# Verification of MPLS Traffic Engineering Techniques

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Abstract—MultiProtocol Label Switching (MPLS) provides a framework for doing more flexible traffic engineering via its explicit routing capability. In this paper, MPLS routing models with two different objectives that utilise MPLS explicit routing are presented and discussed. The objectives are to minimise the network cost and maximise the minimum residual link capacity. The model that maximises the minimum residual link capacity is found to perform substantially better, in terms of network throughput and packet loss. The performance is verified by using the well-known ns-2 simulator under different network loads. The MPLS techniques described in this paper can substantially improve network throughput and user perception of quality in comparison to traditional intra-domain routing methods.

#### I. INTRODUCTION

Recent years have seen a tremendous growth in Internet traffic. This on-going growth increases the need for Internet Service Providers (ISPs) to operate and manage their networks efficiently to avoid congestion on their customers' traffic flows. Throwing an abundant amount of bandwidth into the network to address customers' demand for bandwidth is neither a sensible nor an efficient solution to improving network performance. ISPs, typically control one or more Autonomous Systems (AS). To avoid the high cost of network assets, another solution is required which emphasises the need for maximum operational efficiency.

Congestion typically occurs when network resources are insufficient or inadequate to accommodate the offered load or when traffic streams are inefficiently mapped onto network resources. Traffic Engineering (TE) addresses the latter, which causes some subsets of the network to become over-utilised while others remain under-utilised [1]. A major goal of Internet Traffic Engineering is to facilitate efficient and reliable network operations while simultaneously optimising network resource utilisation and traffic performance.

Interior Gateway Protocols (IGP), such as Open Shortest Path First (OSPF) [2] or Intermediate System-Intermediate System (IS-IS) [3], are typically used to route IP traffic inside an AS. Currently, these IGP protocols have very little traffic and resource control capabilities. These protocols operate according to a shortest path paradigm by using a suitable distance metric on the links (without taking load and network resources into consideration). To overcome this problem, an overlay model is proposed in [4]. The overlay model creates virtual links between every node in the network. However, this solution does not scale well in large networks. To overcome the scalability problem with the overlay model, weight setting has been proposed [5] [6]. The idea is to find a set of "good" link weights, assuming a known traffic demand matrix, to balance the link loads. Unfortunately, finding a good set of weights can take a very long time if particular search methodologies are employed. On the other hand, a Linear Programming formulation can be solved to attain a set of weights much more rapidly, with an optimality trade-off [7].

Multiprotocol Label Switching (MPLS) [8] has been developed to address the traffic engineering problem from a different angle. The idea is to affix a short fixed length label to packets when packets enter an MPLS domain. Packets with the same MPLS label indicate that they belong to the same Forward Equivalence Class (FEC). Packets in the same FEC will receive the same forwarding treatment. In this work, the FEC granularity is made based on the destination. Hence, packets with the same label will be forwarded along the same path to their destination. This process is accomplished by a Label Distribution Protocol [9]. This label is used to rapidly guide the packet through a pre-defined tunnel, which is known as a Label Switched Path (LSP).

MPLS offers many advantages, namely traffic shaping and policing, class-based routing, traffic monitoring, and most importantly, a framework for traffic engineering [8] [10]. The MPLS forwarding process causes less load on network routers compared to the method of IP forwarding, because IP forwarding is based on longest prefix matching for the nexthop lookup process.

With an increasing number of networks supporting MPLS features, it has become mandatory to use this technology to perform traffic engineering. It is also shown in [5] that MPLS can be used to carry out optimal routing, wherein the objective is to keep the link utilisation for all links below a certain target value. The most important feature of MPLS in the context of this paper is its ability to perform TE using the explicit routing capability. Given an MPLS enabled domain, a network operator can control how traffic flows are routed in their network. In this paper, it is assumed that an Origin

Destination pair (OD-Pair) is associated with a single traffic flow.

Given a traffic demand matrix and a network topology, the question to be addressed is: which path should be chosen for each individual OD-Pair to comply with the performance objective? Two mathematical formulations are developed and discussed in this paper to address this problem. Part of the problem has already been discussed in [11]. However, this work did not specifically target MPLS technology. Furthermore, this paper presents simulation results to verify the methods. As shown later, MPLS has enabled the application of the result directly, rather than having to rely on older technology, such as shortest path routing. As an example, in [12] [13], the LSPs are established based on IGP metrics (MPLS over OSPF).

