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PAPER

Robust Path Design Algorithms for Traffic Engineering with Restoration in MPLS Networks*

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SUMMARY In this paper we study traffic engineering in Multiprotocol Label Switching (MPLS) networks. We consider off-line computation of disjoint working and restoration paths where path rerouting is used as the restoration scheme. We first compute maximum number of paths for each demand such that paths satisfy diversity requirements. Using the generated path set we study four different approaches for selecting working and restoration paths, and formulate each method as an Integer Linear Programming (ILP) problem. The first two methods treat working and restoration path design problems separately. We propose two new path design methods that jointly optimize the working and restoration paths. A traffic uncertainty model is developed in order to evaluate performances of these four approaches based on their robustness with respect to changing traffic patterns. We compare these design approaches based on the number of additional demands carried and the distribution of residual capacity over the network. It is shown through simulations that the weighted load balancing method proposed in this paper outperforms the other three methods in handling traffic demand uncertainty.

key words: *traffic engineering, restoration, MPLS networks*

1. Introduction

Multiprotocol Label Switching (MPLS) is an advanced forwarding technology which uses the control plane of the IP routing protocol. Packets in the network are divided into subsets called Forwarding Equivalence Classes (FEC) based on their source and destination IP addresses, network and transport layer protocol sources. The main idea of MPLS is to map the packets to a FEC at the entry of an MPLS domain (called ingress router) and use only FEC based labels to process and forward these packets inside the domain. The mapping of packets into FECs allows a wide range of granularities for packet forwarding. The routing is done at the ingress point and capacities along the selected route are reserved. As a result, a virtual circuit is established between the ingress and egress nodes. All forwarding in an MPLS domain is done only by using the data contained in the label, resulting in an increase in forwarding speed. The label is removed at the exit point of the MPLS domain (called egress router). MPLS architecture is described in detail in [1], [2].

One important goal of MPLS is to combine the scalability and flexibility of routing in layer 3 with the performance, quality of service (QoS) and traffic management of layer 2 switching. Hence these capabilities which traditionally have existed only at layer 2 are made available to the IP layer. The paths can be explicitly routed resulting in Label Switched Path (LSP) tunnels. Constraints, such as maximum delay, minimum bandwidth, maximum transmission impairment, etc., can be imposed for each LSP.

With MPLS it is possible to exercise traffic engineering for using network resources more efficiently. This may be accomplished by forcing some traffic to follow an explicitly specified path in order to avoid congested parts of the network. Traffic engineering problem for MPLS networks is discussed in [3], and the key aspects of MPLS that can be used to solve this problem are emphasized.

Due to the connectionless nature of the IP protocol, the current Internet has some degree of immunity to failures. Dynamic routing protocols react to failures by changing routes when the routers learn about the topology changes via routing information updates such as link state advertisements. Since Internet is currently based on best-effort service, slow convergence of this recovery mechanism is not critical. On the other hand, because of QoS requirements of real-time network applications, reliability is becoming a more important issue. MPLS can react rapidly to failures by switching failed connections to secondary paths.

General specifications and bandwidth reservation for protection are discussed in [4]. Providing reliable services in MPLS is studied and fast rerouting techniques are proposed in [5]. Restoration problems in extending IP-based MPLS protocols to optical networks, called Generalized Multi-Protocol Label Switching (GMPLS), are discussed in [6]. New algorithms for dynamic routing of restorable bandwidth guaranteed paths are presented in [7], [8].

Diversity routing refers to the situation where two paths share no single point of failure. Diversity is a common technique which is used to provide fast protection or restoration capability. A new link attribute called *Shared Risk Link Group (SRLG)* is introduced to support diversity routing [9]. SRLG information is

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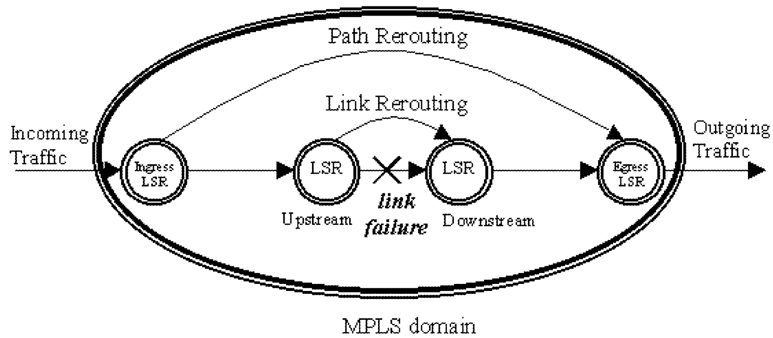

Fig. 1 Path rerouting vs. link rerouting.

used to denote all links subject to a similar type of failure. For example, a fiber cut affects all the fibers in the same conduit, thus there is no point in using a recovery path routed over a fiber which is in the same conduit with the fiber carrying the working traffic. In order to handle node failures, all links adjacent to each node can be assigned to the same SRLG. If SRLGs are properly defined and working/restoration paths are selected to be SRLG-disjoint, the network can recover from all single event failures including link or node failures.

