Formulation of the Traffic Engineering Problems in MPLS Based IP Networks

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Abstract

The growth of the Internet has fueled the development of new technologies that enable IP backbone networks to be engineered efficiently. One such prominent technology, Multiprotocol label switching (MPLS) enables IP networks with Quality of Service to be traffic engineered well. In this paper, we mathematically formulate the traffic engineering problems in MPLS-based IP networks including constraint based routing, connection admission control, rerouting and capacity planning problems. Unfortunately, obtaining the optimal solution of the traffic engineering problems has undesirable computational complexity since they can be shown to be NP-complete. It is intended that this work will articulate the details and provide insights into the inherent structure of the problems as well as motivate the development of efficient solution techniques.

1. Introduction

It is widely believed that the success of next generation IP networking depends to a large extent on the ability to offer and support various Qualities of Service (QoS). It is clear that traffic engineering is imperative for guaranteeing QoS in IP networks and also for efficient or cost effective network resource utilization, network design and operation. The MultiProtocol Label Switching (MPLS) working group at the IETF has been developing a standards-based approach for efficient IP packet transfer. MPLS uses short, fixed-length, locally significant labels in the packet header and the packets are forwarded by network nodes via label swapping similar to layer 2 switching. The ingress node of an MPLS network domain looks into the IP header and inserts an appropriate label based on the policies in effect. The intermediate nodes forward packets by label swapping and the egress node removes the label and forwards the packet based on the IP header information. MPLS is intended to work over any data link layer technology including ATM, frame relay, PPP and Ethernet. A router that supports the MPLS protocol is called a label switching router (LSR). In MPLS, a protocol such as LDP, CR-LDP or RSVP allows label bindings to be exchanged and propagated among the nodes in order to establish and tear down label switched paths. In MPLS, packet flows are mapped to forwarding equivalence classes (FECs) which are mapped to traffic trunks, which in turn are mapped to label switched paths (LSPs). The granularity of packet flows and the number of LSPs are flexible. Therefore, MPLS aims to inherit advantages of connection oriented networks and the flexibility of connectionless networks.

Although MPLS was initially developed with other goals in mind such as faster forwarding of IP datagrams, the most important advantage of MPLS turns out to be its ability to do traffic engineering of IP networks. Though the protocols for establishing traffic engineered paths through a network have been developed, many members in the vendor, service provider and the academic research community have recently begun working on the methods in which these paths can be computed. Moreover, the literature contains hardly any work on this area and the standards bodies have just started work on this: IETF recently established a working group called Internet Traffic Engineering. Therefore, the objective of this paper is to formulate the traffic engineering problems in mathematical form to motivate more work towards the development of efficient solution techniques.

The description of the traffic engineering WG at the IETF defines traffic engineering as "that aspect of Internet network engineering which is concerned with the performance optimization of operational networks". Furthermore, the description adds that "traffic engineering encompasses the application of technology and scientific principles to the measurement, modeling, characterization, and control of Internet traffic, and the application of such knowledge and techniques to achieve specific performance objectives, including the reliable and expeditious movement of traffic through the network, the efficient utilization of network resources, and the planning of network capacity". One of the main interpretations of the above is that traffic engineering deals with efficient resource allocation in a network while guaranteeing the requirements for the traffic flowing through it.

A comprehensive set of requirements for traffic engineering over MPLS were proposed by [1] which motivated our work in this paper. They propose a constraint based routing (CBR) framework which can be solved to come up with explicit routes (ER) for the label switched paths in the network. In our paper, we formulate additional traffic engineering problems as well which are the connection admission control problem, the rerouting problem and the capacity planning problem. The optimal solutions, if they exist, of all of these problems yield best paths for one or more LSPs through the network that are specified explicitly. In other words, an explicit path is described by a sequence of nodes that it traverses. These explicit routes can then be established through an MPLS network dynamically via a signaling protocol such as CR-LDP (constraint based routing capability in LDP is proposed in [6]) or RSVP (modifications to RSVP have been proposed in [2] by specifying appropriate ER objects). Unfortunately, these problems are NP-complete which means that optimal solutions can not be found by any known polynomial time algorithm and hence the computational complexity increases greatly with the size of the problem (refer to [7] for details on NP-complete problems). Moreover, many of these problems have to be solved in real time and that too myriad number of times a day. Therefore, the focus is on the development of heuristics and approximation algorithms that produce solutions that are close to optimal with reasonable and acceptable computation effort. Service providers need fast, robust and reasonably accurate solutions that are simple to implement and execute in a real-time computation environment.

