CONTROL FRAMEWORK FOR HIGH PERFORMANCE ENERGY AWARE BACKBONE NETWORK

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ABSTRACT

Global optimization of the energy consumption in heterogeneous environments has been recently an important research issue in wired and wireless networks. This paper presents a general framework for flexible and cognitive backbone network management which leads to the minimization of the energy utilized by the network. The policy for activity control of all the modules and elements that form a network is introduced and discussed. The idea of the system is to achieve the desired trade-off between energy consumption and network performance according to the traffic load.

INTRODUCTION

Nowadays, information communication technology sector belongs to the group of the big power consumers. Enabling the reduction of energy requirements of wired network is the goal of many research groups in the field of computer networks. There are two main motivations that drive the quest for "green" networking: environmental one, related to the reduction of wastes and impact on CO^2 emissions, and the economic one, stemming from the need of operators to reduce their operational costs. In the last years, large amount of telecoms, Internet service providers and public organizations reported statistics of network energy requirements and the related carbon footprint, showing a growing trend (Bianco et al., 2007; Roy, 2008). For example energy consumption of Telecom Italia network has reached more than 2TWh (1% of the total energy demand in Italy) in 2006, British Telecom 2.6 TWh in 2008, Deutsche Telekom more than 3.5 TWh, and the energy requirement increases every year. Similar trends can be observed in other telecoms and service providers. On the other hand, to support a new generation network infrastructures and related services, telecoms and service providers need a larger number of devices, with sophisticated architectures able to perform more complex operations in a scalable way. Hence, as the Future Internet is taking shape, it is recognized that, about other basic concepts and key aspects, energy awareness is an important part of the network design and management. The main challenge is to design, develop and test novel technologies, integrated control strategies and mechanisms for network equipment enabling energy saving by adapting network capacities and resources to current traffic loads and user requirements, while ensuring end-to-end Quality of Service.

In the recent years various efforts in the green networking field have been undertaken both in the research and industry domain (Bolla et al., 2009, 2010; Chiaraviglio et al., 2009; Coiro et al., 2011; Goma et al., 2011; Zhang et al., 2010). A broad spectrum of green networking activities and scientific projects are carried out. The research focuses on energy aware infrastructures, energy aware applications, energy aware transmission and adaptive control of activity of devices that form a network.

GREEN NETWORKING – RELATED WORKS

Modeling Energy Consumption of Network Devices

The main issue in the design of an efficient power consumption model for wide area networks is the analysis of the multilayer network architecture and classification of all network components based on the power consumption criterion. A significant amount of energy in networks are consumed by all types of IT devices. Physical resources and access points utilize more than 90% of the total power used in the whole network (Chiaraviglio et al., 2009; Goma et al., 2011). The rest of the

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energy is consumed by the core of the system. The modern power management methodologies must deal with the optimization of the energy utilized at all levels of the network structure. In numerous works on the measurements and modeling of network devices (see. e.g. (Zhang et al., 2010; Coiro et al., 2011; Sivaraman et al., 2011; Chabarek et al., 2008)) the authors propose various formal models for the network management, with power consumption and device load as the main optimization (management) criteria. The load of the data transmission nodes of the network such as routers, is usually defined as a measure of the aggregate traffic transmitted by this device. The loads of physical computational node is usually measured by the amount of processed jobs. The generic model of the power management in such system may be defined as follows: $P(l) = P_0 + f(l)$, where l is a traffic or computation load, P_0 is a power consumption in the idle state (this parameter is constant for a given network) and f is an increasing load function. In the simplest cases, the function $f(l)$ is linear (Qureshi et al., 2009), that is to say:

$$f(l) = \frac{P_{max} - P_0}{l_{max}} \cdot l \qquad (1)$$

where: l_{max} indicates the maximal load of the devices in the network, and P_{max} is a power consumption under the maximum load. In complex networks the load function f is usually defined as nonlinear, (Qureshi et al., 2009) polynomial (Bolla et al., 2009) or stepwise function (Vasić and Kostić, 2010).

The main aim of 'green' networking is minimizing the energy required to achieve a given task or service while maintaining the same or similar performance level. Power scaling and standby capabilities are commonly used to decrease energy demands. The *smart standby* capability method assumes putting a device in very low energy mode, in which it can provide only some vital functionalities. Therefore, standby capability can be applied to those devices that will be not used for a longer period of time. The *dynamic power scaling* is the capability of reducing the energy requirement of a network device by scaling its performance. Two main families of power scaling approaches can be distinguished:

- adaptive rate techniques (AR) – scaling the device's processing capacity or the transmission or reception speed of the network interface,
- low power idle techniques (LPI) – exploiting the short inactivity periods by putting a given device into low power state.