In this paper, we study the traffic engineering problem for MPLS networks such that the traffic carried over the network is fully restorable against all single event failures. We assume that the MPLS network has a 2-connected topology with given link capacities. An initial traffic demand set is given which is obtained based on some traffic forecasts. Using this demand set, we design working and restoration paths for all requested connections subject to the constraints that the traffic on each link does not exceed its capacity, and all requested connections can be fully restored against all possible single event failures. After routes are designed, the network is subjected to additional traffic demands in order to model the uncertainty in the forecasts. The main goal is to carry as many additional requests as possible subject to the constraints that all existing working paths remain unchanged, all link capacity constraints are satisfied, and all carried traffic in the network is fully restorable.

In order to increase the number of carried additional connections, we reoptimize restoration paths for existing connections. The goal of the traffic engineering process is to route traffic in such a way that residual capacity in the network can be efficiently used for carrying traffic that may arrive at later times. We develop design algorithms that distribute unused capacity over the network in such a way that links with higher likelihood of carrying additional traffic are assigned larger spare capacity. These algorithms are formulated as Integer Linear Programming (ILP) problems, and the performance of these algorithms are compared through numerical examples.

Restoration techniques for MPLS networks can be classified with respect to different features:

Rerouting Method: Fault recovery can be done by using link or path rerouting, as illustrated in Fig. 1. In the link rerouting case, an alternate path is found between the two Label Switching Routers (LSR) on both ends of the failed link. This approach has the advantage of simplicity. Moreover it is faster, because the downstream LSR notifies only the upstream LSR about the fault. In the path rerouting, an alternate path between the ingress and egress LSRs that is SRLG-disjoint from the failed path is found. Path rerouting is more complicated, and it is slower since larger number of LSRs are involved in rerouting. However better restoration paths can be found since paths considered in path rerouting are supersets of those for link rerouting.

Path Computation: Computation of restoration paths can be performed online or off-line. In the online approach, an alternate path is sought after the detection of failure. In contrast, in the off-line approach an alternate path is computed before the traffic is initially provisioned. The latter approach has the advantage of fast-recovery, since the upstream LSR already has an entry, which specifies the next hop and outgoing label for the incoming label, for the alternate path in its forwarding table. As a result, rerouting is accomplished by simply switching to the entry for the restoration path.

Resource Management: In the off-line approach there are two possible methods for resource reservation. The resources needed for restoration paths may be reserved in advance, or they can be determined after discovery of available resources. If these resources are not reserved beforehand, there is no guarantee that the alternate path will be available and it will be capable of providing the desired QoS in case of a failure. The disadvantage of reservation method is the underutilization of network resources due to the reserved capacity. This effect can be minimized by appropriate design and sharing of restoration capacity between restoration paths of different demands. The reservation approach provides faster restoration, since it does not have the overhead of discovering and reserving capacity after the failure.

In this work, a restoration scheme with off-line path rerouting with resource reservation is studied. We discuss four different methods for solving the network design problem. First two methods treat the problems of designing working and restoration paths separately, and they are used as a reference in evaluating the performances of the third and fourth methods that are proposed in this paper. These latter two methods jointly optimize the working and restoration path design problems. A traffic uncertainty model is introduced which is used to evaluate relative performances of these four network design algorithms. The traffic uncertainty model characterizes additional traffic that may arise due to demand growth and inaccuracies in traffic projections. It is shown through simulations that the last method, called weighted load balancing, can handle traffic uncertainty much better compared to the first three methods by reducing the ratio of additional traffic rejected.

