

On formulation of a network energy saving optimization problem

Piotr Arabas, Krzysztof Malinowski and Andrzej Sikora

Institute of Control and Computation Engineering

Warsaw University of Technology

Nowowiejska 15/19, 06-665 Warsaw, Poland

Email: parabas@ia.pw.edu.pl

Research and Academic Computer Network (NASK)

Wawozowa 18, 02-796 Warsaw, Poland

Email: Piotr.Arabas@nask.pl

Abstract—Possible formulations of mathematical programming problem concerning energy aware network are presented. Two main possibilities of reducing problem complexity are analysed: allocation of predefined paths and reformulation of task using continuous variables. Properties of both methods are analysed and hybrid formulation is proposed. Comparison of complexity is provided.

I. INTRODUCTION

Network optimization concerned with operational traffic management in existing data networks is typically oriented towards either maximizing throughput in congested networks, while providing for adequate transmission quality, or towards balancing the traffic so as to maintain possibly large free capacity for carrying additional (new) traffic. Related optimization problems are then formulated with the use of concave utility functions to be maximized and linear constraints, thus defining convex optimization problems (e. g. [1], [2], [3]). Such well behaved, convex, problems may be rather easily solved using, in particular, decomposition methods with price coordination [4].

Situation, in which one becomes interested in network operation oriented towards saving the energy, especially during periods when the network is not carrying heavy traffic, is vastly different. In such case it would be proper to switch off as many routers, interface cards and communication ports as possible, and to reduce link transfer speeds to minimize the energy usage. This must be done, obviously, while providing for required data transfers of specified quality. It is clear that instead of balancing traffic during energy saving period it will be required to concentrate data transfers along as few routes as possible and to switch off as many energy consuming components as feasible.

In this paper we want to present and discuss several formulations of a centralized operational network energy saving problem. We begin with formulation of a rather simple problem with continuous variables. Then we present another optimization problem formulated with the extensive use of binary variables – this formulation allows for a complete set of energy saving decisions to be considered along with full traffic routing. This problem, having a very large number

of discrete variables, may appear too difficult to solve in case of networks of realistic size. Thus, it appears useful to consider a hybrid formulation, with a limited number of binary variables and with continuous variables representing capacities assigned to particular links – which then may be related to decisions concerning desired energy states of those links. This paper does not present solution techniques for the problems considered as well as example case studies; they are currently being under investigation.

II. GREEN NETWORKING – RELATED WORK

The problem of reducing power consumed by telecommunication networks becomes important as equipment usage demands more and more energy. For example in 2009 energy consumption of Telecom Italia network has reached more than 2.1 TWh [5], France Telecom 3.7 TWh [6] and Telefonica 4.5 TWh [7]. In such situation the need of reduction of energy consumption is obvious for both environmental and economic reasons.

Much work has been done in last years to curb energy consumed by an elementary physical device (e.g. network interface), the most visible result may be the adoption of energy aware standard for Ethernet – 802.3az [8]. However, it is not necessarily true that such techniques will result in a significant reduction of the energy needed by the whole network. On the other hand it is obvious that, at least within 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 and bundled links, i.e., links composed of a number of fibers to multiply their bandwidth. Such links can be relatively easy and safely scaled down by switching off some of the fibers – even without modification of the existing equipment [9]. Solving the resulting task may be, however, difficult as it was stated in Sec. I. Propositions which can be found in the literature call mainly for various heuristics. Among them it is possible to distinguish two stage methods incorporating solving of simpler (e.g. relaxed) tasks for preselected conditions – usually for a set of active links [10], [9] or paths [11], [12]. A step ahead is to build decentralised algorithms operating independently

or as an extension to the existing routing protocols – e.g. OSPF [13], [14]. Adoption (and extension) of some signalling infrastructure allows also to partially overcome the absence of traffic matrix needed to compute demands [10], and replace this information with observation of the past state of the network [13].

What is presented in this paper is an attempt to systematically, by analysing simpler and more complex formulations, find out one which could be solved in acceptable time and with accuracy necessary to implement the solution in the real system. By doing this we do not negate need for heuristics and decomposition – on the contrary, we hope that appropriately constructed task could be decomposed and used to derive decentralised or hierarchical control strategies.