Most personal computers follow ACPI (Advanced Configuration and Power Interface) (Intel, 2010) specification defining a number of power-aware states attained via scaling down processor voltage and clock frequency and idle states when processor is in stand-by mode. Similar propositions for network interfaces (Bolla et al., 2010), (Nedevschi et al., 2008) include employing AR and LPI techniques. Partial implementation of these ideas is 802.3az standard (IEEE, 2012), which defines implementation of LPI for Ethernet interfaces.

It must be noted that for typical network devices the correlation of power consumption and load is weak. It is due to the fact that most of currently available network equipment does not implement any energy saving mechanism. The changes in power consumption may be attributed only to e.g. necessity to change state of transistor keys more often when the load is heavier. The detailed analysis of power dissipation in electronic elements building FPGA router may be found in (Sivaraman et al., 2011). Another problem is relatively large fixed part of energy consumed in the idle state (P_0), which in typical router is needed not only by interfaces but also processors, switching fabric, power supplies and cooling fans, some of these elements being doubled or multiplied for redundancy. It is viable that new equipment will be more energy effective both due to introduction of LPI techniques and better electronics or moving more tasks to passive optical devices, however even greater energy savings may be obtained via optimization and control of the whole network.

Network-wide Reduction of Energy Consumption

Energy aware mechanisms mentioned in the previous section, if introduced, can help to reduce the power consumed by single links, e.g. ports of two routers connected via pair of fibers. However, it is not necessarily true, that adoption of such techniques will result in significant reduction of energy needed by the whole network. On the other hand it is obvious that, at least in the periods of low traffic, some links could be switched off or operate at lower rate, as typical telecommunication networks, specifically in the core part, have redundant links. Additional source of redundancy of some sort are bundled links, i.e., links composed of number of fibers to multiply their bandwidth. Such links can be relatively easy and safely scaled down by switching off some of fibers – even without modification of existing equipment (Fisher et al., 2010). The straightforward solution is to formulate a mathematical programming task – namely optimal routing problem with a cost function defined as a sum of energy consumed by all components of the network. The solution of this task can be used, usually in repetitive manner to decide which of network elements can be switched off or operate at lower rate (Idzikowski et al., 2010) which is often referred as Green Traffic Engineering (Vasić and Kostić, 2010). Therefore, it is possible to build centralized network control system for decreasing the overall energy consumption. Such optimization problem is however much more difficult to solve than typical routing task as selection of paths is not independent, contrary paths should be aggregated allowing to move traffic out of some links and switch them off. The energy consumption functions are often non-convex increasing complexity of the problem which itself cannot be solved by standard methods of convex programming due to presence of integer variables. As the result fully formulated problem is *NP*-complete, while relaxing some constraints introduces sub-optimality or e.g instability (Vasić and Kostić, 2010) of the system. Optimization of energy consumption for large scale networks can be done mainly with heuristics. Various methods are proposed in literature. Simple algorithm which extends single device strategies to network-wide control is presented in (Bianzino et al., 2011). Two stage methods incorporating solving of simpler (usually relaxed) mathematic programming tasks for preselected conditions – usually for a set of active links or paths – are described adequately in (Chiaraviglio et al., 2009; Fisher et al., 2010) and (Zhang et al., 2010; Shen and Tucker, 2009).

Another issue is applicability of such a scheme in the real network where the most common approach is decentralization of control. A complex nature of interconnections that involves many constraints prevents application of direct decomposition (e.g. based on spatial separation) while non-convexity of a cost function makes application of the Lagrange relaxation difficult. Therefore, most of distributed control strategies employ various heuristics that can operate independently or can be used to extend the existing routing protocols – e.g OSPF (Bianzino et al., 2011), (Cuomo et al., 2011), BGP and MPLS. Adoption (and extension) of some signalling infrastructure allows to partially overcome absence of traffic matrix needed to compute flows (Chiaraviglio et al., 2009), and replace this information with observation of the past state of a network (Bianzino et al., 2011).