The rest of this paper is organized as follows. Section 2 outlines some of the key needs of service providers in traffic engineering. The traffic engineering problems that are faced by network operators are formulated in Section 3. In Section 4, some open issues are highlighted and this paper is concluded in Section 5.

2. Service Providers' Needs

In this section, we briefly highlight the needs of service providers in traffic engineering which are based on the presentation [3] that was made at the IETF meeting. It is intended that this can help the researchers and practitioners in targeting their work and efforts towards addressing the issues that are of utmost importance to service providers and network operators.

From an operational perspective, a number of problems arise in the context of traffic engineering. On a frequent basis, one needs to solve the connection admission control problem which determines if a connection or demand request can be admitted or not and if so what is the optimal route of the connection through the network. The constraint based routing problem or the network resource and traffic optimization problem has to do with the determination of the optimal placement of the demands through a given network given a set of demands or connections. The rerouting problem arises due to failure and recovery of one or network elements, preemption or bumping of connections in the network or due to load balancing. On a less frequent basis (but with a longer planning horizon), the network operator has to solve the network design and capacity planning problem which deals with the determination of the optimal network topology for a given set of demands.

Traffic engineering can easily be shown to be an NP-complete problem, but, service providers need efficient solutions for this. In order to solve the above problems, service providers need fast, but not necessarily optimal algorithms. It is desirable that the algorithms quickly converge to solutions which have a bounded deviation from optimality. Moreover, they should be simple, scalable, robust, adaptable and offer the ability to do "what if" analyses. various algorithms may be compared and refined based on extensive empirical and simulation studies and experience. It is desirable that the procedures work in a heterogeneous network environment as many of these problems also appear in various types of connection oriented networks and are not restricted in scope to MPLS networks.

We would like to point out that the next generation traffic engineering's primary application area is MPLS based IP networks. But, one would like it to be applicable to differentiated services based networks as the growing trend is to use differentiated services in the edges of the network (for customer SLA specifications, edge traffic conditioning actions and possible inter-domain QoS) and MPLS in the core (for efficient traffic engineering). Moreover, it would be beneficial to extend this to emerging services such as virtual private networks (IP VPNs).

It is necessary to have on-line traffic engineering tools to solve, in real-time, problems such as the connection admission, constraint based routing and rerouting. In this case, efficient methods to interface with the network routing protocols and network management system are necessary for optimal performance and wider application scope and potential. On the other hand, off-line tools are necessary for solving non-real-time problems such as capacity planning. Direct interface to the routing protocols and network management systems are optional in this case.

3. Problem Formulations

In this section, we formulate the various problems that arise in the context of traffic engineering in MPLS based networks, in particular. They are the constraint based routing problem, the connection admission control problem, the rerouting problem and the capacity planning problem. We denote the set of nodes in the network as V, the set of links in the network (which are defined as directed arcs) as E and the set of capacity and other constraints associated with the nodes and links as C (In other words, $G = (V, E, C)$ is a graph describing the physical topology of the network). In addition, some information needed about the network topology and state are:

- Originating LSR of a link (u_l)
- Terminating LSR of a link (v_l)
- Bandwidth or available bandwidth of a link (μ_l)
- Administrative cost of a link (a_l)
- Maximum allocation multiplier or oversubscription factor of a link (K_l)

We denote the set of LSRs where one or more LSPs originate or terminate as U, the set of LSPs as F and the set of demands associated them as D (where, $H = (U, F, D)$ is the induced MPLS graph). In addition, some information needed about the LSPs are:

- Effective or equivalent bandwidth of a LSP (λ_i)
- Ingress LSR of a LSP (s_i)
- Egress LSR of a LSP (d_i)
- Maximum allowed number of LSR hops through the network for a LSP (h_i)

3.1. The Constraint Based Routing Problem

In the constraint based routing problem formulation, the network topology and a set of attributes pertaining to the resources and the constraints in the network are defined. The demands or LSPs that are to be routed through the network are described by a set of attributes as well. The problem, then, is to select the optimal placement of the LSPs through the network while adhering to the constraints imposed. The unknown variables that need to be determined based on optimizing a certain objective function and satisfying a set of constraints are the following. These binary valued variables indicate whether each LSP is routed over each link or not:

$$x_{il} = \begin{cases} 1, & \text{if LSP } i \in F \text{ is routed on link } l \in E \\ 0, & \text{otherwise} \end{cases}$$

Resource based optimization would lead to an objective function that minimizes the sum over all links of the product of the administrative cost and the total flow in each link, where we assume that the administrative cost can be applicable on a unit flow basis (we would like to point out that more sophisticated objective functions can be constructed as well, if desired). This can be formulated as:

$$\text{Min } Z_R = \sum_{l \in E} a_l \sum_{i \in F} \lambda_i x_{il}. \tag{1}$$