2. Separate Design of Working and Restoration Paths with Minimum Bandwidth Usage

We first compute a path set satisfying the diversity constraints for given set of demands. Suppose the network topology is represented by an undirected graph $G = (V, E)$ where V is the set of nodes and E is the set of links. The path set consists of all possible SRLG-disjoint paths for each demand such that the capacity usage is minimized. The maximum number of SRLG-disjoint paths between the source and destination pair (s, d) can be obtained from max-flow problem formulation [10] with a slight modification, and the corresponding ILP is given by

$$\max D - \epsilon \sum_{(i,j)\in E} (x_{ij} + x_{ji})$$

subject to

$$\sum_j x_{ij} - \sum_j x_{ji} = \begin{cases} D, & i = s \\ -D, & i = d \\ 0, & i \neq s, d \end{cases} \qquad \forall i \in V$$

$$\sum_{(i,j)\in S_m} x_{ij} + x_{ji} \leq 1$$

$$x_{ij}, x_{ji} \in \{0, 1\}, \qquad \forall (i,j) \in E, \quad D \in Z^+$$

where x_{ij} is the decision variable defined as $x_{ij} = 1$, if link (i, j) is included in the path set, and $x_{ij} = 0$, otherwise. S_m corresponds to the set of links belonging to SRLG m, and L denotes the number of SRLGs. The primary objective of the above formulation is to maximize the number of link disjoint paths between s and d, which is denoted as D. The second term in the objective function ensures that the optimization not only maximizes D, but also minimizes the total number of hops in the path set. This term is needed since otherwise the optimal solution may include unnecessarily long paths as long as the number of SRLG-disjoint paths is maximized. The scalar ϵ is a small positive number to ensure that the maximization of D takes higher priority. In order to guarantee this, ϵ can be chosen as $\epsilon < 1/|E|$, where $|E|$ is the number of links in the network. The set of all paths obtained at the end of this computation is denoted by $P = \{P_{ki}\}$, where P_{ki} is the ith path for demand k.

In the separate path design approach, the problems of designing working and restoration paths are treated independently. The goal in designing the working and restoration paths is to minimize the total capacity used in the network. In the first step, working paths are chosen to minimize the total working capacity used in the network while satisfying all demands. ILP formulation for this problem is given by

$$\max \sum_l z_l$$

subject to

$$\sum_i x_{ki} = 1, \forall k$$

$$\sum_k \sum_i x_{ki} r_k \delta^l_{ki} + z_l \leq C_l, \ \forall l$$

$$x_{ki} \in \{0, 1\}, \quad z_l \geq 0$$

where x_{ki} is the decision variable defined as $x_{ki} = 1$, if P_{ki} is chosen as working path for demand k, and $x_{ki} = 0$, otherwise. The other decision variable z_l denotes the amount of residual capacity on link l. The input parameter r_k is the bandwidth requested by demand k, C_l is the capacity of link l, and δ^l_{ki} is the path-link incidence indicator defined as $\delta^l_{ki} = 1$, if P_{ki} passes through link l, and $\delta^l_{ki} = 0$, otherwise. The objective in the above ILP formulation is to maximize the total residual capacity in the network after all demands are routed. The first constraint implies that all demands are satisfied. The second constraint is the link capacity constraint which ensures that the total capacity used on link l does not exceed C_l. The solution of this problem gives the selected path for each demand and the residual capacity on each link after all demands are routed.

In the second step, restoration paths are chosen such that the total unused capacity in the network is maximized after restoration paths are assigned for all demands. The set of all possible restoration paths, P^*, is obtained by excluding all selected working paths from the path set P. The difference in the design of the restoration paths is that the capacity reserved for restoration on a link can be shared by restoration paths whose primary paths are SRLG-disjoint. This sharing is possible since only single event failures are considered. The ILP formulation for the design of restoration paths is given by

$$\max \sum_l z_l$$

subject to

$$\sum_i y_{ki} = 1, \forall k$$
$$\sum_k \sum_i y_{ki} r_k \varepsilon_{lkil'} + z_{l'} \le C^*_{l'}, \quad \forall l, \forall l'$$
$$y_{ki} \in \{0,1\}, \quad z_l \ge 0$$

where the decision variable y_{ki} is defined as $y_{ki} = 1$, if P^*_{ki} is chosen as restoration path for demand k, and $y_{ki} = 0$, otherwise. z_l is the residual capacity on link l. The indicator function $\varepsilon_{lkil'}$ is defined as $\varepsilon_{lkil'} = 1$, if kth demand uses link l on its active path and P^*_{ki} uses link l', and $\varepsilon_{lkil'} = 0$, otherwise. In this formulation the capacity of link l, C^*_l, is obtained after C_l is decreased by the total capacity used by working paths on link l. The objective is again to maximize the total residual network capacity which is the sum of residual capacities on all links. The first constraint ensures that a restoration path is selected for each demand. The second constraint is the capacity constraint which inherently takes into account possible sharing of capacity between different restoration paths. This constraint states that in case of failure of link l, bandwidth used on each link does not exceed available capacity.

