GreenCoop: Cooperative Green Routing with Energy-efficient Servers

https://hdl.handle.net/2144/1758

Boston University
GreenCoop: Cooperative Green Routing with Energy-efficient Servers

Luca Chiaraviglio
Dipartimento di Elettronica
Politecnico di Torino - Italy
chiaraviglio@tlc.polito.it

Ibrahim Matta
Computer Science Department
Boston University - USA
matta@cs.bu.edu

TECHNICAL REPORT BUCS-TR-2009-034

ABSTRACT
Energy-efficient communication has recently become a key challenge for both researchers and industries. In this paper, we propose a new model in which a Content Provider and an Internet Service Provider cooperate to reduce the total power consumption. We solve the problem optimally and compare it with a classic formulation, whose aim is to minimize user delay. Results, although preliminary, show that power savings can be huge: up to 71% on real ISP topologies. We also show how the degree of cooperation impacts overall power consumption. Finally, we consider the impact of the Content Provider location on the total power savings.

1. INTRODUCTION
Energy-efficient communication has become a sensible problem in the last few years. According to recent studies [1] the next century will be dominated by environmental changes due to global warming, and key players in this process will be the production, distribution and the use of energy. Therefore, actions to reduce power consumption and improve energy efficiency are becoming imperative.

Considering the Information and Communication Technology sector (ICT), current estimates [2] show that ICT is responsible for 1% to 10% of the worldwide energy consumption, and this trend is expected to grow even more in the future. Starting from the seminal work of [3], several approaches have been proposed in order to reduce power consumption of ICT. For example, in [4] the authors consider the minimization of the power consumed by an Internet Service Provider (ISP) network. Moreover, new recent approaches like [5] aim at reducing the power consumption of big Content Providers (CP) considering the variation in electricity prices. Nevertheless, none of these previous studies considers the minimization of the total power consumption of both ISP and CP, so that great power savings can be achieved by considering a mutual objective.

In [6] the authors solve jointly the traffic engineering and content distribution problem, showing that great improvements in Quality of Service (QoS) can be obtained if CP and ISP pursue the same objective. However, this solution does not consider power consumption at all and consequently the power waste can be huge.

In this work we consider a design problem in which both CP and ISP cooperate in order to reduce overall power consumption. In particular, we model the system as an optimization problem in which the objective function is the minimization of the total power consumed by the CP and the ISP, subject to a user delay constraint. We test our model on real ISP topologies and considering realistic power figures. Our preliminary results show that there is a great opportunity to save power through cooperation, so that large power savings can be easily achieved.

While the proposed approach shows that there is a great opportunity to save power through cooperation, it is also true that CP and ISP are not willing to share sensible data such as the network topology or end-to-end traffic demand. We are therefore encouraged to pursue further research in this direction in order to improve our model by limiting the amount of shared information among CP and ISP.

2. PROBLEM FORMULATION
The main goal of our approach is to minimize the power consumption jointly between the CP and the ISP. In particular, we assume that the ISP is the owner of the network infrastructure, so that it manages a physical topology, i.e. a set of nodes and links. The CP instead is composed of a number of servers connected to the ISP. When a user (terminal) asks for a CP’s resource, we assume that the resource is replicated over the CP infrastructure, so that the user can potentially be served by any of the servers of the CP.

More formally, we represent the ISP topology as a digraph \( G = (V, E) \), where \( V \) is the set of vertices and \( E \) is the set of edges. Vertices represent network nodes, while edges represent network links. We denote by \( N := |V| \) and \( L := |E| \) the total number of nodes and links, respectively. Let \( C_l \) be the capacity of link \( l \), and let \( U_{MAX} \in [0,1] \) be the maximum link utilization that can be tolerated. \( S \) is the set of servers of the content provider. Denote by \( M_{MAX} \) the maximum load allowed on server \( s \in S \). Let \( M^t \) be the traffic demand between terminal \( t \in T \) and the content provider \( S \). Moreover, let \( x_{st} \) be continuous variables representing the amount of traffic between a node \( s \) and a terminal \( t \). We divide \( x_{st} \) into \( x_{st}^{CP} \) and \( x_{st}^{BG} \) to denote the amount of traffic originating from the content provider under consideration and from other content providers, respectively. Actually, \( x_{st}^{CP} \) and \( x_{st}^{BG} \) are constants, i.e. the considered CP can not modify these traffic demands. On the other hand, we assume that \( x_{st}^{BG} \) are continuous variables so that a traffic demand \( M^t \) from terminal \( t \) can be served by anyone of the \( s \in S \) CP servers, while satisfying load and delay constraints.

