RLA-ENAR: A Realistic Near-Optimal Energy-Aware Routing

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***Abstract*—Energy consumption is an important issue due to its environmental and economic effects; hence, recently there is significant effort to reduce energy consumption in all areas including computer networks, which is realized by the Green Networking concept. As an approach of green networking, some energy-aware routing algorithms have already been proposed in the literature. However, most on them are based on artificial power models and cannot reach the optimal performance because of the NP-Hardness of the problem. In this paper, by analyzing a *realistic power model*, we propose a two-phase routing algorithm to minimize network power consumption while satisfying a set of given traffic demands. The second contribution is the near-optimal performance of the algorithm. Simulation results in a real network topology and practical power consumption parameter settings, show that the algorithm achieves 40% energy saving in comparison with OSPF-TE and 18% in comparison with OSPF-EC. Comparing the result with the optimal solution which is obtained by an Integer Linear Programming model shows that the proposed algorithm gives near optimal solution.**

I. INTRODUCTION

Energy conservation has become a key issue in recent years since it has economic effects on industries and environmental concerns for the whole world [1]. Due to its fast growth, Information and Communication Technology (ICT) sector shows great increase in its energy footprint [2]. ICT sector constitutes 2% of total Green House Gases (GHG) production [3]. In fact, each 1 TeraWatt Hour (TWH) of energy consumption generates 0.75 million tons of CO_2 [3]. This volume of GHG shows how energy consumption has impact on environment. In addition to environmental effects, the ICT sector has large economical impact as it consumes 2% to 10% of total energy consumption [4]. Thus, energy reduction would cause less operational costs and GHG emission.

Green networking is a concept denoting a way to reduce energy consumption of network whereas maintaining the same level of performance [1]. There are some approaches to reach a green network. Energy aware routing is one of them which aims at aggregating traffic flows over a subset of the network devices and links, allowing other links and interconnection devices to be switched off [1]. These solutions should not violate QoS parameters, for example by limiting the maximum link utilization. The flow aggregation methods cause fewer nodes to be turned on which means less energy consumption. Formally, energy aware routing is a particular instance of the general capacitated multi-commodity flow problem [5], which was proven that these kinds of problems are NP-hard [6]; thus, typically offline heuristic solutions are proposed for them. In this problem, the power model plays an important role since it determines the equipment that the energy aware routing should try to keep them in sleep mode.

Energy aware routing was introduced for the first time in [7] where the authors tried to reduce energy consumption by setting the network equipments and their components to sleep mode. They assumed ON-OFF power model in their proposed algorithms. In this model, the devices consume fixed constant power while turning on, and consume no energy in the case of being asleep. In [8], Garroppo et al. assumed each link is consist of some sublinks which can be set to sleep in low traffic. They also supposed the ON-OFF power model for each sublink, and gave a heuristic algorithm to route the demands. Later, some other works like [9] and [10] used rate dependent power model which has a rate-independent fixed constant part and a rate-dependent part. The rate-dependency can be linear [9] or exponential [10].

Recently, Vishwanath et.al, showed that power consumption of network equipments depends on packet length in addition to the flow rate over them [11]. Similar to rate dependent models, power consumption of a network equipment is composed of a constant traffic-independent part and a rate-dependent part. However, in this model, the rate-dependent part is influenced by packet length because of power consumption for storing and forwarding packets [11].

This paper propose an energy aware routing algorithm using the power model introduced by [11]. To the best of the authors' knowledge, this is the first time that the mentioned power model is used in green routing. Analyzing the power model for real routers and switches shows that the main power consumption of the device is due to the constant traffic-independent part in the case of low demand rate. Hence, the routing algorithm tries to use turned on devices rather than using turned off devices. This approach will result in more energy saving while the links are underutilized. Using Abilene research network, energy consumption and link utilization of the proposed routing algorithm is evaluated. Results show that the algorithm has more than 40% energy saving in comparison with OSPF-TE and 18% in comparison with OSPF-EC, while the network is underutilized and average link utilization is under 20%. The routing problem is also formulated as an Integer Linear Programming (ILP). Comparison with the optimal solution shows that the proposed heuristic routing algorithm gives near optimal solution. In summary, the main contributions of the paper are as follows:

- By analyzing the realistic power model, a two-phase heuristic routing algorithm is proposed. The first phase is based on the traffic-independent part of the power model while the second phase emphasizes the dependency of power consumption on flow-rate and packet length.
- The proposed heuristic algorithm gives near optimal solution in significantly less time. According to NP-hardness of the optimization problem, it cannot be solved in polynomial time, whereas the order of the heuristic algorithm is polynomial.

