Edge Router Selection and Traffic Engineering in LISP-Capable Networks

Ke Li, Sheng Wang, and Xiong Wang

Abstract: **Recently, one of the problems with the Internet is the issue of scalability. To this end, locator/identifier separation protocol (LISP), which separates end-system identifiers and routing locators, has been proposed as a solution. In the LISP deployed network, the ingress and egress nodes of inter-AS traffic is determined by edge router selection (ERS) and endpoint identifier-routing locator mapping assignment (ERMA). In this paper, joint optimizations of ERS and ERMA for stub networks with and without predetermined link weights are studied and the mixed integer linear programming (MILP) formulations for the problems are given. To make the problem with optimizable link weights tractable, a revised local search algorithm is also proposed. Simulation results show that joint optimization of ERS and ERMA enables better network performance.**

Index Terms: **Edge router selection (ERS), endpoint identifier (EID)-routing locator (RLOC) mapping assignment (ERMA), locator/identifier separation protocol (LISP), mixed integer linear programming (MILP), traffic engineering (TE).**

I. INTRODUCTION

Factors such as single numbering space, multi-homing, and traffic engineering (TE), have been identified as the major factors contributing to the current border gateway protocol (BGP) routing tables growth [1]. This has led to the need for new routing architectures. As a result, groups like the routing research group (RRG) of the Internet research task force (IRTF) have put forward several proposals. Most of these proposals assume that next generation Internet has two different types of addresses: Identifiers and locators. An identifier is used to identify a host as a connection endpoint, while a locator refers to a node attachment point in the Internet topology. Proposals thus far can be divided into two categories: Those attaching locators directly to hosts (such as site multihoming by Internet protocol version 6 (IPv6) intermediation (SHIM6) [2] or identifier-locator network protocol (ILNP) [3]) and those attaching locators to routers (such as locator/identifier separation protocol (LISP) [4] or six/one [5]). For simplicity, the rest of the paper is discussed in locator/identifier separation (LISP) context.

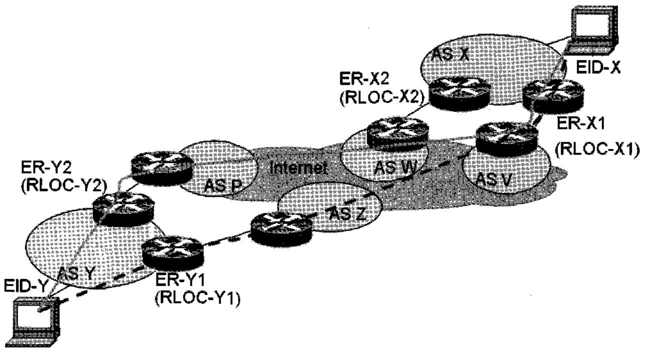

Fig. 1. Example of LISP deployment.

In the LISP terminology [4], the address of an end host in a LISP domain is called endpoint identifier (EID), in contrast to EID, globally routable IP address is called routing locator (RLOC). Two end hosts in the same autonomous system (AS) communicate with each other using EIDs, that means EIDs are locally routable. End hosts in different AS communicate with each other through the edge routers, which can map EIDs to globally routable RLOCs. Fig. 1 illustrates the inter-AS routing in a LISP network. Here, host X is reachable via either of two edge routers (ER-X1 or ER-X2). Hence, its EID, i.e., EID-X, can be mapped to either of the two RLOCs, RLOC-X1 or RLOC-X2. EID-Y can also be mapped to RLOC-Y1 or RLOC-Y2. Host X could send packets to host Y according to the following process. First, the packet's source and destination addresses are specified as EID-X and EID-Y, respectively. This packet is then forwarded to the closest edge router, say ER-X1. Upon receipt of this packet, the edge router ER-X1 sends a map request through the mapping system to determine the RLOC-Y1 associated with EID-Y. Then, ER-X1 encapsulates the packet with RLOC-Y1 as destination address and RLOC-X1 as source address and tunnels it through the Internet to the destination. Finally, the destination edge router decapsulates the packet which is then carried to the destination using EID-Y.

In this paper, we assume that ISP operators could designate any node as edge router of local network. The selection of edge routers has impact on traffic distribution in local domain. Usually more than one node will be selected as edge routers for multihoming. For inbound traffic to one host, one of the edge routers will be selected as its ingress point. The first kind of selection is called edge router selection (ERS). The second kind of selection could be accomplished by setting the EID-to-RLOC mapping in LISP-capable network. We call one set of all the EID-to-RLOC mappings as EID-RLOC mapping assignment (ERMA) of local network.

An example of edge router selection is shown in Fig. 2, and another example of EID-RLOC mapping assignment is shown in Fig. 3. Suppose that there are two hosts, EID-X1 and EID-X2, in AS X. And three nodes, A, B, and C, are the candidate

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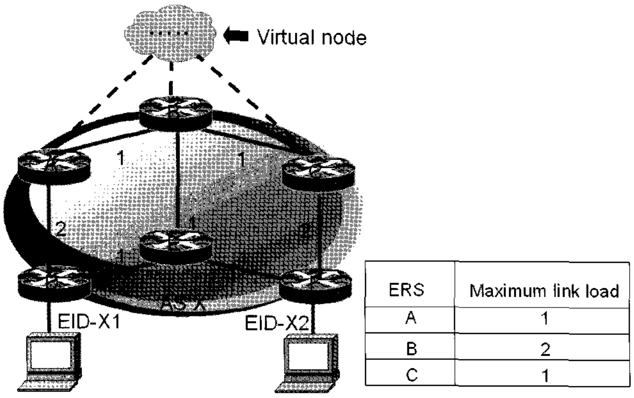
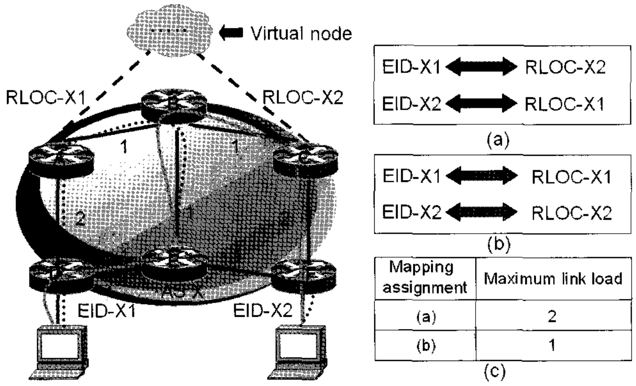


ERS	Maximum link load
A	1
B	2
C	1

Fig. 2. Example scenario explaining ERS.



