Energy-Fair Routing in Multi-Domain Green Networks

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***Abstract*—Providing energy-fairness in multi-domain green networks is a vital but hitherto unexplored issue. In this paper, we address energy-fair routing in multi-domain green networks by formulating an optimization problem as an integer linear program. Our problem maximizes the energy saving of the domain with minimum energy saving while ensuring that the energy consumption of each domain is below a given threshold. We design an efficient heuristic algorithm called Balanced Multi-Domain Green Routing (BMDGR) for this problem. We evaluate the performance of BMDGR by comparison to the results obtained from our integer linear program using optimization software CPLEX. The simulation results show that BMDGR yields close results to the values obtained from CPLEX in terms of energy efficiency while having low computational complexity.**

***Index Terms*—green networks, energy-fairness, energy-fair routing, multi-domain networks, optimization, integer linear program, heuristic algorithm**

I. Introduction

In recent years, saving energy has become an important issue for both industries and environment. Similar to other business areas, energy consumption of information and communication technologies (ICT) industry increases continuously. Thus, the growth of the network electricity consumption is fast [1]. In 2008, the work in [2] showed that communication networks consume about 0.5% of the electricity supply in the OECD countries. In USA, the cost of powering wired networks is nearly 0.5-2.4 billion dollars per year [3]. According to [4], energy consumption of the network devices is 6 TWh in the US and costs approximately $500 million per year. In addition, the ICT industry accounted for 2% of the global CO_2 emissions [5].

Researchers in ICT industry aim to design environmentally-friendly techniques which minimize power consumption [6]. [7] is the first study that introduced *greening* concept to save energy. In [7], researchers proposed putting the network elements into sleep mode as the approach to save energy. The work in [8] introduced a more precise definition of the greening concept, in particular focusing on wired networking. The works in [9] and [10] propose to put unused devices to sleep mode in order to model energy-aware wired networks. In [11], authors presented a novel network-based model of the power consumption in optical IP networks. They estimated the energy consumption per bit of data on the Internet as a function of access rate and proposed optical bypassing as a strategy to reduce this power consumption.

Networks where different parts have different owners are called multi-domain networks. Authors in [12] analyzed energy efficiency in multi-domain optical networks. We have two major differences from [12]. First, we focus on multi-domain green networks instead of optical networks. Second, we focus on energy-fair routing instead of routing that minimizes the total energy consumption.

Most works in the literature considered energy efficiency and fairness concepts for wireless networks. In particular, researchers discussed these two concepts mostly for wireless sensor networks [13], [14], [15]. In communication networks literature, the concept of fairness is generally discussed within the context of fair bandwidth allocation between different users (demands), Quality of Service (QoS) and the Internet traffic per user [16], [17], [18]. The common purpose of these studies is fair routing for data transmission. For instance, [19] designed algorithms for fair QoS in optical networks.

This paper is the first study that addresses energy-fair routing in multi-domain green networks. We formulate an optimization problem that maximizes the energy saving of the domain with minimum energy saving while ensuring that the energy consumption of each domain is below a given threshold value, which may vary depending on the domain.

The energy-fair routing model we propose in this paper has numerous applications. For instance, a company having multiple offices/departments in different locations may control the energy consumption of each department using this model. This way, the company may provide both energy-fair routing in terms of energy consumption of each department and ensure that the energy consumption of the network in each office is below a predetermined threshold. Moreover, the model in this paper may be used for multiple data center networks where each data center is in a different location. For instance, Google has data centers in different locations such as North Carolina, Oklahoma and Alabama. A centralized entity such as a software defined network controller can determine the traffic paths so that energy-fairness among the data centers is achieved.

