Journal of Communications, Vol. 8, No.1, January 2013

A Integer Non-linear Programming Model of Power Consumption of the Internet under QoS Constraints

Shijia Zhu, Yujing Zeng, Hongke Zhang
Department of Electronic and Information Engineering,
Beijing Jiaotong University, Beijing,100044, China
Email: {09111045, 09111043, hkzhang}@bjtu.edu.cn

***Abstract*— The concept of energy-efficient networking has begun to spread in the past few years, gaining increasing popularity. According to several studies, the power consumption of the Internet accounts for around 10% of the worldwide energy consumption and is constantly increasing. On the other hand, with the increasing demand for various types of data traffic, especially delay sensitive traffic, the traditional best effort delivery no longer meets the Quality of Service (QoS) requirement for the applications, and strict QoS requirement needs to be considered. In this paper, we aim to minimize the power consumption of the Internet, while satisfying the strict QoS constraints in terms of delay. We propose an integer non-linear programming formulation of the power consumption model guaranteeing full connectivity under QoS constraints. Then, we propose simple heuristic algorithm and we use the algorithm on a synthetic topology. We evaluate our model through extensive simulations and it is shown that we could get minimum total cost consisting of power consumption and delay cost of the network when link utilization constraint is set to 75%.**

***Index Terms*— energy saving network; non-integer linear programming; QoS; heuristics**

I. INTRODUCTION

In the last decade the attention on environment friendly solutions has increased drastically. It is estimated that information and communication technologies (ICT) is accountable for around 10 percent of world wide carbon emissions [1]. Worldwide, the growth rate of the Internet users is about 20 percent per year. Thus, ICT is being regarded as a solution with the potential to eliminate about 15 percent of the global carbon footprint [2].

To this extent, networking devices like IP routers consume the largest majority of energy [3]. Therefore, it is not surprising that researchers, manufacturers, and network providers are spending significant efforts to reduce the power consumption of ICT systems from different perspectives [4] [5] [6] [7] [8] [9].

As indicated in a study conducted by the U.S. Department of Energy [10], the current network elements and telecommunication networks are not designed with energy optimization as an objective or a constraint. They are often designed for peak traffic for reasons such as accommodating future growth, planned maintenance or unexpected failures, or quality-of-service guarantees. One opportunity to reap significant potential saving in data networking is achieving proportionality [11]. Proportionality refers to a goal in which the power consumption by a network element is in proportion to the carried traffic load.

Many methods for avoiding waste and improving energy efficiency are being developed. First efforts towards green networking can be traced back to the papers by Gupta and Singh [4] and Christensen et al. [5], but during the last three years the interest has increased tremendously [6] [7]. In the former research, the authors reduce the overall power consumption of a network by shutting off device [9]. And in [8], the authors solve the same problem with load balancing consideration.

However, the energy saving object shall affect both the offered QoS and the network robustness. And, the greedy switch-off approaches considered so far tend to leave little space to redundancy, and even less means to control the redundancy level. The lack of redundancy in the network will result larger transmission delay [12]. In this paper, we aim at controlling the whole network to reduce the total power consumption, so as to find the minimum set of devices that must be used to meet the actual traffic demand and QoS constraints in terms of delay.

The paper is organized as follows. The mathematical formulation of the problem is introduced in Section II.The proposed heuristic approaches are in Section III. The description of the topology used for performance assessment is presented in Section IV. And evaluation results are in Section V. Finally, conclusions are presented in Section VI

II. MATHEMATICAL MODEL FORMULATION

We consider an ISP network, where access nodes are capable of aggregating users' traffic. And we assume that the power consumption of the device is independent from the traffic load, since previous research has shown that the energy consumption of idle device has little difference from the full-speed device [6]. Therefore, a constant

---

Manuscript received August 10, 2011; revised January 2, 2012; accepted April 16, 2012.

This work is partially supported by the National High Technology Research and Development Program ("863" Program) of China under Grant 2011AA010701 and 2011AA01A101, National Natural Science Foundation of China Project under Grant 61102049, 60903150 and 61100219 and National Key Technology R&D Program under Grant 2012BAH06B01.

doi: 10.12720/jcm.8.1.66-72

amount of power is consumed when the device is working and no power is consumed when the device is off. In this section, we first introduce the QoS model in terms of end-to-end delay performance we used in the paper. And then we present the mathematical formulation for the QoS aware energy efficient model.