The principal contributions made in this paper can be summarised as follows: Firstly, the Mixed Integer Linear Programming (MILP) formulation for the LSP allocation problem is outlined and two different objective functions are proposed and evaluated. The solutions from these models are then used to determine the maximum link utilisation in the network. Secondly, the MILP models for MPLS are verified using the well known ns-2 simulator [14] and the statistics of packet loss in the network are presented.

The rest of the paper is structured as follows: Section II outlines different formulations for the optimisation problem with the various different objective measures. Section III describes the setup for carrying out the experimental work. Section IV describes the results obtained from the calculation and the simulation and also gives some detailed discussion of the results. Finally, section V summarises the paper.

## **II. PROBLEM FORMULATION**

This section introduces two MPLS routing allocation problem formulations, namely a single path multi-commodity flow problem (MinCost) in section II-A and the maximum residual capacity single-path problem (MaxResidual) in section II-B.

The classical multi-commodity flow problem (MCF problem) as described in [15] or [16] addresses the problem of how to send a specified amount of commodity from a source to a destination such that the total cost is minimised. In this problem, a graph, which is a collection of nodes and links, is specified and the links have an associated cost. The amount of the commodity can be associated with the size of the traffic flow in the routing problem. The link cost can be associated with an form of routing metric or it may relate directly to real dollar costs. The classical MCF formulation can be represented by a link-flow formulation or by a pathflow formulation. In this paper, the path-flow formulation is used for easier understanding and representation - it also has certain advantages over the link-flow formulation which have been considered in other contexts.

Although the traditional MCF path-flow solution can be used for network resource allocation, the formulation typically requires some adjustment via additional constraints. In particular, the MCF solution does not consider that the flow for an OD-Pair should be limited to a single path. The general formulation allows an OD-Pair flow to be split into two or more separate routes to fill the cheaper route first. In the context of this paper, an OD-Pair needs to be routed on one and only one path from the source to the destination. Hence, additional constraints are required to prevent splitting of the **OD-Pair** flows.

The network is modelled as a uni-directional graph. A path is defined as a series of links that connects the origin and the destination node of the associated OD-Pair. In our analysis, these paths are calculated for each OD-Pair using the k-shortest path algorithm due to Yen [17]. The following notation is used in the formulation:

 $\delta_{ij}^k$  is equal to 1 if link i is used in path j of OD-Pair k and 0 otherwise.

 $d^k$  is the traffic demand for OD-Pair k.

 $u_i$  is the capacity of link *i*.

 $f_i^k$  is a decision variable which denotes the amount of flow on path j for OD-Pair k.

 $c_j^k$  is the sum of link metrics or link costs along path *j*.  $x_i^k$  is a binary decision variable which takes the value 1 if path j is used to carry flow in OD-Pair k and 0 otherwise.

A. Single-Path Multi Commodity Flow Problem (MinCost)

$$\text{Minimise} \sum_{k} \sum_{j} c_{j}^{k} f_{j}^{k} \tag{1}$$

subject to

$$\sum_{k} \sum_{j} \delta_{ij}^{k} f_{j}^{k} \le u_{i}, \forall i$$
<sup>(2)</sup>

$$\sum_{j} x_{j}^{k} f_{j}^{k} = d^{k}, \forall k$$
(3)

$$\sum_{j} x_{j}^{k} = 1, \forall k \tag{4}$$

$$x_j^k \in (0,1) \quad f_j^k \ge 0, \forall j \forall k$$

The above formulation is a single path multi-commodity flow problem version. Whilst the objective is to minimise the total cost to transfer the commodity from the source node to the destination node eq. (1), the total amount of commodity flowing on a particular link cannot exceed the link capacity eq. (2). These constraints are also known as bundle constraints. Equation (3) specifies that the total flow carried on all available paths for a particular OD-Pair must be equal to the traffic demand for that pair. Equation (4) enforces the requirement that only one path is permitted to be used to carry the demand from the source to the destination. The formulation is also presented in [11].