Separate design of working and restoration paths results in the minimum capacity usage for working paths, and after choosing the primary paths the capacity assigned for restoration paths is the smallest possible capacity. One possible disadvantage of this approach is that the network capacity may be used in an unbalanced manner where some links may be congested while other links are underutilized. As a result, it may become difficult to accommodate new offered traffic into the network because of the disproportionate distribution of the residual capacity.

3. Separate Design of Working and Restoration Paths with Load Balancing

One possible solution for avoiding the uneven distribution of network load is to distribute the load for working paths in a such a fashion that at least some unused capacity remains on each link. Then the restoration paths can be computed in a similar manner on the residual network. In this formulation, the minimum residual link capacity, where the minimum is taken over all links, is maximized separately for both working and restoration path design problems. Thus a two step optimization is employed for working and restoration path design problems similar to the previous method.

In the first stage, working paths are designed such that the minimum residual capacity is maximized. The ILP formulation for the first step is as follows.

$$\max z + \alpha \sum_l z_l$$

subject to

$$\sum_i x_{ki} = 1, \quad \forall k$$
$$\sum_k \sum_i x_{ki} r_k \delta^l_{ki} + z_l \le C_l, \quad \forall l$$
$$z \le z_l, \ \forall l$$
$$x_{ki} \in \{0,1\}, \quad z \ge 0, \quad z_l \ge 0$$

where x_{ki} is the decision variable defined as $x_{ki} = 1$, if P_{ki} is chosen as working path for demand k, and $x_{ki} = 0$, otherwise. z_l is the residual capacity on link l, z denotes the minimum residual link capacity over all links, and δ^l_{ki} is the path-link incidence indicator function defined as $\delta^l_{ki} = 1$, if P_{ki} passes through link l, and $\delta^l_{ki} = 0$, otherwise.

The objective is to maximize the minimum residual link capacity while simultaneously maximizing the total unused capacity in the network. The parameter α is chosen very small such that, the maximization of z has higher priority. Consequently, α can be chosen such that $\alpha < 1/\sum_l C_l$.

The first constraint ensures that for all demands exactly one working path is chosen. The second constraint states that the bandwidth used on each link does not exceed the capacity of that link. And the last constraint is used to set z to the minimum of the residual link capacities. The solution for this problem determines working paths for all demands.

Restoration paths are selected in a similar manner. The path set P is updated so that the selected working paths for each demand are discarded, and a reduced path set, P^*, is obtained. The capacity of each link is reduced by the total capacity used by working paths on that link, so the set of modified link capacities, $\{C^*_l\}$, is obtained. The ILP formulation for designing the restoration paths is given by

$$\max z + \alpha \sum_l z_l$$

subject to

$$\sum_i y_{ki} = 1, \quad \forall k$$
$$\sum_k \sum_i y_{ki} r_k \varepsilon_{lkil'} + z_{l'} \le C^*_{l'}, \forall l, \forall l'$$
$$z \le z_l, \forall l$$
$$y_{ki} \in \{0,1\}, z \ge 0, z_l \ge 0$$

where the decision variable y_{ki} is defined as $y_{ki} = 1$, if P^*_{ki} is chosen as restoration path for demand k, and $y_{ki} = 0$, otherwise. z_l is the residual capacity on link l, and z denotes the minimum residual link capacity where the minimum is taken over all links. The indicator function $\varepsilon_{lkil'}$ is defined as $\varepsilon_{lkil'} = 1$, if the working path for k-th demand uses link l and P^*_{ki} uses link l', and $\varepsilon_{lkil'} = 0$, otherwise.

The objective is to maximize the minimum residual link capacity while simultaneously maximizing the total residual capacity in the network. The parameter α is chosen very small such that, the maximization of z has higher priority (α can be chosen such that $\alpha < 1/\sum_l C_l$). The first constraint states that for each demand only one path is chosen as the restoration path. The second constraint is the capacity constraint which ensures that in case of failure of link l, the restoration capacity used on each link $l^{'}$ does not exceed the capacity $C^*_{l'}$. And the last constraint sets z to the minimum of the residual capacities. As a result, restoration paths for all demands are selected in a way that balances residual capacities on all links.

