Paper

Energy-saving Algorithms for the Control of Backbone Networks: A Survey

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Abstract—The rapid growth of energy demand by wired IP networks can be mitigated on hardware and software levels. While upgrading to more efficient transmission media still brings biggest savings, we take a look here at power-saving algorithms that combine the capability of setting networking equipment in arbitrary energy states which, combined with profound knowledge of the network traffic matrix, leads to considerable complex optimization problem formulations. Alternatively, lightweighted heuristic approaches are presented, built on much simpler network model but still capable to perform energy-efficient traffic engineering.

***Keywords*—green routing, mixed integer programming, OSPF heuristics, power-save networks.**

1. Introduction

One may point out several reasons for exponential growth traffic observed in contemporary networks. The increase of the number of connected devices, often related to progress in developing countries, as well as the progress of the Internet of Things, is important but still cannot account fully for the nature of the phenomenon. The main reason of its exponential nature is the type of content being transmitted – the multimedia and machine-to-machine communication still have big growth potential. Although the transmission infrastructure keeps up to the pace of demand, the resulting energy consumption, with its economic and environmental consequences, can be frightening.

There are two main technology domains where power consumption savings can be obtained: hardware and software. In wired networks, being the object of interest here, introduction of optical transmission technologies has become the main factor for reducing energy demand. Likewise, reduction of power consumption by on-board devices due to application of modern material technology has played its positive role.

Considered all the above, there is still room for further savings by exploiting the software domain. Any algorithmic framework for traffic admission and control may now utilize the two general power-saving capabilities, offered by majority of components:

- smart standby – automated or controlled deactivation of a hardware component when there is no load,
- dynamic power scaling – adaptation of power used to the actual load on that component.

The two common techniques of power scaling are: adaptive rate (AR) and low power idle (LPI). AR reduces power demand by scaling the data processing capabilities of a device, while LPI puts the device or its component into a "paused", low power mode during short inactivity periods. While utilizing dynamic power scaling often involves deep modifications in the design of software and hardware components of computing and network devices, the smart standby method requires only coordination among these devices to carefully rearrange the data transmission and processing loads that results from switching off selected devices or their components.

Most personal computers implement both AR and LPI techniques. The Advanced Configuration and Power Interface (ACPI) specification described in [1] defines a number of energy-aware states attained via voltage and clock frequency scaling and idle states in which the processor is in the standby mode. Development of APIs and management tools is, without a doubt, essential for optimal utilization of computing resources. On the other hand, system-wide regulation of power consumption needs to be commanded by a centralized management framework, capable of collecting and processing detailed measurements, and taking real-time coordinated actions across the data computing cloud infrastructure. The taxonomy of the energy and power management in computer networks can be found in [2]–[8]. This paper presents a survey of selected approaches described in literature.

2. Layered Architecture of Network Appliances – Basic Power Consumption Profiles

To design mechanisms for energy saving in computer networks, power consumption profiles of the network appliances and their components have to be identified. The architecture of modern network nodes (switches or routers), in many aspects is similar to that of a PC. Each router is a multi-chassis device composed of many entities: processor, chassis, line cards, communication ports, power supply, fan, etc. Each component must be powered. The only specific element – the switching fabric – may be considered as a kind of a specialized processor connected to communication buses. The main difference with respect to a PC is the number and power consumed by line cards. While a general-purpose PC usually hosts at most several network interfaces consuming only a fraction of its power, in an average switch or router there are usually from tens to hundreds of network ports located on several line cards.

In general, most control mechanisms for energy consumption management take into account such hierarchical internal layout of network devices. The three layers are commonly distinguished, from bottom to the top:

- communication interfaces (ports),
- line cards,
- the whole device (a router or a switch).

In general, each component is powered and can operate in K energy states defined as power settings, enumerated $k = 1,\ldots,K$. When adjusting power state in a higher layer, it is necessary to take into account that layered architecture, e.g. it is not possible to decrease energy state of a line card without affecting (lowering) energy states of the communication ports it hosts.

