The Impact of Practical Network Constraints on the Performance of Energy-aware Routing Schemes

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***Abstract*—Power consumption and CO_2 emission have become a major concern over the last few years. Several recent studies have shown that servers and network equipments consume up to 45% of the energy consumption of data centers [1]. Software-defined networking is a new networking paradigm that decouples the control and data functionalities; thus, makes networks easily manageable and programmable. In software-defined networks (SDNs), the central controller has a global view of the network topology, traffic matrices and QoS requirements, which allows it to optimize the energy consumption of the network through energy-aware routing. In this paper, we investigate the impact of practical constraints, discreteness of link rates and limitation of flow rule space, on the performance of energy-aware routing schemes in SDN. The energy-aware routing problem is modeled as an integer linear program (ILP) with discrete cost function. The problem is modeled in GAMS and solved by CPLEX under real network settings and practical constraints. Results show that considering these constraints is critical in order to exploit the energy saving margin of SDNs.**

***Index Terms*—Energy-aware routing, Software Defined Networks, Network Optimization.**

I. Introduction

Information and Communications Technology (ICT) plays a major role in content delivery and knowledge sharing. As the demand for on-line contents and services is continuing to grow, the network's energy consumption is expected to grow as well. ICT consumes approximately $2\%-7\%$ of the global electricity consumption [2], [3]. Moreover, ICT is responsible for generating 2% of the global CO_2 emissions, posing a severe impact on the environment [4]. The ICT's energy consumption has not only severe negative environmental impacts but also economical impacts; the expenditure on electricity bills is rising annually at 15 to 20% of the network's operational cost [5].

In response to the aforementioned impacts of the rising energy consumption, great research efforts has recently been focusing on reducing the energy consumption of computer networks [6], [7]. Software-defined networking is a promising enabling technology of energy efficient and optimized networking. SDN decouples the control and data operations of the network and thus provides programmability. The network devices, i.e. switches, routers, firewalls, load balancers and network address translators, forward packets according to rules installed remotely by the central controller. The central controller constructs a global view of the network status based on statistics fed by counters activated on all network devices. Therefore, the network performance can autonomously and dynamically be optimized based on the network status [8]. The scope of this work is limited to the optimization of software-defined networks (SDNs) energy consumption under practical network conditions.

Several recent studies have considered centralized energy efficient routing. Wang *et. al.* [9] formulate the routing problem as an integer program with discrete cost function. The problem is solved over two phases, a relaxation phase and a rounding phase. In the relaxation phase, the non-convexity of the cost function was eliminated by transforming the integer program into a continuous-cost routing problem that can be solved in polynomial time. This was followed by a rounding phase in order to get a feasible solution for the original problem. Although the problem formulation presented in [9] considers a practical discrete cost function, the limit on the number of flow rules installed on each of the network devices was overlooked. In practice, flow rules are implemented in ternary content addressable memory which is limited in size; thus, the number of flow rules that can be installed on each networking device is limited [10]. Furthermore, the traffic demands were assumed to be uniform, i.e. all of the demands have equal bandwidth, and the ratio between any two steps in the cost function was bounded. These features make the solution inapplicable in real networks. Markiewicz *et. al.* [11] posed the energy-efficient routing problem as a mixed integer linear programming problem and proposed a strategic greedy heuristic with four different strategies to solve it. Strategies include: smallest demand first, largest demand first, shortest shortest path first and longest shortest path first. Although simulations show significant energy savings can be achieved during low demand periods, links were modeled to have a single transmission rate and energy cost. In real networks, each link has several discrete rates and several corresponding discrete energy costs. Unless links operate at their highest rate, the strategic greedy heuristic can't be applied in real networks. Giroire *et. al.* in [10] proposed a heuristic algorithm to minimize the energy consumption of backbone SDN networks while respecting the rule space constraint. The algorithm was shown effective for large networks and generates a solution close to the solution obtained by CPLEX [12]. The problem formulation in [10] is the first in literature to capture the flow rules constraint; however, it models link rates as continuous functions. In practice, link rates are discrete step functions with varying

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step sizes; thus, solutions obtained by this algorithm must be rounded to the nearest discrete rate in real networks. It remains unclear how this rounding affects the performance of similar algorithms developed under the assumption of continuous rate functions.