A. Link Cost Definition

The end-to-end delay on the heavy traffic links has to be an important constraint to the energy saving. Because, as we shut down the devices and links in the topology, the traffic demands do not change. So, the devices and links still powered on have to route more traffic. The more devices and links we powered off, the heavier traffic the residual devices have to carry.

One of the performance indicators of routing is the average packet delay, which is the average time that a packet spends in the network. We model the undirected graph $G = (V, E)$, where V is the set of vertices and E is the set of edges. Vertices represent network nodes and edges represent network links. Let PL_{ij} be the power consumption of link from i to j, and PN_i be the power consumption of node i. Let c_{ij} be the capacity of link from node i to node j. Let $\alpha \in (0, 1)$ be the maximum link utilization constraint and β controls the relative cost of delay. Let t^{sd} be the traffic demand from node s to node d, $s, d \in V$. Let f_{ij}^{sd} denote the amount of traffic from s to d which is routed through the link from i to j, and let f_{ij} be the total amount of traffic flowing on the link from i to j.

The average packet delay is usually measured using the Kleinrock delay function [12] given by

$$\Phi = \frac{1}{\gamma} \sum_{(i,j)\in E, i<j} \frac{f_{ij}}{\lambda c_{ij} - f_{ij}} \tag{1}$$

where $1/\lambda$ is the average packet length (bpp), and γ denotes the total number of the packets in the network,*i.e.*, $\gamma = \sum_{s\in V} \sum_{d\in V} f^{sd}$ The derivation of Eq. (1) is based on several assumptions packet arrivals are Poisson distributed, packet sizes are exponentially distributed, there is infinite buffer capacity, and the first-come first-served rule is used at nodes to route packets. Therefore, Eq. (1) is only an approximation to the actual packet delay of a network. However, it has been found that even though Φ is quite different from the actual packet de lay, minimizing it in the design process,or during routing, will lead to good network performance in implementation [13]. Therefore, Eq. (1) has been extensively used in the literature as a measure of network performance.

B. Non-linear Programming Model

We define that P_{tot} is the total power consumption of the network, Φ is the total delay cost of the network, and C_{tot} is the total cost of the network.

Let $x_{ij} \in \{0, 1\}$, $i, j \in V$ be binary decision variables that take the value of 1 if the link (i, j) is powered on, 0 otherwise. Similarly, let $y_i \in \{0, 1\}$, $i \in V$ be binary decision variables that take the value of 1 if node i is powered on, 0 otherwise.

Given the previous definitions, we provide the optimization problem formulation as follow:

$Minimize$:

$$C_{tot} = P_{tot} + \beta\Phi \tag{2}$$

$Subject\ to$:

$$P_{tot} = \sum_{i\in V}\sum_{j\in V} x_{ij} PL_{ij} + \sum_{i\in V} y_i PN_i \tag{3}$$

$$\Phi = \frac{1}{\gamma} \sum_{(i,j)\in E, i<j} \frac{f_{ij}}{\lambda c_{ij} - f_{ij}} \tag{4}$$

$$\sum_{j\in V} f_{ij}^{sd} - \sum_{j\in V} f_{ji}^{sd} = \begin{cases} t^{sd}, & \text{for } \forall s, d, i = s \\ -t^{sd}, & \text{for } \forall s, d, i = d \\ 0, & \text{for } \forall s, d, i \neq s, d \end{cases} \tag{5}$$

$$f_{ij} = \sum_{s\in V}\sum_{d\in V} f_{ij}^{sd} \qquad \forall i, j \tag{6}$$

$$f_{ij} \leq \alpha c_{ij} x_{ij} \qquad \forall i, j \tag{7}$$

$$\sum_{j\in V} x_{ij} + \sum_{j\in V} x_{ji} \leq M y_i \qquad \forall i \tag{8}$$

Equation (2) minimizes the total cost of the network. Equation (3) states the total power consumption of the network and Equation (4) states the sum of delay cost in the network which is a non-linear constraint in this model as we mentioned above. Equation (5) states the classical flow conservation constraints, according to which traffic flows are routed using Kirchhoff Laws, so that several paths can be used to transport traffic from a source until the destination node is reached. Equation (6) evaluates the total flow routed on each link. Constraint (7) constrains the link load to be smaller than the maximum link utilization α. Constraint (8) states that a node can be turned off only if all incoming and outgoing links are actually turned off. The big-M method is used to force this constraint, taking $M \geq 2N$.

