Network-Wide Power Management in Computer Networks

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***Abstract*—An important part of the modern computer networks design is to develop novel technologies, architectures and control mechanisms for network devices enabling power saving by adapting network capacities to current traffic loads and user demands. We describe centralize and hierarchical control frameworks for reducing power consumption in backbone computer networks. The implementation of these frameworks provides the local control mechanisms that are implemented in the network devices level and network-wide control strategies implemented in the central control level. In this paper, we focus on network-wide algorithms for calculating the power status of network devices and the energy-aware MPLS routing for recommended network configuration. We enumerate several possible formulations of a network energy saving optimization problem with continuous and discrete variables. We discuss the limitations of these approaches and problems with their application to power control in real networks. We propose the relaxation of the complete binary problem formulation assuming full routing and energy state of all devices calculation, and the algorithm to solve it. Our formulation is based on a heuristic approach that leads to a continuous optimization. The evaluation of the optimization scheme through simulation is presented in the final part of the paper.**

I. Introduction to Energy-Aware Networks

The optimization of power consumption in today's wire and wireless computer networks has been a considerable research issue. It has been recognized that the information and communication technology sector belongs to the group of big power consumers. Energy consumption trends in the next generation networks are discussed in literature [1], [2], [3]. It is obvious that the energy awareness will play an important role in design, development and management of future, modern networks. The main challenge is to develop novel technologies, architectures and control mechanisms able to reduce energy consumption. Recently, it can be observed that the focus of many research projects is on control and optimization strategies for computer network equipment enabling energy saving, by adapting network capacities and computing resources to the actual traffic load and demands, while ensuring end-to-end Quality of Service (QoS), [4], [5], [6], [7], [3].

Power consumption of currently available networking devices scales with the installed capacity rather than the current load. Thus, for an Internet Service provider the network power consumption is practically constant, irrespectively to traffic fluctuations, since all devices consume always the same amount of power. In turn, devices are underutilized when traffic is low. This represents a clear opportunity for saving energy, since many resources (i.e., routers and links) are powered on without being fully utilized, while a carefully selected subset of them can be switched off or put into low power mode during inactivity periods without affecting the expected QoS. Various solutions have been proposed and developed to reduce the gap between the capacity offered by the network and the resources consumed by users [4], [8], [9], [10], [11]. One can distinguish two main categories: *dynamic power scaling* that adapts the capacity (and thus power consumption) of the devices to the current load and *smart standby* approach, that leverages on the concept of introducing idle mode capabilities (the device or its component is switched off when there is no data to transmit). Two widely used dynamic power scaling techniques for adapting the network capacity to actual requirements, and decreasing the energy demands are *low power idle* and *adaptive rate*. The low power idle method puts a given device into low power mode when traffic is low. The adaptive rate method decreases the energy demands of a network by changing its performance, i.e., scaling the processing capacities of network devices or the transmission or reception speed of network interfaces.

A control scheme for resource consolidation and dynamic power management of the whole network through energy-aware routing, traffic engineering and network equipment activity control have been designed and developed by the ECONET consortium (http://www.econet-project.eu). In general, the idea is to reduce the energy usage by concentrating data transfers along as few routes, line cards and links as possible and to switch off or put into a low energy state as many power consuming components as feasible. The detailed description of the general control framework for reducing energy consumption in a network and algorithms to exploit smart standby and dynamic power scaling capabilities are provided in [12] and [7]. In this paper we present a brief summary of this control system and describe two variants of the implementation of this general control framework. We focus on our network-wide heuristic algorithm for energy-aware traffic engineering, its verification and evaluation through simulation for sample network topologies.