The legacy network devices can operate only in two energy states: deep sleep, $k = 1$, with negligible power consumption, and active with full power, $k = 2$. The resulting power consumption $P_d(q)$ for total traffic q, served by any component ($d := r$ for a router, $d := c$ for a line card, $d := e$ for a link connecting two interfaces), is as follows [9]:

$$P_d(q) = \begin{cases} P_{d1} & \text{if} \quad q = 0, \\ P_{d2} & \text{if} \quad q > 0, \end{cases} \tag{1}$$

where P_{d1} and P_{d2} denote fixed power levels associated to the device d in deep sleep (state 1) and active (state 2) states, respectively.

Modern network components, equipped with mechanisms for dynamic power management (e.g. InfiniBand cards switching between 1x and 4x mode or bundled WAN links [10], [11]), can operate in a number of energy states ($K > 2$), differing by power usage. Those extra states stand for power scaling and standby techniques. The 802.3az standard [12] defines the implementation of low power idle for Ethernet interfaces.

Numerous classes of analytical models have been proposed describing component power consumption as a function of its load. The simplest approach is to extend the basic on-off model (1) by extra states and assuming a fixed power level P_{dk} in each state [7]. Other authors [9], [13] propose a piecewise linear extension to 1.

3. Power Saving in Whole Network is an Optimization Problem

The common approach to power reduction in a network as a whole is to formulate an optimization problem similar to the traditional network design problem [14] or QoS provisioning task [15], [16], but with the cost function defined as a sum of power consumed by all components of the network. If power profiles are as in Eq. (1), then in contrary to the traditional network design problem, transmission paths should be accomplished through as few devices as possible, instead of balancing traffic in a whole network. The aim is therefore to fill up the active links with traffic. Typically, backbone network infrastructure is to some degree redundant to provide the required level of reliability. Therefore, to reduce power consumption some parts of the network may be switched off or the speed of processors and links may be reduced, if there exist adequate technical capabilities. According to recent studies concerning internet service providers' networks [17], [18], the total energy consumption may be substantially reduced by employing such approaches.

Various formulations of a network energy saving problem are provided and discussed in the literature; starting from mixed integer programming formulation, to its relaxation in order to obtain a continuous problem formulation and employ a simple heuristics. Moreover, various energy models of the devices are used. The common aim is to find the optimal network configuration, i.e. the combination of energy states that would bring maximum power saving without degrading service quality. In general, due to high dimensionality and complexity of such optimization problem, linear energy profiles are preferred. Some authors limit the number of energy states of network equipment (routers and cards) to “enabled” and “disabled” [19], and use energy profile (1). To relax the optimization problem further, they also postulate the use of multi-path routing, typically impractical and avoided in reality. However, the recent trend in green networking, as it has been already mentioned, is to develop devices with greater number of energy states ($K > 2$) [20], [21]. It is obvious that handling such cases implies larger dimensionality of the optimization problem and more sophisticated dependencies among network components. Consequently, large mixed-integer linear problems are formulated [22] to determine the most profitable set of devices to be safely brought down. The common approach to mitigate the complexity problem is to aggregate nodes and flows to decrease the dimensionality [19].

Another branch of research tries to exploit specific properties of optical transport layer to scale link rates by selectively switching off fibers composing them [23] or even to build a two-level model with IP layer set upon optical devices layer [11].

To conclude, the major difficulty caused by layered multi-state architecture is the complexity of the optimization problem, much harder to solve than typical graph optimization problems. Such complexity has its roots in NP-completeness problem formulation, interdependencies between data paths, and the requirement for flow aggregation. Furthermore, energy profiles are often non-convex, making continuous relaxation difficult to work properly, introducing instability and solution suboptimality [24].

3.1. Layered Architecture – Definitions

Let us consider a computer network consisting of the following components:

- R routers: $r = 1,\dots,R$,
- C line cards $c = 1,\dots,C$ and
- I communication ports $i = 1,\dots,I$.

As outlined in Section 2, layered architecture of a router is assumed, i.e., each router is equipped with a number of line cards, and each card contains a number of physical communication ports. E links ($e = 1,\dots,E$) connect all ports, pair by pair. The ports and the connecting links support K energy states (EASs) labeled $k = 1,\dots,K$. Assume that two ports connected by the e-th link must be in the same state k. In general, the corresponding power $P_{\text{net}}(q)$ consumed by the whole network can be calculated as a total of power consumed by every network device. Capacity of link e in state k is defined as q_{ek}. V_d denotes the total traffic demand for a link transmitting data from source port s_d to the destination port t_d. The following subsections present selected formulations of network power saving problems.

