An Off-line Traffic Engineering Model for MPLS Networks

Selin Cerav Erbas* Rudolf Mathar

LFG Stochastik, RWTH
Wuellnerstrasse 3, D-52056 Aachen, Germany
{cerav,mathar}@stochastik.rwth-aachen.de

Abstract

In this study, an offline traffic engineering model for Multi-Protocol Label Switching (MPLS) networks is introduced. The model aims at mapping the traffic trunks, consisting of both Best-Effort traffic and traffic with QoS requirements, onto the network. For an optimal network management, three different objectives are taken into consideration, namely minimal routing delay, optimal load-balance in the network, and minimal splitting of traffic trunks. This multi-criteria network optimization problem is formulated as a mixed integer problem. A case study is carried out in order to analyze the basic properties of the model and the trade-off between the objectives for different types of traffic.

Keywords: *Multi-Protocol Label Switching (MPLS), Off-line Traffic Engineering, Multiobjective Optimization*

1. Introduction

As the QoS and policy requirements of service classes bring more complexity to the current Internet, traffic engineering becomes more important for service providers. The service providers need sophisticated network management tools which aim at the optimal utilization of the network resources that are shared between service classes with different QoS requirements. The newly emerging technology Multi-Protocol Label Switching (MPLS) brings more convenience to traffic engineering in autonomous systems [1]. The basic idea in an MPLS network is to forward the packets through *Label Switched Paths* (LSPs) by making use of the labels which are attached to packets at the ingress router of the network. The labels are assigned to the packets according to their *Forwarding Equivalence Class* (FEC) which are then sent through one of the LSPs associated with FEC. The idea behind the classification of the packets into FEC groups is to enable the network manager to distinguish the packets according to their QoS and policy requirements. The core routers throughout the domain use these labels as an index to look up their forwarding table. The label is removed at the egress router. Another concept, called *traffic trunk*, is associated with FEC such that a trunk is an aggregation of traffic flows with the same FEC and ingress-egress router.

One of the main problems in traffic engineering focuses on the question how to map the traffic trunks onto the network [1]. Both on-line and off-line approaches to this problem are possible. In the on-line approach, the traffic trunks are mapped onto the network one at a time, when the demand for a new traffic trunk arrives at the ingress router. This state-dependent approach aims at increasing the network performance, while giving rapid responses to the changes in the network. However, it has the drawback that its solution is sub-optimal, since routing randomly arriving traffic trunks one at a time may cause an unfair utilization of the network resources. Examples for on-line traffic engineering studies can be found in [7], [4], [11], [6] and [9]. Suri et. al. [9] propose an on-line traffic engineering model which has a pre-processing step based on the expected bandwidth requirements between ingress and egress pairs.

This paper develops an off-line traffic engineering model which aims at selecting LSP(s) for traffic trunks with a time-dependent approach. A traffic demand matrix based on the expected bandwidth requirements for each traffic trunk is used as the input to the model. Customer contracts and their profiles can be helpful in obtaining the expected bandwidth requirements. The statistics collected between the ingress and egress routers can also be used in order to estimate the bandwidth requirements throughout the network.

Off-line traffic engineering studies are carried out in [8], [10] and [12]. Thirumalasetty, et. al. [10] develop a traffic engineering model for book-ahead guaranteed services

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in MPLS networks. Xiao, et. al. [12] describe a simple algorithm whose solution is sub-optimal. Our investigation deals with a type of problem first introduced by Mitra, et. al. [8]. Their main objective is to maximize the total throughput. They propose that decreasing the network usage by priority traffic causes an increase in the throughput of the Best-Effort traffic. Our study differs from their study in the way that we consider different objective functions and mostly focus on the trade-off and/or conflict between the objective functions.

2. Problem Definition, Model Formulation

2.1. Problem Definition

The basic problem is to select the optimal LSPs for traffic trunks from different service classes in a capacitated network. The service classes include both traffic with QoS requirements and Best-Effort traffic. Within the QoS context, it is reasonable to put these service classes into priorities, so that the traffic trunks are given a relative importance. For example, when three priority levels are defined as "High", "Medium" and "Low", the traffic trunks for voice and video data can be given the priority level "High", while traffic trunks for World-Wide-Web and Best-Effort data can be assigned to "Medium" and "Low" respectively. The definition of the priority set and assignments can vary from network to network. Let's assume that the set of all traffic trunks is denoted by T, and that they have the following attributes:

- Each traffic trunk has a bandwidth requirement d_t.
- The transmission performance of the traffic from QoS classes is highly dependent on the jitter, delay and reliability. As the number of hops on a LSP decreases, the traffic trunks will experience less jitter and delay. Moreover, using a smaller number of hops increases the transmission reliability of the traffic trunks, since the probability of a failure on the LSP decreases. Therefore, the traffic trunks from QoS classes have a constraint on the number of hops on their LSP(s). In order to implement this constraint, an admissible path set $P_t = \{p_t^1, ..., p_t^{L_t}\}$ is defined for each traffic trunk. Since the traffic trunks for Best-Effort traffic do not have such a constraint, they will have an admissible path set which consists of all possible paths between their ingress and egress router.

