Traffic engineering and regenerator placement in GMPLS networks with restoration

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ABSTRACT

In this paper we study regenerator placement and traffic engineering of restorable paths in Generalized Multiprotocol Label Switching (GMPLS) networks. Regenerators are necessary in optical networks due to transmission impairments. We study a network architecture where there are regenerators at selected nodes and we propose two heuristic algorithms for the regenerator placement problem. Performances of these algorithms in terms of required number of regenerators and computational complexity are evaluated. In this network architecture with sparse regeneration, offline computation of working and restoration paths is studied with bandwidth reservation and path rerouting as the restoration scheme. We study two approaches for selecting working and restoration paths from a set of candidate paths and formulate each method as an Integer Linear Programming (ILP) problem. Traffic uncertainty model is developed in order to compare these methods based on their robustness with respect to changing traffic patterns. Traffic engineering methods are compared based on number of additional demands due to traffic uncertainty that can be carried. Regenerator placement algorithms are also evaluated from a traffic engineering point of view.

Keywords: Regenerator placement, GMPLS, traffic engineering, restoration

1. INTRODUCTION

Multiprotocol Label Switching (MPLS) is primarily developed for Internet Protocol (IP) networks. With MPLS virtual connections are established between two points in an IP network. One of the most important applications of MPLS is traffic engineering.[1, 2] The idea of extending MPLS as a control plane that can be used not only with IP routers, but also with other equipment such as Optical Cross-Connects (OXC) is called the *Generalized Multiprotocol Label Switching(GMPLS)* or *Multiprotocol Lambda Switching (MPλS)*.[3] The idea of a common control plane is essential in the evolution of open and interoperable optical networks, and has many advantages. First, a common control plane simplifies operations and management, thus reduces the cost of operation. Next, it provides a wide range of deployment scenarios ranging from overlay model to peer model. Besides, building the common control plane from a proven signaling and routing protocol minimizes the risk and reduces the time to market. This approach results in a simpler and more cost-effective network architecture which is capable of carrying a wide range of data-streams and very large volumes of traffic. GMPLS-based photonic multilayer routers have already been developed.[4]

Naturally, to adopt to the non-ideal behavior of photonic switches, some modifications and additions to MPLS routing and signaling protocols are necessary, and these are being standardized by IETF under the concept of GMPLS.[5, 6] The issues and challenges involved in developing a standardized optical network control plane have been addressed.[3, 7] Signaling, routing and management enhancements for GMPLS are studied.[6, 8–10] The architectures and algorithms for deploying IP over Optical Networks have recently attracted attention.[11, 12] Although GMPLS has many advantages, there are several issues that must be considered while applying MPLS to the optical layer, such as restoration performance[13] and the effects of physical layer limitations.[14]

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There are major differences between routing in optical and IP datagram networks. In conventional IP networks, packets are forwarded on a hop-by-hop basis while in optical networks, an end-to-end connection or lightpath is established based on network topology and available resources. In optical networks, routing protocols are used to update network topology and resource status information, but are not involved in data forwarding. Another difference is the separation of the control plane from the data plane. In IP networks control channels are embedded in the same data-bearing channels, i.e., in-band control signaling. On the other hand, in optical networks control information is carried in an out-of-band fashion, e.g., via an optical supervisory channel.

There are also physical layer constraints imposed by various analog transmission concerns that affect the routing in optical networks. These impairments can be classified in two categories: linear and nonlinear. Linear effects are independent of the signal power and affect wavelengths individually. Amplifier spontaneous emission, polarization mode dispersion and chromatic dispersion are examples for the linear impairments. Nonlinear effects are more complicated since they not only generate dispersion on each channel but also crosstalk between channels.

Wavelength continuity is another constraint specific to optical networks. If wavelength conversion is not available at each node, wavelength continuity has to be preserved along the path or path-segment. This complicates the routing and wavelength assignment computation and increases the size of the link state information since wavelength resource information must also be considered in the routing process.

In optical networks, since a higher degree of multiplexing is done and much more traffic is carried over a single link, failures can affect much more users. Thus, survivability is a critical issue in optical networking. Diversity routing is a common technique which is used to provide fast protection or restoration capability. Diversity refers to the situation where two lightpaths have no single point of failure. For diversity routing, fiber, conduit and right-of-way diversity requirements can be considered. For this aim, a new link attribute called *Shared Risk Link Group (SRLG)* is introduced to support diversity routing.[6] SRLG information is used to denote all links subject to similar type of failure at a lower layer. For example, it is evident that a fiber cut affects all the fibers in the same conduit, thus there is no point in using a recovery path over a fiber which is in the same conduit with the fiber carrying the working traffic.