The remainder of this paper is organized as follows: Section II describes the system model and formulates the energy aware routing problem as ILP optimization model. In Section III, the details of the heuristic routing algorithm is discussed. The numerical results and analysis of energy saving and link utilization of the proposed algorithm are described in Section IV. Finally, Section V summarizes the paper and discusses future works.

II. System Model and Problem Formulation

It is assumed that the network is modeled as a directed graph $G(V,E)$ and a set of traffic demands D which is fed into it. The architecture of the network is differentiated service, i.e. each demand i requests a class of service w_i with b_i units of bandwidth from a source node s_i to a destination node t_i. Statistics show that different class of service e.g. VoIP or Web, has different average packet length [12] [13]. According to the power model, this variance will cause different energy consumption per class of service; hence, we consider the average packet length of demand i by L_i in this model. Besides, the nodes in G are heterogeneous, i.e. the parameter of power model is different for each node $u \in V$. Furthermore, link capacity is limited to $C_{(u,v)}$. The function $p(u)$ shows total energy consumption of node u. It is assumed that whole traffic of each demand is routed through a single path.

In the problem considered in this paper, the target is to route all demands in D in order to minimize total energy consumption of the network according to the power model.

A. Power Model

In this paper, the rate-length dependent power model introduced by Vishwanath et.al [11] is used. According to this power model, the power profile of network equipment depends on the flow rate and the packet-length of a demand. Formally, the power consumption is

$$p(R,L) = p_{\text{idle}} + R\Big(\frac{E_p}{L} + E_{\text{s\&f}}\Big), \tag{1}$$

where, p_{idle} is startup power of the node, R is total load on the node, E_p is packet processing energy, $E_{\text{s\&f}}$ is store and forward energy, L is average packet length.

B. Problem Formulation

In this section, the problem is formulated as ILP optimization model based on the aforementioned assumption and using the power model introduced by [11]. The notations used in the formulation are explained in the Table I.

TABLE I
NOTATION USED IN THE FORMULATION

Notation	Description
$f(u,v)$	Total load on link (u,v)
$x_{i,(u,v)}$	Binary variable which is 1 if demand i is routed on link (u,v)
$l(u,v)$	Binary variable which is 1 if the link (u,v) is ON
$n(u)$	Binary variable which is 1 if the node u is ON
$r(u,i)$	Binary variable which is 1 if the demand i is routed from node u
$padp(u,i)$	Adaptive power of node u consumed by demand i
$p(u)$	Total power consumption of node u

The objective function of the problem is to minimize network's total power consumption. Therefore, the formulation will be as following:

objective function:

$$min \sum_{u \in V} p(u) \tag{2}$$

This minimization is subject to some constraints which are as following:

define traffic flow on each link (u,v):

$$f(u,v) = \sum_{i \in D} x_{i,(u,v)} b_i \tag{3}$$

capacity constraint for each link (u,v):

$$f(u,v) \leq c(u,v) \tag{4}$$

turn on link (u,v) if there is flow on it:

$$f(u,v) \leq M_1 \times l(u,v) \tag{5}$$

turn on node u if one of it's link (u,v) is turned on:

$$l(u,v) \leq n(u) \tag{6}$$

turn on node u if one of it's link (v,u) is turned on:

$$l(v,u) \leq n(u) \tag{7}$$

define $r(u,i)$:

$$x_{i,(u,v)} \leq r(u,i) \tag{8}$$

define adaptive power of node u consumed by demand i:

$$padp(u,i) = r(u,i) \times b_i \times \Big(\frac{E_p(u)}{L_i} + E_{\text{s\&f}}(u)\Big) \tag{9}$$