3.2. Optimization for Stepwise Profiles

The power profile model of each network device can be defined by a stepwise function describing power consumption in a given state (see Fig. 1a):

$$P_{dk}(q,k) = \begin{cases} P_{d1} & \text{if} \quad q = 0, \\ P_{dk} & \text{if} \quad q > 0, \end{cases} \tag{2}$$

where P_{d1} denotes fixed power level consumed by the device d in deep sleep state and P_{dk} – the power consumed in the k-th active energy state, $k = 2,\dots,K$.
The complete network management problem, stated in terms of binary variables k and assuming that routers and line cards can operate only in two states: $k \in \{1,2\}$, deep sleep or active – cf. (1), and communication interfaces can operate in K states, $k = 1,\dots,K$ – cf. (2) is formulated as follows:

$$\min_{x_r,x_c,x_{ek},u_{ed}} \left[P_{\text{net}} = \sum_{r=1}^{R} P_r x_r + \sum_{c=1}^{C} P_c x_c + \sum_{e=1}^{E} \sum_{k=1}^{K} P_{ek} x_{ek} \right]. \tag{3}$$

This formulation is completed with binary parameters describing network and device topology: $l_{cp} = 1$ if the port p is located on card c, $a_{ep} = 1$ if the link e is wired to port p, $g_{rc} = 1$ if the card c is located in router r. Otherwise, they take zero values.
The whole problem is subject to the following constraints:

$$\forall_{e\in\{1,\dots,E\}} \quad \sum_{k=1}^{K} x_{ek} \le 1, \tag{4}$$

$$\forall_{\substack{d\in\{1,\dots,D\}\\ c\in\{1,\dots,C\}}} \quad \sum_{i=1}^{I} l_{ci} \sum_{e=1}^{E} a_{ei} u_{ed} \le x_c, \tag{5}$$

$$\forall_{\substack{d\in\{1,\dots,D\}\\ c\in\{1,\dots,C\}}} \quad \sum_{i=1}^{I} l_{ci} \sum_{e=1}^{E} b_{ei} u_{ed} \le x_c, \tag{6}$$

$$\forall_{\substack{r\in\{1,\dots,R\}\\ c\in\{1,\dots,C\}}} \quad g_{rc} x_c \le x_r, \tag{7}$$

$$\forall_{\substack{d\in\{1,\dots,D\}\\ r\in\{1,\dots,R\}\\ i=s_d}} \sum_{c=1}^{C} g_{rc} l_{ci} \sum_{e=1}^{E} a_{ei} u_{ed} - \sum_{c=1}^{C} g_{rc} l_{ci} \sum_{e=1}^{E} b_{ei} u_{ed} = 1, \tag{8}$$

$$\forall_{\substack{d\in\{1,\dots,D\}\\ r\in\{1,\dots,R\}\\ i\neq t_d, i\neq s_d}} \sum_{c=1}^{C} g_{rc} \sum_{i=1}^{I} l_{cp} \sum_{e=1}^{E} a_{ep} u_{ed} - \\ - \sum_{c=1}^{C} g_{rc} \sum_{i=1}^{I} l_{ci} \sum_{e=1}^{E} b_{ei} u_{ed} = 0, \tag{9}$$

$$\forall_{\substack{d\in\{1,\dots,D\},\\ r\in\{1,\dots,R\},\\ i=t_d}} \sum_{c=1}^{C} g_{rc} l_{ci} \sum_{e=1}^{E} a_{ei} u_{ed} - \sum_{c=1}^{C} g_{rc} l_{ci} \sum_{e=1}^{E} b_{ei} u_{ed} = -1, \tag{10}$$

$$\forall_{e\in\{1,\dots,E\}} \quad \sum_{d=1}^{D} V_d u_{ed} \le \sum_{k=1}^{K} q_{ek} x_{ek}. \tag{11}$$

The meaning of binary decision variables is as follows: $x_r = 1$ if the router r is switched on, $x_c = 1$ if the card c is switched on, $x_{ek} = 1$ if the link e is in power state k, $u_{ed} = 1$ if a transmission path d traverses link e (zero – otherwise). P_r, P_c, P_{ek} denote the fixed power consumed by router, card and link, q_{ek} denotes the throughput of the link e in the state k, D stands for a number of assumed flows (demands).