In the optical networks presently being deployed, each link is optically isolated by transponders doing O/E/O conversions, hence these networks are called *opaque*. Since these transponders increase the network cost and they are bit-rate and format specific, there is a tendency to introduce all-optical subnetworks called *domains of transparency*.[15] Although this architecture has advantages such as multi-vendor operability, it has some important drawbacks. In each all-optical subnetwork, it is assumed that all routes have adequate signal quality and to ensure that, the geographic sizes of these all-optical islands are limited. With increasing bit rates, e.g., from OC-48 to OC-192 and OC-768), transmit powers are increasing that in turn increases transmission impairments and limits the geographical extents of all-optical subnetworks more severely.

In this work we assume that the standardization of optical network elements and protocols will lead to optical networks where multi-vendor operability is less problematic. Therefore we envision the optical network as a single entity, and we deploy regenerators at selected nodes in order to maintain the connectivity of the network subject to link failures and optical layer impairments at the minimum cost of regeneration. So, smaller number of regenerators are used compared to the architecture of islands of transparency where optical signals are regenerated at the boundaries of optical domains. We also assume in this paper that optical wavelength conversion is available at all nodes.

In the following sections, we first present two heuristic regenerator placement algorithms with the objective of using minimum number of regenerators subject to physical layer constraints and possible link failures. We then develop the traffic engineering approach which is used for comparing the efficiencies of these algorithms with respect to routing. Performances of these algorithms are evaluated in terms of number of required regenerators, computational complexity and capabilities of networks in handling uncertainties in traffic projections. In Sect. 4 we present the numerical results obtained on a sample network.

2. REGENERATOR PLACEMENT

In an optical transport network (OTN), the length of any path segment is limited due to the physical layer impairments. Hence regeneration of optical signals by either optical or electrical means is inevitable. Since cost of regenerations is an important portion of total network cost, it is economically beneficial to have regeneration at some selected nodes instead of regeneration at all nodes. In this section we study the problem of regenerator placement in an optical network. In our model the requirement for regenerator placement is to have at least two feasible SRLG-disjoint paths (one for working path and the other for the restoration path) between each source and destination pair in the network such that both paths satisfy optical transmission constraints.

In the regenerator placement problem there is a trade-off between the number of regenerators and the average path length used by working and restoration paths. Having less number of regenerators causes the paths to be longer since some traffic should pass through regenerators which are not on the shortest paths. This results in increasing fiber cost. On the other hand, in order to be able to use shorter paths, larger number of regenerators have to be placed in various nodes. In this work, the cost of regeneration is assumed to be more important than the fiber cost in determining the total network cost, and our goal is minimizing the number of regenerators in the network.

Regenerator placement problem can be formulated as an Integer Linear Programming (ILP) model. But the complexity of the problem limits the use of this formulation only to small networks. Therefore, heuristic approaches are needed. In the following subsections we first present a method for determining a maximal set of possible paths between a source and destination node pair in an optical network with known regenerator locations, and then develop the heuristic regenerator placement algorithms.

2.1. Path Set Generation in the Optical Network

With known regenerator locations, finding the maximum number of SRLG-disjoint paths in an optical network with optical physical layer constraints is a more complicated operation compared to the case without such constraints. The main reason is the existence of signal regenerators in the network that affect the path set generation process. The maximum range constraint which limits the length of any path segment between regeneration points must be taken into account in this process. Moreover, available SRLG information should be considered for reliability.

The path set generation problem is formulated as an Integer Linear Programming (ILP) model as given below. 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. Each link $l \in E$ has a corresponding capacity C_l and a length (or attenuation) d_{ij}. The locations of regenerators are known a priori, denoted by $r_i = 1$ if a regenerator is placed at node i.

In this formulation D^{sd} corresponds to the maximum number of SRLG-disjoint paths between s and d subject to the optical transmission constraints. In order to determine D^{sd}, we first solve the unconstrained maximum flow problem between s and d. This value of D^{sd} is used as a starting solution for the constrained ILP formulation given below, where D^{sd} is decremented until the following constrained path set generation problem has a feasible solution.