It would thus be of interest to learn how practical constraints of real networks impact the performance of energy-aware routing schemes in SDN. Specifically, we study the impact of rate discreteness and limited flow rules space on the efficiency of energy-aware routing schemes. We pose the energy-aware routing problem as an ILP with discrete cost function and limited flow rule constraint. The model also captures other SDN network constraints like flow conservation and maximum link capacity. The problem is modeled in GAMS [13] and solved by CPLEX under real network settings and traffic demands. The network topology and traffic matrices are test instances available at the library of test instances for Survivable fixed telecommunication Network Design (SNDlib) [14].

The remainder of the paper is organized as follows: In Section II, the system model and problem formulations are presented. Numerical evaluations are presented and discussed in Section III. The conclusions are drawn in Section IV.

II. Network Model and Problem formulation

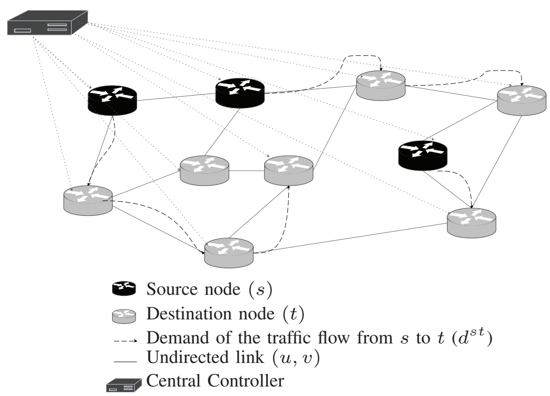

Figure 1. An Illustration of a SDN

We consider a SDN consisting of various type of software-defined-enabled network devices and bidirectional links among them. The network devices are represented by nodes and are connected to the central controller as shown in Figure 1. Nodes form the set $\mathcal{V}$, and links among them form the set $\mathcal{E}$. Each node u has a set of neighbors $\mathcal{N}(u)$. A node u in the network has a limited flow rules table, which can store at most L_u flow rules. Each link (u, v) is operated at one of the available discrete transmission rates $\mathcal{R} = \{R_0, R_1, R_2, \cdots, R_{\max}\}$, and has a capacity C_{uv}; the highest transmission rate is $R_{\max} \leq C_{uv}$. Each link $(u, v) \in \mathcal{E}$, operating at one of the transmission rates $z_{uv} \in \mathcal{R}$ incurs a power cost given by

$$g(z_{uv})= \begin{cases} P_0 & z_{uv} = R_0 \\ P_1 & z_{uv} = R_1 \\ \vdots & \vdots \\ P_{\max} & z_{uv} = R_{\max} \end{cases} . \tag{1}$$

The central controller has a global view of the network, i.e., nodes, links among them and available rates on each link. Based on this global view, the central controller performs centralized routing to route a set of traffic demands $\mathcal{D} = \{d_1^{st}, d_2^{st}, \cdots, d_{|D|}^{st}\}$; each from source node s to destination node t such that $d^{st} \geq 0, s, t \in \mathcal{V}, s \neq t$. The controller transforms the optimized routes into a set of flow rules and pushes them to the network nodes. The network nodes forward arriving packets based on the flow rules installed by the central controller.

In the following, we model the centralized routing problem for SDN while considering the discreteness of the available rates $\mathcal{R}$ and the limitation on the size of flow rules table L_u. The objective of energy-aware routing is to find the optimal routes of all demands in such a way that the energy consumption of the network is minimized. The network energy consumption is a function of active links, their transmission rate and the corresponding power consumption; thus, the objective function can be written as

$$\sum_{(u,v)\in\mathcal{E}} x_{uv} \cdot g(z_{uv}), \tag{2}$$

where x_{uv} is the binary variable to indicate whether the link (u, v) is active or not.

