Zero-budget Network Dimensioning

Wenli Liu, Youssef Iraqi and Raouf Boutaba
School of Computer Science
University of Waterloo
200 University Ave. W.
Waterloo, ON, Canada
{*w7liu, iraqi, rboutaba*}*@bbcr.uwaterloo.ca*

Abstract

Traffic engineering has been widely used to improve network performance while keeping the resource utilization balanced. The existing traffic engineering approaches, however, lead to network upgrades from time to time. While these upgrades might be successfully financed during economic prosperities, it poses a problem when the economic situation deteriorates. We propose in this paper a novel approach that is able to reveal whether a traffic re-engineering is necessary. In case budget is not available for upgrades, this approach can optimally decide which demand to satisfy so as to maximize network operators' revenue. We demonstrate the usefulness and the effectiveness of the approach by conducting traffic engineering on an example network and by describing some of its added values as well.

Keywords

Traffic Engineering, Performance Optimization, Resource Allocation, Metrics, Metrics Tree

1. Introduction

While the Internet evolves into a pervasive global network, mission-critical applications are increasingly deployed on it. How to ensure the Internet's reliability and improve its performance has been the focus of the industry and research community ever since. Traffic engineering, as one of the most commonly used and the most effective methodologies employed by ISPs to increase the reliability and the performance of their networks, handles the routing of traffic through a network in such a manner that over-utilization of some network elements is minimized when some elements is under-utilized. In essence, traffic engineering focuses on satisfying all the demand and network upgrades have to be carried out occasionally. These upgrades, when required during the economic prosperities, like the late 1990's and the year 2000, are feasible since the telecommunications service providers once spent billions of dollars in upgrading their networks during the period. For example, about 55 billions were spent in US alone as telecommunications related venture capital in 1999 and more than 100 billion in 2000 [4]. However, the "bubble" has truly burst. While 2002 saw the decline of 47% in venture capital investment, a slightly over 18 billion was invested in 2003. So far in 2004, only 10 billion was invested in the telecommunication industry. In addition, more than 600,000 productive and rewarding

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jobs from the telecommunications sector were cut in the last few years and the trends are still persisting [5]. Facing such severe economical situations, the telecommunications service providers are unable to resort any congestion problems to simply network upgrades. In this respect, existing traffic engineering approaches appear rather limited.

We propose in this paper a novel approach that differentiates demands for the supported services and weights customers according to their profitability. When the network performance degrades and no budget is available for upgrade, this approach is able to optimally decide what percentage of a demand to satisfy to maximize revenue and how to generate an optimal path for each of the satisfied demands at the same time. Due to the fact that portions of demands are dropped out, networks become less congested and the customer perceived performance can be improved consequently. In addition, the proposed approach incorporates for the first time the metrics tree model [11] into traffic engineering. The metrics tree model correlates measures from the network level, service level, customer level and business level into a coherent system that can effectively reveal the time for a traffic re-engineering and the effects of the traffic re-engineering.

The rest of the paper is organized as follows: section 2 presents some common approaches taken in traffic engineering and briefly describes the metrics tree model. The approach proposed in this paper is illustrated in section 3. We address the scalability issue associated with the approach in section 4. Some added values of the proposed approach are illustrated subsequently in section 5. We conclude this paper with a brief summarization in section 6.

2. Related Works

As one of the most effective and commonly used methodologies, traffic engineering has drawn much attention ever since. Approaches such as OSPF [3], equal cost multi path [2], constraint-based routing [1], DORA [8], etc., are brought up one by one. The overlay model [1] [9], however, is the most related approach to this paper. Within the overlay model, explicit paths between edge nodes are established, either through off-line or on-line procedures, for demands between these nodes, i.e., the traffic matrix. By carefully mapping these explicit paths to the underlying physical links, the network service providers can balance traffic distribution throughout the network, thus minimizing the possibilities for hot spots. In [9], a network is abstracted as a graph $G = (V, E)$ wherein V represents the set of nodes and E the set of links. For each link $(i, j) \in E$, c_{ij} indicates the link's capacity. [9] models the demands between edge nodes as a set K and for each demand $k = (d_k, s_k, t_k) \in K$, d_k, s_k and t_k represent the required bandwidth, the source node and the destination node respectively. In addition, X_{ij}^k represents the percentage of k's bandwidth demand that can be provided by link (i, j) and α is the maximum link utilization in the network. The establishment of the explicit paths and the mapping of these paths to the physical links are then formulated as a linear programming problem as follows.

