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Improved Energy-Aware Routing Algorithm in Software-Defined Networks

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***Abstract*—The growing energy consumption of communication networks has attracted the attention of the networking researchers in the last decade. In this context, SDN allows a flexible programmability, suitable for the power-consumption optimization problem. In this paper we present an energy-aware routing approach which minimizes the number of links used to satisfy a given traffic demand. Different from previous works, we optimize energy consumption in OpenFlow networks with in-band control traffic. To this end, we start formulating an optimization model that considers routing requirements for control and data plane communications. To reduce the complexity of our model in large-scale topologies, a heuristic algorithm is developed as well. Although it is not widely researched, except for quantitative and heuristic results, we also derive a simple and efficient algorithm for the best controller placement in terms of energy saving. Simulation results confirm that the proposed solution enables the achievement of significant energy savings.**

I. INTRODUCTION

Throughout the past decade growing attention has been paid to the energy consumption of communication networks. According to [1] from 2007 to 2012 the annual growth of electricity use in this sector raised to 10.4%. This value was the highest increase showed in that time frame, compared even with the growth rate of the total worldwide electricity consumption (about 3% per year). This implies that the reduction of power consumption in communication networks can contribute to measurable savings in the global energy use.

By decoupling control functions from forwarding devices, the Software-Defined Networks (SDN) [2] architecture allows a flexible programmability suitable for the power-consumption optimization problem. The logically centralized control plane in OpenFlow networks [3], has a global knowledge of the network state information and performs network tasks and device configuration without the need of additional software or hardware in each one of the switching elements. Meanwhile, the network devices only forward traffic according to the rules set by the controller. Therefore, an energy-aware solution can be easily implemented in the control plane. To this end, in this paper we tackle the problem of optimizing the power consumption in SDN by selecting the forwarding routes between network elements that minimize the number of active links needed to route a given traffic demand.

The use of SDN for this purpose has already been included in other research papers. The authors of [4] formulated an optimization problem for finding minimum-power network subsets in hybrid SDN. Giroire et al. [5] proposed an energy-aware routing approach, taking into account the limited rule space of TCAM (Ternary Content Addressable Memory) in SDN devices. The authors of [6] provided two greedy algorithms for minimizing the power of integrated chassis and line-cards used. For this they considered an expanded network topology according to the connections between the forwarding devices. However, in all these works, dedicated links between the controller and forwarding nodes were considered.

Throughout this work we consider a SDN architecture with a single centralized controller and, in contrast with those preceding papers, in-band control traffic. This means that control messages are exchanged using the same links that data traffic without the need of additional links, which is a more realistic scenario for large backbone networks, where dedicated links to transfer the control messages between controllers and forwarding devices are impractical and cost-inefficient. Using this traffic engineering approach, the controller can perform an energy-aware routing and determine the link interfaces that should be put into sleep mode.

In addition to the energy-aware routing problem, the controller placement issue is also addressed in this work. Different from previous works [7], which focus on minimizing the control traffic delay, we propose a simple and efficient approach that aims to determine the best controller location in terms of energy saving.

In summary, in this paper we make the following contributions:

- We develop an Integer Linear Problem (ILP) for energy-aware routing in SDN with a single controller that optimizes the number of active links, considering that links are shared between data and control plane traffic.
- For large network topologies, we propose two heuristic algorithms for the energy-aware routing and controller location problems that reduce the time complexity of our approach. Simulations show that these algorithms achieve solutions very close to the optimal ones.
- To evaluate our model, we use several real-world topologies and traffic demands. Simulations results confirm that the proposed solution enables the achievement of significant energy savings.

The rest of this paper is structured as follows. In Section II we explain the main considerations of our approach together

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with the network model considered and the formulation of our ILP model. The developed heuristic algorithms for energy-aware routing and controller placement are described in Section III. The simulation strategies and the obtained results are analyzed in Section IV. Finally, in Section V we conclude our work and outline future research guidelines.

II. ENERGY-AWARE APPROACH

Turning off unused networks elements is considered as a kind of key technique used to reduce power consumption [8]. Based on this, our solution aims to minimize the number of active links that can be used to route the control and data traffic, subject to the capacity constraint. Since we consider in-band control traffic, our model also determines the control paths between the controller and switches. In addition, we establish that data plane communications cannot be routed through the network controller.