4. Joint Design of Working and Restoration Paths with Load Balancing

Both design methods described in Sect. 2 and Sect. 3 solve the working and restoration paths design problems separately. But it is clear that the two problems interact with each other. The design of restoration paths can be done more efficiently if the working paths are designed such that maximum capacity sharing between restoration paths is obtained. The design methods of Sect. 2 and Sect. 3 try to minimize the capacity used for working and restoration paths independently. This does not guarantee that the total used bandwidth is minimized. When working and restoration paths are chosen jointly, although the primary paths may be using more bandwidth compared to separate design of working paths, the total capacity needed for working and restoration paths can be less compared to separate design models. In this section a design method is introduced that jointly optimizes the working and restoration paths with load balancing. The ILP formulation for this method is given by

$$\max z + \alpha \sum_l z_l$$

subject to

$$\sum_i \sum_j v_{kij} = 1, \quad \forall k$$

$$v_{kij} = 0, \text{ if } i = j, \forall i, j, k$$

$$\sum_k \sum_i \sum_j v_{kij} r_k \delta^{l'}_{ki} + \sum_k \sum_i \sum_j v_{kij} r_k \delta^{l'}_{kj} \delta^l_{ki} + z_{l'} \leq C_{l'}, \forall l, \forall l'$$

$$z \leq z_l, \forall l \tag{1}$$

$$v_{kij} \in \{0, 1\}, z \geq 0, z_l \geq 0$$

where δ^l_{ki} is the indicator function defined as $\delta^l_{ki} = 1$, if P_{ki} uses link l, and $\delta^l_{ki} = 0$, otherwise. The decision variable v_{kij} is defined as $v_{kij} = 1$, if P_{ki} and P_{kj} are choosen as working and restoration paths, respectively, for demand k, and $v_{kij} = 0$, otherwise. z_l is the residual capacity on link l, and z denotes the minimum residual link capacity where the minimum is taken over all links.

The objective is to maximize the minimum residual link capacity while simultaneously maximizing the total residual capacity in the network so that the residual capacity is distributed uniformly and efficiently. In the objective function, the parameter α is chosen small so that the maximization of z takes the higher priority (α can be chosen such that $\alpha < 1/\sum_l C_l$). First constraint ensures that one working and one restoration path is chosen for each demand. Second constraint states that the same path cannot be chosen as both working and restoration path for any demand. Third constraint is the capacity constraint on link $l^{'}$ stating that in the case of failure of link l, the capacity used for working and restoration paths on any other link $l^{'}$ cannot exceed its capacity $C_{l'}$. The last constraint sets z to the minimum of the residual link capacities.

4.1 Joint Design of Working and Restoration Paths with Weighted Load Balancing

This design approach is similar to the joint optimization formulation given above. The difference is that constraint (1) is replaced by $z \leq \omega_l z_l$, where ω_l denotes the relative weight of link l. In the case where all weights are equal to unity, as in the previous method, the goal of the optimization is to try to distribute residual capacity over the network in a uniform fashion, neglecting the relative importance of each link. This approach may cause some links to become bottlenecks since the link capacity utilizations vary depending on the network topology and traffic distribution. It may be a better design approach to have more residual capacities on links that are candidates of being overloaded, i.e., links with high estimated utilization levels. This is accomplished by assigning each link a weight which is inversely proportional with the estimated utilization level on that link.

In this work, link weights are determined based on the expected utilization levels on each link. For each source-destination pair a demand with one unit capacity requirement is assumed, and the corresponding path set comprising all SRLG-disjoint paths between each source-destination pair is obtained. These paths correspond to possible paths to be used by working and restoration traffic. One unit of bandwidth is then assigned to each such path and the amount of bandwidth, B_l, used on link l is computed. The utilization level for link l is defined as the ratio $U_l = B_l/C_l$ where C_l is the capacity of link l. U_l corresponds to expected utilization on link l when traffic is uniformly distributed between all node pairs. Then each link is assigned a weight $w_l \sim 1/U_l$, i.e., it is inversely proportional with the expected utilization level. In a real network, traffic projections can be used in order to compute estimated link loads and assign link weights using the same procedure as described above.

As a separate application, link weights can also be used to increase the reliability of the designed paths by assigning higher weights to links with better reliability. By including the reliability measure into link weights, links with better reliability record will be utilized more which in turn reduces the effects of failures on traffic over working paths.