LOW ENERGY CONSUMPTION NETWORK

We have designed a control framework for high performance energy aware backbone network. The smart standby and dynamic power scaling techniques described in the previous section are employed in our system.

Framework for Power Control

One of the main goals of our project is to design and develop a control framework to reduce the energy requirements of wired network equipment. This framework should provide central and local control strategies and simple internal interface for exchanging data among elements of the network and implementing the decisions of the control units. The architecture of this framework is presented in Fig. 1. It consists of four main components:

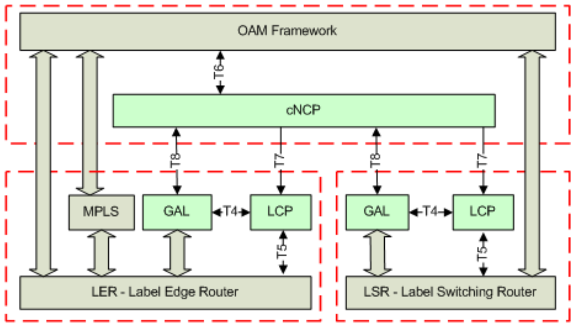

Figure 1: Control framework architecture and data flow.

1. Monitoring and Operation Administration & Management (OAM). The framework that provides monitoring the behavior of the deployed network, and plays a role of middleware between the other components of the system. It should support MPLS TE technology.

2. central Network-wide Control Policy (cNCP). The decision process which goal is to optimize the behavior of the whole network w.r.t. energy consumption. The optimization problem is formulated and solved for a given network topology and expected demands of users. The measurements of current traffic are utilized in calculations. The outcome of cNCP is the routing table for MPLS protocol.

3. Local Control Policy (LCP). The decision process, which objective is to optimize the configuration of the device in order to achieve the desired trade off between energy consumption and performance according to the incoming traffic load measured by OAM framework. The outcome of LCP is calculated based on knowledge about internal architecture of the device, the capability of energy-aware elements and incoming flow. Both cNCP and LCP form control plane layer.

4. Green Abstraction Layer (GAL). The functional abstraction layer – the standard interface between monitoring, control and hardware for exchanging data regarding the power status of the device. The objective is to hide the implementation details of

energy saving approaches, as well as to provide standard interfaces between energy aware technologies and monitoring and control frameworks. The main objective of GAL is to transform the outcome of LCP into power-management configuration of a given device (e.g. shutting off a given card or a given link).

Various control strategies can be applied to manage energy-aware networks. A brief survey of proposed techniques was presented in the previous section. In the next section we formulate the optimization problem that can be applied in cNCP layer of our framework. Our formal statement is similar to the topological design problem for MPLS networks presented in (Pióro et al., 2001). In our approach we assume that the network topology and expected demands are known during the decision calculation.

Network-wide Control Problem Formulation

Let us consider a backbone network formed by the routers labeled with by $r = 1, 2, \ldots, R$. The routers are classified into two groups: transit and edge routers. We provide a hierarchical representation of a router. The router is composed of cards labeled with $c = 1, 2, \ldots, C$, each card can contain a number of ports. All pairs of ports from different routers and cards are linked by direct links labeled with $e = 1, 2, \ldots, E$. Each element can operate in various energy-aware states that are related to the application of standby and power scaling techniques – we distinguish active states of a device, sleeping state and switched off, Fig. 2. The energy-aware states are defined as power settings. These states are labeled with $k = 1, 2, \ldots, K$. We assume that at a given time two ports connected by the link e are in the same energy-aware state k. ξ_{ek} denotes an energy consumption associated with the state k. It depends on a current throughput. Hence, ξ_{ek} implements the power profile model – a stepwise function defining power consumption due to a given throughput. The throughput of the link e in the state k is defined as M_{ek}. Moreover, we assume fixed energy costs associated to routers T_r and cards W_c.