The presented formulation falls in the class of capacitated multicommodity minimum-cost flow problems (CMCF) [14], i.e., the problems in which multiple commodities have to be routed over a graph with capacity constraints. CMCF problems are known to be NP-hard, and therefore finding the optimal solution becomes impractical even for small networks.

III. HEURISTIC APPROACH

Given the NP-hard formulations presented, finding the optimal solution is extremely difficult, especially for large number of nodes. Therefore, a heuristic approach has to be adopted if the problem size is too large.

The heuristics start by considering a network in which all elements are powered on, hence for every existing link and device in the considered topology $x_{ij} = 1$, and $y_i = 1 \quad \forall i, j$. Then, the algorithm checks iteratively if a given element (either a node or a link) can be turned off.

In our simulations, we use shortest-path algorithm to route the traffic flow and each link weight in the topology equals to 1. At each iteration, the chosen element is removed from the topology, and traffic is rerouted on the residual topology. After rerouting, if flow constraint (5) and utilization constraint (7) are still fulfilled, then power off the chosen element. If not, power on the element again.

The energy saving achieved by turning off nodes is higher than by switching off single links [15], and switching off a node is more difficult than switching off a single link. This suggests that the algorithm should try to turn off nodes first then links. On the other hand, we try to power off core nodes first then metro nodes, since core nodes consume more power than metro nodes. In the synthetic topology, the core nodes connect peering routers of other ISPs, at least one core node has to power on, so that users in this ISP can access to the resource in other ISPs. At last we get a subset of links turning on and we can calculate the cost of the network. Algorithm 1 reports a description of the heuristics.

Algorithm 1 Pseudocode Description of the Proposed Heuristics

```
$\%$ node optimization
$sort\_node(nodes);$        $\%core\ then\ metro$
for $(i = 1; i \le N; i++)$ do
    $disable\_node(node[i]);$
    $paths = compute\_all\_shortest\_path();$
    $compute\_all\_link\_flow(paths);$
    $\%compute\ traffic\ flows\ on\ each\ link$
    if $check\_paths(paths) == false$ then
        $enable\_node(node[i]);$
        $continue;$
    end if
    if $check\_flow(paths) == false$ then
        $enable\_node(node[i]);$
        $continue;$
    end if
end for
$\%$ link optimization
$sort\_link(links);$        $\%least\ flow\ then\ more\ flow$
for $(j = 1; j \le N; j++)$ do
    $disable\_link(link[j]);$
    $paths = compute\_all\_shortest\_path();$
    $compute\_all\_link\_flow(paths);$
    $\%compute\ traffic\ flows\ on\ each\ link$
    if $check\_paths(paths) == false$ then
        $enable\_link(link[j]);$
        $continue;$
    end if
    if $check\_flow(paths) == false$ then
        $enable\_link(link[j]);$
        $continue;$
    end if
end for
```

In addition, the route we choose from source to destination has to be a valley-free route, that is, after traversing a core-metro link, a package cannot traverse a metro-core link. In the FT network depicted in Figure 2, for ,instance, this rule will insure that access nodes (the green ones) are not used to forward traffic between core routers (the blue ones). In this way, the package can be routed to the destination just like in the real network.