5. Traffic Uncertainity Modeling

The demands on a network are not deterministic quantities. They are typically obtained from some traffic measurements and forecasts, and link capacities are designed based on these traffic projections. Link capacities are expanded typically every few years in order to cope up with increasing traffic demand and to relieve bottlenecks occurring as a result of deviations from traffic projections. An important performance measure for any working and restoration path deign method is its robustness against traffic uncertainty. The designed network should be able to delay the expensive solution of capacity expansion as much as possible by efficiently using the available capacity.

To compare relative efficiencies of the four methods presented in this paper, traffic uncertainty is modeled as additional demands on top of the given demand set. We compare four path design methods by calculating the number of additional demands that can be carried for each technique. In all methods the working paths are not allowed to be reconfigured so that there is no effect of reconfiguration on existing working traffic. But the restoration paths for existing demands can be reoptimized in order to maximize the number of carried new connection requests. The performance measure for each method is defined as the number of additional demands the network can carry when the network is designed using that technique.

The ILP formulation for traffic uncertainty model is given below. The subscript k is used for existing demands, and k_e is used to denote additional demands. The path set P is updated so that the working paths for existing demands are discarded, and a reduced path set P^* is obtained. P^e is the path set for additional demands. The capacity of each link is reduced by the total bandwidth used by all existing working paths on that link, so the set of modified link capacities, $\{C_l^*\}$, is obtained.

$$\max \sum_{k_e} \sum_i \sum_j v_{k_e ij}$$

subject to

$$\sum_i y_{ki} = 1, \forall k$$

$$v_{k_e ij} = 0, \text{ if } i = j, \forall i, j, k_e$$

$$\sum_i \sum_j v_{k_e ij} \leq 1, \forall k_e$$

$$\sum_{k_e} \sum_i \sum_j v_{k_e ij} r_{k_e} \delta^{l'}_{k_e i} + \sum_{k_e} \sum_i \sum_j v_{k_e ij} r_{k_e} \delta^{l'}_{k_e j} \delta^{l}_{k_e i} + \sum_k \sum_i \varepsilon_{lkil'} y_{ki} r_k \leq C^*_{l'}, \forall l, \forall l'$$

$$v_{k_e ij} \in \{0, 1\}, y_{ki} \in \{0, 1\}$$

where $v_{k_e ij}$ is the decision variable defined as $v_{k_e ij} = 1$, if $P^e_{k_e i}$ and $P^e_{k_e j}$ are chosen as working and restoration paths, respectively, for new demand k_e. The other decision variable y_{ki} denotes the restoration path chosen for existing demand k, which is defined as $y_{ki} = 1$, if P^*_{ki} is chosen as restoration path for demand k, and $y_{ki} = 0$, otherwise. The indicator function δ^l_{ki} is the path-link incidence function defined as $\delta^l_{k_e i} = 1$, if $P^e_{k_e i}$ uses link l, and $\delta^l_{k_e i} = 0$, otherwise. The indicator function $\varepsilon_{lkil'}$ is defined as $\varepsilon_{lkil'} = 1$, if the existing working path for kth demand uses link l and P^*_{ki} uses link l'.

The objective is to maximize the number of additional demands that can be carried. The first constraint ensures that a restoration path is selected for each existing demand. The second constraint states that a pair of diverse working and restoration paths are chosen for each additional demand. The third constraint ensures that at most one working and restoration path pair is chosen for each additional demand k_e. The last constraint is the capacity constraint for link l' stating that in case of failure of any link l the capacity constraint on link l' is not violated. The first term on the left-hand side is the necessary capacity for working paths on link l' corresponding to additional demands, and the second and the third terms are the restoration capacities required for additional and existing demands respectively, in case of failure of link l.

6. Numerical Results

In this section, numerical results for the four working and restoration path design methods are presented. A mesh network with 32 nodes and 50 links with given link capacities, in unit bandwidth per second, is considered which is shown in Fig. 2. This topology is an approximation of a carrier's core network where nodes correspond to major US cities [11].

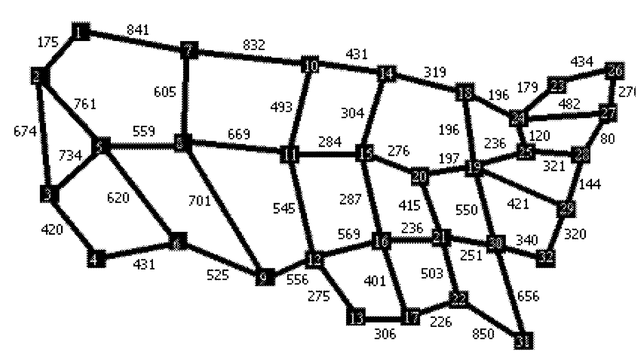

Fig. 2 Network topology used in simulation.