Researchers in [20] consider a scenario where a set of source and destination pairs, each with a set of demands, is given as input and the goal is to determine the routing that minimizes the number of used links while satisfying the demands of all communication pairs and capacity constraints of all links. The motivation behind minimizing the number of used links is to minimize the energy consumption because the unused links, i.e., links that are not on some routing path, are turned off in order to save energy. In this paper, we focus on a similar problem but with a different objective and additional constraints. Our goal is to find the routing paths among the given set of source and destination pairs so that the energy saving of the domain with minimum energy saving is maximized, the energy consumption of each domain is below a given threshold value and all demands are satisfied while adhering to the capacity requirements of all links. We formulate our optimization problem as an integer linear program (ILP) and propose a heuristic algorithm. We comparatively evaluate the performance of our heuristic algorithm together with our ILP formulation and the ILP formulation in [20] by using CPLEX optimization software.

The rest of this paper is organized as follows: In Section II, we provide our optimization problem formulation as an integer linear program. Section III introduces our proposed heuristic algorithm. Section IV presents simulation results and Section V concludes the paper.

II. Problem Formulation

We represent the network as an undirected graph $G = (V, E)$, where the node set V corresponds to the set of network devices and the edge set E corresponds to the set of links. $G_d \subseteq G$ represents the network of domain $d \in D$ and each node $v \in V$ belongs to one domain G_d. $s_i \in V$ and $t_i \in V$ are the source node and terminal node, respectively, of communication pair i. We have a set of source and destination pairs $\mathcal{B} = (B_{s_1t_1}, B_{s_2t_2}, ..., B_{s_nt_n})$, where $B_{s_it_i}$ refers to the amount of the demand from $s_i \in V$ to $t_i \in V$. Our optimization problem aims to find a set of paths such that each source and destination pair is connected to each other (together with some additional constraints).

Figure 1 shows a comparative example of the problem we focus on. In the example, orange and blue coloured values represent the capacity and energy consumption, respectively, of each edge. Demands of source and destination pairs s_1-t_1 and s_2-t_2 are 1. When the aim is to minimize the total energy consumption, path B-C-D-E-F for s_1-t_1 and path A-B-C-E-F-G for s_2-t_2 are found while satisfying all demands and capacity constraints. Since both paths belong to domain A, this allocation is not fair in terms of energy consumption. In contrast, the energy-fair routing model in this paper finds path B-C-D-E-F for s_1-t_1 and path A-B-K-H-F-G for s_2-t_2. In other words, domain A and domain B are used for s_1-t_1 and s_2-t_2, respectively.

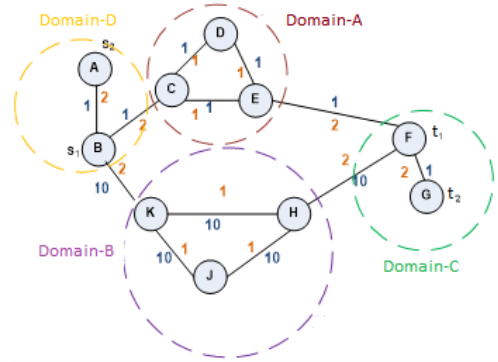


Fig. 1: A comparative example of the problem in this study

In our model, Z is a floating point decision variable and x_e is a binary decision variable that equals 1 if the edge $e \in E$ is used; otherwise it equals 0. Besides, $f_{uv}^{s_it_i}$ is a decision variable that represents the flow between node $u \in V$ and node $v \in V$ corresponding to the demand $B_{s_it_i}$. The input variables c_e, M_d, and W_e represent the capacity of the edge $e \in E$, upper bound of total energy consumption for domain G_d, and the energy consumption of the edge $e \in E$, respectively.

The objective function and the first constraint of our ILP formulation is as follows:

$$\max Z \tag{1}$$

s.t.

$$Z \leq \sum_{e \in E(G_d)} W_e \cdot (1 - x_e); \quad \forall d \in D \tag{2}$$

The objective function in (1) together with the constraint in (2) maximize the energy saving of the domain with minimum energy saving, hence achieving energy-fairness.

