Routing On Demand: Toward the Energy-Aware Traffic Engineering with OSPF

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Abstract. Energy consumption has already become a major challenge to the current Internet. Most researches aim at lowering energy consumption under certain fixed performance constraints. However, since trade-offs exist between network performance and energy saving, Internet Service Providers (ISPs) may desire to achieve different Traffic Engineering (TE) goals corresponding to changeable requirements. The major contributions of this paper are twofold: 1) we present an OSPF-based routing mechanism Routing On Demand (ROD) that considers both performance and energy saving, and 2) we theoretically prove that a set of link weights always exists for each trade-off variant of the TE objective, under which solutions (*i.e.,* routes) derived from ROD can be converted into shortest paths and realized through OSPF. Extensive evaluation results show that ROD can achieve various trade-offs between energy saving and performance in terms of Maximum Link Utilization, while maintaining better packet delay than that of the energy-ignore TE.

Keywords: Traffic Engineering, OSPF, Energy Saving, Routing

1 Introduction

Since plenty of bandwidth-intensive applications (*e.g.*, video-on-demand and cloud computing) have come into service, the amount of data being carried on the Internet has dramatically grown [11]. Traditionally, Internet Service Providers (ISPs) leverage Traffic Engineering (TE) to ensure acceptable network performance. Open Shortest Path First (OSPF) [18] is a commonly used intra-domain routing protocol that can be applied in TE through configuring appropriate link weights. In our previous work [5], we made a change on the traffic splitting scheme in OSPF and proposed an OSPF-based approach to achieve optimal TE.

As bandwidth requirements increase, ISPs need to deploy more and faster network equipments (*e.g.*, routers) to handle these demands, resulting in the growth of energy consumption. Therefore, TE should take both energy efficiency and network performance into consideration rather than merely focusing on the latter. The common idea of the state-of-the-art energy-aware TE approaches [7] [11] is to reduce energy consumption under certain performance constraints. However, we argue that trade-off exists between energy saving and network performance. Intuitively, an ISP can achieve higher network energy efficiency at the cost of sacrificing partial performance without influencing user experience. Thus, there is a set of solutions rather than a unique solution to solve the energy-aware TE problem, where ISPs can make a flexible adjustment among these solutions.

The main challenge to achieve this goal exists that the conventional TE problem is already difficult due to the elastic nature of network traffic. Therefore, considering energy saving and network performance together will make the problem even harder. This problem should be carefully studied to ensure the network free from frequent oscillations and extra long delays.

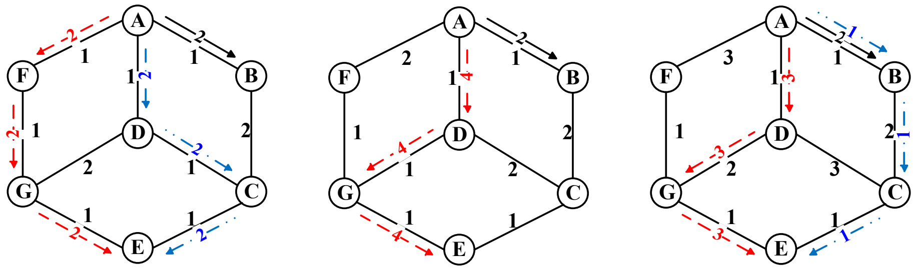
This paper presents Routing On Demand (ROD), an OSPF-based routing mechanism that can achieve energy-aware traffic engineering solutions. ROD is formulated based on the Multiple Commodity Flows (MCF) constrains with a weighted objective considering both energy consumption and network performance in terms of Maximum Link Utilization (MLU). In ROD, a specific trade-off requirement can be derived from adjusting a *green factor* in the objective function, where corresponding solutions (*i.e.,* routes) can be converted into shortest paths with respect to a set of link weights. Then we develop algorithms to achieve these link weights, as well as flow splitting ratios when Equal-Cost Multiple Paths (ECMPs) exist, which can be directly configured through OSPF protocol without introducing additional load to the network. The compatibility with existing network protocols eases the deployment of ROD mechanism.

Using real and synthetic network topologies, we evaluate the effectiveness of the ROD mechanism in multiple metrics, including trade-off between energy saving and performance, link utilization and packet delay. Results show that, through adjusting the green factor, ROD can achieve diverse trade-offs between energy saving and MLU without bias on topology types. Moreover, a promising result for Abilene lies in that a 1% growth of MLU threshold will roughly lead to a 15% decrease in energy consumption. Similar results also hold for other topologies.

The rest of the paper is organized as follows. Section 2 gives an overview of our basic idea. In Section 3, we present the ROD model and proof of the existence of optimal link weights. The implementation issues are discussed in Section 4, which is followed by evaluation of ROD mechanism in Section 5. We summarize the related work in Section 6 and conclude the paper in Section 7.

2 Overview of the Basic Idea

In this section, we illustrate through case studying that trade-off exists between energy saving and network performance.



(a) Case 1 (b) Case 2 (c) Case 3

Figure 1. Optimal Routing in various cases

As shown in Figure 1, each link has a capacity of 5 units. Traffic demands consist of 2 Original-Destination (OD) pairs, namely A→B and A→E, with bandwidth requirements of 2 and 4 units. For simplicity, we assume that each unused link can be put into sleep mode [8] without any power consumption, while each loaded link consumes the same amount of power. Given traffic demands and network topology, we need to identify the optimal routes for these demands according to certain constrains and objectives.