Table 1 Network capacity usage for demand set 1.

Method	Demand Set 1		
	Working	Restoration	Residual
1	689	505	528
2	694	513	515
3	701	416	605
4	708	409	605

Table 2 Network capacity usage for demand set 2.

Method	Demand Set 2		
	Working	Restoration	Residual
1	687	495	540
2	706	456	560
3	714	417	591
4	709	414	599

In our simulations, each SRLG corresponds to a single link. Ten randomly generated demand sets are used where each demand set consists of 80 traffic demands with randomly chosen source-destination node pairs. Bandwidth requirement for each demand is selected randomly from the set {1,2,3} unit bandwidth per second, and a path set is created for each demand.

Working and restoration paths are designed for all demands with the four methods presented in Sects. 2–4: Method 1 to Method 4 correspond to Separate Design of Working and Restoration Paths with Minimum Bandwidth Usage, Separate Design of Working and Restoration Paths with Load Balancing, Joint Design of Working and Restoration Paths with Load Balancing and Joint Design of Working and Restoration Paths with Weighted Load Balancing methods, respectively. The numerical results are obtained by using CPLEX 6.5 running on a Pentium III PC.

To show typical results, Table 1 and Table 2 illustrate total network capacity used by demand sets 1 and 2 with the four design techniques. For the first demand set, although total working capacity used is minimized with method 1, it increases only slightly with other methods. But the restoration capacities reserved are much lower with the last two methods resulting in more residual capacity in the network. This result shows the strong interdependence between working and restoration path design problems. Similar results are observed for the second demand set showing that the joint design methods perform significantly better than separate design techniques in terms of total capacity usage.

The distribution of residual capacity over the network is as important as the amount of total residual capacity. Figure 3 shows residual capacity distributions over the links for demand set 1. Plots on the first row of each figure show the number of links with residual capacity given on the horizontal axis. The residual capacity ratio is defined as the ratio of residual capacity to link capacity. Plots on the second row show the

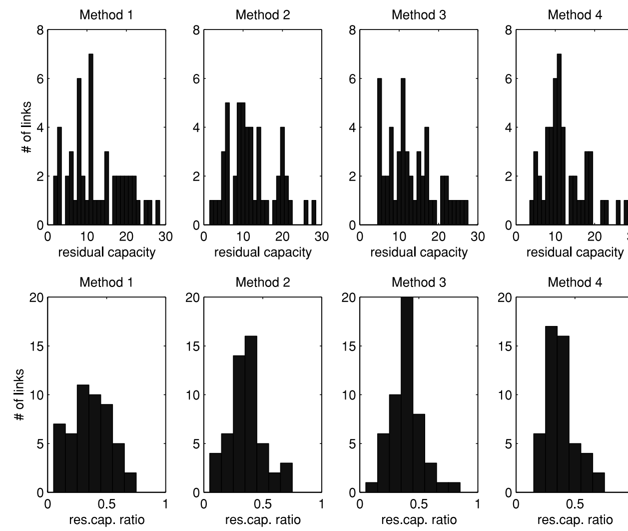

Fig. 3 Residual capacity distribution for demand set 1.

Table 3 Ratio of additional demands blocked by each path design method.

Demand set	Average rejection ratio			
	Met. #1	Met. #2	Met. #3	Met. #4
1	0.222	0.194	0.138	0.128
2	0.208	0.172	0.130	0.112
3	0.063	0.045	0.023	0.023
4	0.095	0.075	0.050	0.063
5	0.098	0.100	0.070	0.068
6	0.138	0.103	0.103	0.095
7	0.175	0.095	0.100	0.080
8	0.058	0.020	0.018	0.018
9	0.140	0.133	0.048	0.033
10	0.123	0.070	0.070	0.063

number of links having a residual capacity ratio given on the horizontal axis. It is seen that the first method results in larger number of links with small residual capacities. With the load balancing approach of the second method, the number of links with small residual capacities decreases, and a more even distribution of residual capacity over the network is obtained. Results for methods 3 and 4 show much more balanced distributions, since the number of links with high utilization are smaller than the first two techniques. Besides, the minimum residual capacity also increases in the last two methods eliminating possible bottlenecks in the network. Still another observation is that, while the third method distributes the residual capacity evenly across the network, the last method balances the utilization levels on the links more uniformly.

