adjusted to improve link load balance without increasing the cost (OSPF recovery, Zipf traffic loads)

![Fig. 20. Standard Deviation among link utilizations with 1) unit weights 2) weights adjusted to reduce cost of network operation 3) weights adjusted to improve link load balance 4) weights adjusted to improve link load balance without increasing the cost (OSPF recovery, Zipf traffic loads)](image1)

![Fig. 21. Cost of network operation for survivability (relative to the cost with unit weights) after weight adjustments for 1) reducing the cost of network operation for survivability 2) reducing the standard deviation among link utilizations 3) reducing the cost of network operation without deteriorating std. dev. among link utilizations (OSPF recovery, Zipf traffic loads)](image2)
increasing the cost of network operation\(^6\). The figure shows that the weight adjustments designed to reduce standard deviation in link utilizations can indeed be effective, however, the weight adjustments designed to reduce the cost of network operation can increase the standard deviation among link utilizations significantly in some cases. The other aspect of the problem is illustrated in Figure 21 which shows that the weight adjustments designed to reduce the standard deviation among link utilizations can result in significantly higher cost of network operation compared to the cost with weights adjusted to reduce the cost. Figures 20 and 21 also show the performance of a compromise solution where the preferred objective (cost reduction or better load balance) is achieved without deteriorating the value of the other objective. It is clear from the figures that the compromise solution works fairly well, i.e., the performances of the weight adjustments to achieve the preferred objective with and without the constraint (of not deteriorating the value of the other objective) do not differ too much in most of the cases.

We also examined if a two step weight adjustment process will help us achieve both goals simultaneously. The first step in this process consists of adjusting link weights so as to reduce the cost\(^\text{protection}\) without deteriorating the degree of load balancing. The second step consists of weight adjustments so as to improve the load balancing without increasing the cost\(^\text{protection}\) on the topology obtained after the first step. However, the experimental results indicate that the second step is largely ineffective with very little improvement in the degree of load balancing. It appears that most of the time it is not feasible to use the weight adjustments to achieve maximum possible reductions in both the cost\(^\text{protection}\) and the standard deviation among link utilizations simultaneously.

Since the weight adjustments can achieve either better load balance or reduced cost\(^\text{protection}\), but not both, a choice needs to be made regarding the main objective for weight adjustments. A better balance in link utilizations can also be achieved by increasing the capacity of highly utilized links. Hence, minimizing the cost\(^\text{protection}\) without deteriorating the degree of load balancing seems to be an appropriate objective for the weight adjustments. Once the link weights have been adjusted so as to achieve the maximum possible reduction in the cost\(^\text{protection}\) without deteriorating the degree of load balance, the link capacities can then be increased so that all the link utilizations are below a threshold value. Increasing the link capacities will necessarily increase the cost\(^\text{protection}\). However, the resulting increase in the cost\(^\text{protection}\) might be less than the corresponding increase if load balancing was attempted as the primary goal of weight adjustments. In Figure 22, we compare the cost\(^\text{protection}\) values (normalized with respect to cost\(^\text{protection}\) with unit weights) for different topologies in the following scenarios: weights adjusted with the objective of improving the load balance (Case 1), weights adjusted with the objective of reducing the cost\(^\text{protection}\) (Case 2), weights adjusted with the objective of reducing the cost\(^\text{protection}\) without worsening the load balance and then increasing the link capacities so that no link utilization exceeds 0.7 (Case 3). Assuming that 0.7 can be considered a reasonable high limit on link utilizations for a good load balance, Figure 22 shows that for many topologies, the approach mentioned above allows desired degree of load balance to be achieved with out sacrificing too much in terms of savings in the cost\(^\text{protection}\) value.

\section*{V. CONCLUSIONS}

In this paper, we examined different aspects of the survivability in IP networks. This work was motivated by the need to make the backbone network robust to single node (PoP) failures, ensuring that a single node failure does not impact the connectivity between any pair of nodes and there is enough capacity to carry the existing traffic over alternate paths. We analyzed the survivability of IP networks using both OSPF routing and the current MPLS protocols using shortest path routing. We observed that the relative cost of survivability essentially depends on the network topology and the link cost model and is relatively insensitive to the traffic matrix variations. We showed that the cost of network operation for survivability can be significantly improved using a combination of careful link additions and weight\(^6\)This is achieved by modifying the weight adjustment process so that an adjustment is accepted only if it does not result in an increase in the cost of network operation beyond the initial value.
adjustments. We also observed that the topological modification process for a given traffic matrix results in weight adjustments/link additions that are beneficial even for a very different traffic matrix. Finally, we investigated the relationship between the load balancing and the cost of network operation for survivability and observed that a straightforward approach of adjusting weights for load balancing often results in sacrificing the savings in the cost of network operation for survivability and vice versa. Regarding future work, it is important to understand the relationship between the network topology and the cost of survivability for different protection mechanisms. Another important issue not addressed in this paper is the speed of failure recovery. OSPF based failure recovery, in its current form, can take as much as several seconds, which may be considered unsatisfactory. MPLS based protocols promise much faster recovery, in its current form, can take as much as several seconds, which may be considered unsatisfactory. Recent research has shown that the OSPF protocol can be suitably altered from failures. However, recent research [18], [19], [20] has shown that the OSPF protocol can be suitably altered to achieve as fast failure recovery as is being promised by MPLS based mechanisms. Investigation into the issues affecting the speed of recovery for different survivability mechanisms constitutes a logical next step to this work.

REFERENCES