In order to ensure flow conservation in the network, the total flows $\sum_{v\in\mathcal{N}(u)} d^{st} f_{vu}^{st}$ entering a router u should be equal to the total flows leaving it, i.e., $\sum_{v\in\mathcal{N}(u)} d^{st} f_{uv}^{st}$. The source and destination nodes are exceptions because the amount of traffic leaving a source and entering a destination is given by $-d^{st}$ and d^{st}, respectively. The flow conservation constraint is given by

$$\sum_{v\in\mathcal{N}(u)} d^{st}(f_{vu}^{st} - f_{uv}^{st}) = \begin{cases} -d^{st}, & \text{if } u = s \\ \ \ d^{st}, & \text{if } u = t \\ \ \ 0 & \text{otherwise} \end{cases}$$
$$\forall u \in \mathcal{V}, (s,t) \in \mathcal{D}. \tag{3}$$

The selected discrete transmission rate z_{uv} should be sufficient to support all demands in $\mathcal{D}$ passing through link (u, v). Furthermore, the transmission rate z_{uv} is limited to one of the available transmission rates in $\mathcal{R}$. These two constraints can be written as follows, respectively,

$$\sum_{(s,t)\in\mathcal{D}} d^{st} f_{uv}^{st} \leq z_{uv} \qquad \forall (u,v) \in \mathcal{E}, \tag{4}$$

$$z_{uv} \in \{R_0, \ldots, R_{\max}\} \qquad \forall (u,v) \in \mathcal{E}. \tag{5}$$

Moreover, the highest transmission rate $R_{\max}$ does not exceed the link capacity C_{uv}, i.e.,

$$R_{\max} \leq C_{uv} x_{uv} \qquad \forall (u,v) \in \mathcal{E}. \tag{6}$$

The flow rules table is limited in size; thus, the number of flow rules installed on a given node u should not exceed its maximum number of rules L_u, which is expressed as

$$\sum_{(s,t)\in\mathcal{D}} \sum_{v\in\mathcal{N}(u)} f_{uv}^{st} \leq L_u \qquad \forall u \in \mathcal{V}. \tag{7}$$

Based on the above formulations, the energy-aware routing problem with discrete transmission rates and limited flow rules space is formulated as the following ILP:

$$\begin{aligned}
&\min \sum_{(u,v)\in\mathcal{E}} x_{uv} \cdot g(z_{uv}) \\
&s.t. \sum_{v\in\mathcal{N}(u)} d^{st}(f^{st}_{vu} - f^{st}_{uv}) = \begin{cases} -d^{st}, & \text{if } u = s \\ d^{st}, & \text{if } u = t \\ 0 & \text{otherwise,} \end{cases} \\
&\qquad\qquad\qquad\qquad\qquad \forall u \in \mathcal{V}, (s,t) \in \mathcal{D} \\
&\sum_{(s,t)\in\mathcal{D}} d^{st} f^{st}_{uv} \le z_{uv}, \qquad \forall (u,v) \in \mathcal{E} \\
&z_{uv} \in \{R_0, \dots, R_m\}, \qquad \forall (u,v) \in \mathcal{E} \\
&R_m \le C_{uv} x_{uv}, \qquad \forall (u,v) \in \mathcal{E} \\
&\sum_{(s,t)\in\mathcal{D}} \sum_{v\in\mathcal{N}(u)} f^{st}_{uv} \le L_u, \qquad \forall u \in \mathcal{V} \\
&x_{uv}, f^{st}_{uv} \in \{0,1\}, \qquad \forall (u,v) \in \mathcal{E}, (s,t) \in \mathcal{D}
\end{aligned} \tag{8}$$

The binary variables x_{uv} and f^{st}_{uv} make the problem in (8) NP-hard [15], [10]. Furthermore, the discreteness of the objective function make the problem harder to approximate [9]. Although they are computationally inefficient, modeling softwares, i.e. GAMS [13], and solvers, i.e. CPLEX [12], have widely been applied and provide a close-to-optimal solution [16]. The focus of this study is on evaluating the impact of SDNs practical constraints on the performance of energy-aware schemes. Therefore, the computational efficiency is not a concern and commercial packages can be utilized to solve the problem in (8).