2.2. Model Formulation

For the mathematical model, the network is represented as a directed graph, where $V = \{1, 2, ..., N\}$ and $E = \{1, 2, ..., M\}$ define the set of the routers and links respectively. The directed link m has capacity u_m. Three objectives are taken into consideration for this model. These objectives are combined into a single objective function, by assigning a relative weight to each of them. The following sections explain these objective functions.

2.2.1. Minimizing the routing cost. The first objective in the model aims at minimizing the routing delay which is experienced by the traffic trunks. Link m is assigned a value c_m to represent the delay on the link. We now introduce indicator variables $a_{t,m}^l$, which is equal to 1 if path p_t^l uses link m, and 0 otherwise. The cost of p_t^l is denoted by C_t^l and,

$$C_t^l = \sum_{m \in E} c_m a_{t,m}^l.$$

Let x_t^l represent the amount of bandwidth that is routed on the path p_t^l from the admissible path set P_t of traffic trunk t. There exists the constraint that the sum of the routed traffic should meet the demand for each traffic trunk. In order to avoid infeasibility, an artificial decision variable, v_t, is added for each traffic trunk in the system. When a very high objective function coefficient is assigned to these artificial variables, the network is forced to admit as much traffic as it can carry. The following constraints are related to this objective:

$$\sum_{l \in P_t} x_t^l + v_t = d_t \qquad \forall t \in T, \tag{1}$$

$$x_t^l \geq 0, \quad v_t \geq 0, \qquad \forall l \in P_t, \text{ and } t \in T. \tag{2}$$

The first objective function may be written, as follows:

$$min \sum_{t \in T} \sum_{l \in P_t} C_t^l x_t^l.$$

There exist two approaches which handle the distribution of the traffic trunks with various priority levels within the network. The first one is based on differentiating the links' cost for each priority level, while all the traffic trunks are mapped onto the network at once. When the links cost more for the traffic with higher priority, the model attempts to assign the shorter paths to the traffic trunks with higher priority.

The other approach is to solve the model a series of times, each time for one priority level. The model is first solved for the traffic trunks with highest priority level. Then the model is executed for lower priority levels on the graph with reduced resources which are utilized by the higher priority levels. Our case study is based on this approach, since the visualization of the relationship between the objective functions becomes more apparent.

2.2.2. Balancing the load. The second objective aims at avoiding extreme utilization of some links while leaving

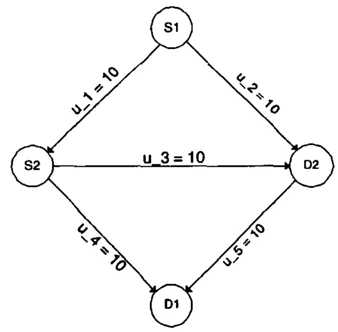

Figure 1. An Example for the Explanation of the Load Balance Function

others nearly idle. Minimizing the maximum link utilization in the network is the most widely used objective function for this aim. However, a modified version of the function that was proposed in [2] is suggested in our model. In their study, for each link a cost function based on its utilization is defined. The aim is to minimize the sum of the links' costs. The idea behind the function is to penalize sending packets over a link as the utilization gets higher.

Using this function results in an LSP assignment which is more sensitive to the balanced load distribution. This reasoning is illustrated in Figure 1. In this network there exists 4 routers and 5 unidirectional links (e_1,..., e_5) which are indicated by directed arcs. There are two traffic trunks, one of them has a bandwidth demand of 10 units/sec from S1 to D1 and the other one has a demand of 10 units/sec from S2 to D2. The first traffic trunk has to be sent through link 3, since it is the only available path to its destination. So, the maximum utilization in the network is forced to be 1. Minimizing the maximum utilization as an objective would not care of the rest of the network, and transmitting all of the demand of the second trunk through e_1 and e_4 will be probably its proposed solution. The solution obtained by minimizing the specified cost function proposes sharing the demand of the second trunk equally over the paths through e_1 following e_4 and e_2 following e_5.