EID-X1 ⟷ RLOC-X2
EID-X2 ⟷ RLOC-X1

(a)

EID-X1 ⟷ RLOC-X1
EID-X2 ⟷ RLOC-X2

(b)

Mapping assignment	Maximum link load
(a)	2
(b)	1

(c)

Fig. 3. Example scenario explaining ERMA.

for edge routers. We assume that the amount of incoming traffic to any host is one unit, and a hop-by-hop routing protocol, such as open shortest path first (OSPF), is deployed in local network. The weight of each link is shown in the bold black font. Note that we use a virtual node to represent the outer domains, and connect this virtual node to each edge router/RLOC of the local domain with an inter-AS link.

Fig. 2 shows the effect of edge router selection. If only router B is selected as edge router, and the maximum link load is larger than that of any other single edge router selection.

Suppose that nodes A and C with RLOC-X1 and RLOC-X2 are designated as edge routers, respectively. The selection of ingress edge router also affects the traffic loads of local links. As showin in Fig. 3, the dashed lines show the paths from edge router A to two hosts, while the solid lines indicate the paths from edge router C to each host. Two different ERMAs are given in Fig. 3 (captioned (a) and (b)). In the ERMA of Fig. 3(a), EID-X1 and EID-X2 are mapped to RLOC-X2 and RLOC-X1, respectively. In that of Fig. 3(b), EID-X1 and EID-X2 are mapped to RLOC-X1 and RLOC-X2, respectively. Fig. 3(c) indicates the maximum link load corresponding to the ERMA of Fig. 3(a) is two, while that of Fig. 3(b) is one.

To the best of our knowledge, our study is the first attempt to jointly optimize ERS and ERMA in LISP-capable networks. The main contributions of this paper are as follows. First, we formulate the joint optimization problem using mixed integer linear programming (MILP). Finally, to make the problem with optimizable-link-weight solvable, a revised local search algorithm (RLS) is also introduced.

The rest of the paper is organized as follows. Section II is related work. In Section III, two variants of joint optimization problems as well as their MILP formulations are discussed. RLS algorithm is given in Section IV. Sections V and Section VI present experiment setup and results, respectively. Section VII concludes the paper.

II. RELATED WORK

TE is an important mechanism for Internet network providers to optimize network resource usage and traffic delivery. It aims to determine and configure the best routing strategy so that the overall network performance is optimized. With respect to traffic optimization scope, TE can be classified into intra-AS TE and inter-AS TE. For intra-AS TE, the operator/administrator of the AS controls traffic routing within the network by either setting the link weights of the corresponding interior gateway protocol (IGP) [6]-typically OSPF or intermediate system-intermediate system (IS-IS), or establishing label switched paths (LSPs) through multi-protocol label switching (MPLS) [7]. The main drawbacks of MPLS-TE are the expenses and complexity associated with setting up and maintaining large quantities of LSPs in large networks. In OSPF-TE, several equal-cost multipath (ECMP)-based [8] link weight optimization algorithms have been proposed for tuning the link weights and constructing multiple paths to achieve close-to-optimal bandwidth utilization [6], [8].

On the other hand, inter-AS TE [9] aims to control traffic entering or exiting an AS (inbound TE or outbound TE) with optimization objectives such as load balancing over inter-AS links that are common congestion points [10]. In current practice, BGP policy is commonly used to enforce inter-AS TE with classical scheme for selecting edge routers being typically enforced by configuring BGP route attributes [9] such as local preference, AS path length, etc.

Most of the existing literature (e.g., [6], [7], [10]) deals with intra-AS and inter-AS TE separately, however, in practice, the interaction between intra-AS and inter-AS routing is complicated [11]. Separating IP addresses into EID and RLOC not only provides an advantage for considering the interactions between intra- and inter-AS TE, but also provides another method for enhancing traffic engineering.

A number of studies have already been conducted on TE in locator and identifier separation context. D. Farinacci *et al.* [4] suggest that the separation of end-systems identifiers and routing locators can be used to improve traffic engineering capabilities. Similar ideas are also espoused by B. Quoitin *et al.* [12], who state that traffic between end-systems and routing locators can be redistributed by taking advantage of this separation. However, none of these studies provide any concrete method for making use of this separation. To the best of our knowledge, only four TE solutions using this separation have so far been proposed. N. Yao *et al.* [13] propose a new method for implementing TE and compare it to the conventional method currently being used for the Internet. Their stated goal is to mitigate the negative effect TE has on routing table size growth. S. Secci *et al.* [14] propose modeling the routing interaction between distant, independent edge networks using non-cooperative game theory. They also propose a rationally justified method for achieving Internet-wide load-balancing. D. Saucez *et al.* [15] point out that locator/identifier separation offers the possibility of associating several locators with a specific identifier, resulting in multiple paths becoming available between two identifiers in different domains. They verify this in the context of inter-AS TE. The effect of optimizing ERMA is discussed in [16]. However, the focus of our paper is on finding optimal ERS and ERMA.

III. PROBLEM STATEMENT

In this section, network model and optimization objective are introduced. Then, constraints for ERS and ERMA are considered. Finally, two variants of joint optimization of ERS and ERMA problems are analyzed and formulated using MILP.