III. ENERGY SAVING NETWORK OPERATION PROBLEM WITH COST FUNCTIONS RELATED TO AGGREGATE LINKS AND CONTINUOUS VARIABLES

We assume that in order to achieve the reduction of energy usage the following decisions can be made, while providing for required serviceability of the network:

- to switch off, whenever possible, core or – occasionally – edge routers,
- to switch off, within any given router, as many interface cards as possible,
- to switch off, within any interface card, as many ports as possible,
- to slow down transmission speed over links between specified output and input ports, i. e. to reduce the energy consumption at those links; several energy states of each link may be taken into account.

The above decisions define a hierarchy of energy saving actions. Let us, however, begin with a problem that one might call a reverse congestion problem – when one just wishes to concentrate traffic along as few links as possible to be able then to switch off as many energy consuming active devices as possible. To formulate this problem we assume that the energy consumption (cost) functions associated with aggregate links between routers may in a reasonable way approximate the actual costs of operating aggregate link interface ports, cards and routers.

A. Formulation with predefined paths: TALCA – Traffic Allocation and Link Capacity Assignment

This problem is stated in terms of continuous variables, with strictly concave cost functions to be minimized. The links are aggregated and the constraints are linear. Solution of such problem with strictly concave cost function over convex (simplex) feasible set might be approached by choosing a vertex point of a feasible set with the smallest value of the performance function. The problem is as follows:

$$\min_{\substack{0 \leq x_{i,k}, \\ k \in P(i)}} \sum_{l=1}^L h_l(y_l) \quad (1)$$

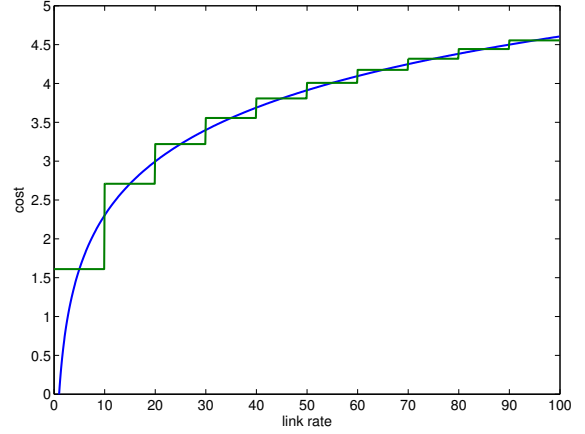


Fig. 1. Link cost function (green step-wise line) and its smoothed estimate (blue line) used in the formulations with continuous link rate.

subject to the following constraints:

$$\forall_{i=1,\dots,N} \sum_{k \in P(i)} x_{i,k} = x_i^* \quad (2)$$

$$\forall_{l=1,\dots,L} \sum_{(i,k) \in S(l)} x_{i,k} \leq y_l \quad (3)$$

where:

$i = 1, \dots, N$	source-sink pairs,
$l = 1, \dots, L$	links,
$P(i)$	predefined set of paths for i -th source-sink pair,
$x_{i,k}$	part of traffic between source sink pair i directed through the path $k \in P(i)$,
y_l	transmission speed of link l ,
$S(l)$	set of (source-sink, path) pairs using link l : $(i, k) \in S(l)$ if path $k \in P(i)$ and path k includes link l ,
x_i^*	traffic generated by i -th source-sink pair,
$h_l(\cdot)$	strictly concave link operator cost function.

Such formulation of the problem allows to distribute flows between source-sink pair i over several paths chosen from set $P(i)$. This way provides for better utilisation of resources and minimizes the risk of traffic disruption. The energy consumed by the network is minimised by choosing appropriate speed of links which in this formulation substitutes the energy state of the link eliminating binary variables. The function $h_l(\cdot)$ is a smooth estimate of energy cost of the link (in monetary or simply power units) at a given transmission rate, which typically is step-wise function (see Fig. 1). Yet, the above problem might appear to be vastly oversimplified. In particular, it would be very difficult to build such cost functions that may properly account for the costs of operating the routers, and of keeping active or inactive the interface cards. The other issue is that of necessity to predefine the sets of possible paths for

all traffic relations. To avoid this one may transform problem TALCA to a form in which routing of all traffic relations is not predetermined.

