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Power savings in packet networks via optimised routing

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Abstract This paper examines the use of a gradient-based algorithm for Quality of Service (QoS) and power minimisation in wired networks to result on reduced energy consumption. Two distinct schemes, conventional shortest-path routing and an autonomic algorithm energy aware routing algorithm (EARP) are investigated as the starting point for the gradient algorithm. Comparisons are conducted using the same network test-bed and identical network traffic under conditions where routers and link drivers are always kept on so as to meet the needs for network reliability in the presence of possible failures and unexpected overload. Since splitting traffic flows can increase jitter and the arrival of packets which are out of sequence, we also do not allow the same packet flow to be conveyed over multiple paths. In the experiments that we have conducted we observe that power consumed with the gradient-optimiser that is proposed in this paper is a few percent to 10% smaller than that consumed using shortest-path routing or EARP. Although the savings are small, they can be very significant for the Internet backbone as a whole over long periods of time, and further power savings may be obtained by judiciously putting to sleep equipment when it is under-utilised.

Keywords Energy optimisation · QoS · Computer networks

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1 Introduction

Energy efficiency in Information and Communication Technology (ICT) has become a major priority especially for Internet Service Providers and data center network operators. ICT alone is responsible for 2% of the global carbon footprint production [1], a figure similar to the one for the airline industry. Especially in the case of more developed countries, this figure can be as high 10% and it is expected to grow by 4% per year until 2020 [2]. On the other hand, network devices are highly over provisioned in order to endure peak period demands and to withstand failures. Thus they are often under utilized and there is a real opportunity to achieve large energy savings. However since over provisioning is standard practice that is needed to tackle the lack of QoS support in the Internet architecture, energy efficiency is not an easy problem to address in wired networks and it requires careful trade-offs regarding network performance and the quality of service (QoS) that needs to be offered to end users.

In this paper we examine a queuing network model and a gradient-based algorithm for power optimization under QoS constraints. In the following, we first review the relative literature of power management in wired and wireless networks. We then briefly sketch the model and algorithm which we first introduced in [3] and is used to optimize both power consumption and QoS. Then we present our results based on a real testbed and the measured power consumption of its nodes, comparing our approach to shortest path and to autonomic energy optimization algorithm (EARP) [4].

2 Related work

Much work has been devoted to power savings in wireless sensor networks where battery power can be crucial, including Topology Control [5–7], where radio transmission power and hence range is dynamically adjusted so as to preserve connectivity of each potential source-destination pair. In [8] it is indicated that the radio transceiver, which is the dominant energy consumer within a sensor, consumes almost the same amount of energy in transmit, receive and idle mode, therefore switching off the transceiver is examined. In [9] energy efficient routing for ad hoc networks is presented using the CPN protocol [10, 11] when smart packets are used to strike compromises between QoS and energy savings.