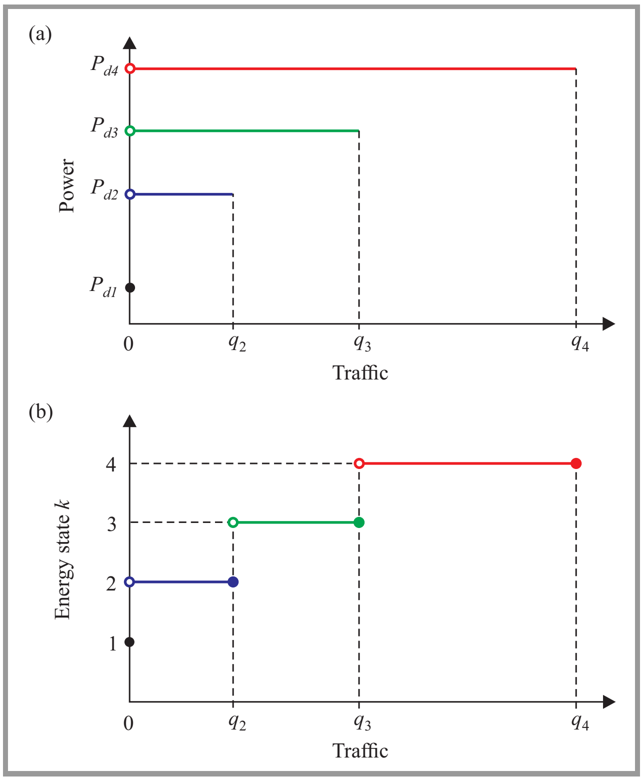

Fig. 1. Power consumption model – K states.

In the problem defined as above the constraints (4) assure that each link can be in one energy-aware state, the constraints (5)–(7) determine the number of routers and cards used for data transmission. The constrains (8)–(10) are formulated according to Kirchhoff's law applied for source, transit, and destination routers, and the constraint (11) assures that the flow will not exceed the capacity of a given link. In the effect of optimization, all components are put in energy states just appropriate to handle the traffic load, without unjustified waste of power. See Fig. 1b where an example power state activation strategy is presented.

To decrease the complexity and size of defined above optimization problem, a formulation of the network energy saving problem in proposed in [25] that is based on subsequent flows aggregations.

3.3. Optimization for Profiles Approximated by Piecewise Linear Functions

Let us assume that power profile of each link is a piecewise linear approximation of the correlation between an amount of transmitted data and energy consumed by a link. Such a model can be defined as follows (see Fig. 2a):

$$P_{ek}(q,k) = \begin{cases} P_{e1} & \text{if} \quad q = 0, \\ \alpha_{ek} + \gamma_{ek} q & \text{if} \quad q > 0, \end{cases} \tag{12}$$

where α_{ek} and γ_{ek} are coefficients of linear empirical approximation in k-th energy state, $k = 2, \ldots, K$.

The problem of energy-efficient network configuration, i.e. optimal routing and choosing energy states, for router and linecard power profiles as in (2), and the link link profiles as in (12), is stated as follows:

$$\min_{x_r, x_c, x_{ek}, u_{ed}} \Bigg[P_{\text{net}} = \sum_{e=1}^{E} \sum_{k=1}^{K} P_{ek} x_{ek} + \tag{13}$$

$$+ \sum_{e=1}^{E} \frac{\psi_{ek}(q_{ek})}{q_{ek}} \left(\sum_{d=1}^{D} V_d u_{ed} - \sum_{k=2}^{K} q_{ek} x_{ek} \right) +$$

$$+ \sum_{c=1}^{C} P_c x_c + \sum_{r=1}^{R} P_r x_r \Bigg],$$

subject to the constraints (4)–(11). P_r, P_c, P_{ek} denote the fixed power consumed by router, line card and link, as in (3), while ψ_{ek} is the linear power profile in the energy state k.

In optimal configuration, each link is in a state that is adequate to its traffic load (cf. actual power profile in Fig. 2b), giving power savings wrt. the case with unmanaged ports, configured for best throughput.