Objective:

$$\mathit{Minimize} \quad \sum_{\{(i,j)\in E\}} \sum_{k=1}^{D^{sd}} y_{ijk} + \alpha \sum_{\{(i,j)\in E\}} \sum_{k=1}^{D^{sd}} y_{ijk} r_i$$

Subject to:

$$\sum_{\{j:(i,j)\in E\}} y_{ijk} - \sum_{\{j:(j,i)\in E\}} y_{jik} = \begin{cases} 1, & i = s \\ -1, & i = d \\ 0, & i \neq s, d \end{cases} \qquad \forall i \in V,\ 1 \leq k \leq D^{sd} \tag{1}$$

$$\sum_{k=1}^{D^{sd}} \sum_{(i,j)\in S_m} (y_{ijk} + y_{jik}) \leq 1, \quad \forall m \tag{2}$$

$$w^+_{ik} - w^-_{jk} + y_{ijk}(d_{ij} + M) \leq M, \quad \forall (i,j) \in E,\ 1 \leq k \leq D^{sd} \tag{3}$$

$$w^+_{ik} = w^-_{ik}(1 - r_i), \quad \forall i \in V,\ 1 \leq k \leq D^{sd} \tag{4}$$

$$w^-_{ik} \leq R_{max}, \quad \forall i \in V,\ 1 \leq k \leq D^{sd} \tag{5}$$

$$w^+_{sk} = w^-_{sk} = 0, \quad 1 \leq k \leq D^{sd} \tag{6}$$

$$y_{ijk} \in \{0, 1\}$$

where y_{ijk} is the decision variable defined as $y_{ijk} = 1$, if k^{th} path uses link (i, j), and $y_{ijk} = 0$, otherwise. The variables w^-_{ik} and w^+_{ik} denote the path lengths for k^{th} flow into and out of node i, respectively. The set of links belonging to SRLG m is given by S_m. Finally, R_{max} denotes the maximum allowable length (attenuation) of a path segment.

In this formulation, the objective is to minimize the total number of hops in the path set. The secondary objective is to minimize the total number of regenerators used by all paths. This is established by using a small number, α, as a coefficient for the second summation in the objective function.

Constraint (1) is used to ensure path continuity for each path. Equation (2) is the constraint which limits the total flow on links belonging to the same SRLG to 1. The second term in the summation is needed since the links are bidirectional. Constraint (3) is used to determine the length of the path segment from the last regeneration or source node to any node on the path. M is a big number used to include the effects of only selected links, while others are ignored. Constraint (4) sets the length of the path segment to zero if regeneration occurs. Constraint (5) limits the length of any path segment to be smaller than the maximum range, and constraint (6) is used to initialize the w values at the source node.

If this problem turns out to be infeasible, the number of link disjoint paths, D^{sd}, is decremented, and the same problem is solved with this new value. This problem is solved for each node pair s and d, and the set of all feasible paths is obtained. The traffic engineering methods to be presented in the Sect. 3 select appropriate working and restoration path pairs from these path sets. The ILP formulation for the path set generation problem can be extended such that other additive optical transmission impairments can be incorporated into the formulation by adding extra constraints similar to (3)-(6).

After presenting the constrained path set generation we are now ready to discuss the regenerator placement algorithms.

2.2. Maximum Infeasibility Reduction (MIR) Algorithm

This method is similar to the maximum-descent algorithm. At each iteration, a regenerator is placed at the node which eliminates the maximum number of total infeasible paths between all source and destination pairs. The method aims to place minimum number of regenerators needed to guarantee existence of at least two feasible SRLG-disjoint paths between each source and destination pair. MIR is described below where N corresponds to the number of nodes in the network.

1. Initialization: $r_i = 0 \ \ \forall i \in V$, $n_{reg} = 0$, $done = 0$, $g_{ij} = 0 \ \ \forall [i, j] \in T$.
2. Solve the path set generation formulation given in Sect. 2.1 for each source and destination pair with number of paths $D = 2$. Set $g_{sd} = 1$ for the source and destination pairs for which a feasible solution exists.
3. If $g_{ij} = 1 \ \ \forall [i, j] \in T$, set $done = 1$.
4. While not $done$ and $n_{reg} < N$,

   4.1 Set $f_i = 0 \ \ \forall i \in V$.

4.2 For all nodes i with $r_i = 0$ do

4.2.1 Set $r_i = 1$.

4.2.2 Solve the path set creation formulation for all source and destination pairs $[s, d]$ for which $g_{sd} = 0$.

4.2.3 Set f_i = number of feasible solutions.

4.2.4 Set $r_i = 0$.

4.3 Set $r_i = 1$ for i which maximizes f_i; increment n_{reg}; set $g_{sd} = 1$, for which feasible solutions for source-destination pairs (s, d) are obtained by setting $r_i = 1$.

4.4 If $g_{ij} = 1 \;\; \forall [i, j] \in T$, set $done = 1$.

5. If not *done*, there is no feasible solution for this problem.

   Else the solution is the set of nodes for which $r_i = 1$.