Energy efficiency in wired networks which are massive consumers of power at least at a par with data centres, has only recently drawn attention. Early work for wired networks [12] proposed traffic aggregation along a few routes, a modification of network topology by route adaptation and putting certain nodes and devices to sleep. A network-wide approach (coordinated sleeping) as well as a link layer approach (uncoordinated sleeping) were discussed and the possible effects on routing protocols were examined. In [13] an energy saving algorithm for Ethernet links using local data to make sleeping decisions was suggested, while powering components on/off in combination with an offline multicommodity network-flow problem for traffic assignment was considered in [14]. An online technique was proposed [15] to spread load through multiple paths, based on a step-like model of power consumption as a function of the hardware's processing rate and the ability of nodes to automatically adjust their operating rate to their utilization. Rate-adaptation for individual links was examined in [16] based on the utilization and the link queuing delay, where traffic is sent out in bursts at the edge routers enabling other line cards to sleep between successive bursts. Rate adaptivity is compared to sleeping of devices and the operation ranges where each solution is preferable are presented. In [17] the reduction of power consumption in wired networks in the presence of users' QoS constraints and experiments with dynamic traffic management in conjunction with the turning on/off of link drivers and/or routers is discussed, and using the Cognitive Packet Network (CPN) [18] routing protocol for energy awareness in conjunction to QoS is considered. Energy efficiency is examined for Cloud Computing in [19]. A set of publications model the problem of optimizing routing energy efficiency as an integer linear program which is NP-hard and propose heuristics. In [20] the authors select the active links and routers to minimize power consumption via simple heuristics that approximately solve the related NP-hard problem. In [21] a case study based on specific backbone networks is discussed, and an estimate of the potential overall energy savings in the Internet is presented in [22]. In [23] they seek to find a routing that optimizes the number of active network interfaces and propose a heuristic that turns off the least loaded links first. Several realistic network topologies are studied under all-to-all routing conditions and present the gain as percentage of shut off network interfaces and the impact on route lengths. Another important set of problems that must be addressed when one attempts to design power management schemes for networks concerns the proper choice of power consumption models for network components and sub-systems. In [24] the authors present a network-based model that estimates Internet power consumption including the core, metro, and access networks. In [14] a generic model for router power consumption is presented. Two widely used routers are measured in terms of system power demand with different configurations of line cards. The measurements indicate that the base system is the largest power consumer, so it is best to maximize the number of cards per chassis. In [25] the authors present a power measurement study of a variety of networking devices such as hubs, edge switches, core switches, routers and wireless access points in both stand-alone mode and within a production data center. They find that the actual energy consumed by switches and routers depends on various factors such as device configurations and traffic workload. The authors also identify the challenge for device manufacturers to ensure that networking devices such as hubs, switches and routers are energy proportional to their load and define the energy proportionality index(EPI).

Here we propose a queuing theory based gradient method described in [3] for QoS and power minimisation in wired networks to improve upon (i) shortest-path routing and (ii) an experimental autonomic algorithm (EARP) [4] for QoS and power optimisation. The algorithm is limited to a single step of the gradient descent in order to provide fast computation, and the algorithm is initiated for (i) with the shortest path algorithm, and for (ii) with EARP. Comparisons are conducted using the same test-bed and the same network traffic. We assume that due to the need for network reliability and resilience we do not turn off routers and link drivers, and that for QoS reasons (notably with regard to jitter and packet desequencing) we do not split traffic from the same flow into different paths. Under these assumptions we observe that the energy consumed using the the gradient-optimiser when it is started with known shortest-paths or with paths discovered by EARP is smaller by a few percent, and savings are greater when starting with paths provided by EARP which selects paths based on power optimisation. We note that even a few percent in power savings, scaled up to the power consumed in high-speed routers over long periods of time, can lead to significant economic and CO2 savings in energy.

3 Network Optimisation

Probability models of computer systems have long been used for performance evaluation and optimisation [26]. Thus the algorithm we design in this paper is based on a class of probability models that have been proposed for networked systems and which are known as G-networks [27,28]. G-Networks are queuing networks which have ordinary customers in addition to other customers that were initially inspired by neural networks [29]. In contrast with normal positive customers, negative customers do not receive the normal service at the queues. Negative customers or triggers can act in the network in several ways: they can destroy a positive customer in a queue, trigger the instantaneous passage of a customer to another queue or cause the departure of a batch of customers. However G-networks contain many additional constructs, and in particular triggers [30] which are special customers whose role is merely to reorient the flow of ordinary customers.

Our model is based on G-networks with triggered customer movement, where the negative customers or signals correspond to the control packets used to apply control on the routing decisions of user packets and the trigger corresponds to the act of re-routing. As routers and links have different power consumption and performance behaviour and in order to provide larger flexibility to the model, we have modeled separately the queues that are formed in links and in routers. Thus, we treat both router and links as 'nodes' or 'queues'. In these queues both the payload packets and the control packets used to re-route traffic are considered. Control packets add to congestion and power consumption, so the model includes their effect on performance but also on the overhead that they induce.

