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Combined Calculation of Optimal Routing and Bandwidth Allocation in Energy Aware Networks

Przemysław Jaskóła*, Piotr Arabas*†, Andrzej Karbowski*†
*Naukowa i Akademicka Sieć Komputerowa Instytut Badawczy
ul. Wąwozowa 18, 02-796 Warszawa
Email: pjaskola@nask.pl
†Instytut Automatyki i Informatyki Stosowanej Politechniki Warszawskiej
ul. Nowowiejska 15/19, 00-665 Warszawa

***Abstract*—Efforts to reduce power consumption in telecommunication networks follow in two mutually related directions – design of a more efficient equipment and development of energy-aware network control strategies and protocols. The paper presents a formulation of two-criteria traffic engineering problem, which takes advantage of energy saving capabilities in software routers. The first optimization criterion is the energy consumption, and the second one is the quality of service and service sustainability. Models and traffic engineering strategy were verified in laboratory experiments.**

Keywords*—network optimization, green networking, nonlinear programming, mixed integer programming

I. MOTIVATION AND RELATED WORKS

Methods for increasing energy efficiency of computer networks gained much attention last years. Initial efforts were aimed at assessment of energy characteristics of network equipment and building elementary models [1], [2], [3], [4]. Upon this knowledge some local, i.e. concerning single device, strategies were built – see e.g. [5], [6].

However, it is possible to save even more energy by employing network-wide solutions. The reasons for this are twofold: first the traffic load tends to follow some pattern, allowing to exploit predictable periods of reduced utilization by for example flow consolidation [7], [8]. The networks are moreover provisioned with some margin of capacity to increase reliability. Controlling the whole network allows to reroute traffic and switch off or reduce the performance of some devices while user needs are satisfied by remaining equipment [9], [10]. Such a task resembles QoS provisioning problems e.g. [11], [12] but with additional energy saving objective,

Network problems typically consist of a large number of binary variables necessary to compute routes so their application is limited to relatively small networks. To speed up computations, authors apply linear models [2], [13], [14], build multilevel control scheme or apply heuristics [15], [16].

A study of an energy-aware traffic engineering in TCP/IP network was undertaken in [17]. Authors have proposed therein a model of energy-aware router, an architecture of a control framework and various formulations of a network-wide energy saving optimization problem. A total power consumption is incorporated into the objective function of a MIP problem, while demand matrix is represented by a set of constraints.

We propose instead an approach in which flow rates are represented by variables rather than constants. It exploits the fact, that Internet traffic used to be elastic in a large part, which means that a quality of service is little aggravated by small deviations from assumed flow rate. The combined routing and rate control problem has to be solved, which leads to the solution feasible in terms of formulated model, even when the traffic demand is greater than the capacity offered by a network.

The similar problem of simultaneous routing and rate control was addressed by Bertsekas and Gallager in [18]. They noticed, that the problem formulation must contain an incentive to allocate some bandwidth to flows. Otherwise the optimal bandwidth allocated to flows would always be zero. Proposed specific convex and decreasing function is a penalty for not achieving an eligible flow rate. Multi-path routing analyzed by authors can however lead to TCP packets reordering. It can contribute to QoS deterioration, so throughout the paper a single path routing is assumed. Adopted linear link cost functions are not sufficient to describe energy characteristics of network equipment.

II. ELECTRICAL ENERGY DISSIPATION IN TYPICAL IP NETWORK DEVICES

The power consumed by a typical network device exhibits some nonlinear dependency on carried traffic. Several computational models [3], [1] consist of at least two components - constant and load related, and may be hence reduced to the following formula:

$$\pi(l) = \pi_0 + \sum_{i \in I} \pi_i(l_i) \tag{1}$$

where π_0 represents the power consumed by fans, bus and other common functions, e.g. management, I is the set of all network device ports, $\pi_i(l_i)$ is the power consumed by the port i itself and data plane functions attributed to it under load l_i carried by this port.