The load balancing function used in this study differs from the original function in the way that it is scaled down by the capacity of the corresponding link. In its original format the function attains higher values for the links with higher capacity at the same utilization level, in which case the model would intend to utilize the links with lower capacity. Furthermore, in our model it is not allowed that the links will be utilized more than their capacities. The modified cost function is illustrated in Figure 2.

The mathematical formulation of this objective is as follows. The total amount of bandwidth carried on link m is denoted by f_m,

$$f_m = \sum_{t \in T} \sum_{l \in P_t} a^m_{t,l} x^l_t \qquad \forall m \in E, \tag{3}$$

$$f_m \le u_m \qquad \forall m \in E. \tag{4}$$

For link m with capacity u_m, the link utilization is equal to $\lambda_m = \frac{f_m}{u_m}$ and the following constraints are used to determine the value of the load balance cost function ϕ_m:

$$\phi_m \ge \lambda_m, \tag{5}$$

$$\phi_m \ge 3\lambda_m - \frac{2}{3}, \tag{6}$$

$$\phi_m \ge 10\lambda_m - \frac{16}{3}, \tag{7}$$

$$\phi_m \ge 70\lambda_m - \frac{178}{3}. \tag{8}$$

Our second objective is stated as,

$$min \sum_{m \in E} \phi_m.$$

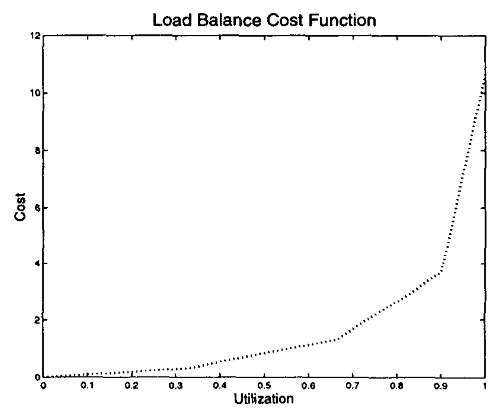

Figure 2. The Load Balance Cost Function

2.2.3. Minimizing the number of LSPs. Our third objective is related to the number of LSPs used by the traffic trunks. The more traffic trunks are split over the network, the more LSPs will be established and the more complex the network management will be. Splitting the traffic trunks over multiple paths will bring more messaging and labeling overhead. When the traffic flow is sent through multiple paths, the packets may experience more variant delay from each other and need to be reordered. Thus, the model aims at minimizing the number of LSPs assigned to the traffic trunks and a goal programming approach is used to implement this objective [3].

It is assumed that the network manager defines an upper-bound of the number of LSPs utilized by each traffic trunk. Our model then minimizes the amount of the positive deviations, by which these upper-bounds are exceeded. For this purpose, we introduce decision variables y_t^l, which are equal to 1, if the path p_t^l is utilized, and 0 otherwise. For every candidate path in the admissible set of each traffic trunk, the following constraint is added to the model to settle the value of y_t^l's:

$$x_t^l \leq d_t y_t^l \qquad \forall l \in P_t \text{ and } \forall t \in T, \tag{9}$$

$$y_t^l = \{0, 1\} \qquad \forall l \in P_t \text{ and } \forall t \in T. \tag{10}$$

Let b_t and p_t^+ denote the upper-bound for traffic trunk t, and the corresponding deviation, respectively. The relationship between these is given by,

$$\sum_{l \in P_t} y_t^l - p_t^+ \leq b_t \qquad \forall t \in T, \tag{11}$$

$$p_t^+ \geq 0 \qquad \forall t \in T. \tag{12}$$

Hence, our third objective function has the following form:

$$min \sum_{t \in T} p_t^+$$

2.2.4. Combining the objective functions. The above objective functions explained are combined into a single function by using a weighting mean. However, due to the differences in their scale, the objective functions should be renormalized by a factor. Let us represent the first, second and third objective functions by F_1, F_2 and F_3 respectively. The corresponding scaling factors Δ_1, Δ_2 and Δ_3 for the objective functions can be determined by,

$$\Delta_i = \frac{\max_{j=1,2,3} Range_j}{Range_i} \qquad i = 1, 2, 3. \tag{13}$$