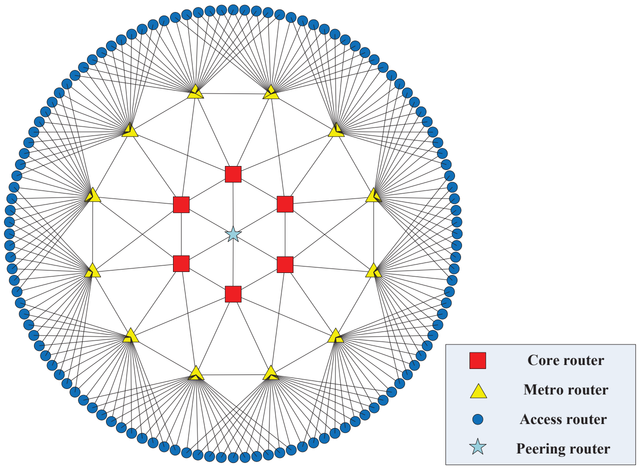

Figure 1. The synthetic topology

IV. SIMULATION ENVIRONMENTS

A. Synthetic Topology

Considering an ISP network, we assume a random hierarchical topology. We design the synthetic topology according to the synthetic topology in [9] which is similar with the real ISP topology. In the topology, all links are supposed to be bidirectional, so that if link (i, j) exists, then link (j, i) exists as well. We power off as many network elements as possible to maximize the power saving, while we guarantee the full connectivity between traffic sources and destinations under the constraint of a link utilization threshold. There are three hierarchies in the topology as depicted in Figure 1.

The core level is composed by “core nodes”and “core links”. The core nodes connect to each other with the core links randomly. The core links also connect the core nodes and a peering router of other ISPs, the link capacity of core links is 50 Gb/s.

The metro level is composed by “metro nodes”and “metro nodes”. The metro nodes connect to core nodes by metro links, whose capacity is 20 Gb/s. Each metro node connects to the other two metro nodes nearby, and connects to the two closest core nodes.

The access level is composed by “access nodes”and “access nodes”. The access nodes connect to metro nodes by access links, whose capacity is 10 Gb/s. Each access node is multi-homed. It connects to the closest pair of metro nodes in order to guarantee the robustness of network when the unpredicted failure happens. The capacity of links we assumed in each hierarchy is according to the measurement in real topology [9].

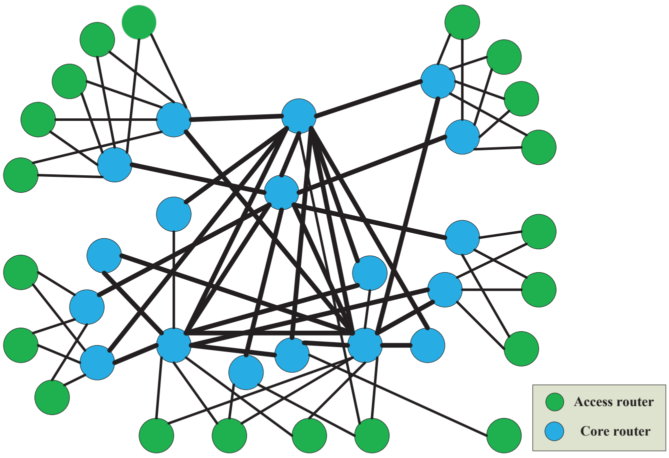

Figure 2. The FT topology

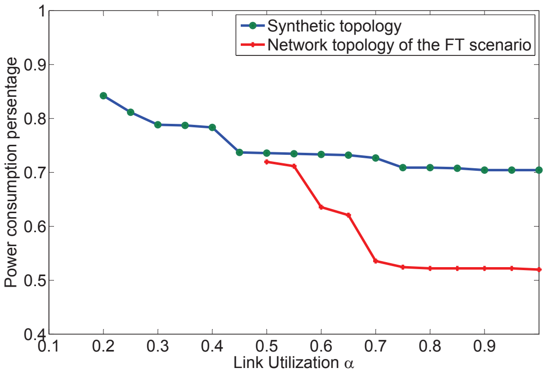

Figure 3. Power consumption versus α

TABLE I.
POWER CONSUMPTION

Device Type	Power Consumption	Fraction of Power
Core Nodes	10 kW	5.48%
Metro Nodes	1 kW	3.66%
Access Nodes	2 kW	37.9%
Links [average]	0.6 kW	41.94%

B. *Real topology **FT***

The FT scenario represent an actual backbone IP network of France Telecom, whose topology is composed by 38 nodes and 72 bidirectional links ,as shown in Figure 2. In the FT network depicted in Figure 2, the core nodes are blue at the center of the figure ,while the access nodes are green at the edge around the core nodes.