In the above formulation π_0 represents fixed part of power consumed irrespectively of traffic traversing a device. In the remaining part of the equation (1) the traffic dependent part of power is assigned to the ports adequately. If e.g. network processor of the device exhibits some dependence on the load, it is assumed that it is related to port i and included in $\pi_i(l_i)$.

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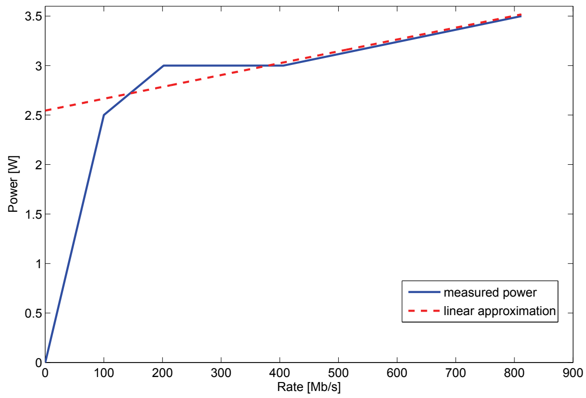

Fig. 1. Power consumed by a single port – $\pi_i(l_i)$, and its piecewise linear approximation.

Currently available network devices are generally not equipped with advanced power-saving functions. In consequence their energy consumption does not depend much on the network load. Recent efforts tend to increase power proportionality of network equipment, i.e. to reduce the traffic independent part of the power – π_0 in (1) by means of transition into low power state during idle periods, and frequency scaling techniques. The adoption of results in the industry is relatively slow, with power saving Ethernet IEEE 802.3az [19] being the most important standard.

The presented results of measurements were collected using software router based on PC computer equipped with Linux OS and 4 port 1 Gb/s Ethernet card. It is important to note, that the energy consumed by such setup is influenced by other elements – like e.g. hard disks, which take marginal or no part in transferring network traffic. This is the reason why π_0 component may be relatively high. Furthermore, the dependence on network load should be mostly attributed to frequency scaling and idle mechanisms of Linux kernel. The Fig. 1 presents measured values of power assigned to single interface. The fixed part π_0 was estimated at 31W.

III. FORMULATION OF THE PROBLEM

A. *The model of a network*

All the subsequent discussions apply to a network based on gigabit ethernet, which is a full-duplex technology. It can be then represented by a digraph $(N, \mathcal{A})$, where

N – the set of nodes
$\mathcal{A}$ – the set of arcs.

Let A be the matrix containing description of the topology of the network, that is

$$a_{ij} = \begin{cases} 1 & \text{if } (i,j) \in \mathcal{A}, \quad \text{where } i,j \in N \\ 0 & \text{otherwise.} \end{cases}$$

For convenience let's define also L – the set of link labels, and an one-to-one mapping $\kappa : \mathcal{A} \rightarrow L$.

The traffic is described in terms of arrival rates on network links, it is so-called fluid model [18].

The term "traffic flow" or simple "flow" is used here in the meaning adopted in documents RFC 2722 and RFC 3697, namely some sequence of packets sharing the same source, destination address, and possibly other classifiers, like flow label or port number.

W – the set of flows. Each flow $w \in W$ is related to a directed pair of nodes (s,d): source node $s(w) \in N$ and destination node $d(w) \in N, s(w) \neq d(w)$.
x_w – the rate achieved by the flow w.
$\bar{x}_w$, $\underline{x}_w$ – box constraints on x_w
c_l – the capacity of the network link $l \in L$

Flow based, single-path routing is assumed in the article. It means first, that the routing mechanism must use information about flow membership of the datagrams and preserve this information throughout the network. Second - flow cannot be split across different links in any node. These characteristics can be met for example by Multi Protocol Label Switching or Policy Based Routing. In consequence, there is no need for separate description of the path rate in the model, as it is equal to the corresponding flow rate. The routing is represented by a binary matrix:

B – the routing matrix.

$$b_{wl} = \begin{cases} 1 & \text{if } l \in r_w, \\ 0 & l \notin r_w. \end{cases} \quad ; \; l \in L, w \in W$$

where $r_w \in \mathcal{P}_w \subseteq 2^L$,

r_w – the path of flow w,
$\mathcal{P}_w$ – the set of all potential paths connecting s with d, where $(s,d) = w$.