A. Network Model

Given the controller location Ct, we modeled the SDN by a directed graph $G = (V, E)$ where V is the set of nodes (being $Ct \in V$) and E denote the set of links. Each link $e \in E$ has associated its capacity, denoted by c_e. Considering D as the set of traffic demands between any pair of nodes, let D_{dp} denote the subset of data plane communications. We use d_k to denote the throughput of a demand $k \in D$. In addition, considering P_k as the set of paths that can be used to route each $k \in D$, let $P_e^k \subset P_k$ be the subset of paths that use link $e \in E$ and $P_c^k \subset P_k$ denote the subset of paths that pass through the controller Ct.

B. Optimization Problem Formulation

To minimize the number of links used to route a given traffic demand, we define the following binary variables:

x_e: describes the state of a link $e \in E$.

$$x_e = \begin{cases} 1 & \text{if } e \text{ is active,} \\ 0 & \text{otherwise.} \end{cases}$$

$t_{k,p}$: describes the selection of a path $p \in P_k$ to route each $k \in D$.

$$t_{k,p} = \begin{cases} 1 & \text{if } p \text{ is selected to route } k, \\ 0 & \text{otherwise.} \end{cases}$$

Considering the notation of binary variables given above, the optimization model can be formulated as:

$$\text{minimize} \sum_{e \in E} x_e \tag{1}$$

subject to the following constraints:

$$\sum_{p \in P_k} t_{k,p} = 1 \qquad \forall k \in D \tag{2}$$

$$t_{k,p} = 0 \qquad \forall k \in D_{\mathrm{dp}}, \forall p \in P_c^k \tag{3}$$

$$\sum_{k \in D} \sum_{p \in P_e^k} t_{k,p} d_k \le c_e x_e \qquad \forall e \in E \tag{4}$$

Algorithm 1 ENERGY-AWARE ROUTING

```
Require: $G = (V, E)$ network graph, $Ct$ controller placement, $D$ data traffic demands
Ensure: $R$ data and control routes, $X$ active links, $U$ links utilization
$L \leftarrow$ Sorted list of $(Sw, Ct)$ pairs followed by $(Ct, Sw)$ pairs (in corresponding order)
$F \leftarrow$ First $(Sw, Ct)$ pair in $L$
$P \leftarrow$ Get_All_Paths$(G, F)$
for $p \in P$ do
    Initialize$(R', X', U')$        ▷ Local temporary variables
    $(R', X', U') \leftarrow$ Route$(p)$
    for $(u, v) \in L - \{F\}$ do
        $C \leftarrow$ Get_All_Paths$(G, u, v)$
        $c_p \leftarrow$ Select_Best_Path$(C)$
        $(R', X', U') \leftarrow$ Route$(c_p)$
    end for
    for $(Sw_1, Sw_2) \in D$ do
        $B \leftarrow$ Get_All_Paths$(G, Sw_1, Sw_2)$
        $d_p \leftarrow$ Select_Best_Path$(B)$
        $(R', X', U') \leftarrow$ Route$(d_p)$
    end for
    if $len(X') \le len(X)$ then
        $(len(X), R, X, U) \leftarrow (len(X'), R', X', U')$
    end if
end for
```

The objective function in (1) minimizes the number of active links, i.e. the number of links used to route the control and data traffic.

Constraints in (2) ensure that only one path $p \in P_k$ is selected to route each $k \in D$. Constraints in (3) force that paths passing through the controller cannot be used to route data plane communications. Constraints in (4) ensure that the total traffic in each active link $e \in E$ is less than its capacity c_e.

Since the difficulty of the energy-aware routing problem is known to be NP-Hard [9], solving this model on large and even medium-scale topologies becomes non-practical. In the next section we introduce a heuristic algorithm that reduces the consumption of resources and time complexity of our approach.

III. HEURISTIC ALGORITHMS

The proposed energy-aware routing algorithm is shown in Algorithm 1. The algorithm starts storing in L a sorted list of all control pairs. This list contains the switch-controller pairs (Sw, Ct) sorted according to the ascending order of the number of paths between them. The downstream direction of control paths, i.e. from the controller to switches (Ct, Sw), is also included in this list after the switch-controller pairs, following the same order. Going through this list, the algorithm starts satisfying the most critical cases and the solution can be found with fewer iterations. The first switch-controller pair in L, i.e. the one with the fewest number of paths between them, is stored in F.