$$\min(\alpha) \tag{1}$$

$$s.t.$$

$$\sum_{j:(i,j)\in E} X_{ij}^{k} - \sum_{m:(m,i)\in E} X_{mi}^{k} = 0 \qquad \forall k \in K, i \neq s_k, t_k \tag{2}$$

$$\sum_{j:(i,j)\in E} X_{ij}^{k} - \sum_{m:(m,i)\in E} X_{mi}^{k} = 1 \qquad \forall k \in K, i = s_k \tag{3}$$

$$\sum_{k\in K} d_k X_{ij}^{k} \leq c_{ij}\alpha \qquad \forall (i,j) \in E \tag{4}$$

$$0 \leq X_{ij}^{k} \leq 1, \qquad \alpha \geq 0 \tag{5}$$

While the objective function (1) intends to minimize the maximum link utilization over the entire network, equation (2) requires that traffic flowing into and out of any intermediate node has to equal to each other for any demand and equation (3) specifies that traffic flowing out of a source node has to equal to 1 for any demand that originates from the source node. The fact that all the traffic passing through a link should not exceeds the link's maximum utilization is captured in equation (4). The range of X_{ij}^{k} and α are specified in equation (5). The optimization result, namely α and X_{ij}^{k}, will reveal whether upgrades are necessary and the mapping of demands to the physical links. If α has a value that exceeds a pre-specified utilization threshold, some upgrades are either mandatory in order to satisfy all the demands or necessary to bring the utilization level lower than the threshold. As mentioned before, the overlay approach, as well as its variants ([12], [7], [10]), does not tell how to optimally sacrifice some demands when α has a high value and there is no budget available for network upgrades.

Another related work is the metrics tree model [11], which correlates technology and network layer metrics all the way up through service layer and customer layer metrics with business layer metrics. As metrics are organized and aggregated layer by layer in a bottom-up fashion, a pyramid of metrics is created. The model, once being instantiated upon a network, can generate a metrics tree for the network. Figure 1 depicts the model on the left and a tree on the right. The value of the root metric of the tree, which is located in the business layer such as estimated churn rate in this paper, can then be computed from the tree leaves once the values of the leaf metrics are available. The leaf metrics are mostly located at the technology layer and the network layer, such as ATM cell loss ratio, Ethernet frame rate, IP one-way delay, and end-to-end error ratio, etc., and the values of these leaf metrics can be measured using the off-the-shelf tools such as Surveyor and Pinger, or can be retrieved from the MIBs that are already present in the network. Due to the space limit, readers are referred to [11] for more detailed information on how metrics from different layers are correlated with each other and how the values of a tree is computed.