III. Numerical Results

In this section, we compare the energy efficiency of energy-aware routing schemes that consider practical SDN constraints to the energy efficiency of routing schemes that ignores it. In order to facilitate this comparison, we curve fit the discrete function in (1), $g(z_{uv})$ to a continuous linear function denoted by $\bar{g}(r)$. Therefore, we compare the solutions of two programs, one with discrete cost function $g(z_{uv})$ and one with continuous rate function $\bar{g}(r)$. Furthermore, we limit the flow rule space on all nodes in the network to 50% of the the number of the network demands for both problems and compare it to the energy consumption of the network when the flow rule space is unlimited.

We adopt the Intel Ethernet Controller X540 power measurements [17] for the discrete transmission rates power costs. The X540 supports three transmission rates 100 Mbps, 1 Gbps and 10 Gbps. The cost function of the discrete transmission

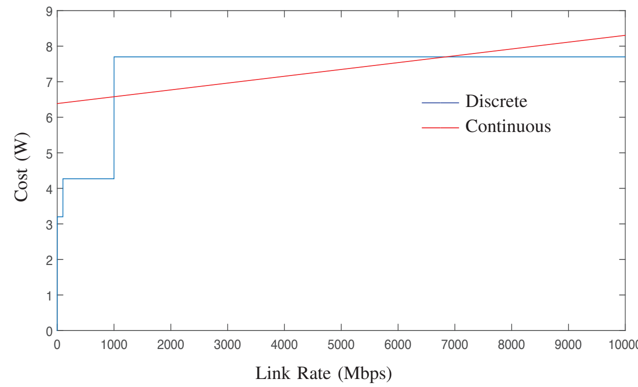

Figure 2. The discrete and continuous (curve fit) cost functions

rates is given by

$$g(z_{uv}) = \begin{cases} 2.53 \text{ W} & z_{uv} = \text{idle} \\ 3.2 \text{ W} & z_{uv} = 100 \text{ Mbps} \\ 4.27 \text{ W} & z_{uv} = 1 \text{ Gbps} \\ 7.7 \text{ W} & z_{uv} = 10 \text{ Gbps} \end{cases}. \tag{9}$$

While the link is idle, the essential circuitry, e.g., timing recovery, remains ON and the link consumes an average power of 2.53 Watts. This function was curve-fitted to a linear function using "cftool" available in Matlab. The power cost function of the continuous rate was evaluated to

$$\bar{g}(r) = mr + c, \tag{10}$$

where r is the continuous adaptive rate variable, $m = 1.9196 \times 10^{-4}$ is the line slope and $c = 6.3858$ is a constant. The discrete and continuous cost functions are shown in Figure 2.

The GAMS modeling language and CPLEX solver were used to solve both problems. In order to mimic a real-world network, we adopt a network topology and traffic matrices available at SNDlib [14]. Specifically, we simulate a network called "Janos-us", which is a high-performance network that links twenty six regions over the United States as shown in Figure 3. The network consists of 26 routers, 84 links, and 650 demands. We limit our evaluations to the first 50 demands of the "Janos-us" network, but with random sources and destinations.

Existing routing schemes that adopt continuous cost functions generate routes and continuous link rates for each of the active links. In real networks, the continuous link rates are rounded to the nearest available discrete transmission rate. This rounding is implemented in our evaluations and all of the results generated by CPLEX for the program with continuous rate cost are rounded to one of the rates in (9). In the following three subsections, we compare the results of solving both programs in terms of the total power cost, average number of hops, and link utilization.