3.4. Optimization for Stepwise Profiles, Relaxed to Continuous Formulation

Although the approach presented in Subsection 3.3 is easier to solve thanks to fewer constraints, it turns out to be still too complex for medium-size networks. In [7], the authors propose to apply a widely used technique of problem relaxation to continuous case, to cope with the complexity. The problem presented in Subsection 3.2 gets reformulated, with the decision variables x_r, x_c, x_{ek} and u_{ed} made continuous:

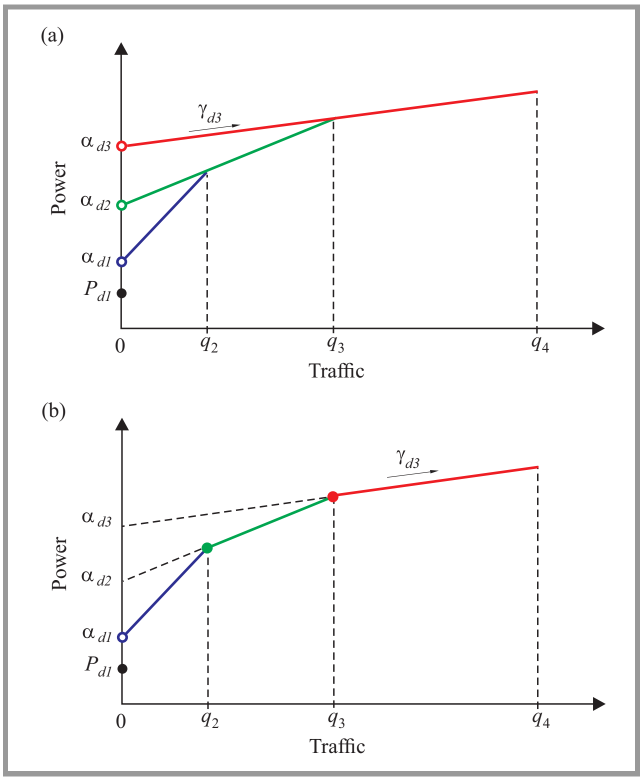

Fig. 2. Power consumption model – K energy states and piecewise linear approximation.

$$\min_{x_c, x_{ek}, x_r, u_{ed}} \left[P_{\text{net}} = \sum_{r=1}^{R} P_r x_r + \sum_{c=1}^{C} P_c x_c + \sum_{e=1}^{E} \sum_{k=1}^{K} P_{ek} x_{ek} \right] \tag{14}$$

subject to the constraints (7)–(11) and additional constraints:

$$\forall_{e \in \{1,\ldots,E\}} \quad x_{e1} \geq x_{ei} \geq \ldots \geq x_{eK}\,, \tag{15}$$

$$\forall_{\substack{e \in \{1,\ldots,E\} \\ k \in \{1,\ldots,K\} \\ c \in \{1,\ldots,C\}}} \quad \sum_{p=1}^{P} l_{cp} a_{ep} y_{ek} \leq x_c\,, \tag{16}$$

$$\forall_{\substack{e \in \{1,\ldots,E\} \\ k \in \{1,\ldots,K\} \\ c \in \{1,\ldots,C\}}} \quad \sum_{i=1}^{I} l_{ci} b_{ep} x_{ek} \leq x_c\,, \tag{17}$$

In the above formulation the power consumption and link load, for link e in state k, are related in the form of an incremental model wrt. the state. The current values of P_{ek} and q_{ek} are calculated recursively: $P_{ek} = pow_e(k) - pow_e(k-1)$ and $q_{ek} = load_e(k) - load_e(k-1)$, where $pow_e(k)$ is the power taken by link e in state k, and $load_e(k)$ is the respective link load. It is also assumed that each link supports more than one energy state. To account for that, the constraint (15) for loads in various states was added. Additionally, the utilized throughput in subsequent states must be sorted. The constraints (16) and (17) guarantee that x_r, x_c will effectively take binary values only.

Although this approach is much easier to solve thanks to decision variables continuity, it is hard to find a sufficiently efficient optimization routine for real-sized networks. The widely used approach to solve such complex optimization problems is to employ heuristics [23], [26]–[28]. A heuristics that proved capable to solve the relaxed optimization problem (14)–(17) was reported in [7], [29].