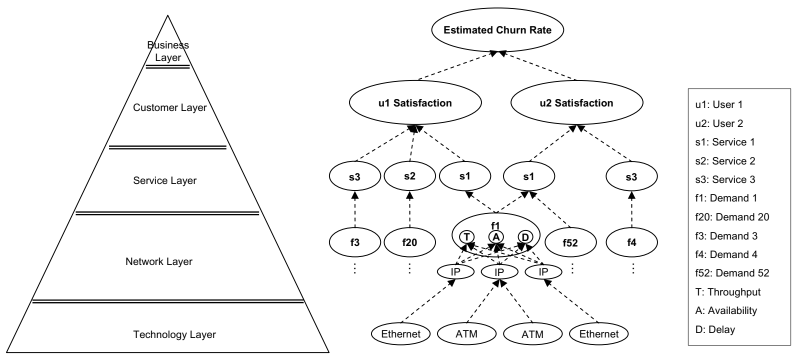

Figure 1: The Metrics Tree Model

3. The Approach

3.1 Overview

Figure 2 depicts an overview of the proposed approach. Lying at the center is the metrics tree model, which accepts inputs from the statistics acquisition component and decides whether a network dimensioning is necessary. Another vital component is the the network dimensioning component, which is named according to [7] and is responsible for computing the optimal mapping of end-to-end connections to the physical links based on the traffic matrix and the capacity of each physical link. The optimal mapping will be subsequently validated in a simulated environment and necessary statistics will be acquired accordingly. These will be taken care of by the the network simulation component. The control component dynamically manages the resources and the routes inside the network in a way that the accepted optimal mapping can be enforced onto the network automatically, such as in a MPLS enabled network. The last but not the least is the statistics acquisition component, which deploys necessary monitoring facilities in the network, efficiently and economically gleaning performance data in the format of the well-defined metrics.

The detailed data flow chart of the proposed approach is illustrated in Figure 3. After the performance data are acquired from the network, along with the topology of the network, the metrics tree model is instantiated and a metrics tree is created. The tree is computed subsequently using the acquired data. From the values of the metrics tree, the revenue expected by the network operator can then be estimated base on the customer perceived performance. When the expected revenue is acceptable, a network dimensioning is not necessary. Then no control is taken and the data flow can return to the beginning. When the expected revenue is not acceptable, an optimal mapping will be computed through network dimensioning and the mapping is then validated in a simulated environment. The simulation results are subsequently plugged into the metrics tree and the expected revenue is re-computed. If the expected revenue is still not acceptable, the allowed maximum link utilization can be lowered and the network is dimensioned again.

This cyclic process is repeated until an acceptable revenue is computed. Afterwards, the mapping from the last network dimensioning is enforced via the control component. The overall data flow then returns to the beginning and marks the beginning of the next iteration.

This paper will concentrate on the network dimensioning component, which will be illustrated in detail in the next sub-section.

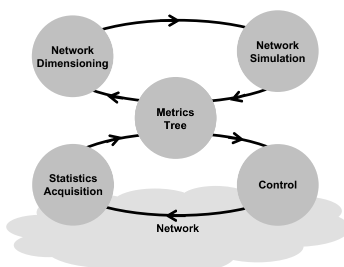

Figure 2: The approach

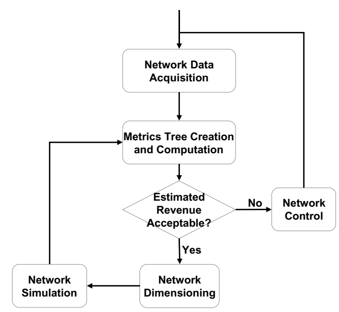

Figure 3: The data flow

3.2 Network Dimensioning

As mentioned before, network dimensioning is responsible for computing the mapping between the logical connections and the physical links. Figure 4 describes the overall process involved in network dimensioning.

Depending on whether sufficient budgets are available for network upgrades, two alternatives are available for dimensioning the network. When budget is available for upgrades, it can be done exactly the same as in [9], which has been described in the related works in this paper. While X_{ij}^k indicates the percentage of traffic from demand k that can be provided by link (i, j), $\sum_{k \in K} d_k X_{ij}^k$ indicates the total amount of traffic that link (i, j) needs to support. When $\sum_{k \in K} d_k X_{ij}^k > c_{ij}$, link (i, j) has to be upgraded to accommodate the traffic and otherwise, $c_{ij} - \sum_{k \in K} d_k X_{ij}^k$ indicates the unused bandwidth on link

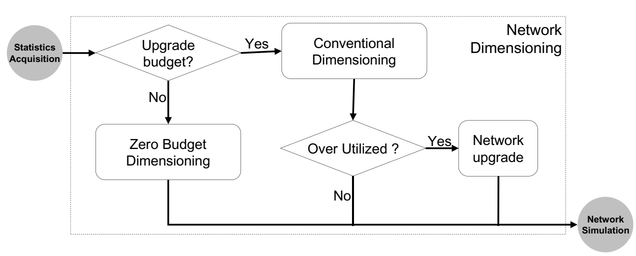

Figure 4: Network Dimensioning

(i, j). The zero-budget network dimensioning alternative has to be employed in case no budget is available for network upgrades.