Through the following three cases, we illustrate the existence of trade-offs between energy saving and network performance in terms of Maximum Link Utilization (MLU).

Case 1: *Minimizing MLU*. The most widely used objective function of the conventional TE is simply to minimize MLU [14], which aims at reducing the risk of network congestion. The optimal routes are shown in Figure 1 (a), where each path is marked with the same line type and its traffic load. In this case, the optimal routes altogether leverage 7 links with a 2-unit load on each link. Thus the MLU is 40%.

Case 2: *Minimizing energy consumption without MLU constraint*. Based on the energy assumption, this goal is equivalent to minimize the number of loaded links. The optimal routes are presented in Figure 1 (b), where altogether 4 links are involved and the MLU is 80%. Comparing to Case 1, energy consumption of the entire network is reduced approximately by $(7-4)/4 = 42.9\%$.

Case 3: *Minimizing energy consumption with certain MLU upper bound*. TE with only energy consideration might increase the risk of network congestion on heavy loaded links when facing with traffic bursts. Therefore, an ISP may desire to minimize energy consumption while keeping MLU within certain safety threshold, say 60%. The optimal routes exhibit in Figure 1 (c), where the energy saving rate compared to Case 1 is about 14.3% and the MLU is exactly 60%.

The figures marked beside links indicate the OSPF link weights, under which the optimal routes in each case are exactly the OSPF shortest paths. We notice that traffic is not equally split over two ECMPs serving the same OD pair A→E in Case 3. This can be realized by modifying hardware components, which will be discussed later.

3 ROD Model

In this section, we first present Routing On Demand (ROD) model to formulate energy-aware TE problem, which extracts the trade-off between energy saving and network performance. Then we prove that the optimal link weights always exist under each considered TE objective function.

3.1 Network Model

We consider a directed network $\mathcal{G} = (\mathcal{N}, \mathcal{E})$, where $\mathcal{N}$ is the set of nodes (*i.e.,* routers) and $\mathcal{E}$ is the set of edges (*i.e.,* links). We assume that all links are directional and each link $(i, j) \in \mathcal{E}$ is attached with its own capacity c_{ij} which is the maximum amount of traffic it can take. Let $\mathcal{M}$ denote the set of source-destination pairs. For each $m \in \mathcal{M}$, a traffic demand of (s_m, t_m) is d_m, which represents the average intensity of traffic volume entering the network at node s_m and leaving from node t_m. Hereafter we use notations N, E and M to denote the cardinalities of sets $\mathcal{N}, \mathcal{E}$ and $\mathcal{M}$, respectively.

A customary way to treat the TE problem is to formulate it based on MCF constraints. For ease of illustration, here we regard all traffic flows to the same destination as a commodity, which somewhat misuses the terminology. We denote the destination node set with $\mathcal{D} = \{t \in \mathcal{N} : \exists\ m \in \mathcal{M} \text{ s.t. } t_m = t\}$. The traffic volume of commodity flow t along edge (i, j) is denoted by f^t_{ij}.

1) Minimizing MLU. The conventional TE problem prefers to minimize MLU to balance traffic distribution over all links, which can be formulated as

$$\text{minimize} \quad \max_{(i,j)\in\mathcal{E}} \frac{f_{ij}}{c_{ij}} \tag{1a}$$

$$\text{subject to} \quad f_{ij} = \sum_{t\in\mathcal{D}} f^t_{ij} \le c_{ij}, \forall (i, j) \in \mathcal{E} \tag{1b}$$

$$\sum_{i:(s,i)\in\mathcal{E}} f^t_{si} - \sum_{j:(j,s)\in\mathcal{E}} f^t_{js} = d^t_s,\ \forall t \in \mathcal{D}, s \in \mathcal{N} \tag{1c}$$

$$f^t_{ij} \ge 0,\ \forall t \in \mathcal{D}, (i, j) \in \mathcal{E}, \tag{1d}$$

where $d^t_s \ge 0$ in (1c) is the expected traffic entering the network at node s and destined to node t. For $s \ne t$, set $d^t_s = d_m$ if there exists $m \in \mathcal{M}$ such that $s_m = s$ and $t_m = t$, or set $d^t_s = 0$ otherwise. For $s = t$, according to the previous definition of commodity, we set $d^t_t = -\sum_{m:t_m=t} d_m$.

Constraint sets (1b) and (1c) represent the capacity and flow conservation constraints, respectively. All of three constraint sets together are called MCF constraints. We say a traffic distribution $\mathbf{f} = (f_{ij}, (i, j) \in \mathcal{E})$ is feasible if there exists $(\mathbf{f^t}, t \in \mathcal{D})$ such that $(\mathbf{f}, \mathbf{f^t}, t \in \mathcal{D})$ satisfies the MCF constraints.