3.5. Energy Optimization Problem – Discrete Formulation and Utility Function

All the above optimization problem formulations share the disadvantage of relying heavily on the assumption that the origin-destination traffic, V_d is known. In practice, however, its estimation, let alone the prediction, is very costly and error prone. It happens because of the nature of the traffic: flows are self-similar, long-tailed and correlated, which makes the classical, general and elegant estimation method [30] completely useless here. Contemporary approaches try to employ principal component analysis [31], traffic sampling on selected links [32] and traffic mixture identification [33] to do the job, but without apparent success worth the measures taken.

Therefore, it has been proposed in [34], [35] to redefine the optimization problem as a two-criteria one, and to employ the notion of user utility function (i.e. valuation of transmission service) instead of an inflexible traffic demand vector. The reformulated optimization problem is in fact a mixture of the original goal function from (3), taken with weight α, and the total user utility, calculated over all flows and taken with weight $1-\alpha$. The utility can be perceived as a QoS-related criterion, Q_d for each flow d, which represents a penalty for not meeting the demanded flow rate V_d. $Q_d(v_d)$ is a convex and continuous function, decreasing in interval $[0, V_d]$. It is reaching its minimum (zero) at V_d, i.e. the point where user expectations are fully satisfied. Finally, the two criteria – power and QoS – get scalarized into a mixed integer problem of bandwidth allocation and routing:

$$\min_{\substack{x_r, x_c, x_{ek}, u_{ed}, v_d \\ r\in\{1,\dots,R\}, \\ e\in\{1,\dots,E\}, \\ k\in\{1,\dots,K\}, \\ d\in\{1,\dots,D\}}} \Bigg\{ P_{\text{net}} = \tag{18}$$

$$= \alpha \left[\sum_{e=1,3,5,\dots}^{E-1} \sum_{k=1}^{K} P_{ek} x_{ek} + \sum_{c=1}^{C} P_c x_c + \sum_{r=1}^{R} P_r x_r \right] + $$

$$+ (1-\alpha) \sum_{d=1}^{D} Q_d(v_d) \Bigg\},$$

subject to constraints (5)–(8) and the following additional constraints:

$$\sum_{d=1}^{D} v_d u_{ed} \le \sum_{k=1}^{K} q_{ek} x_{ek}, \; e = 1,3,\dots,E-1, \tag{19}$$

$$\sum_{d=1}^{D} v_d u_{ed} \le \sum_{k=1}^{K} q_{\tilde{e}k} x_{\tilde{e}k}, \; e = 2,4,\dots,E, \tag{20}$$

$$0 \le v_d \le V_d, \; d \in \{1,\dots,D\}. \tag{21}$$

4. Control Frameworks for Dynamic Power Management

Various control frameworks for dynamic power management of the backbone network through energy-aware routing, traffic engineering and network equipment activity control have been designed and investigated [7], [8], [10], [36], [37]. They utilize smart standby and dynamic power scaling, i.e. the energy consumed by the network is minimized by deactivation of idle devices (routers, line cards, communication ports) and by reduction of the speed of link transfers. Implementation of such framework is described and discussed in [7]. It is assumed there that network devices can operate in energy-aware states differing by power usage (2). Two implementations: of a centralized and of a hierarchical framework operate at two control levels:

- local control level – algorithms executed by networking devices.
- central control level – algorithms executed in a dedicated node that controls the whole infrastructure.

4.1. Hierarchical Implementation Architecture of the Proposed Optimization Problems

In case of optimization problems formulated in Subsections 3.2 and 3.4, one may balance the scope of decisions made at central and local levels. In the centralized approach, the suggested power states of network devices are broadcast by the central unit, along with the optimal MPLS paths. Then, the activity of a local controller is reduced to effectuate central control signals, taking into account constraints related to current local load and incoming traffic. Meanwhile, in the hierarchical scenario the central unit does not directly force the configuration of the devices, specifying MPLS paths only. Then the local algorithms optimize the configuration of each component autonomously in order to achieve a preset trade off between power consumption and performance.

Usefulness and efficiency of the two abovementioned optimization problem formulations were verified by simulation and by laboratory tests for networks of various sizes and topologies, yielding power saving up to 50% in some cases.