3.1 Model description

We denote by $\mathbf{N} = \{1, ...N\}$ a network of N queues. A subset of them are the router queues R and the remaining subset are the link queues L, such as $\mathbf{N} = \mathbf{R} \cup \mathbf{L}$. We use r and l to denote a router or link, $r \in \mathbf{R}$ and $l \in \mathbf{L}$. Traffic class $k \in \mathbf{U}$ is a flow of packets between a source-destination pair (s, d), which travels on a path to destination. $\lambda(r, k)$ is the packet rate of user class k arriving from outside the network to router r and $\lambda(r, k) > 0$ only if r is the source node for class k. The total arrival rate of user traffic class k at router r and link l respectively are given by $\Lambda_R(r, k)$ and $\Lambda_L(l, k)$. The default routing scheme before control is applied is represented by the probability matrix $\mathbf{P}$ which contains the probabilities that a packet of class k travels in one step from node i to node j denoted by $P(i, k, j)$.

We also have multiple control traffic classes denoted by (r, k), where k is the class and r is the router on which they can act. $\lambda^-(i,(r, k))$ is the rate at which such control packets may enter the network via router i. This notation gives us the possibility to represent control traffic that enters the network in a specific position and travels through the network until it reaches its target router r and act on the user class k for which it is responsible to redirect traffic. When a control packet travels through the network it obeys to the usual queuing phenomena while when it reaches the target router it does so instantaneously and disappears. The probability that a control packet of class (r, k) travels from node i to j in one hop is $p((r, k), i, j)$. The control classes may also be virtual representations of rerouting decisions; in that case these "virtual packets" will not create traffic overhead but will generate computational overhead at the nodes where decisions are taken. The probability that a user of class k is directed from router r to neighbour l by a control packet is $Q(r, k, l)$. Links will have only one predecessor and successor, while routers may have one or more successors that are links. Note also that some models may abstract the existence of links, and just represent the manner in which routers are connected without detailing the links.

The equations of the network model are:

$$\begin{aligned}\Lambda_R(r,k) &= \lambda(r,k) + \sum_{l\in\mathbf{L}} q(l,k)P(l,k,r)\mu_l(l)\\ &= \lambda(r,k) + \sum_{l\in\mathbf{L}} P(l,k,r)\Lambda_L(l,k),\ r\in\mathbf{R} \qquad (1)\end{aligned}$$

$$\begin{aligned}\Lambda_L(l,k) = \sum_{r\in\mathbf{R}} [&P(r,k,l)q(r,k)\mu_r(r,k)\\ &+\Lambda^-_R(r,(r,k))q(r,k)Q(r,k,l)],\ l\in\mathbf{L} \qquad (2)\end{aligned}$$

$$q(r,k) = \frac{\Lambda_R(r,k)}{\mu_r(r,k)+\Lambda^-_R(r,(r,k))},\ r\in\mathbf{R} \qquad (3)$$

$$q(l,k) = \frac{\Lambda_L(l,k)}{\mu_l(l)},\ l\in\mathbf{L} \qquad (4)$$

where $\Lambda_R(r, k)$, $\Lambda_L(l, k)$, $q(r, k)$, $q(l, k)$ denote the total arrival rates to the routers and links, and the utilisation rate for the routers and links, respectively, for user traffic class k. The corresponding quantities for control traffic class (i,k) and $r \in \mathbf{R}$, $l \in \mathbf{L}$ are given by:

$$\Lambda_R^-(r,(i,k)) = \lambda^-(r,(i,k)) + \sum_{l\in\mathbf{L}} p((i,k),l,r)c_L(l,(i,k))\mu_l, \quad (5)$$

$$\Lambda_L^-(l,(i,k)) = \sum_{r\in\mathbf{R}} p((i,k),r,l)c_R(r,(i,k))\mu_r, i \neq r, \quad (6)$$

$$c_R(r,(i,k)) = \frac{\lambda^-(r,(i,k)) + \sum_{l\in\mathbf{L}} p((i,k),l,r)c_L(l,(i,k))\mu_l}{\mu_r} \quad (7)$$

$$c_L(l,(i,k)) = \frac{\sum_{r\in\mathbf{R}} p((i,k),r,l)c_R(r,(i,k))\mu_r}{\mu_l}, \ i \neq r. \quad (8)$$