A. Network Model

Consider a network represented by a directed graph *G*= (*V*, *E*), where *V* consists of the set of internal router V_I and that of virtual node v, and *E* consists of the set of internal links E_I and that of virtual links E_v. The edge routers of an AS are selected from router set V_I. The network model is based on an extension of the Intra-AS topology with external virtual node and virtual links. Other domains are combined and abstracted as a single virtual node. Accordingly, traffic flow entering or leaving the local domain are sent or received by this virtual node.

Additionally, in an edge/local network running LISP, each host has one EID, and each host is attached to an internal node/router. The traffic between two hosts can be viewed as part of the traffic between the two routers the hosts are attached to. Without loss of generality, we assume that all hosts attached to one router are denoted by their common EID-prefix in the rest of this paper. An ERMA of a network consists of all known EID-prefix to RLOC mappings.

B. Optimization Objective

B. Fortz and M. Thorup [6] proposed that the total costs of all internal links could be used as the objective function for intra-AS routing, as shown in (1). To avoid very unbalanced traffic on inter-domain links, we include the cost of inter-domain link in our objective function (2).

$$\text{Minimize} \sum_{(m,\,n)\in E_I} \varphi_{mn} \tag{1}$$

$$\text{Minimize} \sum_{(m,\,n)\in E} \varphi_{mn} \tag{2}$$

$$\text{Subject to } u_{mn} = \frac{\sum_i \sum_j y^{ij}_{mn} d_{ij}}{C_{mn}} \quad \forall\, i \neq j \in V, (m,n) \in E \tag{3}$$

$$\varphi_{mn} = f(u_{mn}) \tag{4}$$

$$f(u) = u,\ 0 \leq u < \frac{1}{3} \tag{5}$$

$$f(u) = 3u - \frac{2}{3},\ \frac{1}{3} \leq u < \frac{2}{3} \tag{6}$$

$$f(u) = 10u - \frac{16}{3},\ \frac{2}{3} \leq u < \frac{9}{10} \tag{7}$$

$$f(u) = 70u - \frac{178}{3},\ \frac{9}{10} \leq u < 1 \tag{8}$$

$$f(u) = 500u - \frac{1468}{3},\ 1 \leq u < \frac{11}{10} \tag{9}$$

$$f(u) = 5000u - \frac{16318}{3},\ \frac{11}{10} \leq u < \infty \tag{10}$$

Equations (3) define the link utilization, where d_{ij} is intra-AS traffic demand or inter-AS traffic demand. Note that inter-AS traffic is both originated and terminated at the virtual node. For each traffic flow, we use integer variables y^{ij}_{mn} to denote the traffic demands d_{ij} flow along the link $(m,\ n)(y^{ij}_{mn} = 1)$ or not $(y^{ij}_{mn} = 0)$. $\sum_i \sum_j y^{ij}_{mn} d_{ij}$ is the sum of all demands that are sent over link $(m,\ n)$. C_{mn} is the capacity of link $(m,\ n)$. The utilization of link $(m,\ n)$ is denoted as u_{mn}. The piecewise linear function $f(u_{mn})$ are given as (5)–(10). By adopting such cost function, it is cheap to send flow over a link $(m,\ n)$ with a small utilization. As the utilization approaches 100%, it becomes more expensive. If the utilization goes above 100%, there is a heavy penalty.

C. Problem Formulation

Notations used in this paper are summarized in Table 1.

C.1 Constraints for ERS

$$\sum_{j\in V_I} y^{vj}_{vk} + \sum_{j\in V_I} y^{jv}_{kv} \leq 2a_k|V_I|,\ k \in V_I \tag{11}$$

$$\sum_{k\in V_I} a_k \leq R \tag{12}$$

$$\sum_{k\in V_I} y^{vj}_{vk} = 1,\ j \in V_I \tag{13}$$

$$\sum_{k\in V_I} y^{jv}_{kv} = 1,\ j \in V_I \tag{14}$$

$$y^{vj}_{vk} = y^{jv}_{kv},\ j,\ k \in V_I \tag{15}$$

Constraints (11) ensure that if there exists any traffic flowing through virtual link (v, k) or (k, v), node k must be an edge router. In other words, node k will be designated as edge router and virtual links (v, k) and (k, v) are actually inter-AS links. Constraint (12) guarantees that only R nodes are selected as edge routers. Constraints (13) and (14) guarantee that the inbound traffic to one internal node or the outbound traffic from it flows through only one inter-AS link. Constraints (15) are optional, which could ensure that inbound traffic to a node goes through the same edge router as that for outbound traffic originated from the same node [17].

C.2 Constraints for EID-to-RLOC Mappings

$$y^{vj}_{vn} = g_{nj},\ j,\ n \in V_I \tag{16}$$

Constraints (16) ensure that if EID j is mapped to RLOC n, the inbound traffic to node j must pass through edge node n. The

Table 1. Notation used in this paper.

Notation	Description
a_k	Binary variable, whether node k is allocated as RLOC ($a_k = 1$) or not ($a_k = 0$).
b_{mn}	Binary variable, whether inter-AS link (m, n) is established ($b_{mn} = 1$) or not ($b_{mn} = 0$).
g_{nj}	Binary variable, whether EID j is mapped to edge router/RLOC n ($g_{nj} = 1$) or not ($g_{nj} = 0$).
R	Integer constant, the number of edge routers allocated as RLOCs.
y_p^{ij}	Binary variable, the traffic demand from i to j flows through the path $p \in P(i,j)$ ($y_p^{ij} = 1$)or not ($y_p^{ij} = 0$).
ω_{mn}	Real variable, link weight of link (m, n).
μ_{mn}^j	Binary variable, such as $\mu_{mn}^j = 1$, if link (m, n) is on the shortest path to node j ($\mu_{mn}^j = 1$) or not($\mu_{mn}^j = 0$).
L_v^j	Non-negative variable, the length of the shortest path from v to j.

general formulation of joint optimization of ERS and ERMA problem is: (2)–(16).