A. Total Power Cost

Figure 4 shows the total power cost of routing all demands under both discrete and continuous rate cost assumptions. It

Figure 3. Janos-us network topology

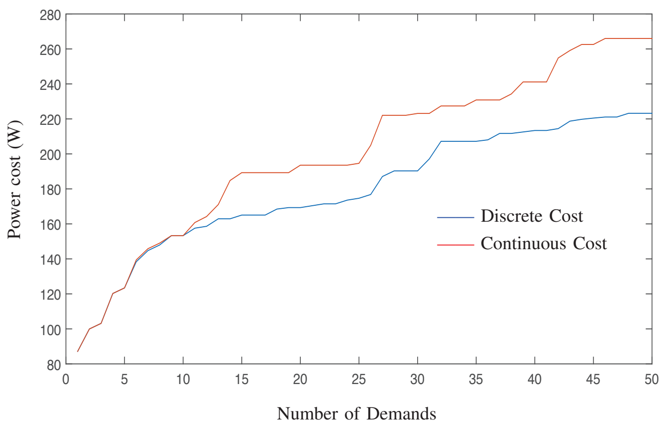

Figure 4. The total network power cost of routing all traffic demands

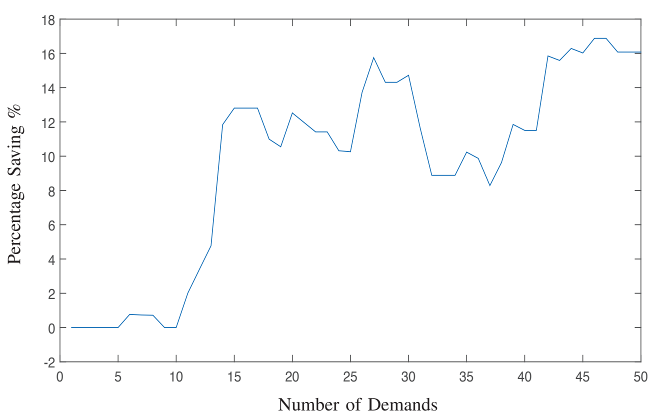

Figure 5. The percentage energy saving of the discrete program over the continuous program

can be clearly observed that the total power cost of using continuous link rates is higher than the one obtained by using discrete link rates. The gap between the two solutions increases as the number of demands increases. The percentage saving achieved by the discrete program over the continuous one is shown in Figure 5; The figure demonstrates that even for a small number of demands, i.e., 50 demands, a power saving larger than 16% can be achieved. Therefore, energy-aware routing schemes that consider discrete rate cost functions achieve higher energy savings than schemes that consider continuous rate cost functions.

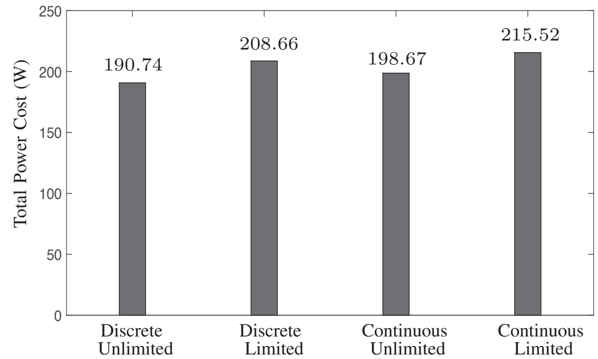

Figure 6. The total power cost of routing all demands by discrete and continuous programs under both limited and unlimited flow rule constraint

The second practical constraint we focus on is the limitation of flow rules space at each router. We consider two scenarios: in the first scenario, the number of flow rules space is limited to 26 rules on each router; whereas, the number of flow rules is unlimited for the second scenario. The results are shown in Figure 6. In the first scenario and with discrete link rates, the total network cost is 208.66 W, while with continuous link rates the network cost is 215.52 W. In the second scenario and with discrete link rates, the total power cost is 190.74 W; however, with continuous link rates the network consumes up to 198.67 W. Results show that solutions of the ILP with discrete link rates in both scenarios are more energy efficient. Furthermore, results demonstrate that the limited flow rules constraint increases the energy consumption of the network because demands have to traverse extra links when the maximum number flow rules installed on one of the routers is reached.