The steady-state probability that router r is busy is

$$B_R(r) = \sum_{k\in\mathbf{U}} [q(r,k) + \sum_{i\in\mathbf{R}} c_R(r,(i,k))] \quad (9)$$

and the steady-state probability that link l is busy is

$$B_L(l) = \sum_{k\in\mathbf{U}} [q(l,k) + \sum_{i\in\mathbf{R}} c_L(l,(i,k))] \quad (10)$$

The average network delay for the user traffic is then:

$$T_N = \frac{1}{\Lambda_T^+}[\sum_{r\in R} \frac{B_R(r)}{1-B_R(r)} + \sum_{l\in L} \frac{B_L(l)}{1-B_L(l)}] \quad (11)$$

where $\Lambda_T^+ = \sum_{k\in U}\sum_{r\in R} \lambda(r,k)$ is the total user traffic entering the network. The cost f to be minimised via judicious routing will contain a function of the probabilities that nodes and links are busy, and the power consumption of the network:

$$P_N = \sum_{r\in R} P(r) + \sum_{l\in L} P(l) \quad (12)$$

where router power consumption is represented by

$$P(r) = \alpha_r + g_R(B_R(r)) + c_r \sum_{k\in\mathbf{U}} \Lambda_R^-(r,(r,k)), r \in \mathbf{R} \quad (13)$$

and α_r is the router's static power consumption, $c_r > 0$ is a constant, $g_R(.)$ is an increasing function of the packet processing rate, c_r is a proportionality constant related to router processing for re-routing control, and power consumption in a link is:

$$P(l) = \beta_l + g_L(B_L(l)), l \in \mathbf{L} \quad (14)$$

where β_l is the static power consumption and $g_L(B_L(l))$ is an increasing function. The routing optimisation algorithm [3] minimises f which in general includes both network power consumption and average user packet delay:

$$\mathbf{Minimise}_{\mathbf{Using\ Q(i,k,j)}}\ f = P_N + cT_N \quad (15)$$

where $c \geq 0$ is a constant the establishes the relative importance of delay with respect to power.

3.2 Improving upon Shortest-Path Routing

The comparisons we report are carried out based on the 23 node test-bed of Figure 1. The measured power consumption of the fourteen nodes located on the circle are shown in the lower Figure 1. The service rate of the links are their 100 Mbps speeds and virtual delays have been added to service times so as to introduce more realistic values of delay; indeed the very short physical links used in the laboratory do not provide realistic values of network delays so that we have to delay each packet in software at the nodes so as to arrive to a more realistic value. The comparisons are carried out

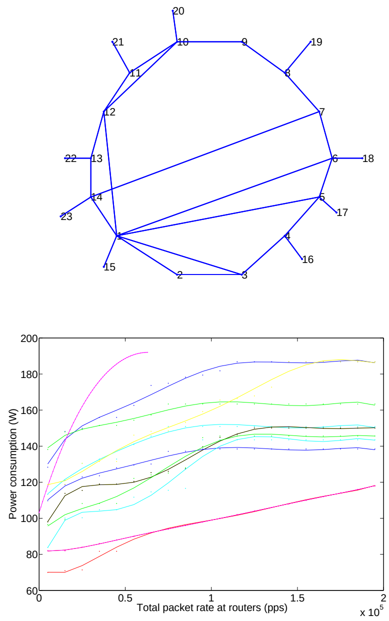

Fig. 1 Experimental network (top) and power profiles of 14 routers on the circle (bottom)