The basic set of constraints for the optimization problem are:

$$\sum_{i \in F} \lambda_i x_{il} \leq \mu_l K_l, \ \forall\, l \in E \tag{2}$$

$$\sum_{l \in E} x_{il} \leq h_i, \ \forall\, i \in F \tag{3}$$

$$\sum_{\forall l | u_l = n} x_{il} = 1 \ \forall\, n \in U \ \forall\, i | s_i = n \tag{4}$$

$$\sum_{\forall l | v_l = n} x_{il} = 1 \ \forall\, n \in U \ \forall\, i | d_i = n \tag{5}$$

$$\sum_{\forall l | u_l = n} x_{il} - \sum_{\forall l | v_l = n} x_{il} = 0, \ \forall\, n \in V \quad \forall\, i | s_i \neq n, d_i \neq n \tag{6}$$

$$0 \leq x_{il} \leq 1, \ \forall\, i \in F, \quad l \in E \text{ and integer} \tag{7}$$

Constraint (2) ensures that the link capacities are not exceeded. Note that the virtual link capacity is used here as the link may be oversubscribed or undersubscribed. Constraint (3) restricts the number of LSR hops in the path of a LSP. Constraints (4) and (5) assure that all LSPs originating and terminating, respectively, in a LSR are routed. Constraint (6) ensures that the LSPs are routed through intermediate nodes, thereby, ensuring an end-to-end path through the network. Finally, Constraint (7) specifies that all decision variables are either 0 or 1. Additional constraints may be defined depending on specific requirements in networks. For example, [1] identified a comprehensive list of constraints that may have to be imposed in networks and these can be formulated as well effectively.

3.2. The Connection Admission Control Problem

In production networks, the network operator gets a request for a new LSP. The operator in concerned with determining whether this LSP can be admitted or not and if yes, the path of this LSP. We show that this problem can be formulated easily. Let us say that the new LSP is LSP N. The decision variables assume a binary value and denote if the

LSP is routed over a link in the network. In mathematical form,

$$x_{Nl} = \begin{cases} 1, & \text{if LSP } N \text{ is routed on link } l \in E \\ 0, & \text{otherwise} \end{cases}$$

A simple objective function minimizes the total administrative cost of the new connection and can be expressed as

$$\text{Min } Z_R = \sum_{l \in E} a_l \lambda_N x_{Nl}.$$

Of course more sophisticated objective functions can be constructed similar to the constraint based routing problem. Note that we have to modify the link capacities μ_l to be the available bandwidths on those links. For efficient implementation, it might be useful to prune the network topology such that only those links that have sufficient resources left are considered. In terms of the constraints, the link capacities should not be exceeded with the addition of the new LSP along its path through the network. Then, the number of LSR hops should not exceed the allowed value. Then, the aggregate flow in a node via all links equals the allowed value. Moreover, one has to ensure that the ingress and egress LSRs have the LSPs originating and terminating in them, respectively. The final constraint ensures that the decision variables are either 0 or 1. In mathematical form, the constraints can be expressed as:

$$\begin{aligned}
\lambda_N x_{Nl} &\leq \mu_l K_l, \ \forall\, l \in E \\
\sum_{l \in E} x_{Nl} &\leq h_N, \\
\sum_{\forall l | u_l = n | s_N = n} x_{Nl} &= 1 \\
\sum_{\forall l | v_l = n | d_N = n} x_{Nl} &= 1 \\
\sum_{\forall l | u_l = n} x_{Nl} - \sum_{\forall l | v_l = n} x_{Nl} &= 0, \\
&\quad \forall\, n \in V | s_N \neq n, d_N \neq n \\
0 \leq x_{Nl} &\leq 1, \ \forall\, l \in E \text{ and integer}
\end{aligned}$$

Note that the additional constraints described earlier can be incorporated into this problem if desired. If no feasible solution exists for this problem, then the LSP request cannot be honored by the network. But, if this problem has one or more feasible solutions, then the optimal solution provides the route of this LSP through the network and CR-LDP or RSVP can be used to establish an explicit path through the network.