define total power of node u:

$$p(u) = n(u) \times pidle(u) + \sum_{i \in D} padp(u,i) \tag{10}$$

routing binary variables:

$$n(u) \in \{0,1\} \qquad \forall (u) \in V \tag{11}$$

$$l(u,v) \in \{0,1\} \qquad \forall (u,v) \in E \tag{12}$$

$$x_{i,(u,v)} \in \{0,1\} \qquad \forall (u,v) \in E, \forall i \in D \tag{13}$$

$$x_{i,(u,v)} : flow\ conservation \tag{14}$$

flow conservation means that traffic is only eliminated in destination nodes and produced in source nodes.

Whereas solving this model provides the optimal solution of the problem, it was proven that optimization model for energy-aware routing problem is NP-hard [6] [14]. So that, since solving the problem is time-consuming for large networks, heuristic algorithms with near optimal performance is valuable which is proposed in the following section.

III. Routing Algorithm

In this section, by analyzing the power model, we propose a near optimal single-path energy-aware routing algorithm. To the best of the authors' knowledge, this is the first time that bandwidth and packet length are used as two factors for routing, whereas, former works used only bandwidth. The algorithm is called Rate-Length Adaptive Energy-Aware Routing (RLA-ENAR).

According to the study performed in [11] using real network devices, it is known that equipment energy consumption is mainly depends on start-up power of network nodes. So, firstly, it is important to wisely choose minimum number of nodes to route all demands. To involve this fact, RLA-ENAR contains two phase: preprocessing and main.

A. Preprocessing Phase

In the preprocessing phase, the goal is to organize the demands, so that, a good anticipation about the ON nodes and the OFF nodes can be obtained. For this purpose, the following definition is used.

Definition 1: Minimum number of nodes between source and destination of a demand is called ***distance***.

Demands with lower distance have fewer minimum hop count routes to fulfill their required service and bandwidth, whereas, demands with higher distance have more. Moreover, demands with higher distance can choose nodes in the routes of demands with lower distance, hence, fewer nodes should be turned on. As a result, it is better to route demands with lower distance, as it has fewer options for energy efficient routing with lowest hop count. Therefore, the demands should be sorted ascending from the lowest distance to the highest. In fact, it implies that the demand with lowest distance should be routed first.

The importance of preprocessing phase can be clarified by an example. Suppose there is grid network (Fig. 1), and a demand set containing B-to-I and D-to-I is fed into the network. If there is no sorting, B-to-I should be routed first. There are 6 possible minimum hop count path for it: BACFI,BADFI,BADGI, BEHGI, BEDGI, and BEDFI. Randomly, a path is selected, e.g. BACFI. Then, D-to-I should be routed. It has two possible minimum hop count path: DFI and DGI. As BACFI is selected for B-to-I, it is better to choose DFI path for D-to-I rather than the other. The total number of turned on nodes will be 6. In the case of sorting, D-to-I has less distance than B-to-I, therefore, it should be routed first. Suppose, DFI is selected as the candidate path for the demand. Hence, it is better to select BADFI as the path for the demand B-to-I. In this case, the total number of turned on nodes will be 5. By comparing the two discussed cases, the second one use fewer nodes for routing rather than the first one. This shows the effect of sorting to energy reduction.

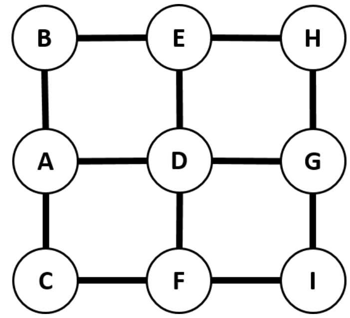

Fig. 1. A 3*3 grid network

B. Main Phase

In the main phase, routing of each demand is computed as the shortest path where the weight of each link is determined *per demand* according to the power model. For each demand in demands matrix, the power consumption of the link is anticipated from the rate-length adaptive power model described earlier. So, the anticipated power is used as weight w_l of the link l which is ended to the node v. According to the model, if the node is OFF, then:

$$w_l = p_{\text{idle}}(v) + R\Big(\frac{E_p(v)}{L} + E_{\text{s\&f}}(v)\Big) \tag{15}$$

and if the node is ON:

$$w_l = R\Big(\frac{E_p(v)}{L} + E_{\text{s\&f}}(v)\Big) \tag{16}$$

With the declared weight for the links, Dijkstra algorithm can be performed.