B. Number of Hops

Figure 7 shows the average number of hops in routes computed by both programs. Results demonstrate that the shortest routing length is observed in the case of discrete link rates. For 50 demands, the average number of hops in routes computed based on the program with discrete rates is half of that computed based on the program with continuous rates. Larger average number of hops implies longer average packet delay and higher energy consumption.

C. Link Utilization

Figure 8 shows the probability of link utilization in routes computed by the discrete rates and continuous rates programs. It is interesting to see that the model with discrete rates shows higher link utilization than the model with continuous rate function. The interface utilization in the case of continuous

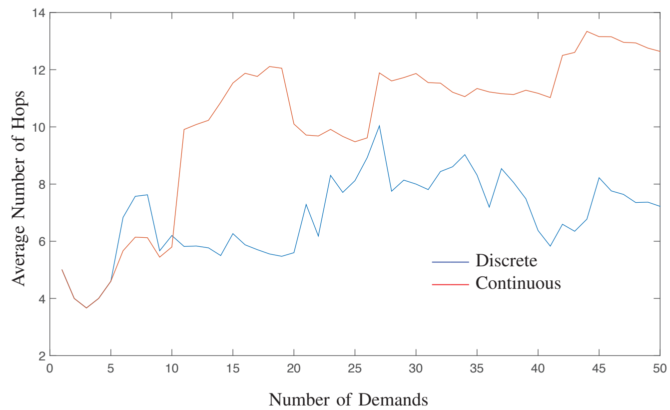

Figure 7. Average number of hops of routes computed by the continuous and discrete programs

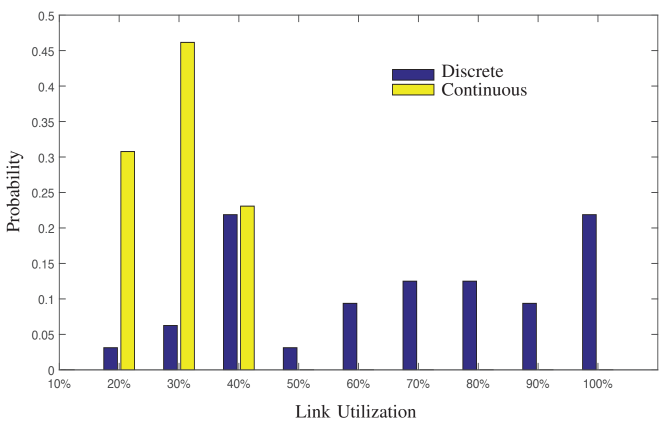

Figure 8. The probability of interface utilization

link rates ranges from 20% to 40% with a maximum probability of 45%. On the other hand, in the case of discrete link rates, the interface utilization ranges from 20% to 100%. Hence, a higher link utilization is observed for routing solutions computed based on the formulation with practical constraints.

IV. Conclusions

In this paper, we evaluate the significance of performance differences between energy-aware routing schemes that considers practical SDN constraints and ones that ignore it. Results confirm that discreteness of link rates and limitation of flow rules space has major impact not only on the energy efficiency of SDNs but also on routes length and links utilization. The energy-aware routing problem was formulated as an integer linear programming problem. The program was modeled in GAMS and solved using CPLEX under real network settings. Results show that for 50 demands, an energy saving of 16% can be achieved when schemes are designed based on practical assumptions. In addition, the limited flow rules space constraint increases the energy consumption of the network because extra links are activated when the maximum number of flow rules is reached on one of highly utilized links. Considering practical constraints have shown effective in increasing links utilization. These findings suggest that energy-aware routing schemes should be designed based on practical assumptions to exploit the energy saving margin of SDNs. In the future, we will design an energy-aware routing scheme that optimizes the energy consumption of SDN networks by activating discrete rates on used links such that the maximum number of flow rules is not exceeded on all nodes.