MIR requires the solution of the path set generation problem for each source-destination pair for each candidate regenerator location, i.e., for each regenerator location the path set generation problem is solved $O(N^3)$ times. In the next section, a more efficient algorithm is developed for solving the regeneration placement problem.

2.3. Maximum Regeneration Demand (MRD) Algorithm

MRD algorithm uses a different approach: Instead of trying all nodes for each regenerator placement, which is computationally inefficient, all paths are first determined so that the number of required regeneration is minimized. Then the regenerator is placed at the most demanding node, i.e. the node where maximum number of paths require regeneration. The algorithm for this method is given below.

1. Initialization: $r_i = 0 \;\; \forall i \in V$, $n_{reg} = 0$, $done = 0$.

2. While not *done* and $n_{reg} < N$,

   2.1 For each source-destination pair $[s, d] \in T$, calculate two link disjoint paths, using the $ComputeBestPaths(s, d)$.

   2.2 Determine $\{t_i\}$, where t_i is the number of regeneration points assigned to node i by calling $ComputeRegenerationPoints(i)$.

   2.3 Set $t_{max} = \max_i \{t_i\}$.

   2.4 If $t_{max} = 0$, set $done = 1$,
   Else, set $r_i = 1$, for node for which $t_i = t_{max}$, increment n_{reg}.

3. If not *done*, there is no feasible solution for this problem.

   Else, the solution is the set of nodes i for which $r_i = 1$.

The formulation for determining the path set for node pair $[s, d]$ which is used by the $ComputeBestPaths(s, d)$ in step 2.1 tries to find two SRLG-disjoint paths with minimum number of regenerators. The formulation is given below

Objective:

$$Minimize \qquad \sum_{i \in R_{sd}} \sum_{k=1}^{2} m_{ik} + \alpha \sum_{\{(i,j) \in E : i \in R_{sd} \setminus \{d\}\}} \sum_{k=1}^{2} y_{ijk}$$

Subject to:

$$\sum_{\{j:(i,j)\in E\}} y_{ijk} - \sum_{\{j:(j,i)\in E\}} y_{jik} = \begin{cases} 1, & i = s \\ -1, & i = d \\ 0, & i \neq s, d \end{cases} \qquad \forall i \in V,\ k = 1,2 \tag{7}$$

$$\sum_{k=1}^{2} \sum_{(i,j)\in S_m} (y_{ijk} + y_{jik}) \leq 1, \quad \forall m \tag{8}$$

$$w_{ik}^{+} - w_{jk}^{-} + y_{ijk}(d_{ij} + M) \leq M, \quad \forall (i,j) \in E,\ k = 1,2 \tag{9}$$

$$w_{ik}^{+} = w_{ik}^{-}(1 - r_i), \quad \forall i \in V,\ k = 1,2 \tag{10}$$

$$\frac{1}{R_{max}}\ {w_{ik}}^{-} - m_{ik} \leq 1, \quad \forall i \in R_{sd},\ k = 1,2 \tag{11}$$

$$w_{sk}^{+} = w_{sk}^{-} = 0, \quad k = 1,2 \tag{12}$$

$$y_{ijk} \in \{0,1\}, \quad m_{ik} \geq 0, \quad m_{ik} \in Z$$

In this formulation y_{ijk}, w_{ik}^{-}, w_{ik}^{+}, r_i, R_{max}, and M are the same as defined in Sect. 2.1. R_{sd} is the set of nodes defined as $R_{sd} = \{i : i = d \ \text{ or } \ r_i = 1\}$. The auxiliary variable m_{ik} denotes the smallest number of regenerators required to make the section of the k^{th} path between s and d up to node $i \in R_{sd}$ feasible. For instance, if a path length into some node i is smaller than R_{max}, m_{ik} is 0, which indicates that there is no need to place a regenerator on this path segment. On the other hand if ${w_{ik}}^{-} = 2.5 \times R_{max}$, then $m_{ik} = 2$, which implies that at least two regenerators have to be placed on this path segment to make it feasible.

The objective of this formulation is to minimize the total number of regenerators needed to make both paths feasible. As a secondary objective, the total number of hops in the path set is minimized. This is accomplished by weighting the second term in the objective function by a small number, α. Equations (7-10) and (12) are the same constraints as in the formulation of Sect. 2.1. Constraint (11) is used to set m_{ik} to the minimum number of regenerators required to make the path feasible.