An edge is called a core edge if the nodes at both ends of the link are in the same domain; otherwise the edge is called a border edge. E_d^c and E_d^b represent the core and the border edge sets, respectively. If an edge belongs to E_d^c, nodes at the endpoints of this edge belong to the same domain and the energy consumption on this edge is added to the energy consumption of this domain. If an edge belongs to E_d^b, nodes at the endpoints of this edge belong to two different domains. In this case, for the sake of simplicity, we consider the situation where the energy consumption on this edge is equally shared by these two different domains. Constraint (3) ensures that the total energy consumption of each domain d is below a predetermined threshold M_d, which may vary depending on domain d:

$$\sum_{e \in E_d^c} W_e \cdot x_e + \sum_{e \in E_d^b} (W_e \cdot x_e)/2 \leq M_d; \quad \forall d \in D \tag{3}$$

The constraints in (4) are the flow conservation constraints, which ensure that each source and destination pair is allocated its required demand along some path. $N(u)$ represents the set of nodes in the neighborhood of node u.

$$\sum_{v \in N(u)} f_{vu}^{s_i t_i} - \sum_{v \in N(u)} f_{uv}^{s_i t_i} = \begin{cases} -B_{s_i t_i} \ ; \ if \ u{=}s_i, \\ B_{s_i t_i} \ ; \ if \ u{=}t_i, \\ 0 \ ; \ otherwise. \end{cases} \quad (4)$$
$$\forall (s_i, t_i) \in V \times V, \ \forall u \in V$$

The total amount of demand on edge $e \in E$ cannot exceed the capacity c_e of edge $e \in E$. The following constraint achieves this requirement:

$$\sum_{s_i t_i \in B_{s_i t_i}} f_{vu}^{s_i t_i} + f_{uv}^{s_i t_i} \leq c_e \cdot x_e, \quad \forall e = (u, v) \in E \qquad (5)$$

The decision variables can be modeled as follows:

$$Z, f_{uv}^{s_i t_i} \in R^{+} \cup \{0\}, x_e \in \{0, 1\}$$

III. Proposed Heuristic Algorithm

Our problem in Equations (1)-(5) is an integer linear programming problem, which is in general NP-Hard. Therefore, efficient heuristic algorithms are needed. In this section, we propose a heuristic algorithm called Balanced Multi-Domain Green Routing (BMDGR).

A. Balanced Multi-Domain Green Routing (BMDGR) Heuristic Algorithm

We explain BMDGR in Algorithm 1. Our heuristic consists of two consecutive phases: demand sorting and path selection for demands. In demand sorting phase, demands are sorted in ascending order (Line 4). Time complexity of this phase is $O(|\mathcal{B}| \log |\mathcal{B}|)$ for $|\mathcal{B}|$ demands. In path selection phase (Lines 5-14), we use edge weights (w_e) to select paths for demands. We use Yen's k-shortest path algorithm to find k-paths by using w_e values. In Yen's k-shortest paths algorithm, k shortest paths mean k loopless paths from the source node to the terminal node in nondecreasing order of total edge cost w_e [21]. Thus, parameter k in BMDGR algorithm is an upper limit for the number of paths for each $B_{s_i t_i}$. Hence, the complexity of this phase is equal to the complexity of Yen's k-shortest path algorithm, which is $O(k|V||\mathcal{B}|(|E| + |V| \log |V|))$ and dominates the complexity of the demand sorting phase and hence is equal to the complexity of BMDGR.

Algorithm 1 Balanced Multi-Domain Green Routing (BMDGR) Algorithm

1: **Require:** $G = (V, E)$, $G_d \subseteq G$, M_d, c_e, w_e, $\mathcal{B}$, k,
2: p: a path, p_{chosen}: the path which is chosen between source s_i and terminal t_i for $B_{s_i t_i}$
3: For each $B_{s_i t_i}$, define a path set $B_{ps_i t_i}$
4: Sort $\mathcal{B}$ in ascending order
5: **for** i = 1 : $|\mathcal{B}|$
6: **if** $|B_{ps_i t_i}| < k$ **then**
  Find the shortest p for $B_{s_i t_i}$ according to the smallest value of w_e using Yen's k-shortest paths algorithm.
  Check Equation (3) for p
7: **if** p is OK **then**
  $B_{ps_i t_i} \leftarrow B_{ps_i t_i} \cup p$
  $p_{chosen} \leftarrow p$
  $c_e \leftarrow c_e - B_{s_i t_i}$
8: **else**
  $i \leftarrow i - 1$
  (Return to $B_{s_{i-1} t_{i-1}}$ and find the next shortest p)
9: **end if**
10: **else**
  return infeasible
  (Reach the limit-k)
11: **end if**
12: **if** i < 1 **then**
  return infeasible
13: **end if**
14: **end for**
15: **return** the set of feasible paths for $B_{s_i t_i} \in \mathcal{B}$