As the speed and capacity of networks are improved dramatically, new services are increasingly introduced. These services, ranging from residential high speed access service to enterprize VPN service, from email service to VoIP service, are of different importance to network service providers. In the zero-budget dimensioning alternative, services are weighted according to their importance to the business. Subsequently, demands that belong to a service are all assigned the same weight as the service. Meanwhile, the aggregated traffic matrix is no longer an input for this dimensioning alternative. Instead, the bandwidth demand for each service is specified for all pairs of edge nodes. The list of traffic demands is now called service differentiated traffic matrix. It is worth noting that the service differentiated traffic matrix can be easily converted into the aggregated traffic matrix and it is impossible to transform an aggregated traffic matrix into a service differentiated traffic matrix.

Customers in the zero budget approach are weighted using the amount of the revenue they can generate as well. To be scalable, customers can be classified into categories, such as VPN users and high speed access users, and all customers from a given category generate the same amount of revenue. The revenue generated by a customer can be attributed to the demands related to the customer in the service differentiated traffic matrix according to the weight and the required bandwidth of each demand. Consequently, the revenue generated by a demand from the service differentiated traffic matrix can be computed as the sum of the revenue allocated to this demand at its source and that at its destination. As such, the goal of the zero budget network dimensioning changes to the maximization of the revenue generated by the satisfied demands from the service differentiated traffic matrix.

Mathematically, the zero budget network dimensioning alternative can be formulated similarly to [9] with the following important exceptions. The revenue generated by customer i is represented as R_i and the set S indicates the collection of services that are available inside the network. For each service $s \in S, W_s$ indicates the weight of the service. An entry k from the service differentiated traffic matrix K is now a four-tuple, (d_k, s_k, t_k, s), where s is the service type of the entry and the other three remain the same as in [9]. In addition, Y^k represents the percentage of the demand k that can be satisfied by the network. Furthermore, α is no longer a variable to be minimized. Instead, it is an parameter indicating the maximum allowed link utilization across the entire network, e.g., 70%. For a demand $k = (d_k, s_k, t_k, s) \in K$, the weighted incoming/outgoing traffic at the source node s_k and the destination node t_k, namely D_{s_k} and D_{t_k}, can be computed via equation (6) respectively.

$$D_{node} = \sum_{(d_l, node, t_l, s) \in K or (d_l, s_l, node, s) \in K} W_s \times d_l \tag{6}$$

The revenue generated by the demand $k = (d_k, s_k, t_k, s)$, P^k, can be formulated as follows in equation (7).

$$P^k = R_{s_k} \times \frac{W_s \times d_k}{D_{s_k}} + R_{t_k} \times \frac{W_s \times d_k}{D_{t_k}} \tag{7}$$

All together, equations from (8) to (12) describe the zero budget network dimensioning.

$$\max(\sum_{k \in K} Y^k \times P^k) \tag{8}$$

$$s.t.$$

$$\sum_{j:(i,j)\in E} X_{ij}^k - \sum_{m:(m,i)\in E} X_{mi}^k = 0 \qquad \forall k \in K, i \neq s_k, t_k \tag{9}$$

$$\sum_{j:(i,j)\in E} X_{ij}^k - \sum_{m:(m,i)\in E} X_{mi}^k = Y^k \quad \forall k \in K, i = s_k \tag{10}$$

$$\sum_{k\in K} d_k X_{ij}^k \le c_{ij}\alpha \qquad \forall (i,j) \in E \tag{11}$$

$$0 \le X_{ij}^k \le 1, \qquad 0 \le Y^k \le 1 \tag{12}$$

Unlike [9], the objective function (8) maximizes the revenue generated by the satisfied portion of the demands. Another major difference exists in equation (10), where the net traffic flowing out of source node s_k is now Y^k instead of the original 1 for any given demand $k = (d_k, s_k, t_k, s)$. Similarly, this problem can be solved by any of the off-the-shelf linear programming tools, e.g., $linprog$ from MATLAB. As the optimization results, X_{ij}^k indicates the mapping as usual while Y^k reveals the percentage of the demand k that can be satisfied by the network under a given link utilization scheme α. It worth noting that it might be impractical to satisfy any portion of a demand in real world networks. This can be adjusted by allowing Y^k to have values of 0 or 1 only, thus either satisfying all of a demand or none of it.