II. Control Frameworks for Energy-Aware Networks

We assume that network devices and their components can operate in different energy-aware states (EAS), which differ in the power usage. The following states are considered: active, sleeping or switched off. All these states are defined as power settings and corresponding throughput. The detailed description of EAS is provided in [13]. We tackle the reduction of the power consumption by putting in low energy states or deactivating selected network devices, such as routers, line cards and ports. The implementation of our control framework requires the presence of a central control unit. The decisions about activity and power status of all devices are determined by solving the problem of minimizing the energy consumption in the whole network. The optimal network performance is calculated based on known network topology and expected demands (traffic matrix). The energy optimization problem is formulated as a mathematical programming problem with various constraints and control parameters. Figures 1 and 2 present the architectures of two variants of the implementation of the general control framework. Both of these variants are composed of four main components: OAM, NCP (cNCP or hNCP), LCP and GAL. The objective of OAM (*Monitoring and Operation Administration & Management*) is to provide tools for network monitoring and configuration in terms of trade-off between energy consumption and network performance. Moreover, this component plays the role of middleware between network equipment. It supports MPLS TE (Multiprotocol Label Switching Traffic Engineering) technology. The NCP (*Network-wide Control Policy*) denotes a central unit which goal is to optimize the network performance to reduce power consumption. The optimization problem is formulated and solved for a given network, taking into account its topology and expected demands of users. The proposed formulations are described in the following section. Each LCP (*Local Control Policy*) component implements adaptive rate and low power idle techniques on a given networking device. Several technologies for dynamic configuration setting of the energy-saving capabilities of the network devices have been developed by the ECONET consortium. The NCP and LCPs components form the control plane layer in our control framework. The last component of our system – GAL (*Green Abstraction Layer*) is the standard interface between monitoring and control plane layers and hardware for exchanging data regarding the power status of each device and all its components. The goal is to hide the implementation details of energy saving techniques, as well as to provide standard interfaces between all components of a system and energy-aware technologies. Thus, GAL transforms the outcome of LCPs into power-management configuration of a given component of the device – a selected router, card or port is switched into energy-aware state. The detailed description of GAL is provided in [9].

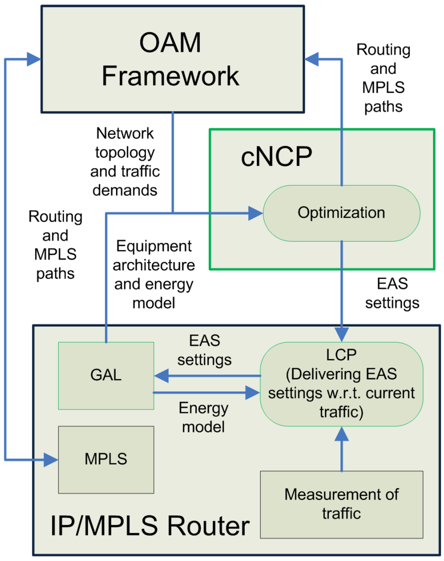

Fig. 1. The architecture of the control framework (centralized control).

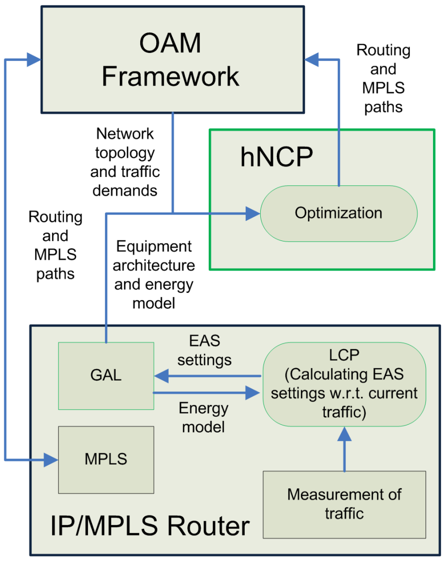

Fig. 2. The architecture of the control framework (hierarchical control).

Two variants of a network-wide control (NCP), i.e., cNCP – centralized (Fig. 1) and hNCP – hierarchical (Fig. 2) were investigated. The outcomes of the components of the control plane depend on the implementation. In the centralized scenario (cNCP) the suggested power status of network devices are calculated by the optimization algorithm executed by the central unit, and then sent to adequate LCPs. Furthermore, the routing tables for the MPLS protocol for recommended network configuration are provided to the OAM framework. Hence, in this scenario, the activity of each LCP unit is reduced to comply with the recommendations calculated by the cNCP, taking into account constraints related to current local load and incoming traffic. In the hierarchical scenario (hNCP) the central unit does not directly force the energy configuration of the devices. The outcome of the hNCP is reduced to routing tables for the MPLS protocol that are used for routing current traffic within a given network. The objective of the LCP algorithm is to optimize the configuration of each component of a given device in order to achieve the desired trade off between energy consumption and performance according to the incoming traffic load measured by the OAM framework.