Pseudo code for RLA-ENAR is showed in Algorithm 1. In the proposed algorithm, the set PATH contains green path for each demand. Computational complexity of the preprocessing phase is $O(|D|\log(|D|))$, and $O(|V|^2)$ for routing of each demand in the main phase, which means $O(|D||V|^2)$ for the demand set D. This implies that:

$$O(RLA{-}ENAR) = O(|D|\log(|D|) + |D||V|^2) = O(|D||V|^2) \tag{17}$$

Algorithm 1 RLA-ENAR

Input: $G(V, E)$,$D(\{s, d, rate, L\})$
Output: The green path ($PATH$) for demand set D

procedure RLA–ENAR
  for each demand d in demand set D **do**
    $d.distance \leftarrow$ minHopCount($d.s$,$d.t$)
  sort(D) by distance
  for each demand d in demand set D **do**
    create set Q of nodes
    for each node v in V **do**
      $v.weight \leftarrow \infty$
      $v.prev \leftarrow null$
      $Q.add(v)$
    $d.s.weight \leftarrow 0$
    while $Q \neq \emptyset$ **do**
      sort(Q) by weight
      $u \leftarrow Q[0]$
      Q.remove(u)
      for each neighbor v of u **do**
        if v is turned on **then**
          $init \leftarrow v.idle$
        else
          $init \leftarrow 0$
        $estm\_pow \leftarrow init + d.rate(\frac{v.ep}{d.L} + v.esf)$
        if $v.weight + estm\_pow < v.weight$ **then**
          $v.weight \leftarrow v.weight + estm\_pow$
          $v.prev \leftarrow u$
    Create set P
    P.add($d.t$)
    $n \leftarrow d.t$
    while $n.prev \neq d.s$ **do**
      P.add($n.prev$)
      $n \leftarrow n.prev$
    P.add($d.s$)
    for each node n in P **do**
      $n.on \leftarrow true$
    $PATH$.add(P)

IV. Performance Evaluation

In this section, the results of the simulations are discussed in details. RLA-ENAR is implemented and compared with two versions of OSPF: OSPF-EC and OSPF-TE. The first one, assigns equal weights to each link, and the later, routes the demands on low congested links. The result of RLA-ENAR is also compared with the optimal solution, obtained from the ILP model, to find its efficiency.

A. Simulation Setup

The simulations are conducted on the Abilene Research Network, which consist of 10 nodes 13 bidirectional links. In each round of simulation, set D contains demands which are uniformly distributed among five classes of services; i.e., FTP, POP3, DNS, WWW, and VoIP respectively with average packet length 1050, 460, 120, 100, and 60 bytes [12] [13].

TABLE II
Power Profile for Different Devices [11]

Device	P_{idle}(W)	E_p $\frac{nJ}{pkt}$	$E_{S\&F}$ $\frac{nJ}{byte}$
Enterprise Ethernet Switch	36.2	40	0.28
Edge Ethernet Switch	631	1571	9.4
Metro IP Router	352	1375	14.4
Edge IP Router	576	1707	10.2

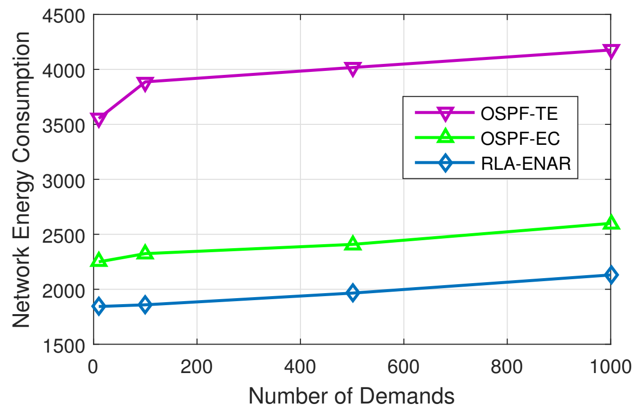

Fig. 2. Energy consumption of RLA-ENAR in comparison with OSPF-TE and OSPF-EC in Abilene reseach network

The simulation is done for 1000 times for each demand set to remove potential errors. Table II shows the power profile for each node (P_{idle},E_p, and $E_{s\&f}$), which is captured from [11].