The following strategy is used to determine the range of each objective functions. The model is run three times, each time only one of the objective functions is minimized, without taking the others into consideration. The respective solutions are denoted by s_1, s_2 and s_3, and each objective function is evaluated at each solution. Then, their range is determined as follows:

$$Range_i = \max_{j=1,2,3} F_i(s_j) - \min_{j=1,2,3} F_i(s_j) \qquad i = 1, 2, 3. \tag{14}$$

After the scaling, the objective functions are multiplied by the corresponding weights $\delta_1, \delta_2, \delta_3 \geq 0$. The objective is a convex combination of these three objectives, hence

$$\delta_1 + \delta_2 + \delta_3 = 1. \tag{15}$$

Finally, the mathematical model has the following objective function:

$$\min \begin{cases} \delta_1 \Delta_1 \sum_{t \in T} \sum_{l \in P_t} C_t^l x_t^l \\ + \; \delta_2 \Delta_2 \sum_m \phi_m \\ + \; \delta_3 \Delta_3 \sum_{t \in T} p_t^+ \\ + \; \sum_{t \in T} h_t v_t \end{cases}$$

where

$$\delta_1 + \delta_2 + \delta_3 = 1. \tag{16}$$

The constraints of the model are given by (1)-(12).

2.3. k-shortest Path Approach for the Best-Effort Traffic

As it is stated in the previous section, the traffic trunks from Best-Effort traffic have an admissible path set that consists of all the paths between the corresponding ingress and egress router. However, as the size of the network gets higher, the number of possible paths between any two nodes grows exponentially. In order to limit the number of possible paths, only the k-shortest paths are considered for each Best-Effort trunk. The algorithm defined in [5] is used in order to find the k-shortest paths without repeated nodes. The admissible path set for each Best-Effort traffic trunk then consists of these k-shortest paths.

3. A Case Study of the Model

The main purpose of this case study is to observe the interaction of the objective functions. We explain what type of trade-off and conflict a network manager could face when routing the traffic trunks over the network. We are also interested in the performance of the k-shortest path approach. For this study, the network topology illustrated in Figure 3 is taken from [7]. The cost to represent routing delay on each link is equal to unity. The links shown by the complete arcs have a bandwidth of 48 units/sec, where the links shown by dashed arcs have 12 units/sec. The network used in this study is a slightly modified version of the original one. Some links are deleted from the original network, so that the ranges between the lengths of the k-shortest paths are increased for a better visualization of the effect of the first objective function. Additionally, due to the assumption of unidirectional links in our model, ingress-egress pairs in the reverse direction are also considered. The network performance is evaluated with the following parameters:

- Total routing cost,
- Average load balance cost per link on the network,
- Total number of LSPs utilized.

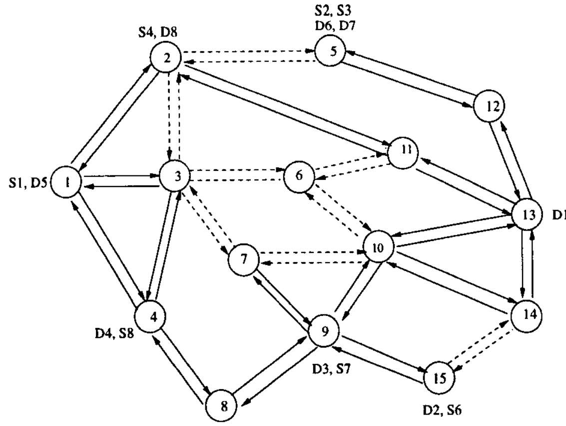

Figure 3. Example Network Topology

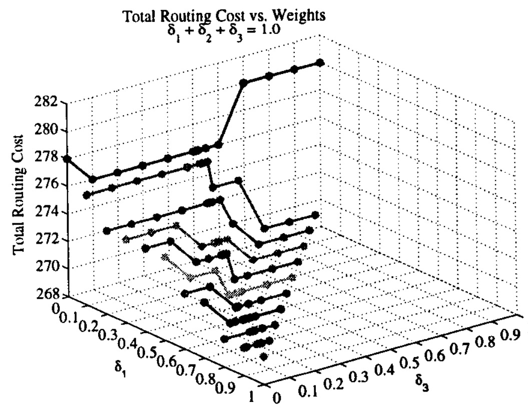

Figure 4. Total Routing Cost vs. Weights (Priority Traffic)