III. NETWORK ENERGY SAVING OPTIMIZATION

A. Problem Formulation

In this section we focus on the implementation of the cNCP and hNCP components from Fig. 1 and 2. Various network-wide formulations of a network energy saving optimization were developed and described in [12]. Optimization problems with continuous and discrete variables were considered, starting from complete problem formulation assuming full routing, and energy states of all devices calculation, then introducing some simplifications and a priori assumptions. Formulations assuming binary and continuous variables were considered.

Problem formulations with binary variables

- *LNPb* - Link-Node Problem: a complete network management problem stated in terms of binary variables assuming full routing calculation and energy state assignment to all devices and links in a network;
- *LPPb* - Link-Path Problem: a formulation with predefined paths (simplification of *LNPb*).

Problem formulations with continuous variables

- *LNPc* - Link-Node Problem: a complete network management problem stated in terms of continuous variables assuming full routing calculation;
- *LPPc* - Link-Path Problem: a formulation with predefined paths (simplification of *LNPc*).

In the aforementioned formulations the total power utilized in a network for finalizing all required operations is minimized. The adequate constraints guarantee ensuring end-to-end QoS. All possible energy saving decisions are directly specified, together with decisions concerning traffic assignment to particular links. In general, the idea is to concentrate network traffic on a minimal subset of network components. Unfortunately, the proposed approaches are of limited use in real networks. Both *LNPb* and *LPPb* are *NP*-complete problems. Although *LPPb* is easier to solve due to smaller number of constraints, but still the complexity grows with the size of a network. Thus, it is difficult to find sufficiently efficient algorithm for determining optimal performance of even medium-size networks. The results of *LNPb* and *LPPb* computational complexity estimations are presented and discussed in [7]. However, the formulations assuming continuous variables (*LNPc* and *LPPc*) are much easier to solve but other problems appear. In case of these approaches the problem is to define appropriate cost function. In practical, it would be very difficult to determine a cost function that may properly account for the costs of operating the routers, and of keeping active or inactive the interface cards and ports. Moreover, the final optimization problem is nonconvex. After a preliminary examination of the presented approaches we decided to develop a new problem formulation employing some heuristics. The basic *LNPb* formulation was relaxed and transformed into the problem with continuous variables. The original formulation of *LNPb* and its transformation to the continuous problem are presented below.

LNPb: Link-Node Problem

$$\min_{x_c, y_{ek}, z_r, u_{ed}} \{F_{LNb} = \sum_{e=1}^{E} \sum_{k=1}^{K} \xi_{ek} y_{ek} + \sum_{c=1}^{C} W_c x_c + \sum_{r=1}^{R} T_r z_r\}, \tag{1}$$

subject to the constraints:

$$\forall_{e=1,\ldots,E} \quad \sum_{k=1}^{K} y_{ek} \leq 1, \tag{2}$$

$$\forall_{\substack{d=1,\ldots,D,\\ c=1,\ldots,C}} \quad \sum_{p=1}^{P} l_{cp} \sum_{e=1}^{E} a_{ep} u_{ed} \leq x_c, \tag{3}$$

$$\forall_{\substack{d=1,\ldots,D,\\ c=1,\ldots,C}} \quad \sum_{p=1}^{P} l_{cp} \sum_{e=1}^{E} b_{ep} u_{ed} \leq x_c, \tag{4}$$

$$\forall_{\substack{r=1,\ldots,R,\\ c=1,\ldots,C}} \quad g_{rc} x_c \leq z_r, \tag{5}$$

$$\forall_{\substack{d=1,\ldots,D,\\ r=1,\ldots,R,\\ p=s_d}} \sum_{c=1}^{C} g_{rc} l_{cp} \sum_{e=1}^{E} a_{ep} u_{ed} - \sum_{c=1}^{C} g_{rc} l_{cp} \sum_{e=1}^{E} b_{ep} u_{ed} = 1, \tag{6}$$

