ECOFEN: an End-to-end energy Cost mOdel and simulator For Evaluating power consumption in large-scale Networks

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***Abstract*—Wired networks are increasing in size and their power consumption is becoming a matter of concern. Evaluating the end-to-end electrical cost of new network architectures and protocols is difficult due to the lack of monitored realistic infrastructures. We propose an End-to-End energy Cost mOdel and simulator For Evaluating power consumption in large-scale Networks (ECOFEN) whose user's entries are the network topology and traffic. Based on configurable measurement of different network components (routers, switches, NICs, etc.), it provides the power consumption of the overall network including the end-hosts as well as the power consumption of each equipment over time.**

***Keywords*-Energy efficiency; Wired networks; Power consumption; Energy cost model; Network simulator**

I. Introduction

A deep understanding of where electricity is wasted in networks is required to develop energy-aware frameworks capable of taking the right decisions to optimize energy consumption without impacting the system's performance.

Wired networks consist of several facilities: routers, switches, bridges, repeaters, hubs, firewalls, wired links, coaxial cables, optical fibers, twisted pair wires, antennas, wireless transmitters, network interface cards, access points, etc. Each of these equipments has its own energy consumption scheme with different parameters influencing this consumption: type of equipment, traffic, load, number of connected equipments, number of switched on interfaces (ports), used protocols (that can add some processing time if high level operations are required such as flow identification, packet inspecting, etc.), energy saving modes that are used on the equipment, etc.

The problem when evaluating new network architectures and protocols is that large testbed platforms are really expensive and difficult to manage. That is why we have designed an End-to-End energy Cost mOdel and simulator For Evaluating power consumption in large-scale Networks (ECOFEN) whose user's entries are the network topology and traffic. Based on configurable measurements of different network component (routers, switches, NICs, etc.), it provides the power consumption of the overall network including the end-hosts as well as the power consumption of each equipment over time.

Several energy models have been proposed to express the electric consumption of particular equipments (routers [1], switches [2], etc.) or particular networks (backbone networks [3], optical networks [4], etc.). Unlike previous studies, our model includes the possibility to use energy savings techniques such as on/off algorithms that switch off unused links and ports, and such as Adaptive Link Rate (ALR) [5] which can adapt the link rate to the actual traffic.

In [6], the author aims at simulating the power and energy consumption of computer networks. But, his simulation models are based on measurements of PC-based equipments which differs from real routers in terms of architecture and energy consumption. An energy-aware Cloud simulator based on NS2 is presented in [7]. The network model used is close to ours, but it assumes a linear relation between energy consumption and load and does not include ALR and on/off capabilities.

The framework presented here is the first, to our knowledge, that can be applied to any network topology with various kind of equipments and supporting energy-efficient techniques such switching off nodes and ALR. Contrary to other propositions, this simulator uses an end-to-end model which gives the consumption of end-to-end communications including the energy consumption of each crossed equipment taking care of other communications sharing these same equipments.

This paper presents the ECOFEN model (section II) and the associated simulator based on NS2 (section III). Section IV describes some possible scenarios and analyzes the obtained simulation results. Section V concludes this paper and presents some future works.

II. ECOFEN Model

A. Energy Considerations

The energy consumption E of an equipment depends on the power consumption P of the equipment which varies over time t. For a given time period with a length equals to T, the energy is given by:

$$E(T) = \int_0^T P(t)\ dt \qquad (1)$$

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As the energy consumption functions (per equipment) are linked to traffic with varying impact, these functions vary over time. For example, the consumption of a router depends on the number of ports that are switched on and this value varies over time depending on the on-going traffic.

In this paper, we mainly consider the energy consumption as the factor to optimize. What about the money cost? The paid price D depends on the energy consumed E and also on the time it has been consumed:

$$D(E) = \sum_{i} NbkWh(t_i) \times Price(t_i) \tag{2}$$

where t_i represents a time period with a fixed energy cost $Price(t_i)$ and $NbkWh(t_i)$ is the number of kWh consumed during that time period. Indeed, the energy price vary over time (during slack periods such as nights, the electricity is cheaper). So, an optimization of the energy consumption does not necessarily leads to an optimization of the billing cost [8]. As our goal is to save energy first, we have chosen to optimize the energy consumption without taking into account the electricity price.