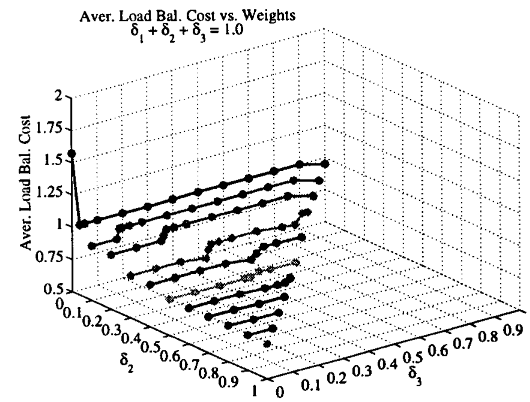

Figure 5. Average Load Balance Cost vs. Weights (Priority Traffic)

Furthermore this case study is based on placing only one type of traffic at a time (either Best-Effort or QoS) for a clear perception of the relationship between the objective functions. The calculations were performed by CPLEX 6.6 Mixed Integer Programming Solver. In all of the runs of the case study the optimal solutions are obtained in reasonable time.

3.1. The relationship between the objective functions

In this study, it is assumed that two types of traffic exist, one level priority traffic and Best-Effort traffic. We start with the priority traffic where the maximum number of hops is bounded by 4 on any possible path. It is also assumed that for each ingress-egress pair, there exists a total traffic demand of 20 units/sec (10 units/sec for each type of traffic). The penalty costs denoted by h_t in (16) for infeasibility are assigned to a very high value and the throughput has a value of 1.0 in these runs. Furthermore, the upper-bounds on the number of LSPs b_t in (11) are assumed to be 1.

Figure 4, 5, 6 show the network performance with respect to various combinations of the weights. Recall that $\delta_1 + \delta_2 + \delta_3 = 1.0$. In Figure 4, it is observed that the total routing costs decrease, as δ_1 increases. If δ_1 is 0, the routing costs attain very high values, which should be avoided. The parameter δ_3 has a positive effect on the routing costs. For the same value of δ_1, it reduces the delay remarkably when it exceeds a certain value. According to Figure 5, δ_2 should never be 0 to avoid a bad load balancing in the network. Keeping δ_2 fixed and changing the values of δ_1 and δ_3 does not have a definite effect on the average load balance of the network. However, in Figure 6, it is observed that δ_2 always has a negative effect on the total number of paths. Thus, in this case we conclude that giving higher importance on load balancing results in worse total routing costs and a higher number of paths.

Supplementary to the above analysis, the following pairwise interactions of the objective functions have been investigated. In Figure 7, 8 and 9, the weight of the first, second and third objective function is fixed to 0.3 once at a time. We should note here that the other two weights sum up to 0.7. Each figure shows the effects of the other two weights on all of the network performance parameters. The observations from the figures confirm our conclusion from the first study. In Figure 7, δ_1 is kept at 0.3. It is observed that there exists a definite conflict between minimizing the total number of paths and balancing the load on the network. Giving higher importance to minimizing the total number of paths results in a decrease in the total routing costs. In Figure 9, where δ_3 is fixed at 0.3, a similar conflict is observed be-

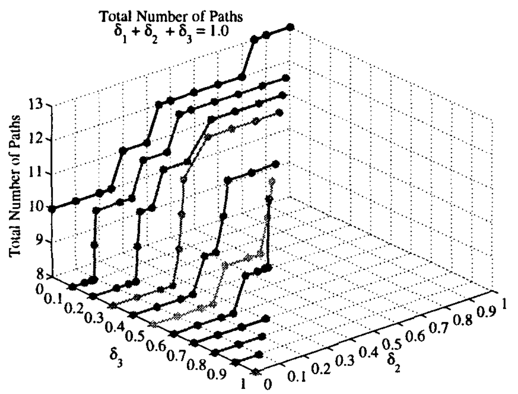

Figure 6. Total Number of Paths vs. Weights (Priority Traffic)

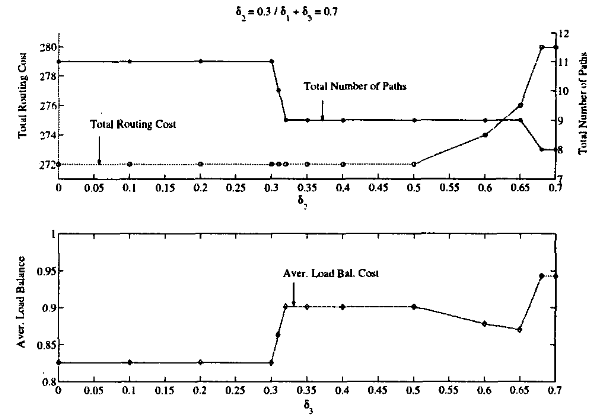

Figure 8. Network Performance vs. δ_3 when $\delta_2 = 0.3$ (Priority Traffic)