The demands imposed on the network and labeled with $d = 1, 2, \ldots, D$ are transmitted by means of flows allocated to given IP/MPLS path under QoS (Quality of Service) requirements. Two nodes (ports): s_d (the source edge node) and t_d (the destination edge node) are associated with each demand; the volume of demand is equal h_d. The set of paths for each demand d may be defined as the set of all paths between nodes s_d and t_d. We assume that all demands between edge routers are given. The energy aware network management problem can be

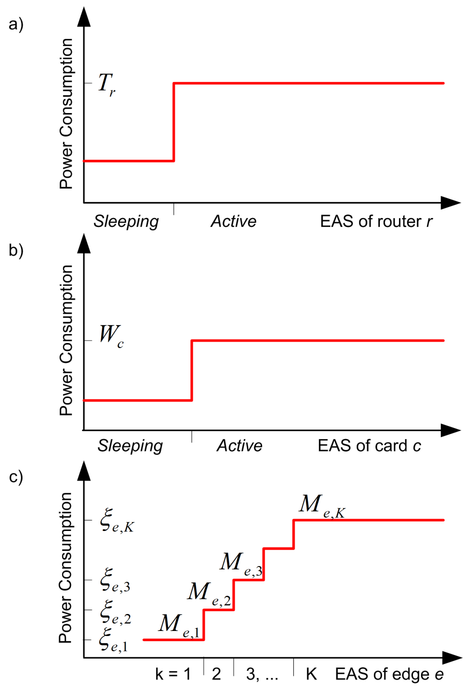

Figure 2: Operating behavior of an Energy Aware States (EAS) – various devices.

formulated as the following mixed-integer optimization problem:.

$$\min_{x,y,z,u_{de}} \{F = \sum_e \sum_k \xi_{ek} y_{ek} + \sum_c W_c x_c + \sum_r T_r z_r\} \tag{2}$$

subject to the following constraints:

$$\forall_e \quad \sum_k y_{ek} \leq 1 \tag{3}$$

$$\forall_{d,c} \quad \sum_p l_{cp} \sum_e a_{ec} u_{dc} \leq x_c \tag{4}$$

$$\forall_{d,c} \quad \sum_p l_{cp} \sum_e b_{ec} u_{de} \leq x_c \tag{5}$$

$$\forall_{r,c} \quad g_{rc} x_c \leq z_r \tag{6}$$

$$\forall_{d,p=s_d} \quad \sum_e a_{ep} u_{de} - \sum_e b_{ep} u_{de} = 1 \tag{7}$$

$$\forall_{d,t_d,p\neq s_d} \quad \sum_e a_{ep} u_{de} - \sum_e b_{ep} u_{de} = 0 \tag{8}$$

$$\forall_{d,p=t_d} \quad \sum_e a_{ep} u_{de} - \sum_e b_{ep} u_{de} = -1 \tag{9}$$

$$\forall_e \quad \alpha_e \sum_d h_d u_{de} \leq \sum_k M_{ek} y_{ek} \tag{10}$$

indices:
$r = 1, \ldots, R$ backbone routers in a network,

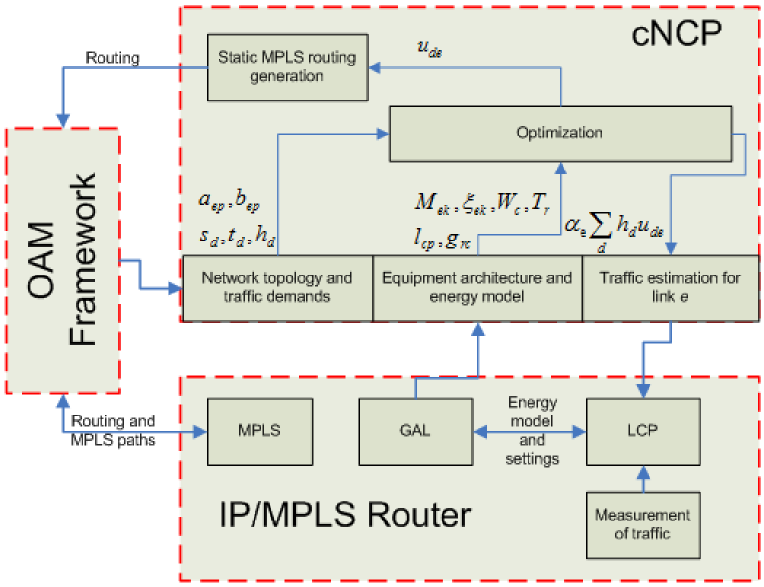

Figure 3: The control plane operation.