We assume the capacity of the core links is 50Gb/s and the capacity of the access links is 20Gb/s in the FT topology.

C. *Power Consumption*

To model the energy consumption of routers and links, we consider the power requirements of actual devices [9]. We ignore air conditioning costs, which can almost double the total power consumption. Table I shows the power consumption of different classes of nodes and the corresponding fraction of power over the total network power consumption.

Let N_c, N_m, and N_a be the number of core nodes, metro nodes, and access nodes. According to the previous research [16], the access network consume 70-80% of the overall energy going into powering wired networks in the Internet. In our synthetic topology, we choose $N_c = 6$, $N_m = 12$, $N_a = 120$. In this way, the access network consumes 79.5% of the total power that the network consumed.

As shown in the Figure 1, the synthetic network topology is composed by 138 routers: 6 core nodes, 12 metro nodes, 120 access nodes. The number of links equals to 285. The total power consumption of the network is 483 kW according to the Table I.On the other hand, the FT network is composed of 18 access nodes, 20 core nodes and 72 links. The total power consumption is 263.2kW.

D. *Traffic Matrix*

In all simulations, we assume that access nodes are sources and sinks of traffic, and other transit nodes are neither sources nor destinations of information. They only route the traffic from the access nodes. According to the previous research [17], the authors observe a very low average utilization throughout the day that does not exceed 9% even during the peak hour. On the other hand, the backbone link utilization is up to 30-50% typically. So, in the synthetic topology we suppose that each access node sets up 5 communication sessions with other 5 different access nodes randomly. The traffic flow of each session is uniformly distributed in the region [0.05, 0.15]. In this way, the average traffic load on each access link is 1 Gb/s and the average link utilization is 10%, a little bigger than the link utilization rate in the Internet. In FT topology, the each access node also sets up 5 communication sessions with other 5 different access nodes randomly. And the traffic flow of each session is uniformly distributed in the region [0,1]. In this way ,the average traffic load on each access link is 5 Gb/s.

V. PERFORMANCE EVALUATION

A. *Evaluation Results*

In this section, we evaluate the power saving effort and the impact on network performance. We performed a study on the impact of the α parameter, in order to observe the possible range of network elements that can be successfully switched off while guaranteeing a maximum offered load on links.

Figure 3 reports the number of links switched off for $\alpha \in [0.2, 1]$ in the considered scenario. In Figure 3, it shows that in the synthetic topology power consumption decreases for α up to 0.9; after that, little improvement is noticeable. The power consumption percentage of network decreases from 84.2% to 70.4%. In the FT topology, the power consumption percentage of network decreases from 75.2% to 47.7% .The fact is due to when α is