However,' multiplying two unknown variables in equation (3) results in non-linear constraints. The constraints need to be written differently to form linear constraints. Since only one path can carry the whole OD-Pair flow, there exists one and only one of  $f_j^k$ s which must be non-zero. Furthermore, the value of this non-zero  $f_j^k$  must be equal to  $d^k$ . Hence, equation (3) can be re-written as follows:

$$\sum_{j} x_{j}^{k} d^{k} = d^{k}, \forall k$$

Dividing both sides by  $d^k$  yields the same constraint as equation (4). Hence, equations (3) can be discarded because they are redundant. Substituting  $f_j^k = x_j^k d^k$  in the above problem for simplicity gives the reduced formulation as follows:

Minimise 
$$\sum_k \sum_j c_j^k x_j^k d^k$$

subject to

$$\sum_k \sum_j \delta^k_{ij} x^k_j d^k \leq u_i, orall i$$
 $\sum_j x^k_j = 1, orall k$ 

 $x_j^k \in (0,1), \forall j \forall k$ 

## B. Maximum Residual Single-Path Problem (MaxResidual)

To minimise the delay and packet loss while sending packets from the source to the destination, it is necessary that the traffic be spread such that none of the links are congested. In this formulation, the objective is to avoid a bottleneck in the network. In other words, the objective is to maximise the minimum residual link capacity. The residual link capacity of link i,  $R_i$ , is defined as the difference between the link capacity and the total of the traffic carried on that link. A common Ris defined as min<sub>i</sub>  $R_i$  for every link.

Maximise 
$$R$$
 (5)

$$\sum_{k} \sum_{j} \delta_{ij}^{k} x_{j}^{k} d^{k} + R \le u_{i}, \forall i$$
(6)

$$\sum_{j} x_{j}^{k} = 1, \forall k \tag{7}$$

$$R \ge 0 \qquad x_j^k \in (0,1), \forall j \forall k$$

In the initial feasible solution, some links might have no residual capacity at all ( $R_i = 0$  for some links, hence R = 0). In order to perform practical calculations of the required variables in this project, a well-known standard package for solving Linear Programming problems, known as CPLEX has been used. Through the branch and bound process in CPLEX, a better solution can be attained by moving flows away from these links to "push up" the values of  $R_i$  (equation (5)) resulting in a better objective value. Equation (6) denotes the total flows on the link and the minimum residual capacity must be less than the link capacity. The single path flow allocation is enforced by introducing equation (7).



Fig. 1. Simulated topology

## C. Models Application in MPLS

When the above formulations are solved using an LP solver (such as [18]), the outputs will be a series of decision variables  $x_j^k$ . OD-Pair k will be routed on path j, whose value  $x_j^k$  is equal to one. In MPLS, this can be easily implemented by setting up an explicit route.

Upon receiving a request for an explicit route in MPLS, the Label Edge Router (LER) will send out a message to its neighbour to pin down the path to be used to reach the desired destination. This neighbour then propagates the request down the path to the destination. When the request is successful, the LER creates a label associated with this path to the destination.

## III. EXPERIMENTAL SETUP

Figure 1 depicts the network topology used in this study. It consists of 8 routers. Each of these routers is connected to a single workstation that acts as a traffic generator and a traffic sink. 10 Mbps and 100 Mbps links are used to connect between the routers. 300 Mbps links are used to connect between the workstation and the router. 10 Mbps and 100 Mbps links are assigned OSPF weights of 1 and 10, respectively. Assuming a traffic demand exists between every pair of workstations, there will be a total of 56 possible traffic flows. The size of these traffic flows has been generated randomly for this experiment.

Throughout this study, 3887 different traffic matrices have been used; each will be referred to as an *instance*. These instances are then categorised into 41 different groups according to their load level. These groups will be referred to as group 10 to group 51. Figure 2 depicts the number of instances that belong to the same group. Whilst most of the groups have more than 80 associated instances, there are a few groups that only have a few instances associated with them. This difference will affect the range of the confidence intervals obtained – as discussed in section IV.

Figure 2 also shows the average the total demand for each individual group. An increasing total demand from 26.5 Mbps (group 10) to 120 Mbps (group 51) is intended to simulate the



Fig. 2. Grouping profiles

network under different load conditions, from lightly loaded up to a saturated condition. Instances that belong to groups 10 to 25 are considered to be light loads. Those in groups 26 to 40 and groups 41 to 51 are considered as moderate and heavy loads, respectively.

In this study, OSPF will be used to provide benchmark performance, because it is widely used in practice. Nowadays, OSPF link metrics are often used for establishing LSPs in MPLS; the MPLS Traffic Engineering feature is rarely utilised. In addition, the performance of the two MILP schemes described earlier will be compared. The link utilisation in the OSPF case is calculated by assuming an even splitting whenever equal cost paths to the destination exist. This is commonly achieved by employing Equal Cost Multi Path (ECMP) in a router's forwarding plane to balance the load.

Ns-2 with the MPLS extension module [14] was used as the simulator in this study. Since such routing is only done in the core networks (i.e. among the 8 routers, see Figure 1), only these 8 routers need to be included in the MPLS domain. Explicit routes exist within these 8 nodes in MPLS domain.