In order to describe the network topology, we can either choose between a node-link formulation or a path-link formulat
mulation [7]. In particular, in the node-link formulation each node computes the flow conservation law, while in the path-link formulation the flow conservation is done on the entire path. We decided to choose the path-link formulation since: i) it requires a lower number of variables than the node-link formulation ($O(V^2)$ instead of $O(V^3)$); ii) ISP can easily control the paths since they are pre-computed prior to launching the problem; iii) additional constraints, such as a minimum number of disjoint paths for each source and destination pair, can be easily enforced.

More formally, let $\delta_{lp}^t$ be constants which take the values of 1 if link $l$ belongs to path $p$ carrying demand from $s$ to $t$, 0 otherwise. Let $x_{st}^p$ and $q_{st}^p$ be continuous variables representing the amount of traffic from $s$ to $t$ on path $p$ for the considered CP and for other CPs, respectively. Let $p \in P(s,t)$ the set of pre-computed paths from $s$ to $t$. Additionally, let $f_l$ be the total amount of flow on link $l$, split into $f_{lp}^i$ and $f_{lp}^{bg}$ for the considered CP and for other CPs. Let $D_l$ be the delay on link $l$, which can be modeled as $D_l = 1/(C_l - f_l) + p_l$, where $1/(C_l - f_l)$ and $p_l$ denote the queueing delay and the propagation delay of link $l$, respectively.

Finally, we consider the power consumption of devices. Let $y_s$ and $y_t$ be binary variables which take the value of 1 if node $n$ and server $s$ are powered on, respectively. $P_{cn}^n y_n$ and $P_{cp}^s y_s$ represent the static amount of power consumed by node $n$ and server $s$ when powered on. Moreover, let $P_{c}^{n}(f_l)$, $P_{c}^{s}(f_l)$ be monotonically increasing convex functions representing the dynamic power consumption of link $l$, node $n$ and server $s$, respectively. $L(n)$ denotes the set of links incident to node $n$.

Given the previous notations, we recall the classic formulation of [6] and then present a new green formulation.

### 2.1 Classical Design

The objective of the classic design problem presented in [6] is the minimization of the overall delay experienced by all users in the network. The problem is formalized as follows:

**ClassicCoop** $\min \sum_{p \in P(s,t)} f_{lp}^i D_l(f_l) \text{ subject to:}$

$$\sum_{t} p_{st}^x = x_{st}^p \forall s,t$$  \hspace{1cm} (1)

$$x_{st}^p = \sum_{p \in P(s,t)} x_{st}^p \forall s,t$$  \hspace{1cm} (2)

$$\sum_{t \in T} x_{st}^p = M_t \forall t \in T$$  \hspace{1cm} (3)

$$\sum_{t \in T} x_{st}^p \leq L_{s}^{MAX} \forall s \in S$$  \hspace{1cm} (4)

$$f_{lp}^i = \sum_{s,t \in P(p,t)} \delta_{lp}^{st} x_{st}^p \forall l \in E$$  \hspace{1cm} (5)

$$f_{lp}^{bg} = \sum_{s,t \in P(p,t)} \delta_{lp}^{st} q_{st}^p \forall l \in E$$  \hspace{1cm} (6)

$$f_l = f_{lp}^{bg} + f_{lp}^i \leq C_l U_{l}^{MAX} \forall l \in E$$  \hspace{1cm} (7)

Control variables: $z_{st}^p \geq 0$, $q_{st}^p \geq 0$.

More precisely, Eq.1 splits the traffic demand $x_{st}^p$ among the different paths, Eq.2 computes the total amount of traffic from each server to each terminal of the CP, Eq.3 ensures that the total traffic demand $M_t$ from terminal $t$ is served by the CP. Eq.4 limits the total traffic on each server by the maximum load. Finally, Eq.5-7 compute the total flow on each link and impose the maximum link utilization constraint. This formulation does not take into account power consumption at all: we therefore compute the power consumption of devices as a post-processing phase.