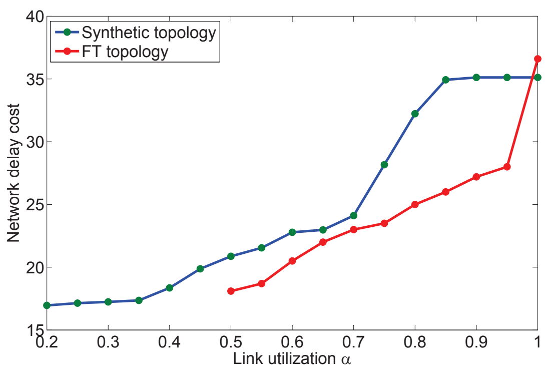

Figure 4. Network delay cost versus α

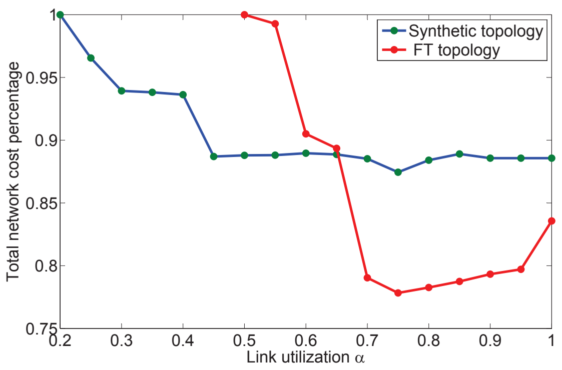

Figure 5. Total network cost versus α

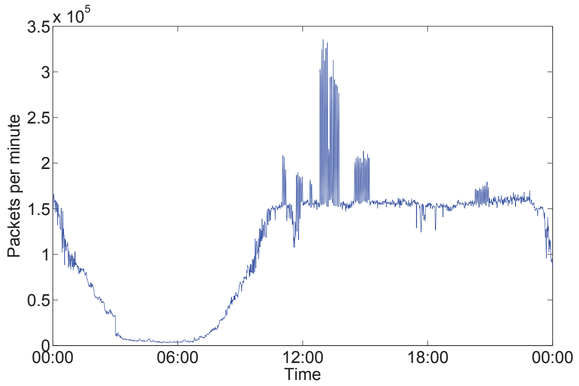

Figure 6. One day trace of campus

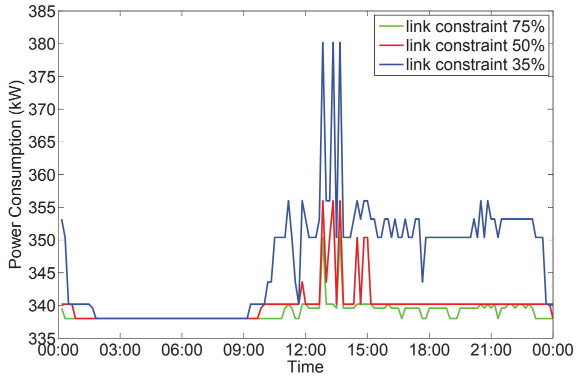

Figure 7. Power consumption in one day under different link utilization constraints in synthetic topology

higher, more nodes and links can actually be switched off. When α is more than 0.9, many elements in the network are powered off, the topology gets close to $minimum\ Steiner\ Tree$, so little element in network can be shut down. The figure is a stepwise curve, because when a router is switched off, it will take great improvement in power saving. On the other hand, when a link is powered off, the improvement is relatively small.

Figure 4 shows variation of the sum of link cost for increasing values of α. In the synthetic topology, the link cost increases from 17.0 to 35.1. On the other hand, in the FT topology, the link cost increases from 16.9 to 35. In Figure 4, it shows that the cost of the network increases with the parameter α.

Figure 5 shows in both topologies the total network cost considering power consumption and network delay when β equals to 1. In this case, the total cost decreases when α increases to 0.75 and, after that, the cost increases and gets steady as α increases.

We collected traces of the traffic from and to our campus, Beijing JiaoTong University (BJTU), network during the day of Oct. 12, 2008. Our campus network counts about 40,000 users and there are over thirteen thousand active users/day. Figure 6 shows the outbound traffic of the Beijing JiaoTong University campus network. We use the traces as the traffic matrix of each access node in the topology. We can get the power consumptions under different link utilization constraints in Figure 7 and Figure 8. We can get the same maximum power saving at early morning under different link constraints, because the topology can become a Steiner tree topology. Moreover, we can see the power consumption increasing as the traffic increases during the day. The figures also show that in the synthetic topology the model reduces the power consumption more significantly for higher traffic demands compared to lower traffic demands at day time.

In the Figure 7, when we set the link utilization 75%, we can reduce the network energy consumption by a maximum of 7% (average of 2%) compared with the situation when the link utilization is set to 50%. The result in Figure 7 shows that optimizing link utilization for each link saves up to 30.3% of the network total energy consumption.

In Figure 8, when the link utilization is 75%, we can reduce 7% of the network energy consumption compared with the situation when the link utilization is set to 50%. We can save up to 52.2% of the network energy consumption.

The total cost gets the minimum when α equals to 0.75. At the same time, we can get a better trade off between energy saving and QoS.