$$\forall_{\substack{d=1,\ldots,D,\\ r=1,\ldots,R\\ p\neq t_d, p\neq s_d}} \sum_{c=1}^{C} g_{rc} \sum_{p=1}^{P} l_{cp} \sum_{e=1}^{E} a_{ep} u_{ed} - \sum_{c=1}^{C} g_{rc} \sum_{p=1}^{P} l_{cp} \sum_{e=1}^{E} b_{ep} u_{ed} = 0, \tag{7}$$

$$\forall_{\substack{d=1,\ldots,D,\\ r=1,\ldots,R,\\ p=t_d}} \sum_{c=1}^{C} g_{rc} l_{cp} \sum_{e=1}^{E} a_{ep} u_{ed} - \sum_{c=1}^{C} g_{rc} l_{cp} \sum_{e=1}^{E} b_{ep} u_{ed} = -1, \tag{8}$$

$$\forall_{e=1,\ldots,E} \quad \sum_{d=1}^{D} V_d u_{ed} \leq \sum_{k=1}^{K} M_{ek} y_{ek}, \tag{9}$$

where $r = 1, \ldots, R$ denote routers, $c = 1, \ldots, C$ cards, $p = 1, \ldots, P$ ports and $e = 1, \ldots, E$ links in a network. Each router contains C cards and each card contains P ports. Routers, cards and ports can operate in one of K energy states – EAS ($k = 1, \ldots, K$). All routers and cards can operate in two states: active and sleeping ($K = 2$) and ports can operate in at least two states ($K \geq 2$). Two ports connected by the e-th link are in the same state k. M_{ek} and ξ_{ek} denote respectively, the throughput and the power consumption of link e in state k, W_c and T_r fixed power levels associated to card c and router r. D denotes number of demands transmitted by means of flows allocated to given MPLS paths under QoS requirements ($d = 1, \ldots, D$), V_d the volume of demand d that is associated with a link connecting two ports: s_d and t_d – ports of the source and destination nodes.

The following constants are used in the problem formulation: $g_{rc} = 1$ if the card c belongs to the router r (0 otherwise), $l_{cp} = 1$ if the port p belongs to the card c (0 otherwise), $a_{ep} = 1$ if the link e is outgoing from the port p (0 otherwise), $b_{ep} = 1$ if the link e is incoming to the port p (0 otherwise), $z_r = 1$ if the router r is used for data transmission (0 otherwise), $x_c = 1$ if the card c is used for data transmission (0 otherwise), $u_{ed} = 1$ if the path d belongs to the link e (0 otherwise), $y_{ek} = 1$ if the link e is in the state k (0 otherwise).

The conditions (2) assure that each link can be in one energy-aware state, the constraints (3)-(5) determine the number of routers and cards that are used for data transmission. The constrains (6)-(8) are formulated according to Kirchhoff's law applied for source, transit and destination nodes, and finally the constraint (9) assures that the flow will not exceed the capacity of a given link.

LNHP: Link-Node Heuristic Problem

In this formulation the energy consumption and throughput utilization of the link e in the state k are described in the form of incremental model. The current values of ξ_{ek} and M_{ek} are calculated as follows: $\xi_{ek} = pow_e(k) - pow_e(k-1)$ and $M_{ek} = load_e(k) - load_e(k-1)$; where respectively $pow_e(k)$ denotes power used by the link e in the state k and $load_e(k)$ denotes load of the link e in the state k. Due to the presented relaxation we can transform a linear optimization problem with binary variables to a linear optimization problem with continuous variables.

$$\min_{x_c, y_{ek}, z_r, u_{ed}} \{F_{LNH} = \sum_{e=1}^{E}\sum_{k=1}^{K}\xi_{ek}y_{ek} + \sum_{c=1}^{C} W_c x_c + \sum_{r=1}^{R} T_r z_r\}, \tag{10}$$

subject to the constraints (2)-(5) and additional constraints:

$$\forall_{e=1,\ldots,E} \quad y_{e1} \geq y_{ei} \geq \ldots \geq y_{eK}, \tag{11}$$

$$\forall_{\substack{e=1,\ldots,E,\\ k=1,\ldots,K,c=1,\ldots,C}} \quad \sum_{p=1}^{P} l_{cp}a_{ep}y_{ek} \leq x_c, \tag{12}$$

$$\forall_{\substack{e=1,\ldots,E,\\ k=1,\ldots,K,c=1,\ldots,C}} \quad \sum_{p=1}^{P} l_{cp}b_{ep}y_{ek} \leq x_c, \tag{13}$$

In *LNHP* formulation a given link can operate in more than one energy state. Therefore, the constraint (11) for utilized throughput in various states was added. Moreover, the utilized throughput in different states are sorted. The constraints (12) and (13) force binary values of variables z_r, x_c in case when y_{ek} takes a binary value.