$c = 1, \ldots, C$ modules (cards) in a network,
$p = 1, \ldots, P$ ports in a network,
$e = 1, \ldots, E$ links (between two ports),
$d = 1, \ldots, D$ demands,
$k = 1, \ldots, K$ energy-aware states of links.

constants:
g_{rc} = 1 if card c belongs to router r (0 otherwise),
l_{cp} = 1 if port p belongs to card c (0 otherwise),
a_{ep} = 1 if direct link e is outgoing from port p (0 otherwise),
b_{ep} = 1 if direct link e is incoming to port p (0 otherwise),
h_d volume of demand d,
s_d origin edge node (port) for demand d,
t_d destination edge node (port) for demand d,
M_{ek} capacity of link e in energy-aware state k,
ξ_{ek} cost of energy of link e in energy state k (sum of energy costs of two ports connected via link e),
W_c fixed cost of energy of card c,
T_r fixed cost of energy of router r,
$\alpha_e \in < 0, 1 >$ overbooking factor.

variables:
u_{de} =1 if path d belongs to link e,
y_{ek} =1 if link e is in energy-aware state k,
x_c =1 if card c is used to data transmission,
z_r =1 if router r is used to data transmission.

The constraints defined in Eq. (3) assure that each link can be in one energy state, the conditions specified in Eqs. (4), (5) and (6) determine number of cards and routers that have been used to data transmission. The constrains (7), (8) and (9) are defined according to the Kirchhoff's law applied for source node, transit node and destination node. Finally, Eq. (10) assures that the flow does not exceed the capacity of a given link. In this problem the cumulative cost of the energy utilized in the system for finalizing all network operations is assumed to be minimized.

Concluding, as the solution of the problem (2) – (10) we obtain a set of active routers and cards, and the routing table for the MPLS protocol that minimizes the energy consumption in a network and fills all constraints, mainly concerned with expected QoS. Fig. 3 depicts the implementation of the control plane strategy in the control framework defined in this paper. Note that the above optimization problem is known to be *NP*-complete, therefore one can not expect to find time efficient algorithm for exact solving of this problem for large size networks. Techniques based on branch-and-bound approach are proposed for solving smaller size, and similar problems. For more realistic size of networks the formulation (2) – (10) is often relaxed and various heuristics are employed.

Case Study Results

We validated our control framework through simulation We solved the optimization problem (2) – (10) for three network configurations, examples E1 - E3 describing different model size, i.e., E1: r = 6, c = 8,

e = 10, d = 7, k = 5; E2: r = 12, c = 16, e = 20, d = 14, k = 5; E3: r = 18, c = 24, e = 30, d = 15, k = 5; where r, c, e, d, k denote respectively numbers of routers, cards, links, demands and energy-aware states. The branch-and-bound implementation – Lp_solve (http://lpsolve.sourceforge.net/5.5/) was used to calculate the optimal solutions. All tests were performed on Intel Core2 Duo CPU, 2.2 GHz, 2GB RAM. The detailed description of the problems E1 - E3, i.e. their dimensions and complexity are given in Table 1. Moreover, the table presents the execution times for all examples. The results indicate that the calculation time

Task	n_var	n_const	$B\&B\ nodes$	$time$ in [s]
E1	134	182	1608	0,415
E2	408	672	46627	90,820
E3	642	1074	186985	652,575

n_var - number of decision variables, n_const - number of constraints, $B\&B\ nodes$ - number of calculated subtasks generated by the Lp_solve, $time$ - time of calculation in seconds.

Table 1: Problem complexity and results of calculations.

strongly depends on the complexity of the optimization problem. It is obvious that complexity of the problem grows with the size of the network to be considered. It was observed that d (number of demands) is a key parameter that seriously increases the calculation time. From the depicted results, we can see that simplified formulation of the problem and more efficient branch-and-bound implementation supported by efficient heuristics must be considered, especially for medium and large networks. The second approach to speed up calculations is parallel implementation of the optimization task.

SUMMARY AND CONCLUSION

This paper presents the control framework for energy-aware wired networks. We designed hierarchical control structure composed of two decision layers, namely central control layer, which is responsible for the power management in the whole network, and local control layer, which is responsible for the management of the configuration of individual network devices. We formulated a topological design problem for IP/MPLS networks under the assumption of applying standby and power scaling techniques in order to reduce the cumulative energy consumption in a network. This problem is indicated as *NP*-complete challenging optimization task, and very difficult for many conventional optimization methods, such as deterministic branch-and-band algorithms. The simplification of the problem formulation and application of the metaheuristic solvers, and integration of these methods and models with OMNetC++ (http://www.omnetpp.org/) based network simulator is one of the main aims of our recent research. We plan to provide a comprehensive empirical evaluation of the proposed control structure in the testbed network.

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