Algorithm 2 CONTROLLER LOCATION

```
Require: $G = (V, E)$ network graph
Ensure: $Ct$ controller placement
$Search\_Space \leftarrow$ NULL
$N_v \leftarrow$ Set of neighbours of node $v \in V$
$A \leftarrow$ Sorted list of nodes in ascending order of $N_v$
$neigh \leftarrow \infty$                ▷ best number of neighbours
$h \leftarrow 0$                          ▷ minimum number of hops
while $Search\_Space$ = NULL do
    for $v \in A$ do
        for $i, j \in Combination(N_v, 2)$ do
            if $i, j$ are connected through $h$ hops and
              $len(N_v) \leq neigh$ then
                Add $v$ to $Search\_Space$
                $neigh \leftarrow len(N_v)$
            end if
        end for
    end for
    increment $h$
end while
$ES \leftarrow 0$
for $c \in Search\_Space$ do
    $ES' \leftarrow$ ENERGY-AWARE ROUTING($Ct = c$)
    if $ES' > ES$ then
        $Ct \leftarrow c$
    end if
end for
```

The main loop of the algorithm consists in determining for each control path of F, the number of active links in the network after routing all control and data traffic. Inside this loop the algorithm first determines the control path for the rest of control pairs stored in L (line 7) and then, the data paths for each one of the data traffic demands stored in D (line 12). The selected control path c_p for a control pair, is the best route between them in terms of minimizing the number of active links in the network. In addition, the path only can be selected if it has sufficient link capacity to route the demand volume. Similarly, this is hold for the selected data path d_p, but in this case only paths that do not pass through the controller could be considered in the search. Notice that a feasible configuration of paths would always be returned since we assume that the SDN has sufficient capacity to meet the demand requirements. After iterating for all the control paths of F, the algorithm returns the configuration of paths with fewer active links as the one with the lowest power consumption.

A. Energy-aware location of SDN controller

In addition to the route scheduling used, the energy saving in a network is also impacted by the choice of the controller location. Thus, based on the proposed energy-aware routing approach, the controller location problem is investigated. This analysis aims to define the best network node where to place the controller and to yield the minimum power consumption. In particular, we evaluate the energy saving for all possible controller locations and select the one with the maximum value as the *energy-aware controller placement*. Although the maximum energy saving is attained, if the size of the network is large, a thorough search among all locations becomes challenging to solve. Therefore, in Algorithm 2 we present a simple heuristic approach that reduces the space search to find the energy-aware controller location, considering the number of neighbour nodes and the connections between them. Since our model establishes that data plane communications cannot be routed through the network controller, locations with neighbours directly connected between them require a fewer number of links to meet the data and control traffic demands. In the first part, the algorithm starts evaluating each node in A, list sorted in an ascending node degree order. The locations with neighbours connected between them, either directly or through the fewest number of hops h (without considering the connections through v) and with fewer number of neighbour nodes (i.e. $len(N_v)$), are stored in the $Search\_Space$ list. Then, for each of these possible locations, the algorithm determines the number of links needed using the proposed energy-aware routing (Algorithm 1). The one with the greater energy saving is selected as the most convenient location to place the controller.

IV. PERFORMANCE EVALUATION

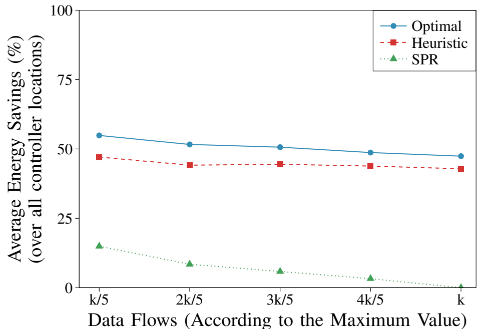
To solve the ILP model we used the solver Gurobi Optimizer [10] and the heuristic algorithms were developed using Python. All computations were carried out on a computer equipped with 3.30 GHz Intel Core i7 and 16 GB RAM. We conducted our simulations using real network topologies and traffic demands collected from SNDlib [11], considering each router in the network as a SDN node or as a possible controller placement. The energy saving was computed as the number of links in sleep mode over the total amount of network links.