D. Two Variants

We consider two variants of the joint optimization problem, that is, link weights are predetermined as in Version I or optimizable as in Version II.

D.1 Version I: With predetermined link weights

- **Given**

1) Network topology $G = (V, E)$ and traffic demand d_{ij}.
2) Set of internal nodes that can be used as edge routers with RLOCs.
3) P_{mn}^{kj}: $k, j \in V_I, (m,n) \in E_I$, constant, P_{mn}^{kj}=1, if link (m, n) is on the shortest path from edge node k to node j; otherwise, P_{mn}^{kj}=0. All the shortest paths between nodes in local network are known.
4) S_{mn}: $(m, n) \in E_I$, constant, the intra-AS traffic load of link (m, n). Given the intra-AS traffic demand and the shortest paths between nodes in local network, it is quite straightforward to calculate. For simplicity, only one shortest path between any node pair is used.

- **Additional constraints**

$$\Big(\sum_{j\in V_I}(y_{vk}^{vj}P_{mn}^{kj}d_{vj} + y_{kv}^{jv}P_{mn}^{jk}d_{jv}) + S_{mn}\Big)/C_{mn} = u_{mn},\ k\in V_I,\ (m,n)\in E_I \quad (17)$$

$$\Big(\sum_{j\in V_I} y_{vk}^{vj}d_{vj}\Big)/C_{vk} = u_{vk},\ k\in V_I, (v,k)\in E_v \quad (18)$$

$$\Big(\sum_{j\in V_I} y_{kv}^{jv}d_{jv}\Big)/C_{kv} = u_{kv},\ k\in V_I,\ (k,v)\in E_v \quad (19)$$

According to the above condition, constraints (3) can be replaced by additional constraints. The utilizations of internal links, inbound and outbound virtual links are computed in (17), (18), and (19), respectively.

D.2 Version II: With optimizabe link weights

- **Given**

1) Network topology $G = (V, E)$ and traffic demand d_{ij}.
2) Set of internal nodes which can be used as edge routers with RLOCs.

In this version, link weights could be jointly optimized with ERS and EMRA. In [8], an MILP model was formulated for the optimization of ECMP-based link weights inside a domain, and additional constraints are needed to address Version II problems. First, ECMP is not supported by a virtual node, that is, inter-AS traffic to any internal node must be sent through only one inter-AS link. Second, routing through inter-AS links for intra-AS traffic is prohibited. These constraints are given as follows.

- **Additional constraints**

$$\sum_{(m,n)\in E} y_{mn}^{ij} - \sum_{(k,m)\in E} y_{km}^{ij} = \begin{cases} 0, & m \neq i,\ j \\ 1, & m = i \\ -1, & m = j \end{cases}$$
$$\forall\, i \neq j \in V,\ m \in V \quad (20)$$

$$y_{mn}^{ij} \leq \mu_{mn}^{ij},\ \forall i \neq j \in V,\ (m,n) \in E \quad (21)$$

$$L_n^j + \omega_{mn} - L_m^j \geq (1 - \mu_{mn}^j)M,\ j \in V,\ (m,n) \in E \quad (22)$$

$$L_n^j + \omega_{mn} - L_m^j \leq 1 - \mu_{mn}^j,\ j \in V,\ (m,n) \in E \quad (23)$$

$$y_{mn}^{ij} = 0,\ i,\ j \in V_I,\ (m,n) \in E_v \quad (24)$$

Constraints (20) represent the flow conservation constraints for intermediate, source, and destination nodes. Constraints (21)–(23) ensure that traffic is split to the shortest paths. If $\mu_{mn}^j = 0$ (link (m, n) is not on any of the shortest paths to node j), $L_n^j + \omega_{mn} - L_m^j \geq 1$ must be hold, otherwise, $L_n^j + \omega_{mn} - L_m^j \geq 0$. In addition, when $\mu_{mn}^j = 0$, constraints (22) become redundant if artificial constant M is sufficiently large. In line with common practice, routing through inter-AS links for intra-AS traffic is prohibited. This can be restricted using constraints (24).

IV. REVISED LOCAL SEARCH ALGORITHM

For version I with unadjustable-link-weight, standard LP solvers, CPLEX [18], can be used to get optimal solution. For version II with adjustable-link-weight, the complexity of MILP limits its applicability to only small networks. As shown in last subsection, there might be lots of binary variables μ_{mn}^j in the model for version II. The number of binary variables μ_{mn}^j is $|V| \times |E|$ for a network with $|V|$ nodes and $|E|$ links. Even for a mid-size network, it would be very difficult to compute the optimal solution in reasonable time by CPLEX. Thus, we present a new heuristic algorithm, i.e., revised local search (RLS) algorithm, to solve version II with adjustable-link-weight problem. RLS is based on Forts and Thorup's (F&T's) local search [6].

In the remainder of this section, we first describe the new neighborhood structure that is applied in link weight setting

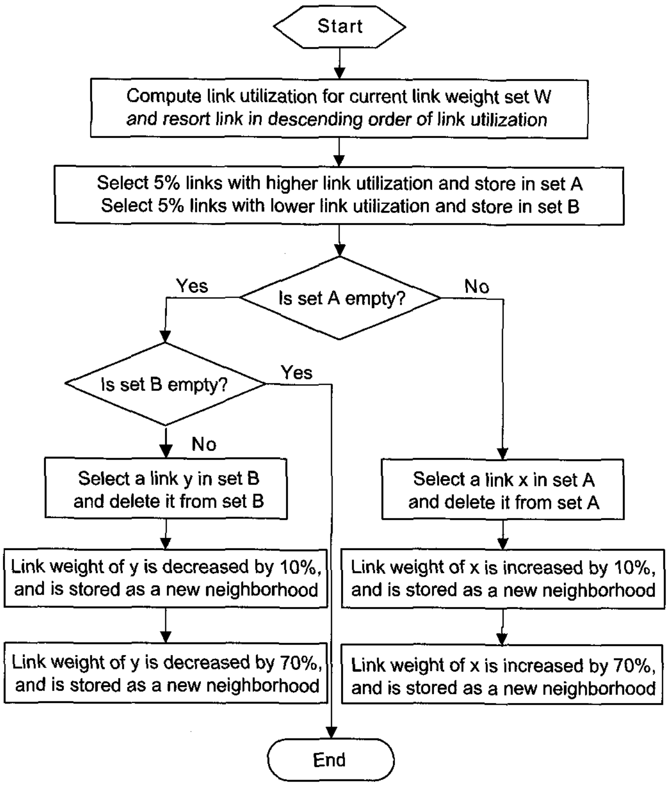


Fig. 4. Neighborhood generation process for RLS.