in the presence of flows travelling from source to destination with average traffic rates: Flow 1 (22,18) traffic rate 30kpps, Flow 2 (23,19) traffic rate 10kpps, Flow 3 (21,17) traffic rate 20kpps. First, we apply the optimisation algorithm to the network started in a state where all flows follow the shortest path, and we focus on power ($c = 0$). We can select among seven alternate paths for each flow, and the optimisation yields a saving of 10 Watts, down from 1531 watts, at the cost of an increase in average end-to-end delay of 3.3ms. Then we vary the input traffic of the 3 flows from 0.1 to 1.5 times their initial value, and the results in Figure 2 show a modest average power savings of 8.2 Watts while average packet delay increases. If we opt for both power and delay optimisation by adjusting c in (15) we can avoid the increases in average delay seen in Figure 3

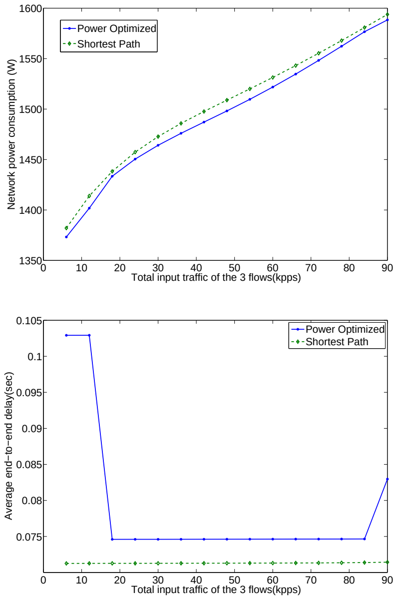

Fig. 2 Power consumption (top) and average end-to-end packet delay (bottom) against varying traffic load in Kpps (kilo-packets per second) for power-optimised versus shortest path routing

and the average power savings is a modest but real 6.4 Watts. If we add another flow Flow 4 (20,16) at traffic

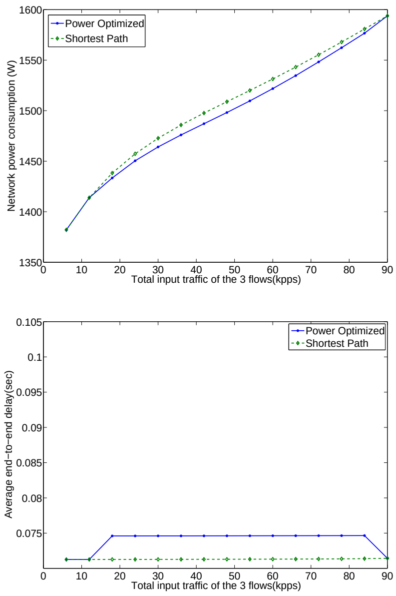

Fig. 3 Power consumption (above) and end-to-end delay with power and delay optimisation (below)

rate 5kpps, and vary the traffic of the four flows from 0.1 to 1.5 times their nominal values, the average power savings increase to 13.1 Watts as shown in Figure 4.

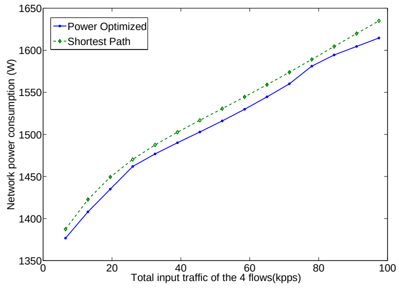

Fig. 4 Power consumption for proposed algorithm compared to shortest path with four flows and power optimisation

3.3 Improving upon EARP

We now use the gradient based otimisation scheme to improve upon the on-line adaptive power and QoS protocol EARP [4]. EARP uses CPN to search for the paths that minimise a mixed QoS and power consumption criterion. The log files of observed paths for the three flows as they are generated by EARP are then used to initiate the optimisation algorithm. From each EARP path we can generate a new path using the gradient algorithm, and the outcome is shown in Figure 5 where we observe a significant power saving with respect to EARP. In order to limit out of order packet