IV. Simulation Results

We have evaluated the performance of our heuristic algorithm, our ILP formulation and the ILP formulation in [20] on networks generated by the Waxman topology generator [22], which is a random generator using a probabilistic model. Each node in the Waxman model has integer coordinates and is uniformly distributed over a square coordinate grid. The size of the grid, $n \times n$, is referred to as domain size. In other words, a graph based on the Waxman topology may have at most $n \times n$ nodes. We take the domain size as 15×15 in our experiments. The number of nodes is between 115 and 225 in our produced Waxman topology. In the Waxman model, parameters α and β are in the range $(0, 1]$. The probability of the existence of a link depends on parameters α and β, where a higher α indicates a higher number of links (a denser output graph) and a higher β indicates that the density of long links is higher than the density of the short links [23]. In our experiments, we set parameter β to 0.2 and parameter α to 0.5. Furthermore, we set $k = 5$ in Yen's k-shortest path algorithm.

Using Matlab, we generate 100 input graphs based on the Waxman topology. In our simulations, we analyze the impacts of upper bound of total energy consumption for each domain (M_d) and the number of demands ($|\mathcal{B}|$) on the average energy consumption of the network, the number of feasible solutions and energy-fairness in terms of energy consumption. When the problem size becomes large, CPLEX running times become prohibitively high [24]. Therefore, we set the value of gap parameter (*epgap*) to 5% in our experiments.

We evaluate the performance of the ILP in [20], our ILP formulation and our heuristic algorithm (BMDGR) for randomly generated $|\mathcal{B}| = 5$ demands. We set the M_d value of each domain equal to each other. We firstly set $M_d = 2000$ Watts and the number of domains to 4. We evaluate the impact of the number of demands on the average total energy consumption. We then evaluate the impact of M_d on the number feasible solutions when $|\mathcal{B}| = 5$.

Table I shows the range of values for the number of demands and M_d which are used in our experiments.

TABLE I: Range of Values for Parameters in Our Experiments

Parameter	Values
Number of Demands	{1, 2, 3, 4, 5}
M_d	{0, 50, 100, 200, 400, 600,..., 1200,..., 2000}

We use the power consumption values of various 48-port switches from [25] to measure the average total energy consumption of BMDGR, ILP formulation of [20] and our ILP formulation for varying number of demands. Table II shows these values.

TABLE II: Power Consumption of Various 48-Port Switches for Different Configurations [25]

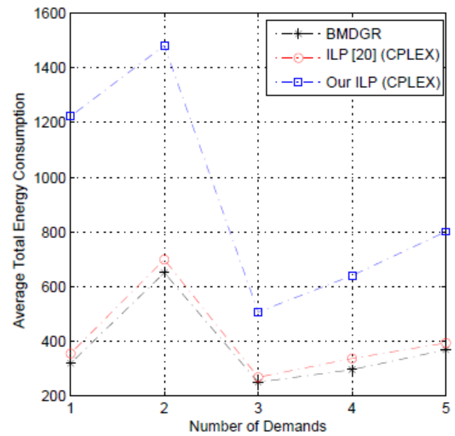
Active port	Port Trafic	Model-A (W)	Model-B (W)	Model-C (W)
-	-	151	133	76
All	-	184	170	97
All	1 Gbps	195	175	102

We use values of Model-A in Table II for endpoints of border edges of the graph, while for endpoints of core edges of the graph we use the values of Model-B and Model-C. We assign these values uniformly randomly. Energy consumption of each edge is equal to the sum of the energy consumption of the ports at its endpoints.