B. The Effect of β

In this section, we discuss the impact of parameter β. β which is a constant and independent from α controls the

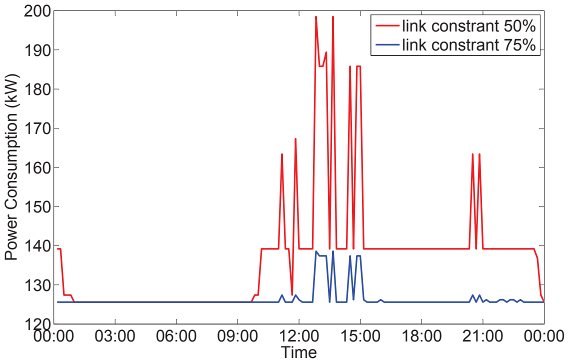

Figure 8. Power consumption in one day under different link utilization constraints in FT topology

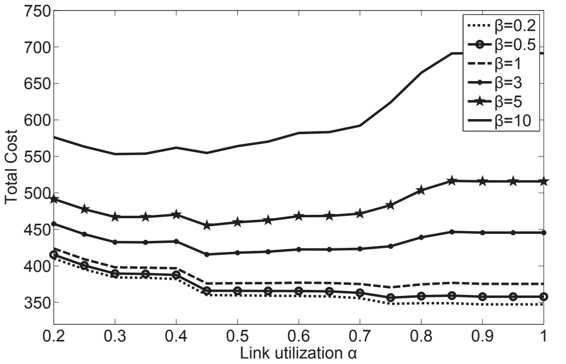

Figure 9. Total network cost versus α when β has different values

relative cost of delay. Larger values of β lead to smaller values of α_{min}, the maximum link utilization constraint when the minimum of cost happens.In Figure 9, we show the impact of parameter β.

As β is bigger, the weight of delay cost gets bigger. When the network is sensitive to delay, β can be set to a bigger value, so that the network can guarantee the delay of service. On the other hand, for the network not sensitive to delay, we can set β to be a smaller constant. In this way, we can get more power saving.

VI. CONCLUSIONS

In this paper, we have solved the problem of reducing the power consumption of networks with strict QoS constraints. We have proposed to find the minimal set of routers and links considering a minimum cost routing problem where cost function is comprised of the power consumption and delay cost of a network.

We propose a simple heuristic to resolve the multi-commodity flow problem. And we further evaluate the optimization on a synthetic topology which is close to real topology in terms of power and traffic model and we use one day trace of a campus network to evaluate the power saving. Results have shown the increasing of link utilization will lead to more power saving but larger network delay. And we obtained an optimized link utilization minimized the total cost of network considering power consumption and delay cost of the network when the utilization is 75%. And we could get 2.7% more power saving in the whole network than when the link utilization is 50%. In addition, the results have shown the situation when the changes of the minimum value of power and delay cost caused by the relative cost parameter β, which indicates how QoS constraint influences energy saving strategy.

Our future work is to extend the model to consider the robustness of the network, in which the network performance is not influenced by unpredicted fail when a lot of devices are powered off.

ACKNOWLEDGMENT

The authors are grateful to the anonymous referees for their valuable comments and suggestions to improve the presentation of this paper.

REFERENCES

[1] M. Pickavet, W. Vereecken, S. Demeyer, P. Audenaert, B. Vermeulen, C. Develder, D. Colle, B. Dhoedt, and P. Demeester, "Worldwide energy needs for ict: The rise of power-aware networking," in *Advanced Networks and Telecommunication Systems, 2008. ANTS'08. 2nd International Symposium on*. IEEE, 2008, pp. 1–3.

[2] M. Webb, "Smart 2020: Enabling the low carbon economy in the information age," *The Climate Group London*, 2008.

[3] R. Tucker, J. Baliga, R. Ayre, K. Hinton, and W. Sorin, "Energy consumption in IP networks," in *Optical Communication, 2008. ECOC 2008. 34th European Conference on*. IEEE, 2008, pp. 1–1.

[4] M. Gupta and S. Singh, "Greening of the internet," in *Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications*, ser. SIGCOMM '03. New York, NY, USA: ACM, 2003, pp. 19–26. [Online]. Available: http://doi.acm.org/10.1145/863955.863959

[5] K. Christensen, B. Nordman, and R. Brown, "Power management in networked devices," *Computer*, vol. 37, no. 8, pp. 91 – 93, Aug. 2004.

[6] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright, "Power awareness in network design and routing," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, Apr. 2008, pp. 457 – 465.