B. Simulation Analysis

In this subsection, energy saving and average link utilization of RLA-ENAR are compared with OSPF-EC and OSPF-TE. Fig.2 and Fig.3 show the energy consumption and average link utilization of the algorithms. As is shown in the figures, RLA-ENAR has more than 40% energy saving in comparison with OSPF-TE, and 18% in comparison with OSPF-EC, in low network load. This gives enough evidence that significant energy saving can be obtained by green routing. Moreover, preprocessing phase of RLA-ENAR will turn off unnecessary network nodes, which leads to lower network energy consumption.

By increasing the demand count, i.e, highly loaded network condition, all of the network devices are turned on independent of the routing protocol in use. Therefore, all algorithms have almost the same performance which leads to small energy saving by RLA-ENAR in comparing to OSPF (Fig. 4).

The optimization problem is also solved with CPLEX solver to obtain the theoretical lower-bound on energy consumption. Fig.5 shows the comparison between RLA-ENAR and the optimal solution. It is clear from the figure that RLA-ENAR provides near optimal solution while it's running time is significantly lower than the ILP.

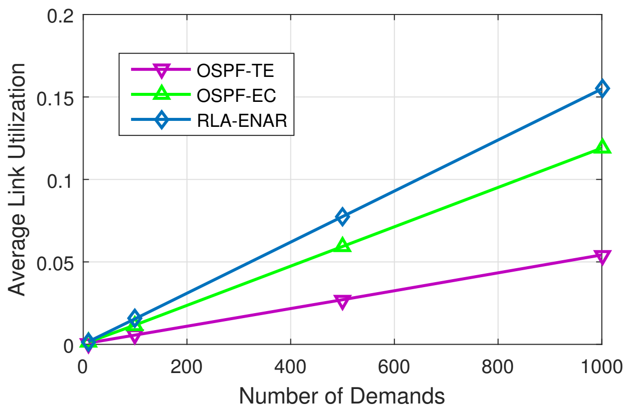

Fig. 3. Average link utilization of RLA-ENAR in comparison with OSPF-TE and OSPF-EC in Abilene reseach network

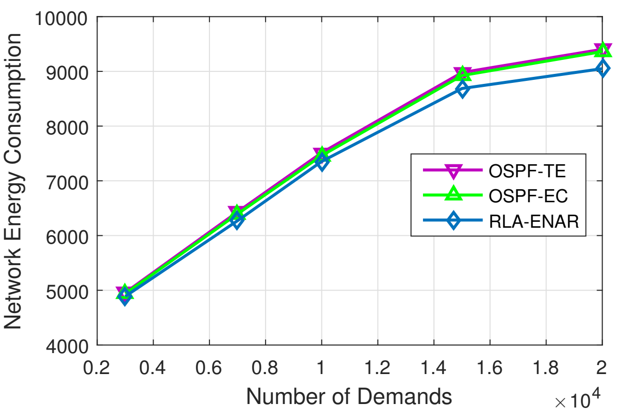

Fig. 4. Average energy consumption of RLA-ENAR in comparison with OSPF-TE and OSPF-EC in Abilene reseach network under high load

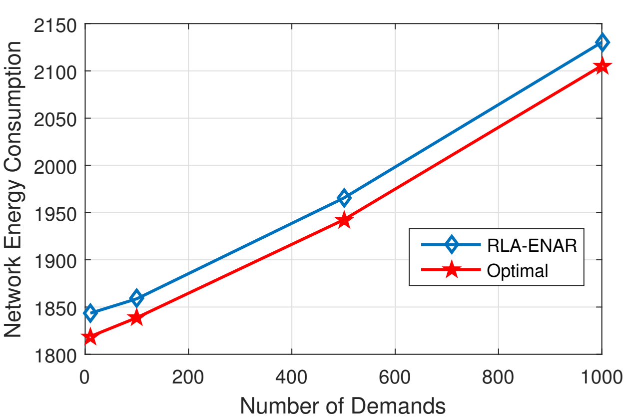

Fig. 5. Energy consumption of RLA-ENAR in comparison with the optimal solution in Abilene reseach network