3.3 An Example

To have a concrete idea on how zero budget network dimensioning approach works, this section illustrates it further using an example. Figure 5 depicts a network with each link having a capacity of 3 units. For simplicity, physical links are assumed to carry traffics in one direction only. Table 1 describes the service differentiated traffic matrix, with each entry bearing a service type and a weight for the service. The second row of table 2 describes the revenue generated by each node and the third row of the table sums the weighted incoming and outing traffic at each node according to equation (6). By instantiating equation (7), the revenue generated by each demand is computed as in table 3.

Both the conventional traffic dimensioning approach [9] and the zero budget dimensioning approach are conducted on this example network with the above setting. The results from the conventional dimensioning is depicted in Figure 6, which indicates that about 2 extra units of bandwidth are needed on about 7 links to satisfy all the demands. The traffic, unfortunately, has to compete for stringent resources until the budget becomes available and the corresponding links are upgraded. Until then losses of data on some links will be inevitable. Table 4 lists the loss ratios under different link utilization schemes on

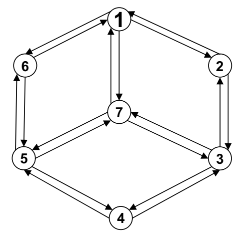

Figure 5: An Example Network

Table 1 The service differentiated traffic matrix

DemandID	Src	Dst	Required Bandwidth	Service Type	Service Weight
1	1	2	3	1	5
2	1	6	4	2	10
3	2	6	6	3	15
4	1	4	5	3	15

Table 2 The revenue and weighted total traffic of each node

Node	1	2	3	4	5	6	7
Revenue	5	10	15	10	5	5	5
Weighted Total Traffic	130	105	0	75	0	130	0

Table 3 The revenue generated by each demand

DemandID	Src	Dst	Revenue($)
1	1	2	$P^1 = 5 \times \frac{3\times5}{130} + 10 \times \frac{3\times5}{105} \approx 2.005$
2	1	6	$P^2 = 5 \times \frac{4\times10}{130} + 5 \times \frac{4\times10}{130} \approx 3.077$
3	2	6	$P^3 = 10 \times \frac{6\times15}{105} + 5 \times \frac{6\times15}{130} \approx 12.033$
4	1	4	$P^4 = 5 \times \frac{5\times15}{130} + 10 \times \frac{5\times15}{75} \approx 12.885$

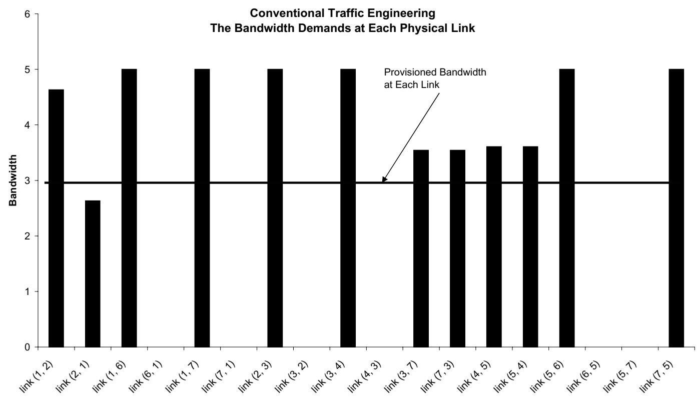

Figure 6: The results of the conventional network dimensioning

all links except those that have no data loss. In this paper, the loss ratios are computed via equation (13) based on the results from the conventional dimensioning under different link utilization schemes α.

$$lossratio = \frac{\sum_{k\in K} d_k X_{ij}^k - \alpha \times c_{ij}}{\sum_{k\in K} d_k X_{ij}^k} \qquad \forall (i,j) \in E, \sum_{k\in K} d_k X_{ij}^k \geq \alpha \times c_{ij}$$
$$lossratio = 0 \qquad \forall (i,j) \in E, \sum_{k\in K} d_k X_{ij}^k < \alpha \times c_{ij} \qquad (13)$$

Without loss of generosity, the traffic will be forwarded using best-effort service through routes generated by OSPF using hop count as the routing metric when there is no budget available to upgrade the network. As a result, table 5 shows the shorted paths and the accumulated loss ratio for each demand. The accumulated loss ratio for a path P is calculated using $1 - \sum_{(i,j)\in P}(1 - loss_{ij})$ where $loss_{ij}$ is the loss ratio on link (i, j).