OD-Pairs are modelled as constant bit rate (CBR) sources. This has been done for simplicity reasons. The CBR rate is governed by the size of the individual traffic flows and the packet size. The packet size is chosen to be 500 bytes. The packet inter-arrival time is uniformly randomised to avoid synchronisation among traffic sources. The CBR sources are activated at the start of the simulation and CBR datagrams are carried by UDP packets. On the receiving end, a loss monitor is set up to collect statistics on the number of packets that are received or lost.

The ns-2 simulation is run for 20 seconds. The first one second is regarded as the simulation warm-up period and measurements during this period are discarded. At the end of the simulation, the statistics of packet lost and received for each individual OD-Pair are collected and analysed.

#### IV. RESULTS AND DISCUSSIONS

This section presents the calculation results after evaluating the MILP models using the simulator. The results that have



Fig. 3. Maximum Link Utilisation in the 8 node test network

been obtained are discussed in Section IV-A. The model solutions are also used as the inputs for the ns-2 simulation. The simulation results are discussed in Section IV-B.

## A. Models Comparison

The solution of the MILP formulation, which is a set of paths used to carry flows for each of the OD-Pairs, is used to determine the amount of traffic on every link in the network. Given that the link capacities are known, the utilisation can be calculated directly. The parameter of interest in this comparison is the maximum link utilisation. It is used to determine the severity of a congestion bottleneck in the network.

Figure 3 depicts the maximum link utilisation when three different routing schemes are used with the different load groups. The 95% confidence intervals for the results are shown as error bars in the graphs. In the lightly loaded region, the OSPF performance and the MPLS MinCost are exactly the same. This can be explained as follows: OSPF is a routing protocol that routes the traffic without considering link capacities, instead it uses the "distance" metric known as an OSPF weight on the links. A path to a given destination that has the lowest sum of OSPF weights will be chosen. The MPLS MinCost model will do exactly the same; it will route the traffic on the path with the lowest cost. The bundle constraints in this particular situation have not "kicked in" yet because none of the links is fully utilised yet. As a result, OSPF and MPLS MinCost routing both yield maximum link utilisations varying from 40% to 95%. As expected, the MPLS MaxResidual has the lowest utilisation as it spreads the load throughout the network (30% to 65% utilisation).

Figure 3 also shows the results when the load is increased. With the increased load, OSPF routing yields a proportional increase in the maximum link utilisation (correlate this with Figure 2). In cases where the the network is moderately loaded, the bundle constraints in MPLS MinCost formulation start to take effect. They restrict the amount of traffic on a link to be less than the link's capacity. The overflow traffic



Fig. 4. Average Loss figure in 8 node test network



Fig. 5. Maximum Loss figure in 8 node test network

will be routed on different paths with available capacity. The maximum link utilisation is "kept" at 100% for MPLS MinCost. The flat line in the MPLS MinCost curve in Figure 3 shows that the maximum link utilisation does not change even when the load is increased to 40% (moderate network loads). The MPLS MaxResidual still performs better than OSPF and MPLS MinCost.

However, as the load increases further, the MPLS MaxResidual advantage slowly diminishes. Its maximum link utilisation approaches that of MPLS MinCost. In the highly loaded region, the network is completely saturated. There is no more capacity to accommodate the additional traffic. To deal with the infeasibility problem in MPLS formulations, virtual capacities are made by scaling up the real capacity by a specified factor. In this case, both MPLS models give a similar performance (see Figure 3).

For this problem size, the calculation time for the MPLS MinCost formulation is less than one second using CPLEX. This processing time can be considered negligible. Solving the MPLS MaxResidual formulation takes longer. The optimal solution to within 20% of optimality can be obtained in less than 5 seconds, on average, by using CPLEX. The optimality is calculated assuming no integrality constraints. In some of the heavily loaded cases, the solution search has to be terminated after 40 seconds has elapsed, since it is rare that any improvements can be made after 40 seconds. Surprisingly, the calculated link utilisation still falls into the trend line given by the sub-optimal solutions.

The difference in the run-time is attributed to the nature of the problems. The decision variables in MPLS MinCost are all binaries. This yields a pure integer programming problem. However, the MPLS MaxResidual formulation has an additional decision variable, R, which takes a continuous value. Hence, the problem becomes a mixed integer linear problem.