B. Heuristic-based Optimization Algorithm

We have proposed an efficient algorithm that employs heuristics to solve the *LNHP* problem. This algorithm operates in two phases. First, the preliminary solution is determined by widely used linear solver. Next, the original problem is modified and calculations are repeated for this modified formulation. Thus, the optimization problem *LNHP* is repetitively modified and solved until all decision variables take binary values – 0 or 1, and the calculations are terminated.

Algorithm_LNHP
step 1: Solve the optimization problem *LNHP* using linear solver. The result: the optimal values of the decision variables: $\hat{z}_r$, $\hat{x}_c$, $\hat{u}_{ed}$ and $\hat{y}_{ek}$.
step 2: Check the results of the optimization process. If all calculated variables $\hat{z}_r$, $\hat{x}_c$, $\hat{u}_{ed}$, $\hat{y}_{ek}$ take binary values – stop the calculations. Otherwise:

- *if* the links for which $\hat{y}_{ek} \in (0, 1)$ have been detected *then* create a subset $S_E^* \subset S_E$ consisting all these links and execute *step 3*, otherwise:
- *if* the links for which $\hat{u}_{ed} \in (0, 1)$ have been detected *then* create a subset $S_E^{**} \subset S_E$ consisting all these links and execute *step 4*.

step 3: Create a subset $S_{E_{min}} \subset S_E^*$ consisting of links that operate in the lowest energy-aware state k^*. Select from the set $S_{E_{min}}$ a link e^* for which $\hat{y}_{ek}$ takes a minimal value. Remove $\hat{y}_{e^*k^*}$ from the set S_E^*. Extend the *LNHP* with a new constraint $y_{e^*k^*} = 1$, and back to *step 1*.
step 4: Select from the set S_E^{**} a link e^{**} for which $\hat{u}_{ed}$ takes a maximal value. Remove $\hat{u}_{e^{**}d}$ from the set S_E^{**}. Extend the *LNHP* with a new constraint $u_{e^{**}d} = 1$, and back to *step 1*.

In both *LNPb* and *LNHP* formulations we do not consider directly the delays and packet losses that could be caused by the inaccuracy in forecasting of demands. In our control scheme the goal of the LCP component is to tune on-line the decisions of NCP to the current traffic in a network.

IV. Numerical Evaluation

The problems *LNPb* and *LNHP* were formulated, implemented and solved for several network topologies. The commonly used branch-and-bound solver incorporated from the open source solver Lp_solve (http://lpsolve.sourceforge.net/5.5/) was applied to *LNPb* while our *Algorithm_LNHP* combined with Lp_solve was used to solve *LNHP*. To model the power consumption of routers and links, we considered power requirements of network devices provided in [14]. All tests were done on Intel Core i7-3612QM CPU, 2.1 GHz, 8GB RAM. In this paper we present the results calculated for small-size and two medium-size network topologies.

A. Small-size Networks

The first testing scenarios was a small-size synthetic network *Net_A* composed of 6 routers connected by 20 links (Fig. 3). The objective of the tests was to compare the performance and efficiency of *LNPb* and *LNHP* approaches to energy saving in a network, and show the limitations of the application of *LNPb* to real network problems. We performed multiple

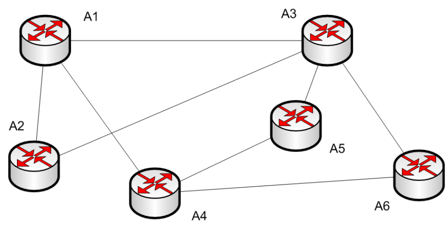

Fig. 3. The synthetic network *Net_A*.