B. *Energy Consumption per Network Equipment*

In our model, we only consider as consuming equipments the facilities that are plugged and that consume electricity. This means that the links are not considered as consuming equipments. However, their "cost" is reflected in the equipments they link. Indeed, if a router, for example, embeds some energy saving features, the power used for the transmissions is related to the length of its output wired links. It requires more power with long links. Currently, by default, this energy saving feature is not applied in the routers: they use full power transmissions on all of their ports.

For a given equipment (router, repeater, Ethernet card), the energy consumed by a transfer is given by:

$$E = E_{boot} + E_{work} + E_{halt} \tag{3}$$

where E_{boot} and E_{halt} can be equal to zero if there is no need to boot and to halt the equipment (due to transfer aggregation for example or if it stays always powered on). Network equipment manufacturers and designers are well placed to influence the energy consumed by the booting and halting periods: they can work on the hardware components to shorten the booting and halting durations. However, protocol designers have also a role to play in the quest for energy efficiency. For example, the re-synchronization protocol between linked nodes needs to be reduced to make the on/off technique usable [5], [9]. The optimization of E_{boot} and E_{halt} is out of the scope of this paper.

Each equipment has a fixed energy cost (E_{idle}) which corresponds to the energy consumed when it does nothing (no transfer), and a variable cost which depends on the traffic. The energy E_{work} consumed during the transfer includes these two costs and depends on:

- BD the bandwidth used by the transfer,
- L the length in time of the transfer,
- the cross traffic on this equipment: we do not want to count several times the consumption of a router for example if several transfers are using it at the same time (we rather want to divide it by the number of transfers for the fixed costs),
- the type of equipment (router, NIC, ...).

The fixed part consists only of the latter parameter, the three other ones are variable and are linked to time [10]. These interactions between network usage and energy consumption are the subject of several power cost models. Classical models include models with link rate switching which have a strong dependence to the link rate and a slight dependence to transmission rate as shown in Figure 1 by the line labeled *Adaptive Link Rate*. This graph does not show the energy and the time required to switch from one link rate to another one.

Another classical but less realistic model is the proportional power cost model. This model is not realistic for current network equipments. However, some studies affirms that efforts should be made to reach this model [11] in order to obtain a fair model.

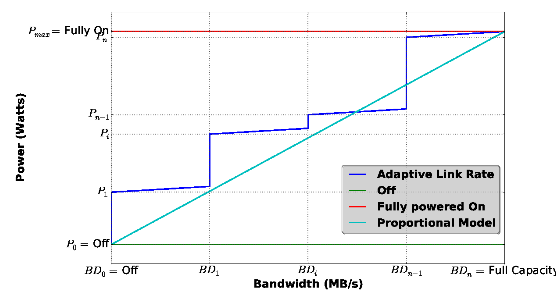

Figure 1. Models of power cost as a function of bandwidth on a router port during a transfer

For a given equipment, like a router, we also divide this consumption in two parts:

- the power consumed by the ports during transfers, which is in fact the variable part of the energy consumption;
- the power consumed by the router itself when there is no transfer (the idle consumption of the router) which represents the fixed part.

Figure 1 theoretically represents the power consumption of a port for example, during a transfer. The line labeled *Adaptive Link Rate* shows how the port power consumption is influenced by the actual transmission rate. With ALR techniques, only several link rates are possible. For example, for a 10 Gb/s port, the possible link rates are: 10 Mb/s, 100 Mb/s, 1 Gb/s and 10 Gb/s. These possible link rates are represented by the parameters BD_i on the x-axis of Figure 1. But, each transmission rate is possible for a port: transmission rate is not a discrete function. Thus, for example, when the port is transmitting at 20 Mb/s, it consumes the energy needed to adapt (with ALR) the link rate to 100 Mb/s (because 10 Mb/s $<$ 20 Mb/s $<$ 100 Mb/s), plus some energy due to the actual traffic (with a linear dependence) as represented on Figure 1.