B. Formulation with full routing: FRALCA – Full Routing and Link Capacity Assignment

The following problem is modification of the former problem (1)-(3) in which all possible paths are taken into account. To do so one has to solve routing task, hence the dimensionality of the problem is much higher due to both: larger number of variables and constraints. However, thanks to simplified description of energy consumption, it is still possible to avoid the binary variables.

$$\min_{y_l, x_{i,l}} \sum_{l=1}^L h_l(y_l) \quad (4)$$

subject to the following constraints:

$$\forall_{i=1,\dots,N} \sum_{j:j=s_i} x_{i,l} = x_i^* \quad (5)$$

$$\forall_{i=1,\dots,N} \sum_{j:j \neq s_i \text{ and } j \neq t_i} x_{i,l} = \sum_{l \in O(j)} x_{i,l}, \quad (6)$$

$$\forall_{i=1,\dots,N} \sum_{j:j=t_i} x_{i,l} = x_i^* \quad (7)$$

$$\forall_{l=1,\dots,L} \sum_{i=1}^N x_{i,l} \leq y_l \quad (8)$$

where:

$i = 1, \dots, N$	source-sink pairs,
$j = 1, \dots, J$	nodes,
$l = 1, \dots, L$	links,
$I(j)$	set of links incoming to the node j ,
$O(j)$	set of links outgoing from the node j ,
$x_{i,l}$	part of i -th relation traffic directed through the link l ,
y_l	transmission speed of link l ,
x_i^*	total traffic on the relation i ,
s_i	source node of relation i ,
t_i	destination node of relation i ,
$h_l(\cdot)$	strictly concave link operator cost function.

Additional constraints (5)-(7) constitute Kirchhoff law. Like in TALCA, it is possible to split traffic into several paths enhancing the reliability of the system. Also all variables are continuous, especially the transmission speeds, and so energy states are interpolated this way. However, as a result of this the issue of a stated hierarchy of energy saving decisions is not tackled. To do so we must consider another formulation with discrete (binary) variables.

IV. ENERGY SAVING NETWORK OPERATION; FULL

PROBLEM FORMULATION WITH DISCRETE VARIABLES

The following problems, stated in terms of binary variables, make it possible to properly and fully account for a stated hierarchy of energy saving actions. In these problems all possible

energy saving decisions are directly specified, together with decisions concerning traffic assignment to particular links. The links as considered in this case should not be confused with aggregate links of the previous formulations. Here the links are defined as physical conducts between given output and input ports on respective interface cards, they may operate at several energy states with respective data transmission speeds related to those states [15].

A. Formulation with full routing: FRRESA – Full Routing and Router Energy State Assignment

The energy aware network management problem can be formally stated as the following mixed-integer optimization problem. The goal of the problem is to minimize the energy cost of network operation.

$$\min_{y_{l,e}, v_c, z_r, x_{i,l}} \left[\sum_{l=1}^L \sum_{e=1}^E \xi_{l,e} y_{l,e} + \sum_{c=1}^C W_c v_c + \sum_{r=1}^R T_r z_r \right] \quad (9)$$

subject to the following constraints:

$$\forall_{l=1,\dots,L} \sum_{e=1}^E y_{l,e} \leq 1 \quad (10)$$

$$\forall_{i=1,\dots,N, c=1,\dots,C} \sum_{p=1}^P l_{c,p} \sum_{l=1}^L a_{l,p} x_{i,l} \leq v_c \quad (11)$$

$$\forall_{i=1,\dots,N, c=1,\dots,C} \sum_{p=1}^P l_{c,p} \sum_{l=1}^L b_{l,p} x_{i,l} \leq v_c \quad (12)$$

$$\forall_{r=1,\dots,R, c=1,\dots,C} g_{r,c} v_c \leq z_r \quad (13)$$

$$\forall_{i=1,\dots,N, p=s_i} \sum_{l=1}^L a_{l,p} x_{i,l} - \sum_{l=1}^L b_{l,p} x_{i,l} = 1 \quad (14)$$

$$\forall_{i=1,\dots,N, p \neq t_i, p \neq s_i} \sum_{l=1}^L a_{l,p} x_{i,l} - \sum_{l=1}^L b_{l,p} x_{i,l} = 0 \quad (15)$$

$$\forall_{i=1,\dots,N, p=t_i} \sum_{l=1}^L a_{l,i} x_{i,l} - \sum_{l=1}^L b_{l,p} x_{i,l} = -1 \quad (16)$$

$$\forall_{l=1,\dots,L} \sum_{i=1}^N x_i^* x_{i,l} \leq \sum_{e=1}^E M_{l,e} y_{l,e} \quad (17)$$

indices:

$r = 1, \dots, R$	backbone routers in a network,
$c = 1, \dots, C$	modules (cards) in a network,
$p = 1, \dots, P$	ports in a network,
$l = 1, \dots, L$	links (between two ports),
$i = 1, \dots, N$	demands,
$e = 1, \dots, E$	energy-aware states of links.

constants:

$g_{r,c} = 1$	if card c belongs to router r (0 otherwise),
$l_{c,p} = 1$	if port p belongs to card c (0 otherwise),
$a_{l,p} = 1$	if direct link l is outgoing from port p (0 otherwise),

$b_{l,p} = 1$	if direct link l is incoming to port p (0 otherwise),
x_i^*	volume of demand i ,
s_i	origin edge node (port) for demand i ,
t_i	destination edge node (port) for demand i ,
$M_{l,e}$	capacity of link l in energy-aware state e ,
$\xi_{l,e}$	cost of energy of link l in energy state e (sum of energy costs of two ports connected via link l),
W_c	fixed cost of energy of card c ,
T_r	fixed cost of energy of router r .

variables:

$x_{i,l} = 1$	if demand i uses link l (0 otherwise),
$y_{l,e} = 1$	if link l is in energy-aware state e (0 otherwise),
$v_c = 1$	if card c is used to data transmission (0 otherwise),
$z_r = 1$	if router r is used to data transmission (0 otherwise).

In our formulation constraints (10) assure that each link can be in one energy state, constraints (11), (12) and (13) determine number of cards and routers that are used for data transmission. Moreover, constraints (14), (15) and (16) are formulations of Kirchhoff law, respectively for source node, transit node and destination node, and the last one (17) assures that the flow does not exceed the capacity of a given link.

In our approach in the optimal solution, the demands are routed on single MPLS paths. Hence, as the solution of the problem (9)-(17) 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 satisfies all constraints, mainly concerned with expected QoS.

The above optimization problem may, however, appear to be far too difficult to be solved in a reasonable time due to a large number of binary variables. It will be necessary then to reduce its dimension and complexity. This can be done, first, by introducing a modification in which, as in TALCA, the possible sets of paths for all traffic relations are predefined.

B. Formulation with predefined paths: PRESA – Path and Router Energy State Assignment

In case of the link-path formulation the lists of candidate paths are predefined. Path generation method can be applied in order to determine the solution of the energy-efficient flow allocation problem with QoS constraints.

$$\min_{x_{i,k}, y_{l,e}, v_c, z_r} \left[\sum_{l=1}^L \sum_{e=1}^E \xi_{l,e} y_{l,e} + \sum_{c=1}^C W_c v_c + \sum_{r=1}^R T_r z_r \right] \quad (18)$$

subject to the following constraints:

$$\forall l=1, \dots, L \quad \sum_{e=1}^E y_{l,e} \leq 1 \quad (19)$$

$$\forall i=1, \dots, N, \quad \sum_{c=1, \dots, C} l_{c,k} x_{i,k} \leq v_c \quad (20)$$

$$\forall r=1, \dots, R, \quad \sum_{c=1, \dots, C} g_{r,c} v_c \leq z_r \quad (21)$$

$$\forall i=1, \dots, N \quad \sum_{k \in P(i)} x_{i,k} = 1 \quad (22)$$

$$\forall l=1, \dots, L \quad \sum_{i=1}^N \sum_{k \in P(i)} \delta_{l,i,k} x_i^* x_{i,k} \leq \sum_{e=1}^E M_{l,e} y_{l,e} \quad (23)$$

indices:

$r = 1, \dots, R$	backbone routers in a network,
$c = 1, \dots, C$	modules (cards) in a network,
$k \in P(i)$	paths predefined for demand i ,
$l = 1, \dots, L$	links (between two ports),
$i = 1, \dots, N$	demands,
$e = 1, \dots, E$	energy-aware states of links.

constants:

$g_{r,c} = 1$	if card c belongs to router r (0 otherwise),
$l_{c,k} = 1$	if path k passes through card c (0 otherwise),
$\delta_{l,i,k} = 1$	if link l belongs to path k transmitting demand i , (0 otherwise)
x_i^*	volume of demand i ,
$M_{l,e}$	capacity of link l in energy-aware state e ,
$\xi_{l,e}$	cost of energy of link l in energy state e – 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 ,

variables:

$x_{i,k} = 1$	if demand i is directed through the path $k \in P(i)$ (0 otherwise),
$y_{l,e} = 1$	if link l is in energy-aware state e (0 otherwise),
$v_c = 1$	if card c is used to data transmission (0 otherwise),
$z_r = 1$	if router r is used to data transmission (0 otherwise).