experiments for various number of demands D (D=3, D=5, D=7, D=13). Each router and card could operate in two states: *active* and *sleeping*. In case of *active* state the power consumption was respectively, 1900 W (router) and 90 W (card). Each link could operate in five EAS ($k = 1, 2, 3, 4, 5$). The throughput of a given link e and the power consumption in k energy-aware state were as follows: (M_{e1}=200 Mb/s, ξ_{e1}=16 W), (M_{e2}=400 Mb/s, ξ_{e2}=32 W), (M_{e3}=600 Mb/s, ξ_{e3}=48 W), (M_{e4}=800 Mb/s, ξ_{e4}=64 W), (M_{e5}=1000 Mb/s, ξ_{e5}=80 W). The results of calculations performed for the *Net_A* network, *LNP* and *LNHP* optimization schemes, and various number of demands D are collected in tables I – IV. The numerical complexities of the *LNP* and *LNHP* optimization tasks, respectively for number of demands D=3 and D=13 were as follows: D=3: number of variables (*LNP* and *LNHP*) = 176, number of constraints (*LNP*) = 176, number of constraints

($LNHP$) = 189; D=13: number of variables (LNP and $LNHP$) = 376, number of constraints (LNP) = 428, number of constraints ($LNHP$) = 354.

Table I shows which network devices (routers, cards and links) were used for data transmission when routing was calculated, respectively by solving *LNPb* and *LNHP* energy saving optimization problems. Moreover, the reductions of energy consumption and times of calculations for both approaches are presented. Tables II and III collect the values of calculated optimal energy states and corresponding throughput of links used for transmitting data in a network. Table IV presents the calculated routing both for *LNP* and *LNHP* approaches.

TABLE I. ACTIVE ROUTERS, CARDS AND LINKS, REDUCTION OF ENERGY CONSUMPTION AND TIME OF CALCULATIONS (*LNP* AND *LNHP*).

Method		$D=3$	$D=5$	$D=7$	$D=13$
LNP	Active routers	4	5	5	6
	Active cards	5	6	6	7
	Active links	10	8	10	16
	Full power [W]	8146	10232	10264	12350
	Power reduction [W]	5754	3668	3636	1550
	Time [s]	0.031	0.125	0.327	31.465
LNHP	Active routers	4	5	5	6
	Active cards	5	6	6	7
	Active links	6	10	10	12
	Full power [W]	8146	10232	10264	12414
	Power reduction [W]	5754	3668	3636	1486
	Time [s]	0.032	0.078	0.094	0.140

TABLE II. ENERGY STATES OF LINKS (*LNP*).

Link (router/card)	EAS (k)	Throughput	Power
A1/2 $\rightarrow$ A2/2	1	200.0Mb/s	16.0W
A1/2 $\rightarrow$ A3/1	2	400.0Mb/s	32.0W
A1/2 $\rightarrow$ A4/1	2	400.0Mb/s	32.0W
A2/2 $\rightarrow$ A4/1	2	400.0Mb/s	32.0W
A2/2 $\rightarrow$ A3/1	2	400.0Mb/s	32.0W
A3/2 $\rightarrow$ A5/1	1	200.0Mb/s	16.0W
A4/2 $\rightarrow$ A5/1	1	200.0Mb/s	16.0W
A4/2 $\rightarrow$ A6/1	3	600.0Mb/s	48.0W
A2/2 $\rightarrow$ A1/2	1	200.0Mb/s	16.0W
A3/1 $\rightarrow$ A1/2	2	400.0Mb/s	32.0W
A4/1 $\rightarrow$ A1/2	2	400.0Mb/s	32.0W
A4/1 $\rightarrow$ A2/2	2	400.0Mb/s	32.0W
A3/1 $\rightarrow$ A2/2	2	400.0Mb/s	32.0W
A5/1 $\rightarrow$ A3/2	1	200.0Mb/s	16.0W
A5/1 $\rightarrow$ A4/2	1	200.0Mb/s	16.0W
A6/1 $\rightarrow$ A4/2	3	600.0Mb/s	48.0W

TABLE III. ENERGY STATES OF LINKS (*LNHP*).