2) Minimizing Energy Consumption. If we only consider minimizing energy consumption of the entire network, the TE problem turns into optimizing traffic distribution under the same MCF constraints in (1) to use as few links as possible. Its objective function is modeled as

$$\text{minimize} \quad \|\mathbf{f}\|_0 + \sum_{t \in \mathcal{D}} \|\mathbf{f}^t\|_0 \tag{2}$$

where $\|\mathbf{f}\|_0$ represents the number of non-zero elements of $\mathbf{f}$.

The above formulation, which seeks the vector whose support has the smallest cardinality, is commonly referred to as cardinality minimization and known to be NP-hard. Since the computation time for medium and large-scale networks is a great concern, the cardinality minimization problem is thus usually heuristically solved by minimizing the ℓ_1 norm [6]. Then the TE problem of minimizing energy consumption with the relaxed objective function is given as follows:

$$\begin{array}{ll} \text{minimize} & \sum_{(i,j)\in\mathcal{E}} f_{ij} \\ \text{subject to} & MCF \quad constrains \end{array} \tag{3}$$

3) Routing On Demand. We introduce a *green factor* θ to combine the above two models together and propose an integrated ROD model as follows:

$$\begin{array}{ll} \text{minimize} & \theta \max\limits_{(i,j)\in\mathcal{E}} \frac{f_{ij}}{c_{ij}} + \sum_{(i,j)\in\mathcal{E}} f_{ij} \\ \text{subject to} & MCF \quad constrains \end{array} \tag{4}$$

3.2 Universal Existence of Optimal Link Weights

We associate the network with an operator, and assume that if the load held by link (i,j) is f_{ij}, then the cost is $\phi(\mathbf{f})$. We also assume that the cost $\phi(\mathbf{f})$ is an continuous *convex* function of $\mathbf{f}$ ($\mathbf{f} \geq \mathbf{0}$). Without loss of generality, we can apply $\phi(\mathbf{f})$ to represent various objective functions of previous models. The goal of TE thus turns into minimizing $\phi(\mathbf{f})$ over MCF constraints.

For simplicity, we rewrite MCF constrains in matrix form. Then the general TE problem is given as TE$(\phi, \mathcal{G}, \mathbf{c}, \mathbf{D})$

$$\text{minimize} \quad \phi(\mathbf{f}) \tag{5a}$$

$$\text{subject to} \quad \mathbf{f} - \sum_{t\in\mathcal{D}} \mathbf{f}^t = \mathbf{0} \tag{5b}$$

$$\mathbf{f} \leq \mathbf{c} \tag{5c}$$

$$\mathbf{A}\mathbf{f}^t = \mathbf{d}^t, \mathbf{f}^t \geq \mathbf{0}, \ \forall t \in \mathcal{D} \tag{5d}$$

where $\mathbf{A}$, an $N \times E$ node-arc incidence matrix for network $\mathcal{G}$, is introduced to represent the multi-commodity flow constraints (1c). The column corresponding to link (i,j) has $(a+1)$ entries in row i and $(a-1)$ entries in row j.

The partial Lagrangian of TE$(\phi, \mathcal{G}, \mathbf{c}, \mathbf{D})$ is

$$\mathcal{L}(\mathbf{f}, \mathbf{f}^t, t \in \mathcal{D}; \mathbf{w}) = \phi(\mathbf{f}) - \sum_{(i,j)\in\mathcal{E}} w_{ij} f_{ij} - \sum_{t\in\mathcal{D}} \mathbf{w}^T \mathbf{f}^t$$

From the general theory of constrained convex optimization [1], it follows that $(\mathbf{f}, \mathbf{f}^t, t \in \mathcal{D})$ solves Problem (5) if and only if there exists a Lagrangian multiplier vector $\mathbf{w}$ such that $(\mathbf{f}, \mathbf{f}^t, t \in \mathcal{D})$ solves

$$\begin{array}{ll} \text{minimize} & \phi(\mathbf{f}) - \sum_{(i,j)\in\mathcal{E}} w_{ij} f_{ij} - \sum_{t\in\mathcal{D}} \mathbf{w}^T \mathbf{f}^t \\ \text{subject to } \mathbf{f} \leq \mathbf{c}; & \mathbf{A}\mathbf{f}^t = \mathbf{d}^t, \mathbf{f}^t \geq 0, \forall t \in \mathcal{D}. \end{array} \tag{6}$$

Problem (6) is a separable optimization, since there is no coupling between variable $\mathbf{f}$ and $\mathbf{f}^t$ for all $t \in \mathcal{D}$. Then Problem (5) can be solved through the following the distributed method, *i.e.,* $(\mathbf{f}, \mathbf{f}^t, t \in \mathcal{D})$ solves problem (5) if and only if there exists the Lagrangian multiplier vector $\mathbf{w}$ such that $\mathbf{f}$ solves the capacity planning problem ISP$(\mathbf{w}, \phi, \mathbf{c})$

$$\begin{array}{l} \text{minimize } \ \phi(\mathbf{f}) - \sum_{(i,j)\in\mathcal{E}} w_{ij} f_{ij} \\ \text{subject to } \mathbf{f} \leq \mathbf{c} \end{array} \tag{7}$$

and for each $t \in \mathcal{D}, \mathbf{f}^t$ solves the minimum cost flow problem MCF$(\mathbf{w}, \mathbf{d}^t)$

$$\begin{array}{l} \text{minimize } \ \mathbf{w}^T \mathbf{f}^t \\ \text{subject to } \mathbf{A}\mathbf{f}^t = \mathbf{d}^t; \quad \mathbf{f}^t \geq 0. \end{array} \tag{8}$$

Here we give some engineering interpretations for the separated Problems (7) and (8) for all $t \in \mathcal{D}$. First, the ISP's Problem (7) can be interpreted as a capacity planning problem where ISP determines the possible virtual link capacity with each link cost w_{ij}, the total cost $\phi(\mathbf{f})$ generated for flow distribution $\mathbf{f}_{ij}$, and the maximal permission capacity for each link c_{ij} and the objective as the net cost. Then the flows of the t-th class with the same destination t finds a solution that minimizes the total cost under the given link cost w_{ij} without considering the link capacity.