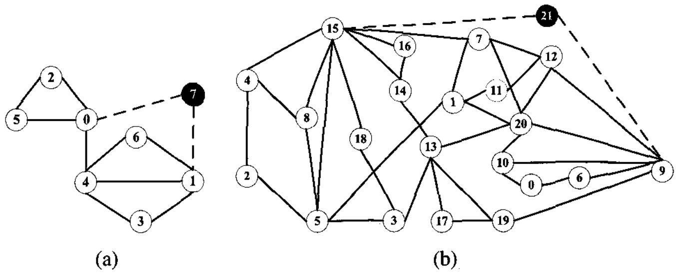


Fig. 5. Network topology: (a) Telstra and (b) exodus.

for each logical topology. Then propose a new diversification scheme to escape from the local optimum.

- **Neighborhood structure** Both F&T's local search [6] and the RLS algorithm use a neighborhood structure that has only one link weight change at each step. The former randomly changes one link weight (increase or decrease randomly) to obtain a new routing and a new traffic distribution. However, RLS generates a neighborhood by means of the following two operations: First, all links are ordered by link utilization. Then, we change one link weight to obtain the neighborhood in terms of link utilization. That is to say, the link with higher utilization is selected, and the link weight is increased a certain value (e.g., 10% or 70% of the weight). Likewise, the link with lower utilization is selected and the link weight is decreased a certain value (e.g., 10% or 70% of the weight). Note that adjusted value (10% or 70%) is experimental test results on a large number of randomly generated topologies with various characteristics. To a certain degree, such a neighborhood structure can make the search process more pertinently, directionally, and effectively. The neighborhood generation process for RLS is illustrated in Fig. 4.

- **Diversification** Another important ingredient for local search efficiency is diversification. The aim of diversification is to escape from regions that have been explored for a while without any improvement, and to search regions as yet unexplored. F&T's local search approach for diversification randomly changes link weight to avoid local-best solution. However, it is stochastic and not sufficient to completely escape from one region and go to a possibly more attractive one. Therefore, a new link weight modification operation is introduced in RLS. The modification operation relies on link utilization information, which is useful for finding a better solution. First, links with maximum link utilization are recorded when each neighborhood is evaluated. Then, once all neighborhoods are evaluated and no better solutions are found, we need modify each neighborhood as follows: The link weight of the recorded link in each corresponding neighborhood is increased. Then, these modified neighborhoods are then re-evaluated in order to escape from the region currently explored.

In line with the joint optimization problem of ERS and ERMA, RLS also considers that a virtual node is prohibited from transmitting intra-AS traffic and virtual links are restricted to splitting inter-AS traffic.

V. EXPERIMENT SETUP

A. Simulation Topologies

We use the Telstra topology (with node 7 as the virtual node) and Exodus topology (with node 21 as the virtual node) from the Rocketfuel [19] dataset to evaluate the optimization effect of ERS and ERMA as depicted in Figs. 5(a)-(b). Since these topologies did not provide link capacity, we utilized link capacity assigned by [20]. The capacity assignment was based on the degree of the cities (nodes) in the network. The maximum capacity of intra-AS links was set to 10 Gbps. Since the overall cost objective involves intra-AS and inter-AS TE cost, inter-AS link capacity was set to 20 Gbps.

B. Traffic Matrices

We generated synthetic traffic matrices for our evaluation. According to [21], inter-AS traffic volumes are top-heavy and can be approximated by Weibull distribution with shape parameter 0.2-0.3. We therefore generated the inter-AS traffic demand using this distribution with shape parameter 0.2, and the average rate of inbound traffic to an EID was varied between 60 and 3000 Mbps in our experiments.

We used the gravity model (GM) outlined in [20] to generate intra-As traffic. The intra-AS traffic demand from node i to j is given in (25), where $c(k, n)$ is the capacity of link (k, n) and σ_i is a weight factor ranging from 0 to 1. We were able to change the network load by adjusting σ_i.

$$d_{ij} = \sum_{\{t|(i,t)\in E_I\}} \frac{\sigma_i c_{(i,t)} \sum_{\{t|(t,j)\in E_I\}} c_{(t,j)}}{\sum_{\{(k,n)|(k,n)\in E_I\}} c_{(k,n)} - \sum_{\{t|(i,t)\in E_I\}} c_{(i,t)}} \tag{25}$$

where $i \in V_I, j \in V_I$. We varied σ_i between 0.005 and 0.25 to simulate fluctuating intra-AS traffic volume.

C. Performance Metric

The following performance metrics were used to evaluate the joint ERS and ERMA optimization strategy. For these metrics, lower values are better than high values.

- Overall TE cost: This metric captured the overall network cost (inter-AS and intra-AS TE costs) of the objective function (2).
- Intra-AS TE cost: The piecewise linear cost function was used for this metric to capture the intra-AS link load cost.
- Total bandwidth consumption: The amount of bandwidth needed to accommodate all traffic flows within the network, being the sum of the traffic loads over the intra-AS links.
- Maximum intra-AS link utilization: It is the maximum utilization on all the intra-AS links in a network. Minimizing this value ensured that traffic was diverted from congested to less utilized links and was balanced across the links.

D. Evaluation Strategies

To explore the effect of ERS and ERMA optimization, we present three strategies to compare network performance.