Link (router/card)	EAS (k)	Throughput	Power
A1/2 $\rightarrow$ A3/1	2	400.0Mb/s	32.0W
A1/2 $\rightarrow$ A4/1	2	400.0Mb/s	32.0W
A2/2 $\rightarrow$ A4/1	2	400.0Mb/s	32.0W
A2/2 $\rightarrow$ A3/1	2	400.0Mb/s	32.0W
A4/2 $\rightarrow$ A5/1	1	200.0Mb/s	16.0W
A4/2 $\rightarrow$ A6/1	3	600.0Mb/s	48.0W
A3/1 $\rightarrow$ A1/2	2	400.0Mb/s	32.0W
A4/1 $\rightarrow$ A1/2	2	400.0Mb/s	32.0W
A4/1 $\rightarrow$ A2/2	2	400.0Mb/s	32.0W
A3/1 $\rightarrow$ A2/2	2	400.0Mb/s	32.0W
A5/1 $\rightarrow$ A4/2	1	200.0Mb/s	16.0W
A6/1 $\rightarrow$ A4/2	3	600.0Mb/s	48.0W

B. Medium-size Networks

The second testing scenario were two medium-size networks: a synthetic network *Net_B* and an access/metropolitan segment of an example network of a telecom operator (*Net_C*). Figure 4 reports the network *Net_B* composed of 12 routers

TABLE IV. MPLS ROUTING (*LNP*) AND *LNHP*.

Routing (*LNP*)	Routing (*LNP*)
A1/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1	A1/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1
A1/2 $\rightarrow$ A2/2	A1/2 $\rightarrow$ A3/1 $\rightarrow$ A2/2
A1/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1	A1/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1
A1/2 $\rightarrow$ A4/1 $\rightarrow$ A5/1	A1/2 $\rightarrow$ A3/1 $\rightarrow$ A2/2 $\rightarrow$ A4/1 $\rightarrow$ A5/1
A2/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1	A2/2 $\rightarrow$ A3/1 $\rightarrow$ A1/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1
A2/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1	A2/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1
A2/2 $\rightarrow$ A4/1 $\rightarrow$ A5/1	A2/2 $\rightarrow$ A4/1 $\rightarrow$ A5/1
A6/1 $\rightarrow$ A4/2 $\rightarrow$ A2/2	A6/1 $\rightarrow$ A4/2 $\rightarrow$ A2/2
A3/2 $\rightarrow$ A5/1 $\rightarrow$ A4/2 $\rightarrow$ A6/1	A3/1 $\rightarrow$ A1/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1
A2/2 $\rightarrow$ A4/1	A2/2 $\rightarrow$ A4/1
A1/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1	A1/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1
A1/2 $\rightarrow$ A2/2	A1/2 $\rightarrow$ A3/1 $\rightarrow$ A2/2
A1/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1	A1/2 $\rightarrow$ A3/1 $\rightarrow$ A2/2 $\rightarrow$ A4/1 $\rightarrow$ A6/1

connected by 42 links. The network *Net_C* is provided and described in literature and used as a benchmark network by many researchers (see [11]), and is presented in Fig. 5. It is formed of 21 routers (13 transit, 8 access) connected by 78 links and 1 peering node. The access routers denoted source and destination nodes. The objective of the transit nodes is to perform traffic switching. The peering node provides access to the Internet. All routers and cards could operate in *active* and

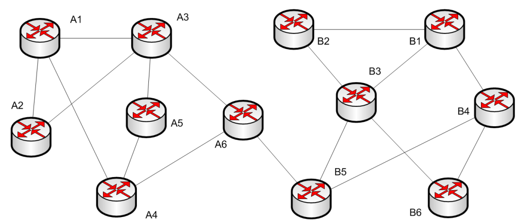

Fig. 4. The synthetic network *Net_B*.

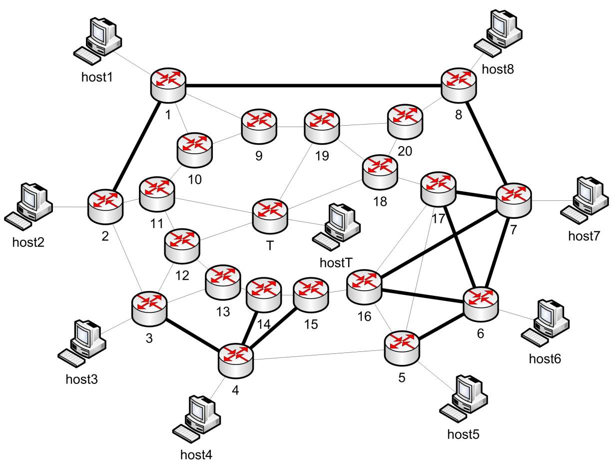

Fig. 5. A network from a telecom operator *Net_C*.