**ClassicCoop** falls into the class of convex optimization problems, for which finding a local optimum is equivalent to finding the global optimum.

### 2.2 A New Green Cooperation

In order to consider the power consumption we propose a novel approach in which CP and ISP share information to minimize the global power consumption. In particular, the problem can be formalized as follows:

**GreenCoop** $\min (P_{TOT} = P_{CP} + P_{ISP}) \text{ s.t.:}$

$$P_{CP} = \sum_{s \in S} P_{c}^{n}(f_{lp}^i) + P_{c}^{y} y_n$$  \hspace{1cm} (8)

$$P_{ISP} = \sum_{t \in T} P_{c}^{s}(f_{lp}^i) + \sum_{n \in V} P_{c}^{n}(f_{lp}^{bg})$$  \hspace{1cm} (9)

$$\sum_{s \in S} x_{st}^p = M_t \forall t \in T$$  \hspace{1cm} (10)

$$\sum_{s \in S} x_{st}^p \leq L_{s}^{MAX} \forall s \in S$$  \hspace{1cm} (11)

$$\sum_{p \in P(s,t)} x_{st}^p = x_{yb}^p \forall s,t$$  \hspace{1cm} (12)

$$x_{st}^p = \sum_{p \in P(s,t)} x_{st}^p \forall s,t$$  \hspace{1cm} (13)

$$f_l = \sum_{s,t \in P(p,t)} \delta_{lp}^{st} (z_{st}^p + q_{st}^p) \leq C_l U_{l}^{MAX} \forall l \in E$$  \hspace{1cm} (14)

$$\frac{S_i}{T} \leq D_{MAX}$$  \hspace{1cm} (15)

$$\sum_{t \in I} f_l \leq M_t y_n \forall s \in S$$  \hspace{1cm} (16)

$$\sum_{t \in I} f_l \leq M_t y_n \forall s \in V$$  \hspace{1cm} (17)

Control variables: $z_{st}^p \geq 0$, $q_{st}^p \geq 0$, $y_n \in \{0,1\}$, $y_s \in \{0,1\}$.

Eq.8-9 compute the total power for the CP and the ISP, respectively. Eq.10 guarantees the traffic demand constraint. Eq.11 limits the maximum load on each server. Routing constraints are specified by Eq.12-13. The total flow on each link is computed and constrained by Eq.14. Then, Eq.15 computes the total delay for each link, using the additional variables $d_l \geq 0$. Here the delay function $D_l(f_l)$ is approximated by $I$ linear segments. Eq.16 bounds the average delay of users. Finally, Eq.17-18 impose powering on a network node and a server, respectively, if their incoming/outgoing flows are larger than zero, adopting a big-M method, i.e. $M_f \geq L_{MAX}$ and $M_y \geq \sum_{l \in L(n)} C_l$.

GreenCoop falls into the class of mixed-integer linear problems, for which optimal solutions can be found for example through the branch-and-bound algorithm.

### 3. PERFORMANCE EVALUATION

We test the effectiveness of the model proposed using ISP backbone topologies obtained from RocketFuel [8]. The topologies are first pre-processed using a simple shortest
path algorithm to obtain the set of paths, using the measured weights as link costs. In particular, for each \((s, t)\) we compute up to two completely disjoint paths. This reflects normal behavior of ISP which guarantees alternate paths for failure protection. Moreover, the capacity \(C_t\) is set to 10 Gbps for each link, since the topology considered is a tier-1 architecture representing the inner core of the network. Links are utilized up to 50% of their capacity, i.e. \(U_{t,\text{MAX}} = 0.5\ \forall t \in E\), to avoid congestion and to guarantee QoS. We assume that nodes are connected by optical links, in which the optical carrier is regenerated by amplifiers. For each link we randomly assign a number of amplifiers \(N_t\) uniformly distributed between 1 and 5.