Upon calculation of the path set using the above formulation, the best node for regeneration is determined. For this aim, at step 2.2 each node i is assigned a t_i value which is initially 0. For each path, at the i^{th} node where the length of the path just exceeds the maximum allowable length R_{max}, the value of t_i is incremented. As a result, the node with the maximum value of t_i is chosen as the best node for regeneration. Regenerator placement is continued until all source and destination pairs have at least two feasible SRLG-disjoints paths. The algorithm used by $ComputeRegenerationPoint(i)$ for computing t_i in Step 2.2 is given by

2.2 For each path do

- 2.2.1 Set length $d = 0$
- 2.2.2 For each link $l = (i, j)$ on the path
  - 2.2.2.1 Set $d_{last} = d$, and $d = d + w_l$ where w_l is the length of link l.
  - 2.2.2.2 If $d > R_{max} > d_{last}$, $t_i = t_i + 1$ and then set $d = 0$.

In placing each regenerator with the MRD algorithm, the above path set generation problem is solved $O(N^2)$ times resulting in less computational complexity compared with the MIR algorithm.

3. TRAFFIC ENGINEERING WITH RESTORATION IN GMPLS NETWORKS

Traffic engineering aims to use the available network capacity in an efficient manner in order to carry as many demands as possible. This requires appropriate routing of all working paths and their corresponding restoration paths. In the following subsections two traffic engineering methods for calculating working and restoration paths are presented. These methods are formulated as ILP models. The performances of the heuristic regenerator placement algorithms are compared in terms of capabilities of resulting networks in handling uncertainties in traffic projections.

These traffic engineering methods are not intended to be used for online calculation or for micro flows. Instead, these methods are suitable for routing aggregate demands in the core of the network which uses GMPLS as a means of fast forwarding. The computations are done in an offline fashion using projected demand and traffic information.

The protection is based on 1:1 protection switching. For each working path the corresponding restoration path is pre-established. The resources needed for recovery on this path are pre-reserved. The capacity needed for restoration on each link is calculated taking into account possible capacity sharing between the restoration paths of different SRLG-disjoint working paths, since only single failure events are considered. An end-to-end restoration (global repair) is used in which the restoration path is completely SRLG-disjoint from the working path.

Given a demand set consisting of K demands $Z = \{z_k = (s_k, d_k, r_k)\}$ where the triple z_k denotes the k^{th} demand with source and destination nodes and bandwidth requirement of s_k, d_k, and r_k, respectively, the path set $P_k = \{P_{ki}\}$ corresponding to k^{th} demand is constructed by using the path set generation formulation discussed in Sect 2.1, where P_{ki} denotes the i^{th} path for the k^{th} demand. Using these sets, traffic engineering methods select a working and restoration path pair for each demand. The efficiency of each method is determined using the traffic uncertainty model, which characterizes the discrepancies of the actual traffic demands from projections. Performances of traffic engineering methods are compared by using the amount of carried additional demands resulting from the traffic uncertainty model.

3.1. Traffic Engineering With Load Balancing (TELB)

In this section a design method which jointly optimizes the working and restoration path design problems with load balancing, is introduced. The ILP formulation for this method is given below, where $|P_k|$ is the number of paths in P_k.

Objective:

$$\mathit{Maximize} \qquad z + \alpha \sum_{l \in E} z_l$$

Subject to:

$$\begin{aligned}
&\sum_{i=1}^{|P_k|}\sum_{j=1}^{|P_k|} v_{kij} = 1, \quad 1 \le k \le K \\
&v_{kij} = 0, \quad \text{if} \quad i = j, \quad 1 \le i \le |P_k|,\ 1 \le j \le |P_k|, 1 \le k \le K \\
&\sum_{k=1}^{K}\sum_{i=1}^{|P_k|}\sum_{j=1}^{|P_k|} v_{kij} r_k \delta_{ki}^{l'} + \sum_{k=1}^{K}\sum_{i=1}^{|P_k|}\sum_{j=1}^{|P_k|} v_{kij} r_k \delta_{kj}^{l'} \delta_{ki}^{l} + z_{l'} \le C_{l'}, \quad \forall l \in E,\ \forall l' \in E \\
&z \le z_l, \quad \forall l \in E \\
&v_{kij} \in \{0,1\}, \quad z \ge 0, \quad z_l \ge 0
\end{aligned} \tag{13}$$

where v_{kij} is the decision variable denoting the working and restoration paths chosen for demand k defined as, $v_{kij} = 1$, if P_{ki} and P_{kj} are chosen as working and restoration paths, respectively, for demand k and $v_{kij} = 0$, otherwise. Auxiliary variables z_l and z denote the residual capacity on link l, and the minimum residual capacity over all links in the network, respectively. The indicator function δ_{ki}^l is defined as $\delta_{ki}^l = 1$, if P_{ki} uses link l and $\delta_{ki}^l = 0$, otherwise.