sleeping states. For *active* state the power consumptions were as follows, *Net_B*: 1900 W (router) and 90 W (card); *Net_C*: 1000 W (access router), 3000 W (transit router), 10000 W (peering router) and 90 W (card). Each link could operate in five EAS. In case of *Net_B* the throughput of a link e and the power consumption in k state ($k = 1, 2, 3, 4, 5$) were the same like in *Net_A*. In the network *Net_C* two types of links were considered: *linkT* (thin line in Fig. 4) and *linkB* (bold line in Fig. 4). The following throughput and power usages in k state were assumed: *linkT*: (M_{e1}=10 Gb/s, ξ_{e1}=100 W),

(M_{e2}=8 Gb/s, ξ_{e2}=80 W), (M_{e3}=6 Gb/s, ξ_{e3} ==60 W), (M_{e4}=4 Gb/s, ξ_{e4}=40 W), (M_{e5}=2 Gb/s, ξ_{e5}=20 W); *linkP*: (M_{e1}=10 Gb/s, ξ_{e1}=1100 W), (M_{e2}=8 Gb/s, ξ_{e2}=1080 W), (M_{e3}=6 Gb/s, ξ_{e3} ==1060 W), (M_{e4}=4 Gb/s, ξ_{e4}=1040 W), (M_{e5}=2 Gb/s, ξ_{e5}=1020 W).

We assumed following number of demands in our experiments: D=21 (*Net_B*) and D=16 (*Net_C*). The numerical complexities of the optimization problem *LNHP* formulated for both networks and assumed D were as follows: *Net_B*, number of variables = 1124 and number of constraints = 1956; *Net_C*, number of variables = 1457 and number of constraints = 1956. We applied the *LNHP* scheme with *Algorithm_LNHP* for energy saving in *Net_B* and *Net_C* networks. The results of calculations are collected in Table V.

TABLE V. ACTIVE ROUTERS, CARDS AND LINKS, REDUCTION OF ENERGY CONSUMPTION AND TIME OF CALCULATIONS (*LNHP*).

	Net_B	*Net_C*
Active routers	10	11
Active cards	14	11
Active links	22	22
Full power [W]	20772	35480
Power reduction [W]	7188	50320
Time [s]	0.733	4.134

In general, we have observed that *LNPb* and *LNHP* give similar results (see Tables I - III). In some cases the power reduction is slightly greater for the *LNPb*. Therefore, for small-size networks we can recommend to use the *LNPb* method. Unfortunately, our experiments confirmed that the application of *LNPb* for *Net_B* and *Net_C* networks needs very high computation overhead. Hence, the *LNPb* is impractical for medium-size networks, and the *LNHP* is recommended.

The effectiveness of cNCP and hNCP control schemes strongly depends on the quality of demands forecasting. We tested the resilience of cNCP on the quality of forecasts. The preliminary results are presented in [15]. In our opinion the hNCP scheme should be more resistant to forecasting inaccuracy, and we recommend this approach to be used in networks with high variability of a network traffic.

V. SUMMARY AND CONCLUSIONS

In this paper, we proposed two control frameworks composed of central and local control layers for energy-aware computer networks. The central decision layer is responsible for the power control in the whole network. The idea is to concentrate network traffic on a minimal subset of network components. Each local decision unit is responsible for the control of the individual network device. We formulated two variants of the energy saving optimization problem to be solved by the central decision unit. These formulations assume applying power scaling and standby techniques in order to reduce the energy consumption in a given network. The complete optimization problem stated in terms of binary variables was compared with the formulation employing heuristics. The main result of our research is the efficient branch-and-bound implementation supported by heuristics for solving optimization tasks for medium-size networks. The algorithm was verified and evaluated in many tests performed for various network topologies. In our opinion the proposed control frameworks with our heuristic algorithm for calculating the optimal configuration of network devices and optimal routing are good compromise between the expected reduction of power consumption in a given network and computational burden. In the future work, we plan to evaluate the performance of our control frameworks and algorithms in the testbed network.

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