- Strategy A: ERS and ERMA are jointly optimized.
- Strategy B: Two nodes with the highest degree are chosen as edge routers. Only ERMA could be optimized.
- Strategy C: Two edge routers are predetermined as in strategy B. An EID is mapped to the RLOC with the shortest distance between the host and the edge routers.

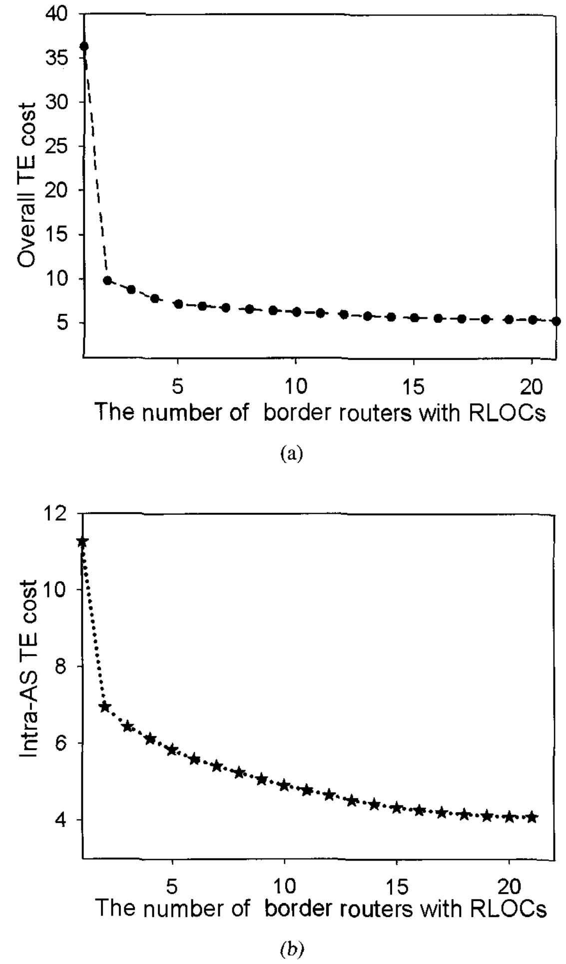
VI. RESULTS OF EXPERIMENT

This section presents and analyzes the evaluation results on the performance metrics achieved using different strategies.

Version I:

A. Evaluation of the Number of Edge Routers with RLOCs

Given intra-AS and inter-AS traffic demand, we have evaluated the overall TE cost (i.e., equation (2)) achieved by version I (joint ERS and ERMA optimization with unadjustable-link-weight) with different number of RLOCs ($R = 1 \cdots |N|$) for Telstra and Exodus networks. We found that the results exhibited common characteristics. Therefore, we present and analyze the result of Exodus topology for brevity. Fig. 6(a) shows how the overall TE cost (y-axis) changed as the number of RLOCs (x-axis) increased. We found that the overall TE cost declined as R increased. In particular, the overall cost decreased by approximately 75% when R increased from one to two. This results from the fact that when there is only one link all inter-AS traffic flows through that single inter-AS link (via the single edge router), and link utilization is large. Hence, the overall TE cost is substantially high. We also analyzed how the intra-AS TE cost (i.e., all the internal link capacity cost) changed as the number of edge routers changed (Fig. 6(b)). Intra-AS TE cost can reflect the performance of maximum intra-AS link utilization and total bandwidth consumption. The intra-AS TE cost showed the same trend as the overall TE cost, that is, it decreased as R increased. However, both the overall and intra-AS TE costs degraded gracefully as the number of edge routers steadily increased. On the other hand, more edge routers may introduce extra placement and configuration costs. Thus, it is reasonable to consider allocating two or three edge routers RLOCs.



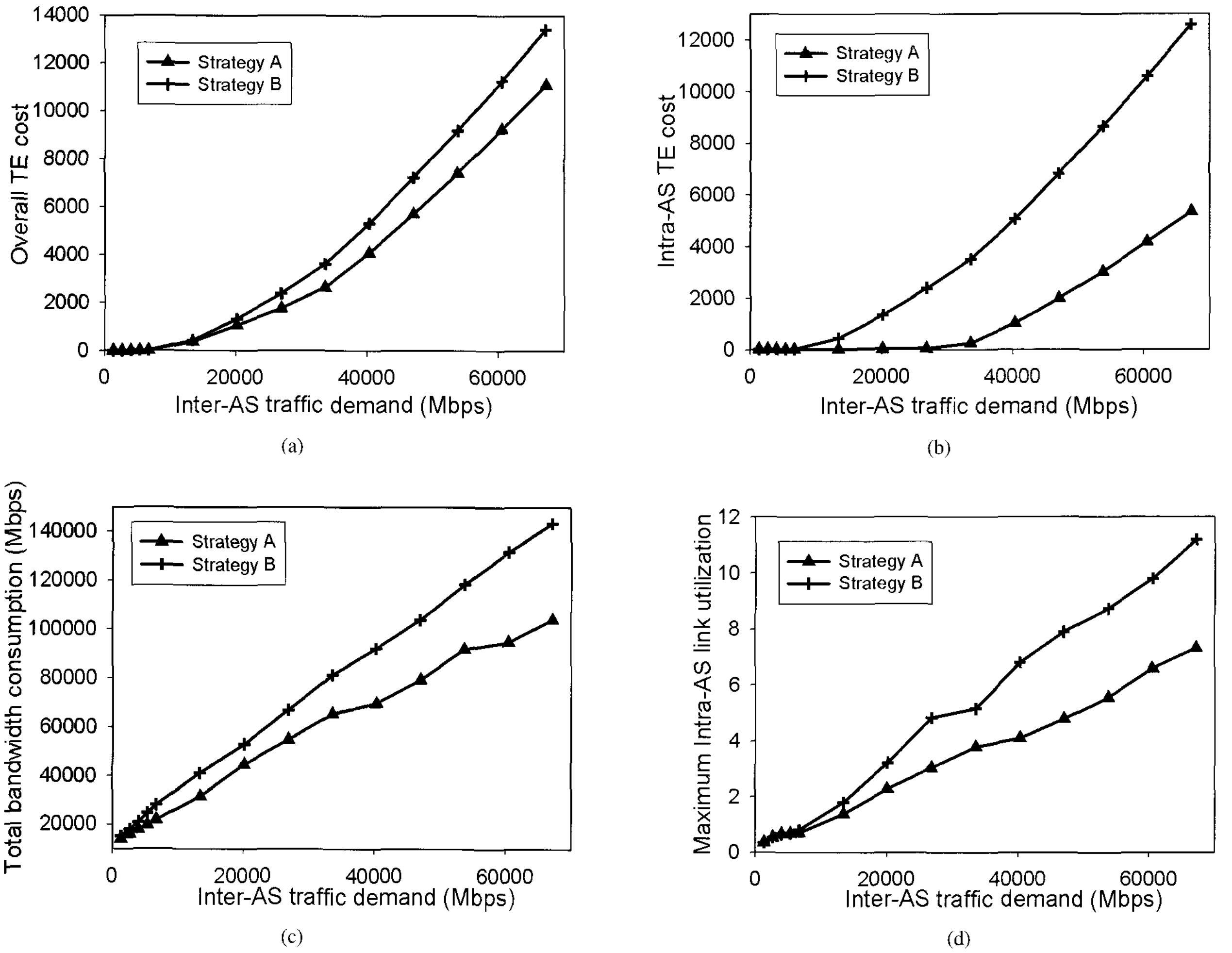
(a)