A. Energy-aware routing

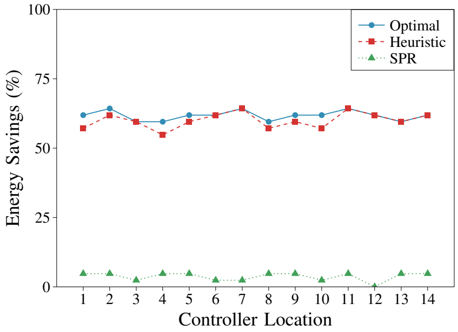
To evaluate the performance of our energy-aware routing algorithm against the optimal solutions achieved by the ILP model, we used Abilene and Nobelus topologies. We also included the analysis of using Shortest Path Routing (SPR), as default routing algorithm, to get a sense of the energy saving values achieved by our approach. Fig. 1 shows the energy savings reached by the three routing models varying: a) the amount of data traffic load and b) the controller location. In both cases our energy-aware routing approach outperforms the SPR in terms of energy saving. Furthermore, the heuristic algorithm accomplishes close-to-optimal energy savings, with differences under 8%. As expected, in Fig. 1(a) the energy saving decreases while the number of data flows grows, since new paths need to be established. The impact of controller placement in the power consumption is shown in Fig. 1(b).

B. Energy-aware controller placement

Table I shows the results of testing our energy-aware controller placement approach (Algorithm 2) for 5 different network topologies. For each network, we also consider two other well-known controller placement strategies: k-median



(a) Abilene topology.



(b) Nobelus topology.

Fig. 1. Energy saving comparison between optimal, heuristic and SPR models.

and k-center, which determine the node that minimizes the average and maximum control delay, respectively, as the controller placement. In addition, an exhaustive search among all locations (Ex_Search) was included to verify the maximum energy saving achieved in each topology using our energy-aware routing algorithm. The four placement strategies use our energy-aware routing to establish the data and control paths, making them comparable models. Therefore, the difference between them relies only on the criterion to select the best controller placement. We compute the maximum improvement (Max_Improv) as the difference between the energy saving reached by our heuristic algorithm and the minimum value, achieved by the k-median or k-center methods. As it is shown, in all cases our heuristic approach improves the energy saving achieved by the k-median and k-center strategies, with increases of about 20% of energy saving in Abilene and Nobel-germany. Moreover, it achieves the maximum energy saving in almost all the topologies, except in Nobel-eu, where the maximum energy saving is achieved placing the controller at Munich or Brussels, locations that do not have the fewest number of neighbour nodes. Therefore, these locations do not appear in the $Search\_Space$ list formed by our algorithm. Even so, differences are under 1.5%.

TABLE I
ENERGY SAVING (%) FOR DIFFERENT PLACEMENT STRATEGIES.

Topologies	**Abilene**	**Nobel-us**	**Nobel-germany**	**Geant**	**Nobel-eu**
Nodes	11	14	17	22	28
Links	28	42	52	72	82
k-median	35.71	59.52	46.15	58.33	52.44
k-center	35.71	54.76	51.92	59.72	52.44
Algorithm 2	57.14	64.29	65.38	66.67	60.98
Ex_Search	57.14	64.29	65.38	66.67	62.20
Max_Improv	21.43	9.53	19.23	8.34	8.54

V. CONCLUSION

In this paper we faced the problem of optimizing the energy consumption of data networks. Such goal is achieved by an energy-aware routing approach that minimizes the number of active links used to route a given traffic demand in SDN with a single controller and in-band control traffic. We propose an exact ILP model as well as a heuristic considering the routing requirements for data and control traffic. In addition, we derive a simple and efficient algorithm to find the best controller placement in terms of energy saving. Based on experimental simulations using real topologies and traffic demands, we showed that our energy-aware approach achieves significant energy savings and outperforms the SPR with noticeable improvements. Moreover, we proved that energy consumption depends on the specific controller location, and the proposed algorithm for controller placement attains comparably good results. As future work, we plan to add reliability constraints to quickly handle controller or data plane failures while maintaining active the minimum number of links needed.

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