The objective is to maximize the minimum residual capacity while simultaneously maximizing the total residual capacity in the network in order to evenly distribute the residual capacity. In the objective function, the parameter α is chosen small so that the maximization of z takes higher priority. The first constraint ensures that one working and one restoration path is chosen for each demand. The second constraint states that the same path cannot be chosen as both working and restoration path for any demand. The third constraint is the capacity constraint on link $l^{'}$ stating that in the case of failure of link l, the capacity used for working (first term) and restoration paths (second term) on link $l^{'}$ cannot exceed its capacity $C_{l'}$. The last constraint is used to set z to the minimum of the residual link capacities.

3.2. Traffic Engineering With Weighted Load Balancing (TEWLB)

In a typical network, the traffic injected to the network from some nodes may be much more than the others. Besides, demands between particular source and destination pairs may be higher than for other node pairs. As a result, some links in the network may face more traffic depending on the network topology and traffic distribution.

In the case where all link weights are equal, as in the previous method, the goal of the optimization is to distribute the residual capacity as uniform as possible over the network, neglecting the relative importance of each link. This approach may cause some links to become bottlenecks since the capacity usage on links vary depending on the factors stated above. It may be a better design approach to have more residual capacities on links that are candidates of being overloaded, e.g. 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. The links with high probability of usage are given less weight, so that maximizing the minimum of the weighted residual capacities ensures that these links will have more residual capacities. Hence, the residual capacity on each link will be proportional with the importance of that link, which may increase the traffic that can be carried over the network. The link weight can also be used to increase the reliability of the network by assigning higher weights to routes with better reliability.

TEWLB is similar to TELB except that in order to take into account the relative importance of each link, the constraint stated in (13) is replaced by

$$z \leq \omega_l z_l$$

where ω_l denotes the relative weight of link l. TEWLB is a generalization of TELB, since giving all links unit weights makes them equivalent.

In this work, link weights are determined based on the expected utilization levels on each link. For each source and destination pair a demand with 1 unit capacity requirement is created and the corresponding path set is determined. The capacity used on each link by these demand sets are taken as the expected utilization level, since it is assumed that the demands between any node pair is equi-probable. Then each link is given a weight which is inversely proportional with the expected utilization level.

3.3. Traffic Uncertainty 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 traffic projections. These capacities are expanded typically every few years in order to cope up with increasing traffic demand and to relieve bottlenecks in some part of the network occurring as a result of deviations from traffic projections. An important performance measure of any working and restoration path design methodology is its robustness against traffic uncertainty. The designed network should be able to delay the trivial and expensive solution of capacity expansion as much as possible by efficiently using the available capacity.

To compare the relative efficiencies of the two traffic engineering methods and two regenerator placement algorithms developed in this work, traffic uncertainty is modeled as additional demands on top of the given demands. We then compare the design approaches by calculating the number of additional demands that can be carried for each design. In all methods designed working paths are not allowed to be reconfigured in order to minimize the effect of reconfiguration on carried traffic. But the existing restoration paths can be re-optimized in order to maximize the number of carried new connection requests. The performance measure is taken as the number of additional demands the network can carry under each design.

The ILP formulation for traffic uncertainty modeling is given below. The subscript k is used for already routed demands and k_e is used to denote the additional demands. K_e is defined as the number of additional demands. The path sets $\{P_k\}$ are updated so that the working paths for existing demands are discarded, and the reduced path sets $\{P_k^*\}$ are obtained. $\{P_k^e\}$ is the path sets for additional demands. The capacity of each link is reduced by the total capacity used by all working paths on that link, so the set of modified link capacities, $\{C_l^*\}$, is obtained. In the following $|.|$ denotes the set cardinality.