In our formulation constraints (19) assure that each link can be in one energy state, constraints (20) and (21) determine number of cards and routers that were used to data transmission. Moreover, constraint (22) assures that each request for traffic will be enforced, and the last one (23) assures that the flow does not exceed the capacity of a given link.

Still, this problem, being NP hard, may appear to be too difficult to solve. To reduce the number of discrete variables

we can combine both approaches presented about and introduce a hybrid, mixed continuous-integer, formulation of energy saving network operation problem.

V. ENERGY SAVING NETWORK OPERATION HYBRID PROBLEM

In this formulation we will use discrete, binary, variables to represent decisions related to the energy states of routers and interface cards, while the energy levels of port-to-port links and traffic routing decisions will be described by continuous variables.

A. Mixed variable formulation: TARESA – Traffic Allocation and Router Energy State Assignment

$$\min_{y_l, x_{i,k}, v_c, z_r} \left[\sum_{l=1}^L h_l(y_l) + \sum_{c=1}^C W_c v_c + \sum_{r=1}^R T_r z_r \right] \quad (24)$$

subject to the following constraints:

$$\forall_{i=1,\dots,N} \sum_{k \in P(i)} x_{i,k} = x_i^* \quad (25)$$

$$\forall_{l=1,\dots,L} \sum_{(i,k) \in S(l)} x_{i,k} = y_l \quad (26)$$

$$\forall_{\substack{c_1, c_2 \in C(r), r=1,\dots,R \\ l: u(l) \in U(c_1) \text{ and } d(l) \in D(c_2)}} 0 \leq y_l \leq y_{lmax} v_{c_1} v_{c_2} \quad (27)$$

$$\forall_{\substack{c \in C(r) \\ r=1,\dots,R}} v_c \leq z_r \quad (28)$$

indices and sets:

- $i = 1, \dots, N$ source-sink pairs,
- $l = 1, \dots, L$ links,
- $r = 1, \dots, R$ backbone routers in a network,
- $k \in P(i)$ paths predefined for i -th source-sink pair,
- $U(c)$ list (set) of output ports of card c ,
- $D(c)$ list (set) of input ports of card c ,
- $C(r)$ list (set) of cards in the router r ,
- $S(l)$ list (set) of relation-path pairs that use link $l - (i, k) \in S(l)$ if $k \in P(i)$,

constants:

- $u(l)$ upstream port of link l ,
- $d(l)$ downstream port of link l ,
- W_c fixed energy cost of operating card c ,
- T_r fixed energy cost of operating router r ,
- y_{lmax} capacity of link l ,

variables and functions:

- $x_{i,k}$ part of demand i directed through the path $k \in P(i)$,
- $v_c = 1$ if card c is used to data transmission (0 otherwise),

TABLE I
ESTIMATION OF OPTIMIZATION TASK COMPLEXITY

Formulation	Predefined paths	No. of variables		No. of constraints
TALCA	yes	continuous	binary	
TALCA	yes	10100	-	2100
FRALCA	no	200100	-	100100
PRESA	yes	-	18250	415200
FRRESA	no	-	3208250	3293200
TARESA	yes	11600	250	29400

- $z_r = 1$ if router r is used to data transmission (0 otherwise),
- y_l capacity (energy state) assigned to link l , so to ports $u(l)$ and $d(l)$,
- $h_l(y_l)$ energy cost of operating link l (with ports $u(l)$ and $d(l)$) at capacity (energy state) y_l .

Solution of this problem should be much easier than of (18)-(23), however it describes the network in the similar manner – the decisions concerning routers and interface card energy states are directly available. As far as operations of links are concerned the obtained values of link capacities may be used to select the energy states of links. The reverse process to that used to define link cost functions $h_l(\cdot)$ may be applied to compute those states (see Fig. 1).

VI. COMPLEXITY COMPARISON

To estimate the complexity of proposed formulations it is necessary to analyse an example of the network. As precise investigation of a real life network is beyond the scope of this paper we will only assume some general properties which will result in rough estimation of task dimensionality. Let us consider relatively sparse network of 50 nodes connected by 100 links which in turn are constructed of 12 fibers each. These fibers may be individually switched off and on, thus providing bandwidth scalability. Only a single router of moderate size – having 4 cards with 8 ports each will constitute each node. It is also assumed that all links in the network have the same speed and can be set in one of five energy aware states resulting in a reduced capacity. Additionally, it is necessary to know how sources and destinations are located in the network. For generality we assume uniform distribution among all nodes – so that one half of them (25) can be sources and second half destinations while all nodes can act as transit nodes. For formulations with predefined paths we assume that 5 paths are available for each source-sink pair. The resulting estimation is presented in the Tab. I.