An promising property of the optimal routing is that they can be converted into shortest paths, *i.e.*, the routes for the $t-$th class flow is the shortest path under the link weights w_{ij}. Let ν^t denote the dual optimal solution of Problem (8). By applying the *complimentary slackness* theorem, we have

$$\nu_i^t - \nu_j^t = w_{ij}, \quad \text{if} \quad f_{ij}^t > 0 \tag{9a}$$

$$\leq w_{ij}, \quad \text{if} \quad f_{ij}^t = 0 \tag{9b}$$

Let $p : i_0 i_1 \cdots i_n$ be a possible path of OD pair (s,t), where $i_0 = s$ and $i_n = t$. For example, if $y_p = \min_{k=1,2,\cdots,n} f_{i_{k-1}i_k}^t > 0$, we have $\sum_{(i,j)\in p} w_{ij} = \nu_s^t - \nu_t^t \leq \sum_{(i,j)\in\bar{p}} w_{ij}$ for any other path $\bar{p}$ that connects the same source-destination pair (s,t) under conditions (9a) and (9b).

Hereafter we refer to these as the optimal link weights and the optimal link loads which are denoted by $\mathbf{w}^*$ and $\mathbf{f}^*$, respectively. The similar results have been shown by Wang et al. [3]. The major difference existing in our approach is that we present a *close form* of the link weights which are *explicitly* determined by the objective and the optimal traffic distribution.

Let $\mathbf{p}$ be a *subgradient* of a convex function f at $\mathbf{x} \in \mathrm{dom} f$ if

$$f(\mathbf{y}) \geq f(\mathbf{x}) + \mathbf{p}^T(\mathbf{y} - \mathbf{x}),\ \forall \mathbf{y} \in \mathrm{dom} f.$$

Subdifferential of f at $\mathbf{x} \in \mathrm{dom} f$ is the set of all subgradients of f at $\mathbf{x}$ and is denoted by $\partial f(\mathbf{x})$. If f is convex and differentiable at $\mathbf{x}$, then $\partial f(\mathbf{x}) = \{\nabla f(\mathbf{x})\}$.

Theorem 1. *There exists one subgradient* $\mathbf{p}$ *of* ϕ *at* $\boldsymbol{f}^*$ *such that* $w_{ij}^* = p_{ij}$ *if* $f_{ij}^* < c_{ij}$ *and* $w_{ij}^* \geq p_{ij}$ *if* $f_{ij}^* = c_{ij}$.

The proof of Theorem 1 can be conducted based on the convex analysis of ISP's Problem in (7) and the calculation rule of subdifferential, which is omitted here due to space limitation.

3.3 Optimal Link Weights for Various Cost Functions

In this subsection, we will illustrate that the optimal link weights can be achieved for those cost functions in Subsection 3.1.

Lemma 1. *Let* $f(\mathbf{x}) = \max\{f_1(\mathbf{x}), \cdots, f_m(\mathbf{x})\}$. *Define* $\mathcal{I}(\mathbf{x}) = \{i : f_i(\mathbf{x}) = f(\mathbf{x})\}$, *and the* active *functions is at* $\mathbf{x}$. *Then it holds that*

$$\partial f(\mathbf{x}) = \mathrm{conv}\left\{\cup_{i \in \mathcal{I}(\mathbf{x})} \partial f_i(\mathbf{x})\right\},$$

1) Minimizing MLU: in this case, we have

$$\phi(\mathbf{f}) = \max_{(i,j)\in\mathcal{E}} \frac{f_{ij}}{c_{ij}}.$$

Let $\mathcal{I}(\mathbf{f}^*) = \{(i,j) \in \mathcal{E} : f_{ij}^*/c_{ij} = \max_{(i,j)\in\mathcal{E}} f_{ij}/c_{ij}\}$, *i.e.,* the set of the link with MLU. By Lemma 1, we have $\mathbf{p} \in \partial\phi(\mathbf{f}^*)$ if and only if $p_{ij} = a_{ij}/c_{ij}$ for $(i,j) \in \mathcal{I}(\mathbf{f}^*)$ and $a_{ij} \geq 0, \sum_{(i,j)\in\mathcal{I}(\mathbf{f}^*)} a_{ij} = 1$, and $p_{ij} = 0$ otherwise.

The results show that the routing minimizing MLU is the shortest path routing for each source-destination pair, where the link weights for the non-bottleneck links are all zeros, and *only* the link weights of the bottleneck links are possibly positive and scale with the inverse of their link capacities.