4.2. Distributed Approaches

For practical reasons (scalability, reliability, protocols available) distributed control over the routes as well as individual configurations is an appealing alternative approach.

Distributed energy-aware network control algorithms extend existing mechanisms, as routing protocols (OSPF, BGP, MPLS) – cf. [37], [38], [39]. An important advantage from close cooperation with signaling protocols is that the network state can be observed easily, and may be used further to estimate flows and to reconstruct the traffic matrix [26].

The algorithm proposed in [40] brings selected nodes down or up; leaving the job of optimal routing to standard OSPF protocol. Classification of the nodes and links into "up" and "down" sets can be done by two heuristic algorithms – the more complex finds cliques in network graph in order to determine which parts of the network can be brought down with the least impact on QoS. The other one simply switches off the least loaded link or node. Simulations prove that the earlier approach gives much better performance. The algorithm has many practical advantages. In particular, it can be implemented in one designated router, while the remaining routers in the OSPF area simply implement the shortest path tree calculated and broadcast by it.

GRiDA algorithm [41] is an agent-based approach, where agents, or homogeneous autonomous local control algorithms, decide upon links that can be switched off in order to save power without impacting performance. Their strategy follows machine learning scheme: if shutting down a link causes congestion, the agent's decision is remembered as a wrong one. Agent algorithm incorporates much practical experience and detailed knowledge of energy profile of the device being under its control. Unlike in [40], it does not take into account information from the routing process itself, i.e. network topology and current routing paths.

Another interesting agent-based heuristic approach to energy-efficient traffic routing is proposed in [8]. Like in [40], agents cooperate closely with local OSPF processes, putting down or up local links. For a decision to be made, agents maintain three lists of links:

- that must be permanently switched on in order to maintain network connectivity,
- that have been switched off in order to reduce power consumption,
- that must be switched on in order to prevent congestion ("bypass" links).

Four strategies for link deactivation are proposed, of varying complexity and demand for extra information about the network state:

- LLL – switch off least loaded link in the network,
- LTL – switch off the least traversed link, i.e. with least number of flows using it,
- LDB – switch off the link that would cause the minimum increase of the total of traffic route lengths,
- LDM – switch off the link that would cause the minimal increase of the total of traffic volume over all links.

The proposed strategies for link activation in case of an overload, are as follows:

- RL – roll-back last deactivation,
- RB – activate the link that would cause the maximum decrease of the total of traffic route lengths,
- RM – activate the link that would cause the maximum decrease of the total of traffic volume over all links.

Performance of reasonable pairs of strategies has been examined, showing that perfect knowledge about the origin-destination matrix (LDM, RM) improves energy savings not much more than when simple local heuristics are applied. On the other hand, imperfect or inappropriate information about origin-destination matrix (LDB, RB) can make the things worse than in case when there is no energy-saving algorithm running at all. The proposed approach is viable to implement on any routing device, through command line and basic OSPF protocol.

An interesting alternative approach which also relies on OSPF operation is presented in [42], where non power saving routers coexist in the network with the power saving ones (PSRs). One of PSRs is selected as the coordinator; the remaining ones try to go offline when their local load is below a threshold – provided that network connectivity be maintained. Coordinator role is to schedule PSRs attempts. While in power-save state, a PSR wakes up periodically to observe the transit traffic it receives after having joined the network again. The approach has been verified through simulation, resulting in overall energy savings up to 18%.

5. Conclusion

The authors have shown here selected but representative approaches to save power in wired IP networks. The solutions can be put roughly into two classes: the proactive ones (Section 3) assume deep knowledge of the technology and the network state, put high technological requirements on the networking devices, and employ advanced optimization techniques to squeeze as much energy savings as possible. Those in the other class (Section 4) might be named the reactive ones: they try to supplement the already well rooted technologies (OSPF), which originally had nothing common with energy saving, with an energy-saving extra layer that tries to do its best with neither traffic matrix knowledge nor capability to choose among versatility of power states of each component. The only means of control there is to switch a device on or off, completely.

Both classes are valuable. While the proactive one constitutes the technological avant-garde (and is still lacking efficiency for larger problems), the reactive tries to makes makeshift but practical, "green" heuristic improvements to the networks in their current technological state.

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