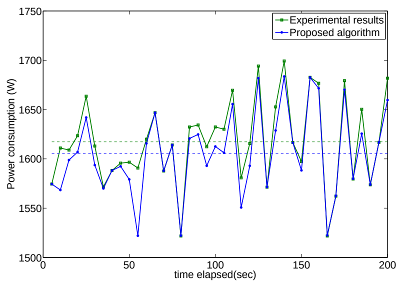

Fig. 5 Power consumption for the gradient algorithm (green) compared to power-based EARP [4]

arrival and jitter, we can change paths only when the path modification improves on the previous power consumption; we then have the greater power savings of Figure 6.

4 Conclusions

This paper has investigated a model based gradient optimisation approach to reduce energy consumption in wired networks. The gradient algorithm has been started with one of two initial conditions: (a) with the

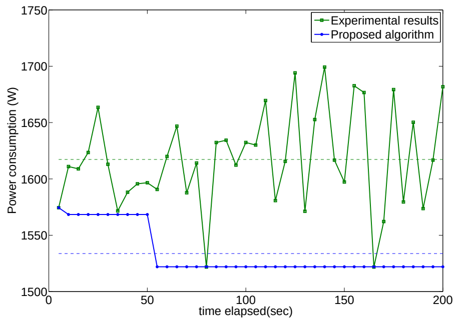

Fig. 6 Power consumption for proposed algorithm with memory

network state set that results from the standard shortest-path algorithm for all of the flows taken together in the network, and (b) using an autonomic routing policy that was previously designed called EARP which adaptively reduces energy consumption provided that a desirable QoS constraint such as maximum delay is satisfied. When the QoS constraint is not satisfied, then EARP simply becomes a QoS driven policy. Our numerical simulations have shown that in all cases a modest real energy saving is to be expected through the use of gradient optimisation. We note that the optimisation itself takes into account in its cost function both the energy consumption and the QoS overhead introduced by the traffic that is used to control the network, on top of the network traffic itself. However the optimisation does not take into account the computational cost of the decisions that need to be taken.

Previous work [3] had shown that the optimisation algorithm we use in this paper is of time complexity $O(N^3)$ where N is the number of links plus routers in the network, which would make it impractical for a large network. However the algorithm can be simplified considerably in several different ways. The gradient optimisation in practice needs only to be carried out for a limited number of nodes and a limited number of paths. For instance when we start with a shortest path, we should not seek an optimum over all possible paths but work with other shortest paths or with paths which are at most longer by just a few hops.

Also the matrix inversion leading to the $O(N^3)$ complexity could be approximated as $(I-W)^{-1} \approx (I+W+W^2)$ which can be faster than the matrix inversion. In any event a practical optimisation would be done in stages, working with successively smaller networks. It may also be carried out hierarchically with a set of subnetworks. We think that this part of the work can lead to fruitful research concerning simplified algorithms and the impact that they will have on energy savings and QoS in the practical network.

While energy consumption in routers and drivers is of primary importance, the induced consumption in cooling equipment including fans and air-conditioning is also of great importance. At the other end of the scale, computer equipment can also contribute positively to the energy balance of buildings which operate in cold climates. Thus these matters are actually more complex than they appear initially, especially if one includes aspects related to cooling the electronic equipment that is being used as well as the effect of rotating secondary memory devices.

The impact of energy savings on CO2 emissions will always depend on the different sources of electrical energy that are being used. These may be nuclear, or fossil, or renewable, such as hydroelectric, wind or electrovoltaic. Any energy savings will reflect at least at the same level in savings in the CO2 footprint of networks. We say "at least" because lower energy consumption will provide a better chance to run network nodes and link drivers for longer periods on renewable energy sources, with the possibility of using batteries when the primary sources are inactive. We note that if the experiments we have reported were scaled to a test-bed having high speed routers and drivers, and large volumes of traffic, the resulting savings in energy costs and CO2 imprint would be substantial over long periods of time.

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