2) Minimizing Energy Consumption: by Theorem 1, routes derived from Model (3) are the shortest paths, where link weights are 1s for unsaturated links (*i.e.,* $f_{ij}^* < c_{ij}$) and greater than 1 for the rest links. Furthermore, any path without including saturated links must be the lowest hop-count path.

3) Routing On Demand: in the Model (4), assume the green factor such that the optimal link load $f_{ij}^* < c_{ij}$ for all $(i,j) \in \mathcal{E}$, *i.e.*, all links are unsaturated. By Theorem 1, the routes minimizing Problem (4) are the shortest paths, where the link weight is $\theta a_{ij}/c_{ij} + 1$ for $(i,j) \in \mathcal{I}(\mathbf{f}^*)$ and $a_{ij} > 0$, $\sum_{(i,j)\in\mathcal{I}(\mathbf{f}^*)} a_{ij} = 1$, and is 1 otherwise. Furthermore, the path of a source-destination pair must be the shortest hop-count path if it does not across bottleneck links.

4 Implementation Issues

In this section, we will briefly discuss implementation issues of ROD mechanism based on the theoretical formulation in Section 3. Similar to the conventional traffic engineering, ROD relies on a centralized controller that is responsible for centrally computing link weights and periodically configuring all routers.

4.1 Collecting and Disseminating Information for ROD

The input information for ROD (*e.g.*, network topology and traffic matrix) can be collected from routers. In OSPF, each router will periodically flood its Link State Advertisements (LSAs) that contain all link state information. In particular, the Traffic Engineering Link State Advertisement (TE-LSA) defined in RFC3630 [17] reports link load information. Thus, the latest topology and traffic matrix could be computed based on this information.

The optimal link weights can be computed through Algorithm 1, which is derived from the dual decomposition of TE($\phi, \mathcal{G}, \mathbf{c}, \mathbf{D}$) defined in (5) in Section 3.2. Given the link weight $\mathbf{w}$ in each iteration, the ISP Problem in (7) and the MCF Problem in (8) will be solved to respectively get their optimal traffic distribution. Then the dual gap

$$\mathtt{gap}(\mathbf{w}(k), f(k), \mathbf{f}(k)) = \sum_{(i,j)\in\mathcal{E}} w_{ij}(k)(\sum_{t\in\mathcal{D}} f_{ij}^t(k) - f_{ij}(k))$$

is applied as an optimality measure. Here γ_k is the step size and $(z)_+ = \max(0, z)$. If the dual gap is smaller than tolerance ϵ, the iteration will terminate with optimal link weights $\mathbf{w}^*$ and traffic distribution $\mathbf{f}^*$. The computational complexity of Algorithm 1 is $O(N + E)$, where N and E are defined in Section 3.1.

The optimal link weight can be configured in routes as OSPF link weights. Due to space limitation, the theoretical proof of the convergence of Algorithm 1 is not shown here. Since the traffic matrix changes over time, the frequency of periodically computation and configuration may have an impact on network overhead and ROD performance. This is a major issue for our further investigation.

Algorithm 1 *Computing the optimal link weights*

Given optimal tolerance ϵ and initial weight $\mathbf{w}(0)$ (such as $w_{ij}(0) = 1), k = 0$;
for the given weight $\mathbf{w}(k)$ **do**
  Solve ISP($\mathbf{w}, \phi, \mathbf{c}$) in (7) to achieve the traffic load $f_{ij}(k)$ for each link (i, j);
  Solve MCF($\mathbf{w}, \mathbf{d}^t$) in (8) to achieve the routing variable $\mathbf{f}^t(k)$
    for each destination $t \in \mathcal{D}$;
  Each link $(i, j) \in \mathcal{E}$ updates its link weight

$$w_{ij}(k+1) = \big(w_{ij}(k) - \gamma_k(\textstyle\sum_{t\in\mathcal{D}} f_{ij}^t(k) - f_{ij}(k))\big)_+;$$

  $k \leftarrow k + 1$;
  Until $\mathtt{gap}(\mathbf{w}(k), f(k), \mathbf{f}(k)) < \epsilon$.
end for

4.2 Data Forwarding under ROD

The packet under ROD mechanism is forwarded hop-by-hop along the destination-based shortest paths, which is the same as in OSPF. The shortest paths are constructed from the optimal link weights derived from Algorithm 1. In case that there are multiple equal-cost shortest paths between the same OD pairs, the flow splitting ratios over these paths can be computed from Algorithm 2. Taking the optimal traffic distribution $\mathbf{f}^*$ derived from Algorithm 1 as input information, Algorithm 2 first topologically sorts all nodes that are involved in data forwarding to a certain destination t, and then calculates the traffic splitting ratio $\tau(s,p,t)$ for each candidate next-hop denoted by p. The computational complexity of Algorithm 2 is $O(N*(N+E))$.

We mentioned the unequal traffic splitting ratios over ECMPs in Section 2. In hardware level, such traffic splitting scheme is usually realized through a hash-based mechanism [9]. Therefore, we can configure the hash table with different weights corresponding to the desired traffic splitting ratios.