B. *The model of energy consumption*

The discussion in section II deals with energy consumption of a single port. Each network link engages two ports on both ends, so the power consumed by a link is a sum of power attributed to related ports, and is illustrated by Fig. 2. The constant component π_0 from equation (1) is here omitted. It is currently impractical to physically turn off the whole router, so it is pointless to include π_0 in the optimization model.

It was observed during experiments, that the energy consumption is independent of a direction of traffic, i.e. the traffic outgoing from and incoming to the port can be summed up. The power related to the connection between nodes i, j is a sum of power dissipated by corresponding ports. Total power dissipated by the network is then expressed by:

$$P(x) = \gamma \sum_{l \in L} e_l + 2\delta \sum_{w \in W} \sum_{l \in L} b_{wl} x_w \qquad (2)$$

where:

$$e_{\kappa(i,j)} = \begin{cases} 1 & \text{if } \exists w \in W : (b_{w,\kappa(i,j)} x_w > 0) \\ 1 & \text{if } \exists w \in W : (b_{w,\kappa(j,i)} x_w > 0) \\ 0 & \text{otherwise.} \end{cases} \qquad (3)$$

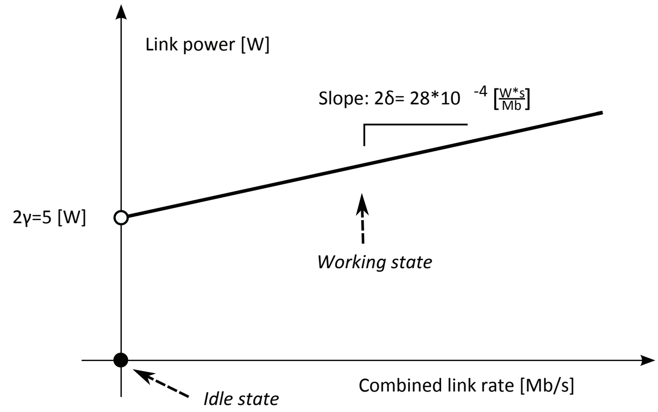

Fig. 2. Model of the power consumed by the link. *Combined link rate* is a total rate of all flows traversing the link in both directions.

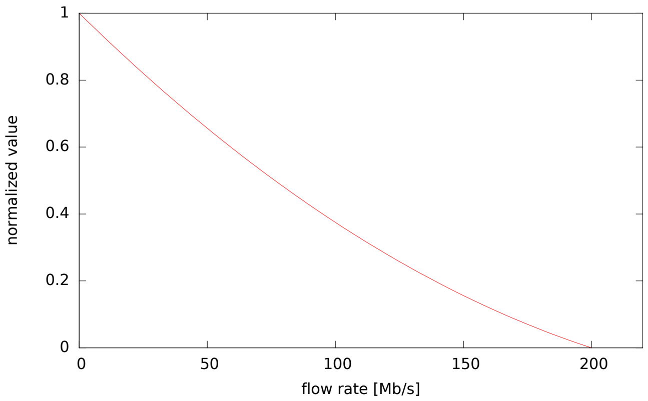

Fig. 3. QoS violation cost function Q_w for $\bar{x} = 200$

is a binary variable denoting whether the port of node i, connected by the link (i, j) with node j is working or idle and γ, δ are coefficients of the power consumption model (see Fig. 2).

C. The quality of service component

The QoS related term being the component of the objective function represents a penalty for not achieving an assumed flow rate $\bar{x}$. It reflects the intention of the operator to fulfill the networks primary objective, which is to carry the traffic with certain quality characteristics.

QoS function can be somehow related to the monetary cost of violating the service level agreement with a customer. It can be also chosen arbitrarily, so as to reflect preferences of a decision-maker, as it was done in this case.

In the optimization model QoS is represented by $\sum_{w\in W} Q_w(x_w)$ – the total cost of violating a quality of service of flows in W. Each $Q_w(x_w)$ is a convex and continuous function, decreasing with respect to the carried traffic on interval $[\underline{x}_w, \overline{x}_w]$. It is reaching minimum (zero) at $\overline{x}_w$, the point in which user expectations are fully satisfied.