V. Conclusion

In this paper, RLA-ENAR energy aware routing algorithm is introduced. It is based on realistic power model and has near optimal performance. It is composed of two phases. In the preprocessing phase, according to the traffic-independent part of the power model, demands are sorted according to their distance. In the main phase, they are routed through the minimum power consuming path. In low network load, RLA-ENAR has significant energy saving in comparison to OSPF-TE and OSPF-EC. Comparing RLA-ENAR to the lower bound obtained from ILP model, shows that the algorithm gives near optimal solution. In highly loaded networks, RLA-ENAR achieves little energy saving in comparison with OSPF. Improving the performance of the algorithm in this condition will be left open for future works.

References

[1] A. P. Bianzino, C. Chaudet, D. Rossi, and J.-L. Rougier, "A survey of green networking research," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 1, pp. 3–20, 2012.

[2] B. Addis, A. Capone, G. Carello, L. G. Gianoli, and B. Sansò, "Energy management in communication networks: a journey through modelling and optimization glasses," *CoRR*, vol. abs/1507.02636, 2015. [Online]. Available: http://arxiv.org/abs/1507.02636

[3] "Global action plan," 2011. [Online]. Available: http://globalactionplan.org.uk

[4] C. Lubritto, A. Petraglia, C. Vetromile, F. Caterina, A. DOnofrio, M. Logorelli, G. Marsico, and S. Curcuruto, "Telecommunication power systems: Energy saving, renewable sources and environmental monitoring," in *Telecommunications Energy Conference, 2008. INTELEC 2008. IEEE 30th International*, San Diego, CA, 2008, pp. 1–4.

[5] L. Chiaraviglio, M. Mellia, and F. Neri, "Reducing power consumption in backbone networks," in *IEEE International Conference on Communications*, Dresden, Germany, 2009, pp. 1–6.

[6] S. Even, A. Itai, and A. Shamir, "On the complexity of time table and multi-commodity flow problem," in *16th Annual Symposium on Foundations of computer science*, 1975, pp. 184–193.

[7] M. Gupta and S. Singh, "Greening of the internet," in *ACM Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications (SIGCOMM 2003)*, Karlsrhue, Germany, 2003, pp. 19–26.

[8] R. G. Garroppo, S. Giordano, G. Nencioni, and M. Grazia Scutell, "Power-aware routing and network design with bundled links: Solutions and analysis," *Journal of Computer Networks and Communications*, vol. 2013, 2013.

[9] S. Antonakopoulos, S. Fortune, and L. Zhang, "Power-aware routing with rate-adaptive network elements," *GLOBECOM Workshops (GC Wkshps)*, 2010.

[10] M. Andrews, A. Fernndez Anta, L. Zhang, and W. Zhao, "Routing for power minimization in the speed scaling model," *IEEE/ACM Transactions on Networking*, vol. 20, no. 1, pp. 285–294, 2012.

[11] A. Vishwanath, K. Hinton, R. W. A. Ayre, and R. S. Tucker, "Modeling energy consumption in high-capacity routers and switches," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 8, pp. 1524 – 1532, 2014.

[12] M. Roughan, S. Sen, O. Spatscheck, and N. Duffield, "ClassofService mapping for QoS: A statistical signaturebased approach to IP traffic classification," in *Proceedings of the 4th ACM SIGCOMM conference on Internet measurement*, New York, USA, 2004, pp. 135–148.

[13] J. Tiso and D. Teare, *Designing Cisco Network Service Architectures (ARCH): Foundation Learning Guide*, 3rd ed., ser. Foundation Learning Guides. Cisco Press, 2011.

[14] L. Chiaraviglio, M. Mellia, and F. Neri, "Minimizing ISP network energy cost: Formulation and solutions," vol. 20, no. 2, pp. 463 – 476, 2012.