3.3. The Rerouting Problem

Rerouting of LSPs can occur due to a number of reasons including failure or recovery of one or more network elements, preemption or bumping of a lower priority LSP by a higher priority one and load balancing. When failure happens in the network or the network recovers from a failure of a link or a node, the paths of the LSPs may need to be altered for feasibility and possible optimality. During a node failure, all links terminating on this node cannot forward packets over the LSPs routed through them. When link g fails, we set $x_{ig} = 0 \ \forall\, i$ (note that for a node failure, we would set $x_{ig} = 0$ for all g that are affected). We then reformulate the problem, similar to the connection admission problem, but with all the LSPs that need to be rerouted along with the above constraints. Then the optimal solution of this problem would give us the new paths for these LSPs. It is possible that this problem has no feasible solution (when there is not enough bandwidth or other resources) resulting in the network not being able to route all the LSPs with their strict QoS requirements being met. We then have to deduce the subset of the LSPs that can be rerouted. When the policies are set to allow negative bandwidth situation in case of rerouting, the problem formulation needs to be modified appropriately.

When a failed link or node recovers from a failure, then the routing of the LSPs may be re-optimized by allowing some of them to be rerouted over the newly available and possibly better preferred paths. This is accomplished by relaxing the constraints associated with the LSPs not being routed on them (which were $x_{ig} = 0$) and then determining the optimal solution for the problem. We would like to point out that when priorities are associated with the LSPs, then the method proposed in Section 3.1 could be used in rerouting in case of failure or recovery.

There is an issue of trying to minimize the rerouting of many LSPs during failure and mainly during recovery in order to prevent oscillations. This happens when a link or a node recovers and then we solve the whole problem again to determine the optimal route of all LSPs which could result in significant changes to the existing LSP routes. This is not desirable as we would like to minimize the number of LSPs rerouted (the rerouting process consumes processing power and is time consuming) to minimize the effect on traffic disruptions and performance degradation. Therefore, a new mechanism, for example, based on sensitivity analysis, would enhance the efficacy of the traffic engineering exercise. An algorithm for rerouting is developed in [4].

3.4. The Capacity Planning Problem

One of the problems that need to be solved by service providers is designing a network to meet a set of demands placed by the LSPs on it. While designing a network topology, a service provider often considers the future demand in the analysis as well. The future demand may be quantified by the factors such as the growth, the expected time horizon for the design, lag time for provisioning nodes and links, variability in the estimates, cost factors and budgetary concerns. While designing network topology, it will be useful to compare the designs associated with changing demand and other factors before making a decision. Methods for estimating the future demands are beyond the scope of this paper. Therefore, we assume that the demand function is well specified.

If it is known a priori the locations of the nodes in the network, then the problem is reduced to determining the optimal trunking scenario. We term this the capacity planning problem. But, when one needs to determine where the nodes are to be located and then the trunking requirements, we call this the network design problem. In this section, we only formulate the capacity planning problem. We assume that the set of nodes, V and the set of nodes in which one or more LSPs originate or terminate, U are fixed in the network and a total of T different bandwidths or types of links are available. A link of type $t \in T$ has a bandwidth of ψ_t. The decision variables are $x_{tjk}, t \in T; j, k \in V$ which are the number of links of type t between nodes j and k and c_{tjk} is the cost of the link. The objective function is to minimize the total cost of the network elements (only links in this case as the nodes are already fixed) and can be formulated as:

$$\text{Minimize } Z = \sum_{j \in V} \sum_{k \in V} \sum_{t \in T} c_{tjk} x_{tjk}$$

Two sets of constraints are needed in this formulation. The first set pertains to the links such that they are able to accommodate the LSP demands. The second set ensures that the LSPs are indeed routed correctly. In mathematical form, the constraints are:

$$\begin{array}{rcl}
\sum_k \sum_t \psi_t x_{tjk} & \geq & \sum_{\forall n | s_n = j} \lambda_n \ \forall \ j \in U \\
\sum_k \sum_t \psi_t x_{tjk} & \geq & \sum_{\forall n | d_n = j} \lambda_n \ \forall \ j \in U \\
x_{tjj} & = & 0 \, \forall \, t, j \\
x_{tkj} & = & x_{tjk} \\
x_{tjk} & \geq & 0, \text{ and integer} \\
\psi_t K_{tjk} x_{tjk} & \geq & \sum_{n \in F} \lambda_n y_{ntjk} \, \forall \, t, j, k \\
\sum_j \sum_k \sum_t y_{ntjk} & \leq & h_n \, \forall \, n \in F \\
\sum_k \sum_t y_{ntjk} & = & 1 \ \forall \ j \in U \\
 & & \forall \, n | s_n = j \\
\sum_k \sum_t y_{ntkj} & = & 1 \ \forall \ j \in U \\
 & & \forall \, n | d_n = j \\
\sum_k \sum_t y_{ntjk} - \sum_k \sum_t y_{ntkj} & = & 0 \ \forall \ j \in V \\
 & & \forall \, n | s_n \neq j, d_n \neq j \\
0 \ \leq \ y_{ntjk} & \leq & 1, \ \forall \, n, t, j, k \\
 & & \text{and integer}
\end{array}$$