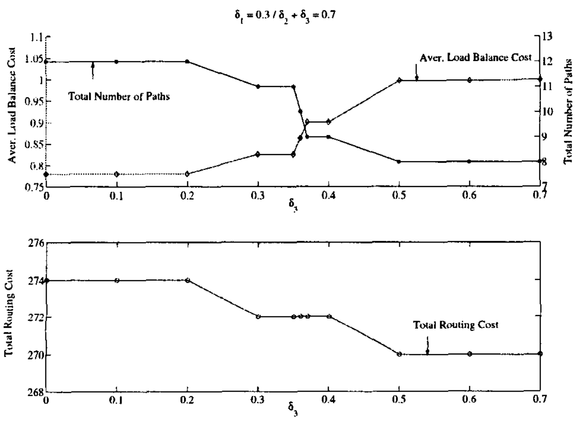

Figure 7. Network Performance vs. δ_3 when $\delta_1 = 0.3$ (Priority Traffic)

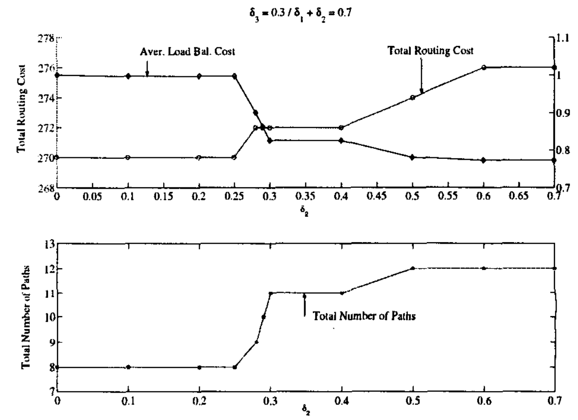

Figure 9. Network Performance vs. δ_2 when $\delta_3 = 0.3$ (Priority Traffic)

tween minimizing the total routing costs and balancing the load. However, as seen in Figure 8, a decrease in the total number of paths does not always yield an increase in the total routing costs.

Before proceeding to the second part of this study, we choose a solution from the first part for the priority traffic. In this case, the network manager can choose a solution which favors a more balanced priority traffic over the network, where the traffic is assigned to relatively long paths and more LSP paths are used. When the rate of priority traffic increases on a link, there exists the possibility that Best-Effort (and/or lower priority traffic in general) can suffer from high waiting times at the routers, since the routers will give precedence to the higher priority traffic during transmission. The network manager can also choose the solution which favors minimizing the total routing cost and the total number of paths for priority traffic. The choice of the network manager depends on the QoS requirements of the traffic and the network conditions, such as the rate of bandwidth requirement of priority traffic.

We assume that the network manager prefers the solution which minimizes both the number of LSPs and the total routing cost. According to this solution, only one LSP is assigned to each traffic trunk, they experience a total routing cost of 270, and the average load balance cost is 0.997. We then tried to accommodate the Best-Effort traffic on the network with the reduced resources. In this study, the parameter k is chosen as 15. Similar types of graphs as in the first part of this study are plotted for Best-Effort traffic.

According to Figure 10, the total routing costs attain very high values, if δ_1 is assigned to 0. The total routing costs decrease, as the value of δ_1 increases. Similar observations can be made in Figure 11 and 12 for average load balancing costs and total number of paths. However, there is no definite relationship or conflict between the objective functions. Interestingly, at some points in Figure 11 increasing δ_3 causes a remarkable decrease in the average load balance costs. Similarly, an increase in δ_2 in Figure 12 gives a significant decrease in the total number of paths. The reason for this observation is that as δ_1 favors the shortest paths (partially utilized by priority traffic and not enough capacitated for all Best-Effort traffic), δ_2 favors the less loaded but longer paths. At some fixed value of δ_2, increasing δ_3 (which means a decrease in δ_1) causes the model to route the traffic totally through the less loaded paths, so a smaller number of paths is used and the network is more balanced. Obtaining a solution, by giving high weights to minimizing the load balance cost and minimizing the total number of paths is preferable for Best-Effort traffic, which is not sensitive to the routing delay.

Figure 13, 14 and 15 clarify the relationship between the objective functions. In these figures, we observe that when a weight is kept at the value of 0.3, the other two objective functions behave anticyclically. For example, in Figure 13, the total number of paths decreases in expense of an increase in the average load balance costs.