(b)

Fig. 6. Evaluation of the number of edge routers with RLOCs: (a) Overall TE cost and (b) intra-AS TE cost.

B. Effect of ERS Optimization

We have compared the overall TE cost and intra-AS TE cost achieved using strategy A (joint ERS and ERMA optimization) and strategy B (unitary ERMA optimization) with an increasing amount of inter-AS traffic. Figs. 7(a) and 7(b) show the overall TE cost and intra-AS TE cost (y-axis) as a function of inter-AS traffic demand (x-axis). We found that the shapes of the results curves described the piecewise linear cost function, with the solutions for strategy A significantly outperforming those of strategy B, especially with increasing inter-AS traffic demand. The overall TE cost of strategy A was at least 7% lower than the result for strategy B when inter-AS traffic volume reached 1344. Because ERS optimization can effectively choose the best edge routers for inter-AS traffic to enter or exit the local domain, it widens the optimization (search) space to find the optimal overall TE cost. Accordingly, intra-AS TE cost was



(a) (b) (c) (d)

Fig. 7. Effect of ERS optimization: (a) Overall TE cost, (b) intra-AS TE cost, (c) total bandwidth consumption, and (d) maximum intra-AS link utilization.

also improved. As a consequence, we can conclude that ERS optimization is helpful in obtaining lower overall and intra-AS TE costs.

We also plotted the corresponding total intra-AS bandwidth consumption versus inter-AS traffic demand (depicted in Fig. 7(c)). From the figure, it can be seen that ERS optimization provides an opportunity for inter-AS traffic to flow through intra-AS routes that are short, and ERS optimization also balances the load in the network. Therefore, the total bandwidth consumption of strategy A was lower than that of strategy B. In other words, ERS optimization significantly improved the overall network performance by accommodating more traffic demands (from 990 to 39520) when inter-AS traffic changed from 1344.756 to 67237.8. This also explains why ERS optimization can achieve better intra-AS cost compared to other strategies.

The maximum intra-AS link utilization for both strategies are depicted in Fig. 7(d). The simulation results demonstrate the same trend as the total bandwidth. Maximum intra-AS link utilization improvement of joint optimization (strategy A) is remarkable as inter-AS traffic demand increases. It is clear to see that strategy A performed much better than the unitary optimization scheme (strategy B) as inter-AS traffic demand increased. This implies that Internet service providers (ISPs) can recoup significant cost savings by moving to a joint RA and ERMA optimization approach. Note that link capacity constraints were not considered in our linear programming models (version I), and each link load was simply the sum of traffic demand. Thus, the value of the maximum intra-AS link utilization is greater than one.

C. Effect of ERMA Optimization

Next, we proceed to quantify and compare the performance of strategy B (unitary ERMA optimization) and strategy C (non-optimization) for an increasing amount of intra-AS traffic. From Fig. 8(a), it is clear that the intra-AS TE cost of strategy B is lower than that of strategy C, especially when intra-AS traffic is high. This is because higher intra-AS traffic makes the ERMA optimization effect more effective.

In order to analyze how the maximum intra-AS link utilization changed with intra-AS traffic demand, we plotted corresponding maximum intra-AS link utilization for both strategies B and C (Fig. 8(b)). In this scenario, ERMA optimization attempted to keep the maximum link utilization low in order to avoid the high cost penalty as the network load increased. In accordance with this, the maximum intra-AS link utilization of strategy B is almost lower than that of strategy C. However,