The convexity of $Q_w(x_w)$ is associated with the belief, that small deviations from nominal throughput: $\Delta = \bar{x}_w - x_w$ are perceived by customers as relatively harmless, while large deviations should be avoided. The slope of the curve becomes steeper, as a rate x_w approaches zero (see Fig. 3). The matter of prioritization of different types of service within flows is beyond the scope of this article. If strict guarantees are required, they should generally be assured by additional mechanism.

Another important reason for not using linear cost function is an ambiguity of the solution and possibly uneven distribution of resources, which can occur in case when many sources compete for the same congested link and their bandwidths must be reduced.

D. Simultaneous optimization of the quality of service and the energy consumption.

After the discussion on the model of the energy consumption, and general remarks on decision maker's and user's preferences regarding the quality of service, a two criteria mixed integer network problem of simultaneous optimal bandwidth allocation and routing can be formulated:

$$\min_{e,b,x} \alpha \sum_{w\in W} Q_w(x_w) + (1-\alpha)\big(\gamma \sum_{l\in L} e_l + 2\delta \sum_{w\in W} \sum_{l\in L} b_{wl} x_w\big) \tag{4}$$

Where α is a weight coefficient, which can be altered to emphasize any of the objectives.

The solution is subject to flow conservation law equations:

$$\sum_{i\in N} a_{ij} b_{w,\kappa(i,j)} - \sum_{k\in N} a_{jk} b_{w,\kappa(j,k)} = \\ = \begin{cases} -1 & \forall w \in W, j = s(w) \\ 1 & \forall w \in W, j = d(w) \\ 0 & \forall w \in W, j \neq s(w), j \neq d(w) \end{cases} \tag{5}$$

which assure that the same amount of traffic related to flow w enters and exits each node, with exception of source and destination nodes. Additionally these equations enforce a single path routing. It means, that each pair source – destination is served by exactly one path.

The variable e must be set according to its definition given in (3)

$$e_{ij} \geq b_{w,\kappa(i,j)} \qquad \forall i \in N, \forall j \in N, \forall w \in W \tag{6}$$

$$e_{ij} \geq b_{w,\kappa(j,i)} \qquad \forall i \in N, \forall j \in N, \forall w \in W \tag{7}$$

The variable b_{wl} represents routing and is binary by definition, while x_w is positive and limited:

$$b_{wl} \in \{0, 1\} \qquad \forall w \in W, \forall l \in L \tag{8}$$

$$0 \leq \underline{x_w} \leq x_w \leq \overline{x_w}, \qquad \forall w \in W \tag{9}$$

The link capacity constraint is a nonlinear equation:

$$\sum_{w\in W} b_{wl} x_w \leq c_l \qquad \forall l \in L \tag{10}$$

which, as nonconvex, is not accepted by most solvers. Fortunately, it can be transformed to its linear counterpart, by means of a substitution described in the section III-E. The resulting mixed integer optimization problem with quadratic objective function and linear constraints is solved by means of CPLEX or Gurobi many times faster than when using general nonlinear solvers.

E. *Elimination of the nonlinearity from constraints*

Nonlinearity can be eliminated from constraint (10) by substituting it with subsequent set of linear inequalities:

$$\sum_{w \in W} y_{wl} \leq c_l \qquad \forall l \in L \qquad (11)$$

$$y_{wl} \geq x_w - M(1 - b_{wl}) \qquad \forall w \in W, \forall l \in L \qquad (12)$$

$$y_{wl} \geq 0, \qquad \forall w \in W, \forall l \in L \qquad (13)$$

$$y_{wl} \leq x_w, \qquad \forall w \in W, \forall l \in L \qquad (14)$$

$$y_{wl} \leq M b_{wl}, \qquad \forall w \in W, \forall l \in L \qquad (15)$$

Auxiliary variable $y_{wl}, w \in W, l \in L$ denotes the part of a traffic rate in the link l assigned to the flow w. Constant M can be chosen arbitrarily, however has to be greater than the greatest x_w in the optimized system:

$$M > \bar{x}_w \qquad \forall w \in W \qquad (16)$$

Objective function can be thus rewritten as:

$$\min_{e,b,x,y} \alpha \sum_{w \in W} Q_w(x_w) + (1 - \alpha)\big(\gamma \sum_{l \in L} e_l + 2\delta \sum_{w \in W} \sum_{l \in L} y_{wl}\big) \qquad (17)$$