Considering the CP, the maximum load on each server is set equal to the network capacity offered at that node, i.e. \(L_{t,\text{MAX}} = \sum_{L \in \text{L}(t)} C_t\). We consider the case in which the CP infrastructure is composed of 15 servers, adopting different strategies for the server placement over the ISP topology. The CP traffic demand \(M_t\) is modeled according to a Pareto distribution, with a variable lower bound \(M_{t,\text{MIN}}\) and a constant upper bound \(M_{t,\text{MAX}}\) limited by the total capacity at that node, i.e. \(M_{t,\text{MAX}} = \sum_{L \in \text{L}(t)} C_t U_{t,\text{MAX}}\). Unless otherwise specified, \(D_{t,\text{MAX}} = 300\ \text{ms}\) and \(M_{t,\text{MIN}} = 100\ \text{Mbps}\).

Table 1 describes the model used to evaluate the power consumption. Here we are assuming next-generation devices able to adapt their power with traffic flow. Considering the ISP, the power consumption of nodes is composed of a constant term \(P_{t,\text{CP}}\) due to the chassis static power plus an additional term \(P_{t,\text{ISP}}\) which scales linearly with traffic flow. The constant values are extracted by interpolating the power measurements of real devices under high load [9]. Moreover, the power consumption of a link \(P_{t}\) depends linearly on both the load and the number of amplifiers \(N_t\) between nodes.

Focusing on CP, the server power consumption is also modeled by a static term \(P_s\) and a dynamic term \(P_d^{\alpha}\): in this case instead the slope is higher due to the presence of backup elements and power supplies, which actually double the server power consumption. Moreover, an additional random variation of 50% in the server power is introduced to model energy price fluctuation as reported in [5]. For the sake of simplicity we do not consider any additional backhaul traffic of other CPs, since our goal is mainly to assess the maximum power savings achievable by the whole system composed of the ISP and the considered CP. Finally, 50% of randomly chosen nodes are selected as terminals \(t\).

In the following sections we investigate potential power savings under different strategies for server placement over the topologies, considering also the impact of variation in the constraints \(M_{\text{MIN}}\) and \(D_{\text{MAX}}\).

### 3.1 Preferential Server Assignment

In this set of experiments we assign the servers of the considered CP to nodes using a preferential degree placement. ISP nodes are first grouped according to the city in which they are located, and then the groups are sorted by decreasing number of links with other cities. Finally, the CP servers are assigned to the cities with the highest connection degree,
4. CONCLUSIONS AND FUTURE WORK

In this paper we have proposed GreenCoop, a new model in which both CP and ISP cooperate to reduce the overall power consumption. Our preliminary results on real topologies show that large power savings are achievable, up to 71% relative to a classic formulation of the joint problem. Moreover, we have shown that a common power minimization objective is crucial to reduce the overall energy costs.

Figure 2: Power consumption components versus $\alpha$. From left to right: SPRINTLINK, EXODUS, EBONE and TISCALI topologies.

Figure 3: Maximum admissible delay for the SPRINTLINK topology.

Link topology\(^2\). Values are averaged over 10 different runs, while error bars report minimum and maximum values. Interestingly, with ClassicCoop the power grows notably with decreasing $D_{\text{MAX}}$, while GreenCoop consumes around the same amount of power even for small $D_{\text{MAX}}$. The intuition suggests that GreenCoop can more wisely adapt to stricter QoS constraints, leading to higher power savings (around 52%) even for small $D_{\text{MAX}}$.

3.2 Random Server Assignment

In this setup we adopt a completely random node selection for placing the servers. In particular, Fig.4 reports a comparison of the power consumed under the random and the preferential assignment. Results are obtained for the SprintLink topology, using the GreenCoop formulation. The minimum amount of traffic varies between 10 Mbps and 100 Mbps. The power saving is computed as relative difference of the amount of traffic varies between 10 Mbps and 100 Mbps.

Moreover, the power saving of the preferential assignment is increasing with traffic, suggesting that a random placement can waste a considerable amount of power.

Figure 4: Preferential and Random placement comparison.

We recognize that this work is a first step towards a comprehensive approach. As future work, we first plan to develop an energy-efficient distributed algorithm to reduce the amount of shared information between CP and ISP. Another possible extension is the interaction of multiple CPs over the ISP to minimize the power consumption. Finally, different classes of QoS can be taken into account.

5. REFERENCES