[7] W. Fisher, M. Suchara, and J. Rexford, "Greening backbone networks: reducing energy consumption by shutting off cables in bundled links," in *Proceedings of the first ACM SIGCOMM workshop on Green networking*, ser. Green Networking '10. New York, NY, USA: ACM, 2010, pp. 29–34. [Online]. Available: http://doi.acm.org/10.1145/1851290.1851297

[8] M. Zhang, C. Yi, B. Liu, and B. Zhang, "GreenTE: Power-aware traffic engineering," in *Network Protocols (ICNP), 2010 18th IEEE International Conference on*, Oct. 2010, pp. 21 –30.

[9] L. Chiaraviglio, M. Mellia, and F. Neri, "Minimizing ISP Network Energy Cost: Formulation and Solutions," *Networking, IEEE/ACM Transactions on*, vol. 20, no. 2, pp. 463 –476, Apr. 2012.

[10] "Proc. vision roadmap workshop routing telecom data centerstoward efficient energy use," Sunnyvale, CA, Oct. 2008 Oct. 2008. [Online]. Available: http://www1.eere.energy.gov/industry/datacenters/pdfs/vision_and_roadmap.pdf

[11] L. Barroso and U. Holzle, “The case for energy-proportional computing,” *Computer*, vol. 40, no. 12, pp. 33 –37, dec. 2007.

[12] A. Konak and A. Smith, “Capacitated network design considering survivability: an evolutionary approach,” *Engineering Optimization*, vol. 36, no. 2, pp. 189–205, 2004.

[13] J. F. Hayes, *Modeling and Analysis of Computer Communications Networks*. Perseus Publishing, 1984.

[14] I. Ghamlouche, T. Crainic, and M. Gendreau, “Cycle-based neighbourhoods for fixed-charge capacitated multicommodity network design,” *Operations Research*, pp. 655–667, 2003.

[15] C. Gunaratne, K. Christensen, and B. Nordman, “Managing energy consumption costs in desktop PCs and LAN switches with proxying, split TCP connections, and scaling of link speed,” *International Journal of Network Management*, vol. 15, no. 5, pp. 297–310, 2005.

[16] R. Bolla, F. Davoli, R. Bruschi, K. Christensen, F. Cucchietti, and S. Singh, “The potential impact of green technologies in next-generation wireline networks: Is there room for energy saving optimization?” *Communications Magazine, IEEE*, vol. 49, no. 8, pp. 80 –86, Aug. 2011.

[17] E. Goma, M. Canini, A. Lopez Toledo, N. Laoutaris, D. Kostić, P. Rodriguez, R. Stanojević, and P. Yagüe Valentin, “Insomnia in the Access: or how to curb access network related energy consumption,” in *Proceedings of the ACM SIGCOMM 2011 conference on SIGCOMM*. ACM, 2011, pp. 338–349.

Shijia Zhu rreceived the B.S. degree in communication engineering in Beijing Jiaotong University, Beijing, China, in 2007. He received the M.S. degree in circuit and system in Beijing Jiaotong University, Beijing, China, in 2009. He is now a PhD candidate in National Engineering Laboratory for Next Generation Internet, Beijing Jiaotong University, Beijing, China. His research interests are green networking, traffic engineering, and routing protocols for next generation networks.

Yujing Zeng received the B.S. degree in telecommunication engineering from Beijing Jiaotong University(BJTU), Beijing, China, in 2009. He has been working on his PhD in communication and information systems in the National Engineering Laboratory for Next Generation Internet Interconnection Devices, BJTU since 2009. His research focuses on the fundamental theoretical issues in the design of content delivery and caching network.

Hongke Zhang received the M.S. and Ph.D. degrees in electrical and communication systems from the University of Electronic Science and Technology of China, Chengdu, China, in 1988 and 1992, respectively.

From September 1992 to June 1994, he was a Post-Doctoral Research Associate with Beijing Jiaotong University (BJTU), Beijing, China. In July 1994, he joined BJTU, where he is currently a Professor with the School of Electronic and Information Engineering. He is also the Chief Scientist of the National Basic Research Program of China. He has published more than 100 research papers in communications, computer networks, and information theory. He is the author of eight books written in Chinese.

Dr. Zhang was the recipient of various awards, including the 2001 Zhan Tianyou Science and Technology Improvement Award, the 2003 Mao YishengScience and Technology Improvement Award, the 2005 First Class Science and Technology Improvement Award of the Beijing Government.