IV. EXPERIMENTS

A. *Comments on computations*

The quadratic objective function, linear constraints problem stated above can be solved by means of very effective CPLEX solver. It proved to be a few times faster than general nonlinear programming, mixed integer solvers.

The time necessary to obtain a solution depends mostly on the dimension of the problem, it is the number of network nodes and traffic flows. The computational complexity of MIP is non-polynomial, but in case of the examples of limited size, as the ones analyzed in the paper the solutions were obtained in a split second.

B. *Testbed network and testing procedures*

The experiments were carried out in the test network (see Fig. 4) consisting of seven PC computers with Linux OS acting as software routers. Each one was equipped with four core i7 processor and four port 1Gb/s Ethernet card. Additionally two of them had fast Ethernet (100Mb/s) cards providing one link of slower bandwidth. Power consumption was measured individually by general grade power meters assigned to computers. Data was gathered on-line during experiments and stored in metering system database.

Paths computed by numeric algorithms were established in the testbed network by means of a policy-based routing (PBR). This way a functionality of MPLS was emulated with standard Linux mechanisms. In order to force the computed flow rates a UDP traffic was generated on selected testbed nodes using `Iperf` - an open source traffic generator. Due to the quantisation of a buffer size used by `Iperf` and imperfections of network adapters, achieved data rates differed from calculated ones in case of some flows, an error was however negligible as it did not exceed 3%. After completing the experiment, the data rates reported by traffic generators were automatically collected and preprocessed.

TABLE I. POWER CONSUMPTION

No.	Experiment	Calculated power [W]	Measured power[W]
1.	High quality	45.16	63.65
2.	Low energy	28.3	51.75

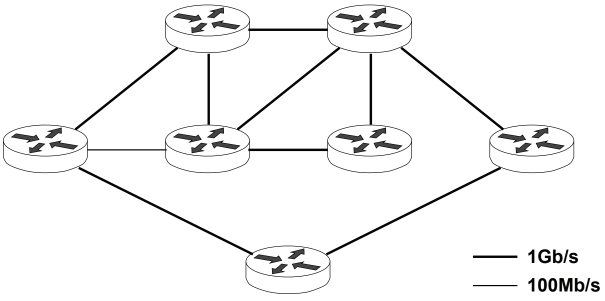

Fig. 4. Testbed network

C. *Results of experiments*

The presented algorithms were evaluated in numerous computational experiments in order to gain insight into the characteristics of the problem. Some of the numerical results were then verified in testbed in order to validate the models of energy consumption, and to check whether they are suitable for the particular application for which they were created.

In the first run of the experiment a stress was put on the quality of service (parameter $\alpha = 0.95$). The challenge was to allocate a capacity to ten flows. Each one declared the requested rate of 200 Mb/s, and was related to the specific source-destination pair of nodes.

The network topology, as well as link capacities reflected those found in the laboratory network, however it was observed that a link bandwidth of 1 Gb/s is never obtained in practice. The adequate headroom was then assumed in calculations, and link capacities were set on the level of 812 Mb/s (measured maximum throughput).

The calculated paths are shown in Fig. 5. All the flows have achieved equal rate of required 200 Mb/s. The bottlenecks between nodes 2-4, and 4-6 were relieved through redirecting flow 1 to the less congested path.