The zero-budget network dimensioning is carried out under the same set of link utilization schemes as well. Figure 7 describes the satisfied rate for each demand and the traffic decomposition on each link when the link utilization scheme is 100%. In this case, all demand 1 and demand 4 are satisfied and about two third of demand 3 is satisfied as well. However, no traffic from demand 2 is satisfied. This is due to the fact that demand 2 has a relatively low revenue demand ratio, which is calculated as $\frac{the\ revenue\ generated\ by\ the\ demand}{Bandwidth\ requirement\ of\ the\ demand}$, and it is more profitable to satisfy traffics from other demands, such as demand 3 and 4. The detailed link traffic decompositions for other link utilization schemes, namely, $90\%, 70\%$ and 50%, are very similar to Figure 7 with the only difference being that the satisfied traffic rate decreases slightly as the allowed link utilization decreases. The link decompositions does not vary very significantly: link $(1, 2)$ carrying traffic from demand 1, link $(1, 7)$ carrying traffic from demand 4, link $(2, 3)$ carrying traffic from demand 3, etc. Please note under all these schemes the appearance of route loops [6], e.g., portions of demand 1 on link (3,7) and (7,3). This is a phenomenon

Table 4 The loss ratio on each link under different link utilization schemes

Links	$(1,2)$	$(2,1)$	$(1,6)$	$(1,7)$	$(2,3)$	$(3,4)$
$\alpha = 100\%$	28.01%	0	40%	40%	40%	40%
$\alpha = 90\%$	35.21%	0	46%	46%	46%	46%
$\alpha = 70\%$	49.61%	3.11%	58%	58%	58%	58%
$\alpha = 50\%$	64.01%	30.8%	70%	70%	70%	70%
Links	$(3,7)$	$(7,3)$	$(4,5)$	$(5,4)$	$(5,6)$	$(7,5)$
$\alpha = 100\%$	0	0	0	0	40%	40%
$\alpha = 90\%$	0	0	0	0	46%	46%
$\alpha = 70\%$	0	0	5.5%	5.49%	58%	58%
$\alpha = 50\%$	24.12%	24.12%	32.5%	32.5%	70%	70%

Table 5 The loss ratio experienced by each demand under different link utilization schemes

DemandID	Route	$\alpha = 100\%$	$\alpha = 90\%$	$\alpha = 70\%$	$\alpha = 50\%$
1	$1,2$	28.01%	35.21%	49.61%	64.01%
2	$1,6$	40%	46%	58%	70%
3	$2,1,6$	40%	46%	59.31%	79.24%
4	$1,7,3,4$	64%	70.84%	82.36%	93.17%

commonly seen in overlay model and its variants and can be removed by adding penalty on the number of such route loops in the objective function. Due to the space limit, the detailed link traffic decompositions are omitted for these link utilization schemes but the satisfied rate for these schemes are shown in table 6.

Compared to the satisfied rate from the conventional network dimensioning without

Table 6 The satisfied rate under different link utilization schemes

DemandID	$\alpha = 100\%$	$\alpha = 90\%$	$\alpha = 70\%$	$\alpha = 50\%$
1	100%	90%	70%	50%
2	0	0	0	0
3	66.67%	51.67%	35%	25%
4	100%	100%	84%	60%