## **B.** Simulation Results

The simulation is carried out to show the performance improvement of MPLS explicit routing based on the MILP models in comparison to OSPF routing. The parameter of interest is the number of packets that are lost. For *every* instance, the number of packets lost per OD-Pair is monitored. The average of these figures is then grouped, averaged and plotted. Another measure is the maximum OD-Pair loss, which is obtained by taking maximum OD-Pair loss figure from a simulation instance. The average of these maxima are then grouped, averaged and plotted. These results are summarised in Figure 4 and 5. The 95% confidence intervals are given as error bars in these graphs.

Figure 4 shows that OSPF routing starts to exhibit packet loss when the network is moderately loaded (group 25). MPLS MinCost model slightly extends the non-loss region up to group 31. However, the most noticeable improvement is shown by MPLS MaxResidual having no loss until group 39. With MPLS MaxResidual, the network can support about 45% more traffic without experiencing packet loss compared with OSPF. When the network is heavily loaded up to its saturation point, the advantages of the MILP models slowly diminish (both MPLS curves curves start to approach the OSPF curve).

In terms of the maximum packet loss statistics as shown in Figure 5, in group 39, MPLS MaxResidual still can perform without experiencing packet loss, whilst OSPF and MPLS MinCost exhibit 30% and 14% loss, respectively. Although the average loss for MPLS MaxResidual is just slightly better than MPLS MinCost, the MPLS MaxResidual gives much better results in terms of the maximum OD-Pair loss figure. In MPLS MaxResidual, most of the OD-Pairs have similar losses because most of the links are saturated. None of them experience more loss than the others. The 95% confidence intervals in MPLS MaxResidual are tighter than those of MPLS MinCost.

It can be concluded that when the network is moderately loaded, having a model that attempts to free up bottlenecks in the network can be very beneficial. This is verified in terms of the average OD loss and maximum OD loss figures. MPLS MaxResidual performs substantially better compared to MPLS MinCost and OSPF. It is advised to "allocate" residual capacity to protect against congestion due to traffic measurement uncertainty and bursty traffic. However, when the network is heavily loaded, the experiment shows that the advantage of MPLS MaxResidual slowly diminishes. Together with an increasing computation time when solving the MPLS MaxResidual formulation, MPLS MinCost may outweigh MPLS MaxResidual.

In the heavily loaded region, the loss figures do not exactly fall into the trend. A small number of instances in these groups contributes to the deviation. A smaller number of instances also results in wider confidence intervals. Most of the groups have 80 instances each, however the last few groups only have less than 30. Maximum time restrictions for solving the MPLS MaxResidual formulation, which yield sub-optimal solutions, may also contribute to the deviation.

Having the available capacity to reroute traffic is particularly important in all traffic engineering methods. In a situation, where there is no capacity available to reroute the traffic, a different congestion management scheme needs to be employed. Congestion control mechanisms that automatically adjust the sending rate depending on the network load is required.

## C. Optimisation on an Operational Network

It is important during the subsequent optimisations that only few LSPs need to be re-configured and re-established. A complete LSP re-shuffling is generally not acceptable, because of the introduced disturbance to customers' flows. The MPLS optimisation process can be influenced to take this factor into consideration.

The MILP formulations in this paper can be extended as follows: The first alternative is to restrict the elements in the path list. The path list for the OD-Pair, whose LSP that are not permitted to be re-configured, should contain only one path. This path must correspond to the path that is currently taken by the LSP. A second alternative approach is to preset the decision variable  $x_j^k$  to one, ensuring that OD-Pair k uses path j. Path j corresponds to the path that should not be changed.

## V. CONCLUSION

This paper has outlined two MILP models for the LSP allocation problem in an MPLS domain. These models make use of the explicit routing capability in MPLS. The output of these models has been compared against the default OSPF routing. The calculation and simulation results for many test scenarios has been presented to verify the formulations. It is beneficial to maximise the minimum residual capacity in the network in order to spread the load which, in turn, balances the link utilisations and reduces the packet loss. The MPLS MaxResidual outperforms OSPF and MPLS MinCost when the network is lightly and moderately loaded. With high loads, it loses its advantage; MPLS MinCost may be a more attractive solution given its faster calculation time. Furthermore, these two MILP models can be extended to allow the optimisation of operational networks without having to reconfigure many existing LSPs.

It is argued that ILP or MILP formulation cannot be solved in medium-sized networks in a reasonable timeframe. It will be interesting to investigate these limits when the MILP formulation cannot be solved. A "multi-staged model" of mixed pure LP / ILP / MILP formulations could be developed to address the problem of maximising residual capacity with different network sizes. Future work also includes the formulation of extensions that allow intermediate nodes to aggregate LSPs with the same destination.

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