In the second example, titled "low energy", the weighting coefficient α was set to 0.5 to put equal emphasis on both criteria. In effect calculated energy was reduced by 16.86 W, which effect is mostly explained by rerouting of the flow no. 1 – see Fig. 6, and turning off some no longer necessary links. The quality of service dropped in this case. Some flow rates had to be reduced, because the declared traffic would not fit into the network under the new routing pattern. The most truncated flows rate was 148 Mb/s vs. requested 200 Mb/s. Decision whether it is acceptable or not belongs to a decision-maker, who can fine-tune parameters.

D. *Real network verification of power consumption models*

The results of experiments number 1 and 2 were transferred to the laboratory network. Calculated versus measured power

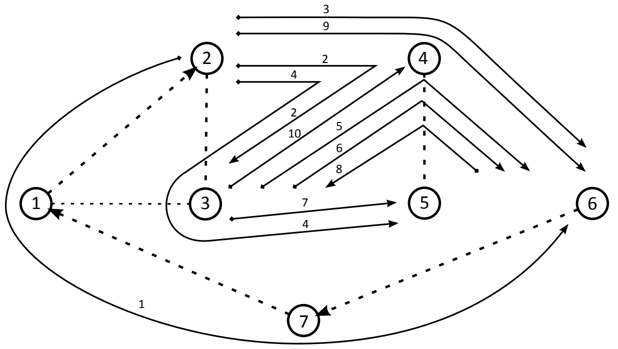

Fig. 5. Distribution of flows - high quality

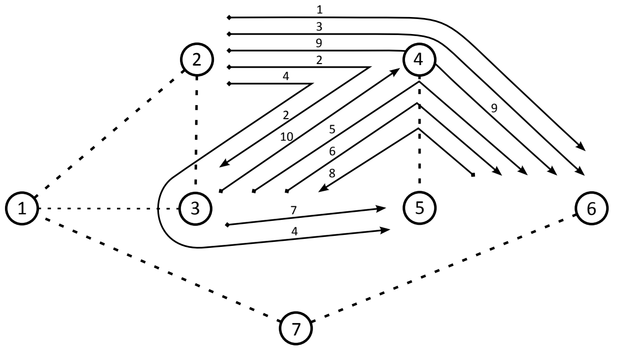

Fig. 6. Distribution of flows - low energy

dissipation values are summarized in Tab. I. The invariable part of energy consumed by computers, designated as π_0 in (1) was not part of the model, and is subtracted from measured values of a consumed power.

The real-life measured power consumption was greater than the calculated value. The estimation error ranged from 11.75 to 23.45 W and averaged at 17.9 W. A mean error is within a 36% of a mean measured power. It must be noted however, that a constant part of a power of each node – π_0 is about 31 W, which means, that estimation error is close to 6.7% of the whole power consumed by the network.

The absolute difference between columns of table I can be explained by additional activities of processors related to the tasks of traffic generation and measurement, which were performed during experiments and were not covered by the model.

V. CONCLUSIONS

The paper presents the computational system created for traffic engineering in TCP/IP networks. It is aimed at simultaneous optimization of a quality of service and energy dissipation. It is made up of an optimisation engine, models of user preferences and energy consumption.

The discussion carried out in the paper provides an analysis of problem properties, covers the subject of a choice of model parameters. Some questions are left opened for future research.

The traffic matrix must be submitted by an external mechanism. It is quite difficult and error prone task, because the procedure must take into account many factors: preferences of users and a decision maker, topology and capacity of the network. The presented system is fortunately immune to the erroneous input thanks to allowing some elasticity of demand.

The computational complexity of the mixed integer programming problem is non-polynomial, so in case of systems bigger or more heavily loaded than the ones presented in experiments, specialized, probably heuristic optimisation algorithms must be used.

The power saving impact of presented traffic engineering strategy is mostly dependent on network topology, and susceptibility of network device energy consumption to load changes. In presented experiments, using contemporary off-the-shelf PC computers, in specific topology, the power consumption could be reduced by about 4.2% with only minor deterioration of a quality of service, making advantage of traffic elasticity (experiment 1 vs. 2). It is worth noting however, that in the first example the QoS was better than would be observed in case when shortest-path principle was applied. Assuming that the future specialized network devices will be able to decrease power consumption in an idle mode much further, the potential of the presented techniques is very large.

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