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References

[1] H. Geng, *Data Centers—Strategic Planning, Design, Construction, and Operations*. John Wiley & Sons, Inc, NOV 2014, ch. 1, pp. 1–14.

[2] Global Action Plan, "An inefficient truth," *Global Action Plan Report*, Dec 2007, http://globalactionplan. org. uk.

[3] W. Vereecken, W. Van Heddeghem, D. Colle, M. Pickavet, and P. Demeester, "Overall ICT footprint and green communication technologies," in *4th International Symposium on Communications, Control and Signal Processing (ISCCSP'10)*, March 2010, pp. 1–6.

[4] L. Chiaraviglio, M. Mellia, and F. Neri, "Reducing power consumption in backbone networks," in *IEEE International Conference on Communications (ICC'09)*, June 2009, pp. 1–6.

[5] G. Fettweis and E. Zimmermann, "ICT energy consumption-trends and challenges," in *Proceedings of the 11th International Symposium on Wireless Personal Multimedia Communications (WPMC'08)*, vol. 2, no. 4, Lapland, Finland, September 2008, p. 6.

[6] T. Feng, J. Bi, and K. Wang, "Joint allocation and scheduling of network resource for multiple control applications in sdn," in *IEEE Network Operations and Management Symposium (NOMS'14)*, May 2014, pp. 1–7.

[7] D. Li, Y. Shang, and C. Chen, "Software defined green data center network with exclusive routing," in *IEEE Conference on Computer Communications (INFOCOM'14)*, Toronto, Canada, 2014, pp. 1743–1751.

[8] W. Xia, Y. Wen, C. H. Foh, D. Niyato, and H. Xie, "A survey on software-defined networking," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 1, pp. 27–51, May 2015.

[9] L. Wang, A. F. Anta, F. Zhang, C. Hou, and Z. Liu, "Routing for energy minimization with discrete cost functions," *Computing Research Repository (CoRR'13)*, vol. abs/1302.0234, 2013.

[10] F. Giroire, J. Moulierac, and T. K. Phan, "Optimizing rule placement in software-defined networks for energy-aware routing," in *IEEE Global Communications Conference (GLOBECOM'14)*, 2014, pp. 2523–2529.

[11] A. Markiewicz, P. N. Tran, and A. Timm-Giel, "Energy consumption optimization for software defined networks considering dynamic traffic," in *IEEE 3rd International Conference on Cloud Networking (CloudNet'14)*, Luxembourg, Oct 2014, pp. 155–160.

[12] *IBM ILOG CPLEX 12.4 User's Manual*, IBM ILOG, 2012.

[13] R. E. Rosenthal, *GAMS–A User's Guide*, Dec 2014.

[14] S. Orlowski, M. Pióro, A. Tomaszewski, and R. Wessäly, "SNDlib 1.0–Survivable Network Design Library," in *Proceedings of the 3rd International Network Optimization Conference (INOC'07)*, Spa, Belgium, April 2007. [Online]. Available: http://sndlib.zib.de

[15] G. Wang, H. Wang, and L. Liu, "Energy efficient routing with a tree-based particle swarm optimization approach," in *Algorithms and Architectures for Parallel Processing*, X.-h. Sun, W. Qu, I. Stojmenovic, W. Zhou, Z. Li, H. Guo, G. Min, T. Yang, Y. Wu, and L. Liu, Eds. Springer International Publishing, 2014, vol. 8631, pp. 659–670.

[16] J. T. Linderoth and A. Lodi, "MILP software," *Wiley Encyclopedia of Operations Research and Management Science*, vol. 5, pp. 3239–3248, 2010.

[17] *Intel Ethernet Controller X540 Datasheet Rev. 2.7*, Intel Corporation, March 2014.