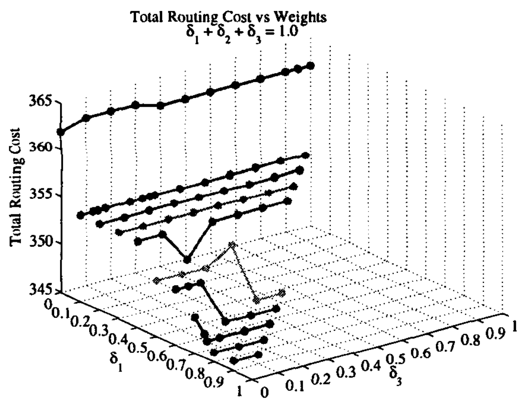

Figure 10. Total Routing Cost vs. Weights (Best-Effort Traffic)

An important observation that is obtained from Figure 13 is that, if δ_3 is increased from 0 to a small number, the total number of paths drops by 3, although the total routing and average load balance costs remain the same. The same situation can be seen for δ_2 in Figure 15. These observations indicate that δ_2 and δ_3 should be strictly positive. It is highly possible that there exist multiple solutions which have the same value for total routing cost and average load balance cost (total number of paths) in the network. However, these solutions can differ in the total number of paths (average load balance cost).

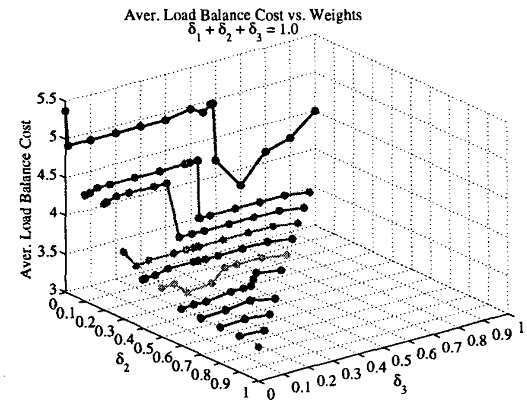

Figure 11. Average Load Balance Cost vs. Weights (Best-Effort Traffic)

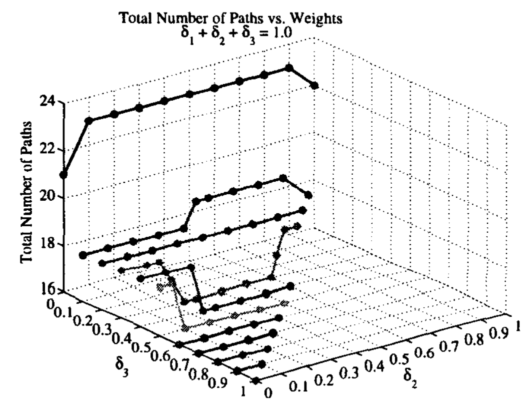

Figure 12. Total Number of Paths vs. Weights (Best-Effort Traffic)

From this case study, we can conclude that as the priority of the traffic trunks decreases, the relationship between the objective functions becomes more complex. According to the observations, each of the objective functions has to be considered in the model. For different types of traffic, different combinations of the weights can be chosen according to the QoS requirements of the traffic trunks and the network conditions. For example, for the priority traffic with low bandwidth requirement, minimizing the total routing cost has the highest preference. As the traffic demand increases, the second and third objective function will have higher importance in the model.

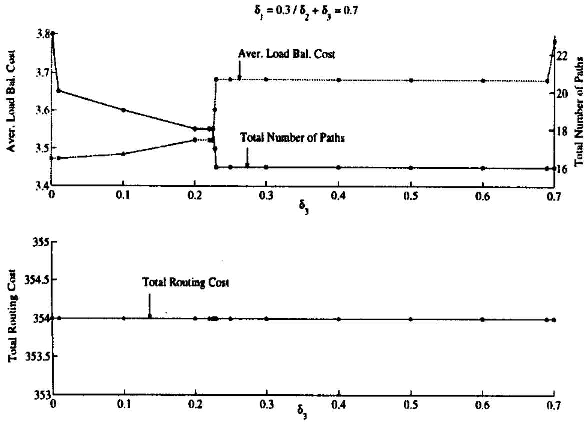

Figure 13. Network Performance vs. δ_3 when $\delta_1 = 0.3$ (Best-Effort Traffic)