Objective:

$$Maximize \quad \sum_{k_e=1}^{K_e} \sum_{i=1}^{|P_k^e|} \sum_{j=1}^{|P_k^e|} v_{k_e ij}$$

Subject to:

$$\sum_{i=1}^{|P_k^*|} y_{ki} = 1, \quad 1 \le k \le K$$

$$v_{k_e ij} = 0, \quad \text{if} \quad i = j, \quad 1 \le i \le |P_k^e|, \; 1 \le j \le |P_k^e|, \; 1 \le k_e \le K_e$$

$$\sum_{i=1}^{|P_k^e|} \sum_{j=1}^{|P_k^e|} v_{k_e ij} \le 1, \quad 1 \le k_e \le K_e$$

$$\sum_{k_e=1}^{K_e} \sum_{i=1}^{|P_k^e|} \sum_{j=1}^{|P_k^e|} v_{k_e ij} r_{k_e} \delta_{k_e i}^{l'} + \sum_{k_e=1}^{K_e} \sum_{i=1}^{|P_k^e|} \sum_{j=1}^{|P_k^e|} v_{k_e ij} r_{k_e} \delta_{k_e j}^{l'} \delta_{k_e i}^{l} +$$

$$\sum_{k=1}^{K} \sum_{i=1}^{|P_k^*|} \varepsilon_{lkil'} y_{ki} r_k \le C_{l'}^*, \quad \forall l \in E, \; \forall l' \in E$$

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

where $v_{k_e ij}$ is the decision variable denoting the working and restoration paths chosen for demand k_e defined as $v_{k_e ij} = 1$, if $P_{k_e i}^e$ and $P_{k_e j}^e$ are chosen as working and restoration paths, respectively, for demand k_e and $v_{k_e ij} = 0$, otherwise, and y_{ki} is the decision variable denoting the restoration path chosen for demand k 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_{ki}^l is the path-link incidence function defined as $\delta_{k_e i}^l = 1$, if $P_{k_e i}^e$ uses link l, and $\delta_{k_e i}^l = 0$, otherwise. The indicator function $\varepsilon_{lkil'}$ is defined as $\varepsilon_{lkil'} = 1$, if the existing 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 number of additional demands that are carried. The first constraint ensures that a restoration path is selected for each existing demand. The second constraint states that restoration paths cannot be same as the working paths for additional demands. 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.

4. NUMERICAL RESULTS

For simulation purposes, the mesh network shown in Fig. 1 is used. The network has a planar topology with 32 nodes and 50 links. Links are thought to be bidirectional and the length of each link is shown next to it in the figure. Demand from any source to any destination node is assumed to be equi-probable. The capacity of each link is determined based on this assumption. Paths for all source and destination pairs are found, and the number of usage of each link is determined. Proportional to this number each link is assigned a capacity. In addition to this capacity assignment a fixed amount of capacity is added to each link. In our numerical results

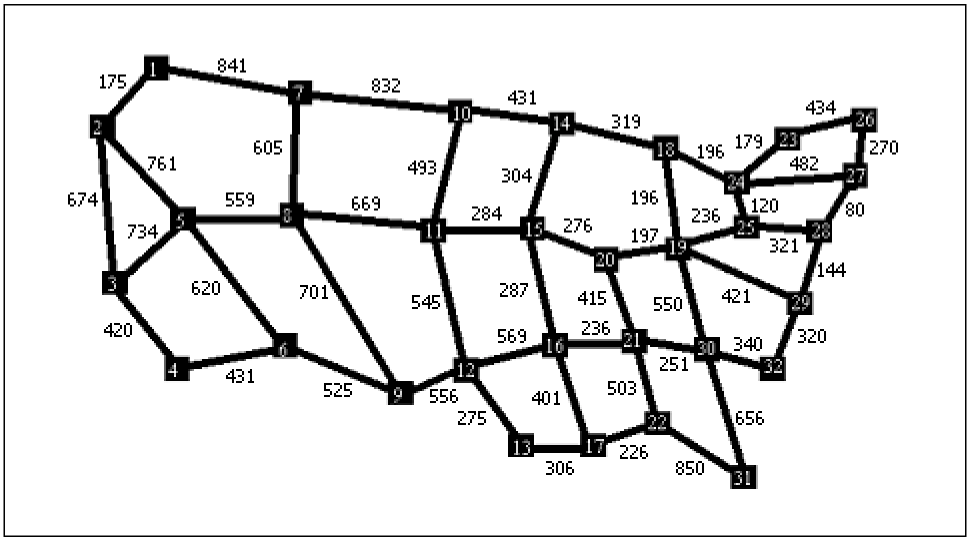

Figure 1. Network topology used in simulation.

we assume that each SRLG contains exactly one link, i.e., there are 50 SRLGs. In this case, SRLG-disjoint paths generated by the formulation in Sect.2.1 correspond to link-disjoint paths.

Optimization problems are solved using the CPLEX optimization software package. Using the heuristic methods developed for regeneration placement, numerical results are obtained for three different values of R_{max}, namely $R_{max} = 1500$, 2000 and 2500. The results are tabulated in Table 1, where the nodes selected for regeneration are written in the order they are selected by the algorithms. For a maximum range of $R_{max} = 2500$, both algorithms find two regeneration points. For other R_{max} values the second method results in one more regeneration node than the first method. Both algorithms find similar nodes for all R_{max} values.