To compare relative performances of each design approach, the traffic uncertainty modeling described in Sect. 5 is used. We use two different methods for generating the set of additional demands. In the first approach, 20 sets of randomly chosen additional demands are generated for each existing demand set. The number of additional demands is 25 for the first two de-

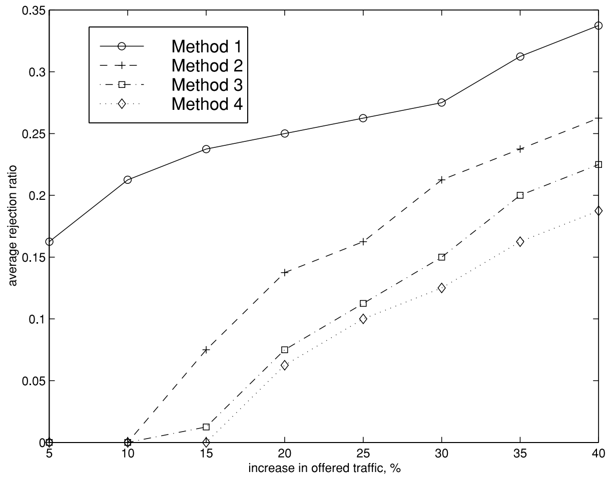

Fig. 4 Average rejection ratios for each path design method.

mand sets, and there are 20 additional demands in the remaining additional demand sets. The average ratio of additional demands that are blocked by each method is tabulated in Table 3. Although the residual capacity obtained by the second method is less than the one that is obtained by the first method, second method can carry more additional demands. With nearly the same residual capacity the last method is more successful in carrying additional demands than the third approach. Except for one case, the worst performance is obtained with the first method. Load balancing feature of the second method improves the rejection ratio by 5–65% compared to the first method, except for demand set 5. The joint optimization method increases the number of additional demands that can be carried, and rejection ratio decreases 0–64% compared to the second method except for demand set 7. Further improvement is obtained by the weighted load balancing approach of the last method. Except for demand set 4, weighted load balancing reduces the average ratio of rejected additional demands by 0–32% compared to joint optimization method.

The second method used for the generation of additional demands corresponds to traffic growth. Each additional demand has the same source and destination nodes with one existing demand, and the bandwidth required by the additional demand corresponds to a ratio of the traffic required by the matching existing demand. In our simulations, the traffic increase ratio is changed between 5% and 40%. For each traffic increase ratio, 10 simulations are performed where a different set of existing demands is generated for each simulation, and the average rejection ratio is calculated. The results for these simulations are shown in Fig. 4 where average rejection ratio for each path design method is plotted as a function of the increase in traffic demand due to additional demands. Order of the relative performances of the methods are same as the previous demand generation technique, and weighted load balancing decreases the rejection ratio by up to 19% compared to the third method.

Table 4 Problem sizes and computation times for the separate and joint design approaches.

Design Method	paths	#vars	#cons	runtime (sec)
Separate (methods 1 and 2)	active	241	130	35
	backup	211	2630	1745
Joint (methods 3 and 4)	joint	271	2630	3345

Finally, we discuss sizes of the problems and corresponding computation times for these four methods. The number of variables and constraints for the separate and joint design ILP formulations are shown in Table 4 for a typical simulation. For separate design there are two parts: active and backup paths. The problem sizes for both subproblems are smaller than the size of the joint design, and the total computation time for the separate design is about half of that for joint design.

7. Conclusion

MPLS is a switching technology that presents advantages of traffic engineering and QoS support on IP networks. Moreover, fast restoration capability of MPLS networks may meet increasing need of reliability in the Internet. In this context, engineering of MPLS networks for efficient use of resources is a critical problem. In this paper, we study the problem of designing working and restoration paths in a robust way, and present four design approaches. We develop a traffic uncertainty model to compare relative performances of these methods. We show that by carefully distributing the traffic load over network resources the joint design approach with weighted load balancing performs better than other design approaches in carrying additional traffic resulting from traffic uncertainty. The problem of extending these robust path design methods to Generalized Multi-Protocol Label Switching (GMPLS) networks where optical transmission impairments place additional constraints on path set selection is currently under investigation.

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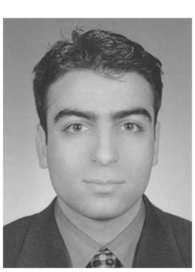

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