Algorithm 2 *Achieving the splitting ratios*

```
Input the optimal traffic distribution f*
for each t ∈ D do
  Define an empty node set V and an empty link set L
  V ← V ∪ {t}
  for each link (i, j) ∈ E do
    if i ∉ V and f_ij^{t*} > 0 then
      V ← V ∪ {i} and L ← L ∪ {(i, j)}
    end if
  end for
  Do topological sorting on V to get the sorted node set V'
  for each node s ∈ V'(s ≠ t) do
    τ(s, p, t) = f_sp^{t*} / Σ_{(s,p)∈L} f_sp^{t*}
    V' ← V' \ {s}
  end for
end for
```

5 Evaluation

In this section, we evaluate ROD with real and synthetic networks to show its effectiveness on achieving trade-offs between energy saving and performance.

5.1 Experimental Setup

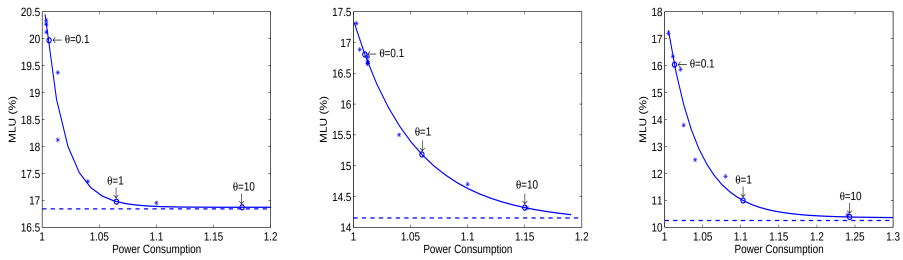
We resort to ns2 simulator [21] to explore the effectiveness of ROD on small- and large-scale topologies. For comparison, hereafter we refer to mechanisms of minimizing MLU and energy consumption as MMLU and MEC, respectively.

Table 1. Topologies for evaluation

Network	Category	Nodes	Links	Flows
Abilene	Backbone	11	28	110
Cernet2	Backbone	20	44	380
Random	Random	50	230	50

Table 2. Power consumption of line-cards

Line-card	Rate/Mbps	Energy/W
1-Port OC3	155.52	60
8-Port OC3	1244.16	100
1-Port OC48	2488.32	140
1-Port OC192	9953.28	174



(a) Abilene Network (b) Cernet2 Network (c) Random Network

Figure 2. Trade-offs between MLU and Energy Consumption for Different Topologies

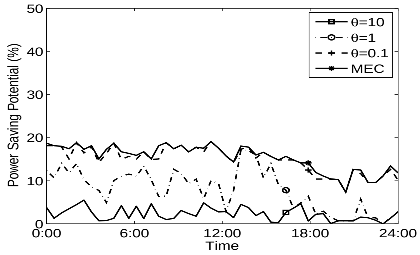
Topologies. The topologies used are summarized in Table 1. The router-level topology of Abilene is available at [16]. For simplicity, we consider the two routers at Atlanta as a single node, the entire network thus has 11 nodes altogether. The Cernet2 is the worldwide largest pure IPv6 research network, which has 44 links with 10 Gbps for 8 core links and 2.5 Gbps for the rest. The Random topology is generated by GT-ITM [20], whose capacity is set to 1 Gbps for each link.

Traffic Matrices. For Abilene, we select a subclass of the online available matrices [16], which are measured on March 1st, 2004. The traffic matrix for Cernet2 is generated by the gravity model [15] based on aggregated link load collected from January 10th to 16th, 2010. We generate a sparse traffic matrix for Random through gravity model to achieve a light traffic load scheme.

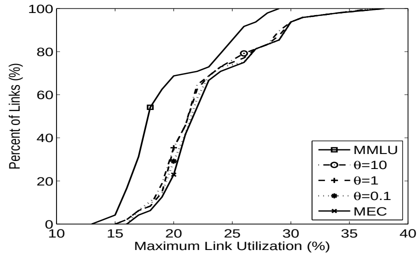
Energy Saving Assumptions. Since line-cards are considered to account for more than 40% of a router's total budget [19], we thus focus on line-cards for energy saving, whose consumption in our evaluation is summarized in TABLE 2. We assume that unloaded line-cards can be automatically put into sleep mode and the time required to enter or wake up from sleep mode is negligible [10].

5.2 Trade-off between Performance and Energy Saving

In this subsection, we explore the trade-off existing between performance and energy saving potential under ROD. MLU is usually a major concern for ISPs in TE and thus employed here as an indicator of network performance. For energy saving indicator, we compute the amount of power consumption of line-cards in each simulation.



(a) Power Saving Potential



(b) CDF of MLU

Figure 3. Simulation Results for Abilene on March 1st, 2004

For each topology, we vary the green factor θ to investigate the trade-off between MLU and power consumption, which is plotted in Figure 2. The x-axis represents power consumption of the entire network and the y-axis represents the MLU. For ease of illustration, we use MEC as a benchmark and normalize the value of energy consumption of ROD. We first asterisk discrete points for a set of selected values of θ and then fit these points to achieve smooth curves.