where we define $y_{ntjk} = 1$, if LSP n is routed on link type t between nodes j and k, and $y_{ntjk} = 0$, otherwise. We note that these additional variables are necessary for the problem to internally determine the routes of the LSPs through the network. Further constraints such as the unavailability of a link between a specific set of nodes (due to geographical or other physical limitations) can be easily added to the problem. The number of nodes may have to be increased if the number of links terminating on a node exceeds the capacity of the node which would also require extra trunking between the nodes. This formulation can be enhanced with various other constraints and requirements such as dual homing (at least two links), preferences in link locations and bandwidths etc.

4. Open Issues

The traffic engineering problems formulated in this paper are NP-complete. The decision variables are integers. If the objective function is simply to minimize the administrative costs, this problem is still NP-complete as it is an integer linear programming problem. Incorporating the load balancing objective makes the objective function non-linear, resulting in a quadratic programming problem with integer variables. No NP-complete problem can be solved by any known polynomial time algorithm (see [7]). Some of the existing techniques are branch and bound and cutting plane methods. One of the main goals of our future research is to develop efficient and computationally manageable techniques for solving this. Development of heuristics, approximation algorithms and exact solutions for simplified versions will be the focus of our work moving forward. Moreover, the following set of issues need to be addressed as well:

- In this paper, we assumed a one-to-one relationship between traffic trunks and LSPs for simplicity and ease of analysis. The differences between traffic trunks and LSPs are articulated in [1]. A traffic trunk is unidirectional and carries packets that belong to the same class and it can be moved from one LSP to another. Ways in which our formulation can accommodate these differences are left for future study.

- In this paper, we focussed only on the effective bandwidth requirements for each LSP. Since LSPs may have resource requirements that are characterized by multiple parameters such as peak rate, average rate, maximum burst size and packet size distribution, a suitable method for estimating the effective bandwidth for an LSP is necessary (for example, see [5]).

- The only resource attribute considered in this paper is bandwidth on links. Other resource attributes such as buffers need to be taken into account as well.
- In our formulation of the constraint based routing problem, we assumed that all LSPs will be routed through the network which is indicated by whether the optimization problem has one or more feasible solutions. In certain network conditions, one may not be able to route all LSPs and hence, decisions to accept which LSPs and to reject which LSPs have to be made. Therefore, this problem has to be addressed.
- Aggregation, de-aggregation and merging of LSPs and traffic flows were not considered in this paper though they are interesting research topics. Aggregation and merging are useful method for increasing network scalability.
- Many LSR vendors have developed traffic engineering solutions by enhancing the network layer routing protocols such as OSPF and IS-IS to carry and disseminate information about the QoS characteristics of the links and nodes, including information such as the utilization of the links, delay and link colors. Then standard Dijkstra algorithms are applied to pruned or constrained network topologies based on the QoS information. But, this method does not allow getting over the NP-complete nature of the problem and so the solution based on the Dijkstra algorithm is suboptimal. Whether the solutions are within reasonable range of the optimality need to be studied in depth. The developers and implementers of this technique have not addressed the performance issues in detail which would be necessary for widespread acceptance and success in the marketplace. In addition, the development of interfaces with the enhanced routing protocols is an area of immense application potential.

5. Conclusions

The success of next generation IP networking depends on the ability to offer and support QoS to customers. It is clear that traffic engineering is critical for this as well as for efficient network resource utilization and operation. Traffic engineering in MPLS based IP networks is an area where work has only recently begun. We formulated the optimization problem for constraint based routing, connection admission, rerouting and capacity planning. The first problem formulated is the constraint based routing or network resource optimization problem which deals with the optimal placement of a set of LSPs in a network. We showed how to mathematically formulate various additional constraints that could be imposed in production networks as well. Then we formulated the connection admission problem of an LSP which helps in deciding if an LSP connection request can be honored by the network and if so what is the optimal route for the LSP through the network. We then outlined how to formulate the rerouting problem. Finally, we formulated the network design and capacity planning problem.

It turns out that the traffic engineering problems that were formulated in this paper are NP-complete optimization problems which cannot be solved exactly and efficiently in polynomial time with any known algorithm, thereby making implementation computationally complex. Nevertheless, various approaches including heuristics and approximations may solve the problem in reasonable computation time. It is desirable to have such algorithms which can come up with solutions within acceptable computation time that have bounded deviation from optimality. Therefore, one of the objectives of this work is to fuel more research towards the development of efficient solution techniques.

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