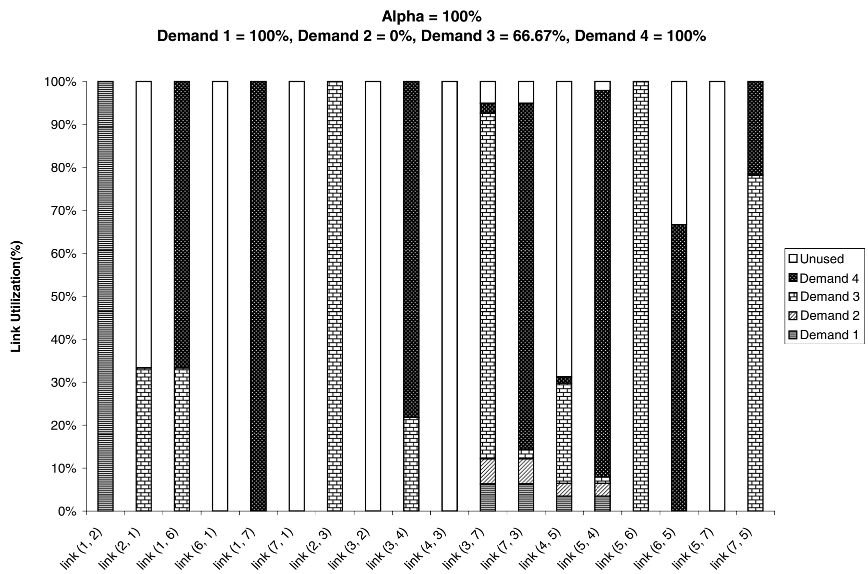

Figure 7: Zero budget network dimensioning with $\alpha = 100\%$

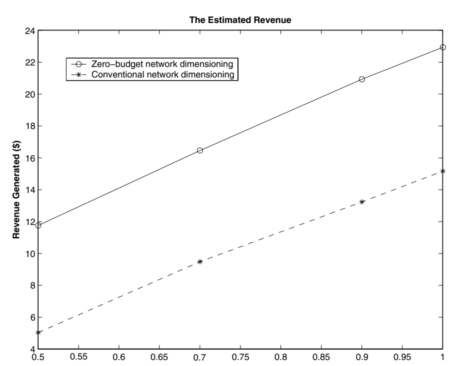

Figure 8: The comparison of the two approaches in terms of profitability

upgrades, which is considered as $1 - loss\,ratio$ in this paper, very high level satisfaction rate for demand $1, 3$ and 4 are produced with the zero-budget network dimensioning. However, zero budget network dimensioning satisfies no traffic from demand 2 while some portion of demand 2 are always being satisfied by the conventional network dimensioning. As analyzed before, it is more profitable to carry traffics from other demands, such as 3 and 4. This can be further verified by Figure 8, which compares the profitability of the results from both the zero-budget network dimensioning and the conventional network dimensioning under different link utilization schemes.

4. Scalability Considerations

As the overlay approach are increasingly employed in traffic engineering large real world networks, its scalability issue, namely the so called ”N-square” problem [12], has drawn a considerable amount of attention. To create a full meshed connections for a network with N edge nodes, $N \times (N-1)$ logical connections have to be established. When the number of edge nodes is large, this approach appears rather limited. This is also the case for the zero budget network dimensioning. To compensate, we propose the network decomposition, a process that divides a large network hierarchically into a collection of smaller ones and the large network is then abstracted as a network interconnecting the smaller ones. In the abstraction, the smaller networks are viewed as compound nodes and a compound node is weighted using the total revenue generated by the customers within the compound node. Meanwhile, the demands that share common source and destination nodes and that are of a given service are aggregated into a single demand. The aggregated demand generates the total amount of revenue of its constituent demands. When necessary, a smaller network can be decomposed further in the same manner. The outcome of the network decomposition will be a tree of networks, with parents being the abstracted networks and the children being the smaller ones.

The traffic engineering can then be carried out in the ”bottom up and then top down” fashion as depicted in Figure 9, which illustrates the process on a tree of networks of height n, with the root network being at level 0 and leaf networks being at level n. During the bottom up iteration, a parent acquires the commonly satisfiable demands from all its child networks and dimensions its network for the commonly satisfiable demands only. This process repeats until the root has been reached and overall traffic matrix can be adjusted accordingly using the commonly satisfiable demands at the root. The top down iteration starts immediately after this. The root network dimensions its network and the overall traffic matrix is segmented into a list of traffic matrices according to the traffic engineering results. A child node then dimensions its network using the corresponding traffic matrix segment independently. The entire process stops once all the leaf networks have been dimensioned.