Table 1. Regeneration nodes obtained by heuristic algorithms.

R_{max}	MIR	MRD
2500	11, 15	7, 15
2000	11, 8, 21, 9	8, 10, 16, 12, 15
1500	21, 11, 9, 5, 19, 7	11, 5, 9, 21, 7, 14, 19

Using the traffic engineering methods developed, the performance of each regenerator placement algorithm is determined. Traffic uncertainty modeling of Sect. 3.3 is used to compare the robustness of each method to uncertainties in the demand structure. 10 different demand sets, each consisting of 80 demands with randomly chosen source and destination points, are created. Each demand has a random capacity requirement of 1, 2 or 3 unit capacities. Corresponding to each demand set, 20 additional demand sets, each having 20 random demands, are created. The average number of additional demands that can be carried is used as the performance measure. Same demand sets are used with each regenerator placement algorithm for comparison purposes.

The results obtained for the tree R_{max} values are shown in Table 2. For each design method, number of additional demands that can be carried is tabulated for both regenerator placement algorithms.

From a path design point of view, the results demonstrate that TEWLB, outperforms TELB with both regenerator placement algorithms and for all the three maximum range values. TEWLB, results in rejection percentages (defined as the percentage of additional demands that can not be carried by the network) which are on the average 30-40% lower than the rejection percentages obtained by TELB.

Table 2. Number of additional demands carried by each method.

	$R_{max} = 1500$				$R_{max} = 2000$				$R_{max} = 2500$			
	TELB		TEWLB		TELB		TEWLB		TELB		TEWLB	
Set	MIR	MRD	MIR	MRD	MIR	MRD	MIR	MRD	MIR	MRD	MIR	MRD
1	18.10	19.55	18.20	19.70	18.55	18.85	18.65	19.00	19.10	19.40	19.20	19.55
2	17.70	19.65	18.00	19.75	17.95	18.45	18.15	18.70	17.15	18.80	17.40	19.10
3	17.95	19.65	18.70	19.80	18.05	19.70	18.25	19.85	19.05	19.50	19.45	19.60
4	16.10	18.05	16.55	18.30	17.20	18.20	17.50	18.55	19.10	18.55	19.25	18.70
5	19.20	19.35	19.45	19.60	17.50	17.50	17.60	17.70	15.75	19.05	16.25	19.30
6	18.20	19.85	18.70	19.95	19.35	19.45	19.50	19.55	18.90	19.70	19.40	19.85
7	16.80	18.45	17.10	18.80	19.50	19.70	19.60	19.90	17.45	19.45	17.75	19.70
8	18.80	19.80	19.05	19.85	18.70	19.70	19.05	19.95	18.90	19.50	19.05	19.65
9	19.40	19.85	19.70	19.95	18.45	19.90	19.00	19.80	17.80	20.00	18.00	20.00
10	18.70	19.45	19.00	19.70	17.60	19.30	17.85	19.55	19.25	19.90	19.30	20.00

Using these results, efficiency of regenerator placement algorithms can also be evaluated from a traffic engineering point of view. For $R_{max} = 1500$, MRD results in one more regenerator than MIR. But the results obtained in this section, show that MRD is much better in terms of its robustness against traffic uncertainties. For each design method MRD has rejection percentages which are nearly one third of the percentages obtained for MIR. Similarly, for $R_{max} = 2000$, MRD uses one more regenerator than MIR, but the rejection percentages are nearly halved for both TELB and TEWLB with MRD. And finally for $R_{max} = 2500$, although both algorithms require two regeneration points, MRD is more efficient from a traffic engineering point of view, since it decreases the rejection percentages nearly to one third of the percentages obtained by MIR for both TELB and TEWLB. In summary, the results show that MRD is much more efficient from traffic engineering perspective.

5. CONCLUSION

In this work, we study regenerator placement and traffic engineering of restorable paths in GMPLS networks subject to optical physical layer constraints and diversity requirements using SRLGs. We propose two heuristic algorithms, MIR and MRD, for the efficient placement of regenerators. We study two traffic engineering approaches, namely TELB and TEWLB, and a traffic uncertainty model in order to compare these approaches based on their robustness with respect to changing traffic patterns. We compare MIR and MRD based on the resulting number of regenerators, traffic engineering aspects and their computational complexities. While MRD algorithm which is computationally more efficient than MIR results in slightly larger number of regenerators than MIR, it generates a network where both traffic engineering methods perform significantly better.

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