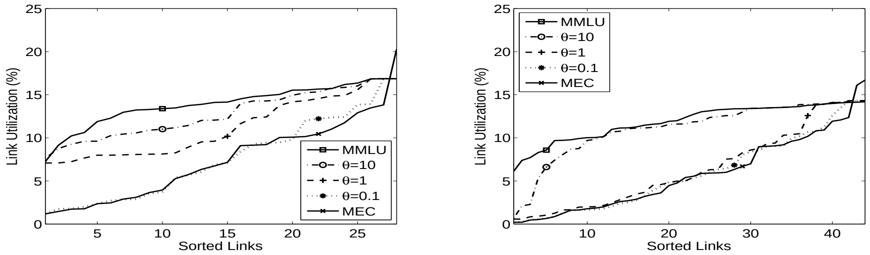
The result for Abilene in Fig. 2(a) reveals that power consumption varies consistently with θ, whereas MLU decreases as θ increases. We also notice that, if the MLU threshold of Abilene network is relaxed a bit (*e.g.*, from 16.8% to 17.5%), the power consumption will considerably lower down (*e.g.*, from 1.25 to 1.05). Similar results also hold for Cernet2 and Random.

From the three sub-figures, we also notice two stages, 1) keeping θ increasing when it is larger than 10 can slightly bring down MLU but dramatically raise up the energy consumption, which we refer to as ***power-sensitive*** stage; 2) continuing turn θ down when it is smaller than 0.1 will make a small contribution on energy saving at the cost of a sharp increase of MLU, which we regard as ***performance-sensitive*** stage. As both power- and performance-sensitive stages are undesirable for ISPs, we choose three typical values of θ between these two stages for the following evaluation, namely 0.1, 1 and 10.

In Figure 3 (a), we show how the green factor θ affects the energy saving potential of Abilene on March 1st, 2004. For each time interval, the power saving ratio is computed with the total power consumption of MMLU as a benchmark. The average energy saving ratio of ROD with $\theta = 0.1$ is about 15%, which is very close to that of MEC and higher than the other two cases with larger θ. The curve with $\theta = 1$ experiences severe oscillation since it can be easily affected by the changes in traffic matrix when equally considering minimizing MLU and power consumption.

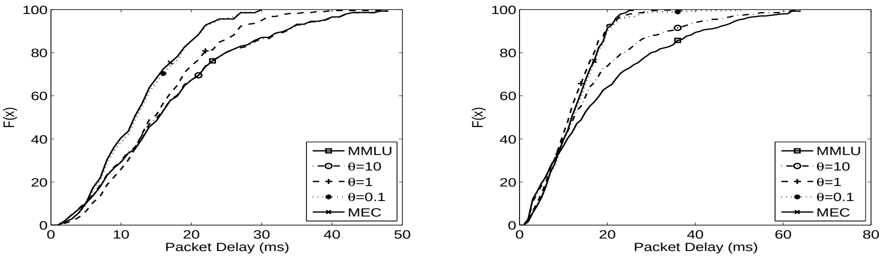
5.3 Link Utilization

In this subsection, we evaluate the impact of ROD on link utilization that is denoted by $\mathbf{f}$ in Section 3. Using the Abilene traffic matrices collected for 24 hours, we first explore changes of MLU under each routing mechanism. We



(a) Abilene Network (b) Cernet2 Network

Figure 4. Sorted Link Utilization for Different Topologies



(a) Abilene Network (b) Cernet2 Network

Figure 5. CDF of Packet Delay for Different Topologies

present the CDF of MLU of Abilene for a whole day in Figure 3 (b). Since the traffic is light, MLU is always under 40% for all cases. The curves for MMLU and MEC mechanisms act as a lower and higher bound, respectively. The three variations of ROD mechanism with different θ have slight difference in terms of MLU over temporal scale.

In Figure 4, we explore utilization of all links for a single traffic matrix, where the x-axis represents the link indices. For Abilene, the traffic of MMLU is more evenly distributed over all links, since nearly 64.3% of the total 28 links achieve the largest utilization. However, MEC goes to the opposite side and concentrates the traffic on fewer links leaving minority of the links with much higher utilization. The curves under ROD mechanism with $\theta = 10$ is similar with that of MMLU, whereas the one with $\theta = 0.1$ is close to MEC, leaving the curve with $\theta = 1$ taking the middle place. The cases for Cernet2 and Random are similar, therefore, we do not present Random result due to space limitation.

5.4 Packet Delay

In this subsection, we evaluate propagation delay under ROD. Figure 5 shows CDF of packet delay of different routing mechanisms for Abilene and Cernet2 topologies. For Abilene, MMLU exhibits the higher bound of packet delay, whereas MEC acts as the lower bound. The reason lies in that MMLU may result in undesirable quite long paths in terms of hop counts in order to avoid the highly utilized links. For this reason, the reciprocal of green factor in ROD could be considered as a penalty on the unnecessarily long paths. Therefore, the variation of ROD with a smaller θ should have a lower packet delay, which is confirmed through the curves in Figure 5(a). Due to space limitation, we omit the discussion on Cernet2 and similar results for Random topology.

6 Related Work

Gupta et al. [8] firstly propose an energy saving approach by shifting network interfaces or devices (*e.g.*, routers) into sleep mode during idle periods. Nedevschi et al. [10] investigate two approaches via sleep and rate adaption. The former approach enables line-cards to sleep between packet bursts while the latter can adjust devices to operate at low frequency when traffic load is light. Vasić et al. [11] consider the above two approaches and present EATe to reduce energy consumption at the expense of increasing massage overhead of routers. In contrast, ROD mechanism is compatible with the current OSPF protocol and thus do not introduce unnecessary message cost.