5. Added Values

Due to the incorporation of the metrics tree model into traffic engineering, the proposed approach joins together the network layer, service layer, customer layer and business layer seamlessly for the first time. Using the metrics tree, any change at the network layer can be propagated to the other layers and its effects to the other layers can be revealed at a glance. As such, the proposed approach can be utilized to address a network service provider’s concern in introducing new customers and services into the network and in deciding whether a performance improvement is possible without conducting upgrades to the exiting network.

When adding a new customer to the existing network, the customer’s demands for each service can be estimated using the average demands from the category that the customer belongs to, and the demand can be incorporated into the service differentiated traffic matrix afterwards. Network dimensioning can be carried out subsequently. The optimal

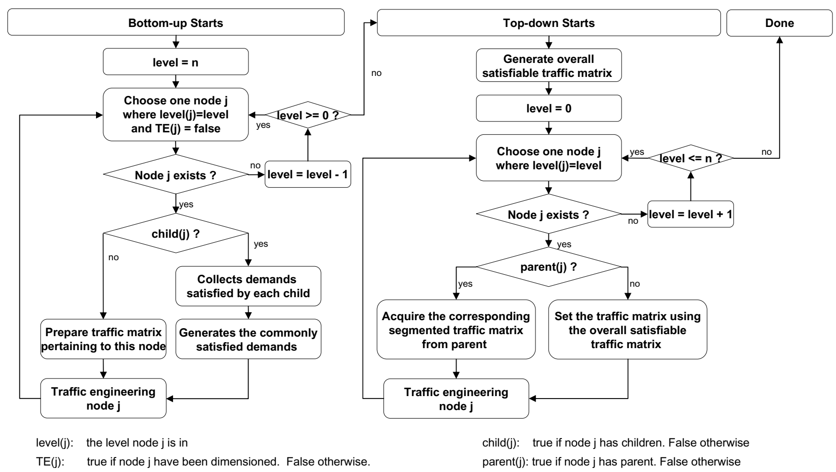

Figure 9: The bottom up and top down traffic engineering

logical connections will then be simulated and the network layer performance data can be acquired. By plugging these acquired data into the metrics tree, the effects to all the services, to other customers and to the business can be revealed. The introduction of a new service can be viewed as an addition of a group of new customers, with each having a demand for the service. Again, the same approach can be repeated and the effects can be analytically obtained as well.

The zero budget network dimensioning can be used to decide whether a performance improvement, e.g., 15% increase in the throughput, is possible without upgrading the network. The 15% increase in the throughput, for example, can be realized by increasing each demand by 15%. Similarly, a zero budget network dimensioning can be conducted with the current link utilization level and the optimal connections can be simulated. By computing the metrics tree using the simulated data, the network service provider is able to decide whether the expected revenue is acceptable. In case it is, the performance improvement is deemed possible. Otherwise, the network service provider can slightly increase the link utilization level and until the link utilization level is considered too high, it can repeat the process again and again. When the link utilization is already high enough and the expected revenue is still not acceptable, the performance improvement can be considered impossible.

6. Conclusion

In this paper, we proposed a novel traffic engineering approach that complements existing approaches during economic depressions. Our approach involves network monitoring, performance data correlation, network dimensioning, network simulation and network control. It allows ISPs to decide analytically whether a traffic re-engineering is necessary. In case a traffic re-engineering is necessary and no budget is available for network upgrades, it helps determining which demand to satisfy in order to maximize revenue. We have also addressed the scalability issue originating from the overlay approach through means of network decomposition. The usefulness and effectiveness of the proposed approach is demonstrated through traffic engineering an example network and describing some of its added values. Up to date, the metrics tree model has been implemented and metrics trees can be instantiated for any network. As a future work, we will implement the other components, e.g., the network simulation component and the statistics acquisition component, and test the overall approach on large operational networks.

Compared to existing traffic engineering approaches, the zero budget approach assumes the knowledge of the revenue generated by each customer and the service differentiated traffic matrix. While the revenue generated by each customer can be acquired without difficulty from billing systems, we agree that the acquisition of the service differentiated traffic matrix is a challenging task. We note that works are emerging in estimating traffic matrices and some are based on subscribed SLAs/SLSs and monitored data. We plan to investigate those works and to devise schemes in estimating service differentiated traffic matrix in the near future.

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