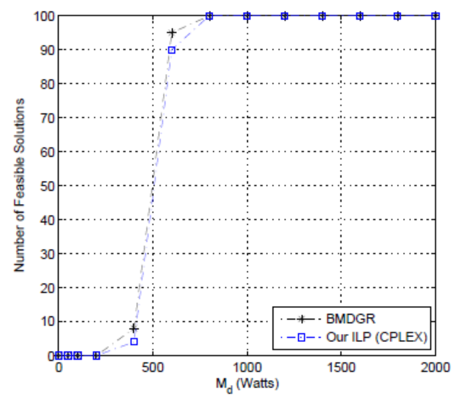
Figure 2a displays the average total energy consumption of BMDGR, ILP formulation in [20] and our ILP formulation by varying the number of demands. Figure 2a demonstrates that BMDGR has the best performance according to the average total energy consumption. The second and the third are ILP formulation of [20] and our ILP formulation, respectively. This behavior of our ILP is expected since its goal is to provide energy-fairness rather than minimizing total energy consumption. BMDGR, on the other hand, puts emphasis on both energy-fairness and adhering to the upper energy consumption limits of each domain. Besides, ILP in [20] assumes that each link has the same energy consumption and ILP in [20] does not adhere to the upper energy consumption limits of each domain; i.e., ILP in [20] does not take M_d values into account.

Figure 2b displays the number of feasible solutions of BMDGR and our ILP formulation for varying M_d (Watts). Both approaches yield feasible solutions for all randomly generated 100 graphs when M_d is greater than 800 Watts. Since ILP formulation of [20] focuses on a single domain network and hence ignores M_d of each domain d, we do not show it in Figure 2b. Figure 2a and Figure 2b together demonstrate that BMDGR gives importance to both total energy consumption and M_d of each domain.

Energy-fair routing has two fairness aspects. M_d is the first measure of fairness. In our experiments, we have observed that some of the results that ILP in [20] yields exceed M_d since



(a) Average total energy consumption of BMDGR, ILP formulation of [20] and our ILP formulation with varing number of demands.



(b) Number of feasible solutions of BMDGR, ILP formulation of [20] and our ILP formulation with varying M_d (Watts).

Fig. 2: Avg. total energy consumption and number of feasible solutions measurements of BMDGR, ILP formulation of [20] and our ILP formulation.

ILP in [20] does not take M_d values into account. However, BMDGR ensures that energy consumption of each domain does not exceed its M_d value. In addition to M_d criteria, we defined the second fairness criteria called Energy Fairness Ratio (EFR), which equals the ratio of the average energy consumption of the domain with minimum energy consumption and the average energy consumption of the domain with maximum energy consumption. EFR is in the range $(0, 1]$. A higher EFR value implies higher fairness according to the total energy consumption of the domains. Table III displays the performance of BMDGR, ILP formulation of [20] and our ILP formulation according to EFR when the number of demands varies. In this experiment, there are 4 domains and M_d has a sufficiently large value so that all solutions obtained are feasible. Furthermore, we set the energy consumption of the endpoints of each border and core edge to 5 units and 1 unit, respectively.

The results in Table III demonstrate that our ILP in general

TABLE III: Performance comparison according to EFR

Number of Demands	BMDGR	ILP [20]	Our ILP
1	0.827	0.775	0.784
2	0.775	0.847	0.972
3	0.942	0.885	0.942
4	0.880	0.875	0.910
5	0.817	0.897	0.969

has the best performance in terms of EFR, followed by BMDGR and the ILP in [20].

V. CONCLUSION

This paper is the first work that addresses energy-fair routing in multi-domain green networks. In particular, we have formulated an optimization problem as an integer linear programming problem and proposed a heuristic algorithm called BMDGR. We have made a comparative evaluation of BMDGR, our ILP formulation and ILP formulation of [20] by using CPLEX optimization software. Our simulations demonstrate that our ILP yields the most energy-fair routing. Furthermore, BMDGR has the best performance in terms of addressing both energy-fairness and satisfying the upper limit of energy consumption of each domain.

As a future work, we plan to investigate the computational complexity of our problem in its special cases and hence provide a combinatorial analysis. We also plan to evaluate the performance of our algorithm in other network topologies.

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