Zhang et al. [7] have recently proposed an MPLS-based intra-domain traffic engineering mechanism, GreenTE, to maximize the number of links that can be put into sleep mode under given performance constrains. However, GreenTE requires excessive management control to achieve its goal because that MPLS tunnels should be frequently set up and adjusted according to the elastic traffic. Panarello et al. [12] put forward a trade-off approach for performance and energy saving in access network. However, since devices in backbone networks consume the large majority of energy [13], we thus focus on exploring trade-off that exists in backbone networks.

7 Conclusion

This paper presents Routing On Demand (ROD), which is an OSPF-based routing mechanism that can achieve trade-off solutions to energy-aware TE problem. We theoretically prove that a set of link weights always exists for each trade-off in energy-aware TE objective, under which solutions (*i.e.,* routes) derived from ROD can be converted into shortest paths and realized through OSPF. Evaluation results show that ROD can achieve different trade-offs between energy saving and performance in terms of Maximum Link Utilization (MLU) while maintaining better packet delay than that of energy-ignore TE. The compatibility of ROD with OSPF eases its deployment. Our future work includes investigating the overhead of realizing ROD mechanism as well as the impact of link failures and traffic bursts.

References

1. Bertsekas, D.P.: Nonlinear Programming, 2nd ed. Athena Scientific, Belmont, MA, USA (1999)

2. Awduche, D.: MPLS and Traffic Engineering in IP Networks. IEEE Communication Magazine 37(12), pp. 42-47 (1999)
3. Wang, Z., Wang, Y., Zhang, L.: Internet Traffic Engineering Without Full Mesh Overlaying. In: IEEE INFOCOM, pp. 565-571 (2001)
4. Sridharan, A., Guérin, R., Diot, C.: Achieving Near-Optimal Traffic Engineering Solutions for Current OSPF/IS-IS Networks. IEEE/ACM Transaction on Networking 13(2), pp. 234-247 (2005)
5. Xu, K., Liu, H., Liu, J., Shen, M.: One More Weight is Enough: Toward the Optimal Traffic Engineering with OSPF. In: IEEE ICDCS, pp. 836-846 (2011)
6. Candès, E.J., Tao, T.: Decoding by Linear Programming. IEEE Transactions on Information Theory 51(12), pp. 4203-4215 (2005)
7. Zhang, M., Yi, C., Liu, B., Zhang, B.: GreenTE: Power-Aware Traffic Engineering. In: IEEE ICNP, pp. 21-30 (2010)
8. Gupta, M., Singh, S.: Greening of the Internet. In: ACM SIGCOMM, pp. 19-26 (2003)
9. Cao, Z., Wang, Z., Zegura, E.: Performance of Hashing-Based Schemes for Internet Load Balancing. In: IEEE INFOCOM, pp. 332-341 (2000)
10. Nedevschi, S., Popa, L., Iannaccone, G., Ratnasamy, S., Wetherall, D.: Reducing Network Energy Consumption via Sleeping and Rate-Adaptation. In: USENIX NSDI, pp. 323-336 (2008)
11. Vasić, N., Kostić, D.: Energy-Aware Traffic Engineering. In: The 1st International Conference on Energy-Efficient Computing and Networking, pp. 169-178 (2010)
12. Panarello, C., Lombardo, A., Schembra, G., Chiaraviglio, L., Mellia, M.: Energy Saving and Network Performance: a Trade-off Approach. In: The 1st International Conference on Energy-Efficient Computing and Networking, pp. 41-50 (2010)
13. Tucker, R., Baliga, J., Ayre, R., Hinton, K., Sorin, W.: Energy Consumption in IP Networks. In: ECOC Symposium on Green ICT, pp. 1-1 (2008)
14. Applegate, D., Cohen, E.: Making Intra-domain Routing Robust to Changing and Uncertain Traffic Demands: Understanding Fundamental Tradeoffs. In: ACM SIGCOMM, pp. 313-324 (2003)
15. Roughan, M., Greenberg, A., Kalmanek, C., Rumsewicz, M., Yates, J., Zhang, Y.: Experience in Measuring Backbone Traffic Variability: Models, Metrics, Measurements and Meaning. In: ACM SIGCOMM Internet Measurement Workshop, pp. 91-92 (2002)
16. Yin Zhang's Abilene TM, http://www.cs.utexas.edu/~yzhang/research/AbileneTM/
17. Katz, D., Kompella, K., Yeung, D.: RFC 3630: Traffic Engineering (TE) Extensions to OSPF Version 2, http://www.ietf.org/rfc/rfc3630.txt
18. Moy, J.: RFC 2328 OSPF Version 2, http://tools.ietf.org/html/rfc2328.txt
19. Power Management for the Cisco 12000 Series Router, http://www.cisco.com/en/US/docs/ios/12_0s/feature/guide/12spower.html
20. GT-ITM, http://www.cc.gatech.edu/projects/gtitm/
21. Network Simulator 2, http://www.isi.edu/nsnam/ns/