Estimated results show great superiority of formulations with predefined paths; it must be noted, however, that the results of their implementation are highly dependent on path generation algorithms. In other words this is suboptimal solution – as good as generated paths allow to cover solution space. Continuous formulations can be significantly faster than binary ones as the solution method can be simpler, however they do not provide directly information necessary to manage

energy states of equipment. Having this in mind the hybrid formulation (TARESA) seems to offer good trade-off between complexity and applicability. It is achieved by providing top level binary decisions concerning router and cards by the cost of introducing relatively low number (250) of binary variables.

VII. CONCLUSION

In this paper several possible formulations of an energy saving network operation problems have been presented. It should be noted that, apart of computational problems discussed above, the success of using such problem solutions to provide for energy efficient operation of computer networks will depend upon many factors including, amongst others, correct assessment of traffic requirements between specified border routers and choosing appropriate timing of operating decisions in view of practical issues, related to switching on and off various devices. Extensive experiments are required to establish adequate approaches. It is hoped that this paper represents a small step in search of practical solutions.

ACKNOWLEDGMENT

This work was partially supported by 7 Framework Program UE grant ECONET (low Energy COnsumption NETworks) No: 258454.

REFERENCES

- [1] C. Courcoubetis and R. J. Weber, *Pricing Communication Networks*. Wiley, 2003.
- [2] S. H. Low and D. E. Lapsley, "Optimization Flow Control, I: Basic Algorithm and Convergence," *IEEE/ACM Transactions on Networking*, vol. 7, no. 6, pp. 861–874, December 1999.
- [3] K. Malinowski, "Optimization network flow control and price coordination with feedback: Proposal of a new distributed algorithm," *Computer Communications*, vol. 25, pp. 1028–1036, July 2002.
- [4] W. Findeisen, F. N. Bailey, M. Brdyś, K. Malinowski, P. Tatjewski, and A. Woźniak, *Control and coordination in hierarchical systems*. Wiley, 1980.
- [5] Telecom Italia, "Telecom Italia 2009 Sustainability Report," 2009.
- [6] France Telecom, "France Telecom 2009 Corporate Responsibility Report," 2009.
- [7] Telefonica, "Telefonica 2009 Corporate Responsibility Report," 2009.
- [8] IEEE, "Institute of Electrical and Electronics Engineers, IEEE 802.3az Energy Efficient Ethernet Task Force," <http://grouper.ieee.org/groups/802/3/az/public/index.html>, 2012.
- [9] W. Fisher, M. Suchara, and J. Rexford, "Greening backbone networks: reducing energy consumption by shutting off cables in bundled links," in *Green Networking 2010*. ACM, August 30 2010, pp. 29–34.
- [10] L. Chiaraviglio, M. Mellia, and F. Neri, "Energy-aware backbone networks: a case study," in *Communications Workshops 2009, IEEE International Conference*. IEEE, 2009, pp. 1–5.
- [11] M. Zhang, C. Yi, B. Liu, and B. Zhang, "GreenTE: power-aware traffic engineering," in *IEEE International Conference on Network Protocols ICNP 2010*. IEEE, 2010.
- [12] G. Shen and R. S. Tucker, "Energy-minimized design for IP over WDM networks," *Journal of Optical Communications and Networking*, vol. 1, pp. 176–186, 2009.
- [13] A. P. Bianzino, L. Chiaraviglio, and M. Mellia, "GRiDA: a green distributed algorithm for backbone networks," in *Online Conference on Green Communications GreenCom 2011*. IEEE, 2011, pp. 113–119.
- [14] F. Cuomo, A. Abbagnale, A. Cianfrani, and M. Polverini, "Keeping the connectivity and saving the energy in the Internet," in *IEEE INFOCOM 2011 Workshop on Green Communications and Networking*. IEEE, 2011, pp. 319–324.
- [15] R. Bolla, R. Bruschi, F. Davoli, and A. Ranieri, "Performance Constrained Power Consumption Optimization in Distributed Network Equipment," in *Communications Workshops, 2009. ICC'09*. IEEE, 2009, pp. 1–6.