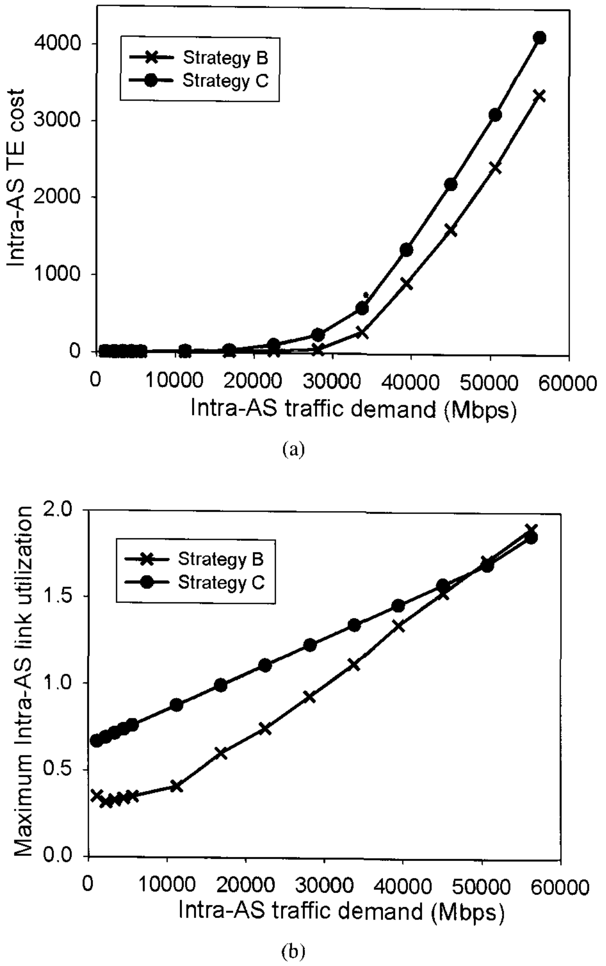


Fig. 8. Effect of ERMA optimization: (a) Intra-AS TE cost and (b) maximum Intra-AS link utilization.

the maximum link utilization of strategy B is larger than that of strategy C. This is because higher maximum link utilization of one link may have lowered the overall TE cost on the links, in aggregate.

Version II:

D. Effect of RLS Algorithm

In this set of experiments, we evaluated the performance of the heuristic algorithm (RLS). For the Telstra topology, intra-AS traffic volume was set to 2250, while inter-AS traffic volume was set to 2397.26. For the exodus topology, intra-AS traffic volume was set to 5625.001, while inter-AS traffic volume was set to 6723.78.

We compared the result obtained using RLS with the optimal solution of MILP (version II) solved using CPLEX. The complexity of the MILP increases exponentially with the size of the network. In our experiments, due to the fact that the MILP optimal solution for the exodus network could not be obtained in acceptable time, we relaxed all binary variables μ^j_{mn} into a continuous variable between zero and one, and solved the corresponding linear programming relaxation (LPR) problem using CPLEX in order to get a benchmark for RLS. The solution of the LPR problem can be viewed as the lower bound for Version II.

Table 2. Results of different numerical calculation methods.

Topo.	RLS		Optimal		LPR	
	Obj.	Time	Obj.	Time	Obj.	Time
Telstra	5.83	46	5.83	612	5.46	25
Exodus	7.24	330	N/A	N/A	6.43	720

Table 3. Results of three optimization schemes.

Topo.	LW	ERS-ERMA	ERS-ERMA-LW
Telstra	7.05	8.73	5.83
Exodus	12.59	10. 99	7.24

Table 4. Results of different local search algorithms.

Topo.	RLS		F&T's	
	Obj.	Time	Obj.	Time
Telstra	5.83	46	5.83	120
Exodus	7.24	360	9.59	3,020

Initially, we did not know how many iterations were required for the algorithm to get a near-optimal solution, so we conducted a large number of experiments on both practical networks and randomly generated topologies, with various characteristics. The result shows that the objective value did not decrease significantly just after 30,000 iterations for a network within 100 nodes, and was very close to the solution given by LPR. On the other hand, larger iteration numbers mean longer computation time, we compromised by setting the maximum number of iterations at 50,000.

Table 2 shows the performance of RLS, MILP, and LPR solved by CPLEX in terms of overall TE cost (Obj.) and computation time(s). As is evident from Table 2, RLS for the Telstra network obtained the same solution as that obtained when MILP was solved using CPLEX. RLS could also find the solution even for Exodus networks in a relatively short time. This is in contrast to CPLEX, which could not obtain an optimal solution within a reasonable time. The solution obtained using RLS closely approximates that given by LPR. This indicates that our algorithm can achieve near-optimal performance.

E. Effect of Joint Optimization of ERS and ERMA

Table 3 compared the overall TE cost of the joint optimization of ERS, ERMA, and the link weight (ERS-ERMA-LW); the unitary optimization schemes, including joint optimization of ERS and ERMA scheme with given link weight (Version I); and the link weight (LW) optimization scheme based on pre-determined ERS and ERMA (strategy C). The same set of traffic demands listed in Table 2 was used. From Table 3, it is clear that the joint optimization of RA, ERMA, and link weight outperformed the other schemes. This indicates that network design (ERS and ERMA) and TE should be performed at the same time to achieve better network performance. These results also verify the effect of introducing link weight adaptations.

F. Comparison between RLS and Local Research

We also compared our heuristic algorithm RLS with the local search algorithm of Fortz and Thorup's (F&T's) (see Table 4). Both algorithms were set the same iteration number (50,000). Both algorithms found the same (equally good) solution for the Telstra topology, but RLS consumed less time in coming up with the solution. This is because RLS can explore neighborhoods according to the network status. As shown in the table, the solution for RLS was also slightly better than that of F&T's for the Exodus topology. Thus, we can state that our heuristic algorithm is better than that of F&T's in terms of solution quality and running time.

VII. CONCLUSION

In this paper, we examined optimum network design and the TE problem in terms of the locator/identifier separation context. We proposed a joint ERS and ERMA optimization scheme as a means of improving overall network performance. Our results can be applied to LISP-capable networks to realize desirable network performance objectives such as minimizing overall TE cost and minimizing maximum link utilization. As discussed in the preceding sections, whether intra-AS traffic engineering is implemented by a local network administrator or not, guiding inter-AS traffic through the appropriate ingress (or egress) edge router will help improve the utilization of local network resources. It will also enable ISPs to manage network resources in a cost-effective manner while meeting consumer demand for quality of service.

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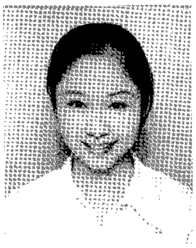

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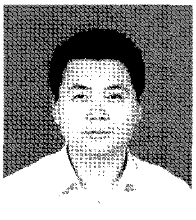

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