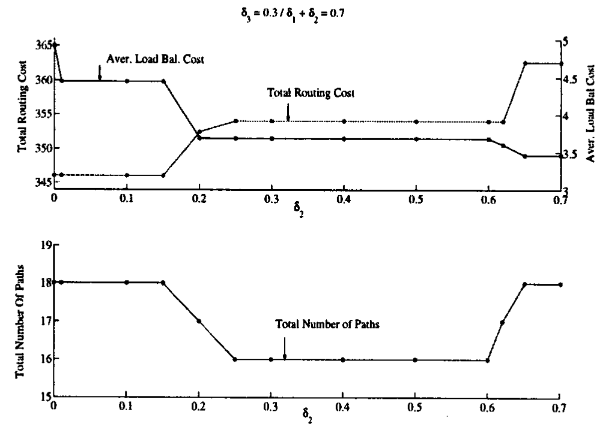

Figure 15. Network Performance vs. δ_2 when $\delta_3 = 0.3$ (Best-Effort Traffic)

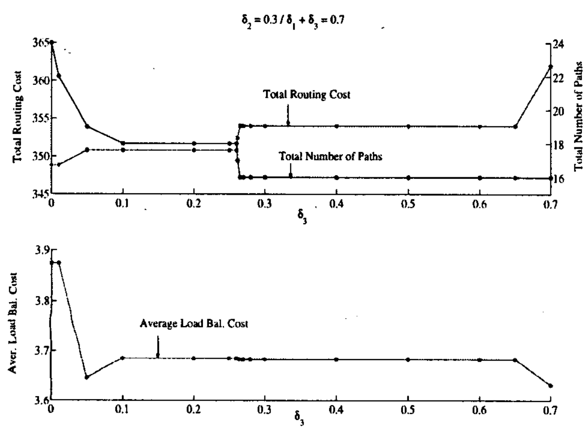

Figure 14. Network Performance vs. δ_3 when $\delta_2 = 0.3$ (Best-Effort Traffic)

3.2. The effectiveness of k-shortest path approach

We conclude with an experiment about the performance of the k-shortest path approach for Best-Effort traffic trunks. Best-Effort traffic trunks are fed into the reduced network, each with a demand of 10 units/sec. The weights are selected as $\delta_1 = 0.5$, $\delta_2 = 0.3$, $\delta_3 = 0.2$. The parameter k is varied between 10 and 22. However, since the throughput is less than 1.0 for $k \leq 13$, the results only for $k \geq 13$ are plotted. The total throughput of the network is 0.925 if $k = 10$, and it is 0.975 if $11 \leq k \leq 13$.

The results are plotted in Figure 16. It can be seen that the total objective function value (the sum of the weighted objective functions) decreases by 0.7 % when k is increased from 16 to 17. The changes in each of the objective functions are also plotted in Figure 16. From this observation we can conclude that the parameter k should be selected carefully, since it may affect the throughput if it is too small. However, larger values of k have only a marginal effect on the quality of the solution.

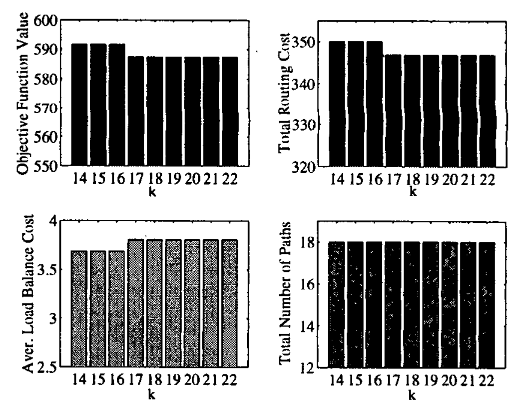

Figure 16. Network Performance vs. k when $\delta_1 = 0.5$, $\delta_2 = 0.3$ and $\delta_3 = 0.2$

4. Summary and Future Research

In this study we have presented an off-line multi-objective traffic engineering model for MPLS networks. The model aims at selecting LSP(s) for both QoS and Best-Effort traffic. Three different objectives are taken into consideration: Minimizing the routing delay, balancing the load over the network, and minimization of traffic splitting. We have studied the relationship between the objective functions on an example network. We have studied how these objectives show different type of trade-offs and conflicts for different types of traffic. According to our solution all of the objectives should be considered in the model. There may exist multiple solutions which have the same performance with regard to the total routing delay and load balancing (the number of paths), but these solutions may differ in the total number of paths (the load balancing costs). Future work will be concerned with the development of heuristics for effectively solving large instances of the proposed model.

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