In the following, our model considers that the power function P_{work} is a piecewise affine function for the ports as presented on Figure 1 by the line labeled *Adaptive Link Rate*. This power function presents a strong dependence to the equipment state (i.e. transmission rate in the case of a port) and a small dependence to the traffic. Using the notations of Figure 1, the power function of a port P_{work} can be written as a function of the bandwidth BD:

$$P_{work} = \begin{cases} P_0 & \text{if } BD = 0 \\ \alpha_1 BD + P_1 & \text{if } BD \in]0; BD_1] \\ \vdots & \\ \alpha_i BD + (P_i - \alpha_i BD_{i-1}) & \text{if } BD \in]BD_{i-1}; BD_i] \\ \vdots & \\ \alpha_n BD + (P_n - \alpha_n BD_{n-1}) & \text{if } BD \in]BD_{n-1}; BD_n] \end{cases} \quad (4)$$

where α_i are the slopes ($\alpha_i > 0$) of the different linear portions (power levels) delimited by the BD_i (the different transmission rate levels) and P_i define the start power of each different level.

C. Energy Consumption per Network Transfer

From this energy model per equipment, it results that the total energy used by a transfer from Node A to Node B on the example displayed on Figure 2 through Router 1 and 2, if there is no cross traffic, is:

$$\begin{aligned} E_{transfer} &= E_{EthernetCard}(NodeA, BD, L) + E_{Router}(Router1) \\ &+ E_{Port}(In, Router1, BD, L) + E_{Port}(Out, Router1, BD, L) \\ &+ E_{Port}(In, Router2, BD, L) + E_{Port}(Out, Router2, BD, L) \\ &+ E_{Router}(Router2) + E_{EthernetCard}(NodeB, BD, L) \end{aligned} \quad (5)$$

The functions E_{router} and E_{port} are different for each router. The energy consumed by an Ethernet card ($E_{EthernetCard}$) depends on:

- its model (capacity, manufacturer, hosting node, etc.): this represents a fixed cost;
- BD the bandwidth used by the transfer;
- and L the length in time of the transfer.

In the same way, the energy consumed by a router (E_{router}) for a given transfer depends only on the router type (size, manufacturer). It is a fixed cost. But, if several transfers are using the same routers (cross traffic for example), this cost is divided among the transfers depending on their duration. The energy consumed by a router port during a transfer (E_{port}) depends on:

- the router's model;
- if the traffic is coming in or out;
- BD the bandwidth used by the transfer;
- and L the length in time of the transfer.

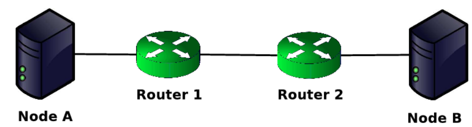

Figure 2. Scenario example

D. Model Calibration

The ECOFEN model gives the energy consumption of a given network (topology, type of equipments, routing protocol) for a given traffic (bandwidth utilization). It is a generic model that can be used for any kind of wired networks and traffic, and with energy saving techniques such as on/off policies and rate adaptation.

ECOFEN assumes that the power function of each equipment (P_{work}) is known. So, α_i, BD_i and P_i are known for each equipment which power consumption depends on the bandwidth and the fixed costs are also known for all the equipments.

With this information, the overall energy consumption per equipment and per data transfer is computable. This requires a preliminary calibration campaign with wattmeters for each type of equipment in order to plot the power profiles (power functions depending on the usage like in the examples of Figure 1) of the utilized network equipments.

For example, in [12], the authors provide power consumption values for a rack switch: the power consumed by the chassis is 146 Watts, and a port consumes 0.12 Watts when working at 10 Mbps, 0.18 Watts when working at 100 Mbps and 0.87 when working at 1 Gbps. So, as we can see the dynamic power is really small compared to the static power. Typically, it represents between 3 and 25% depending on the equipment [10].

In the future, such basic values should be included in the manufacturer specifications for each network equipment. The simulator presented in the next section is based on this ECOFEN model and on such kind of realistic measurements. For the calibration consumptions of the different router types, we have used the values provided in [10], [12], [13], [14], [15], [16].

III. THE ECOFEN SIMULATOR

The aim of this simulator is to compute the energy consumed by a network with a given traffic. A module for NS2 is developed to bring this functionality. NS2 is undoubtedly one of the most used simulation tools in the networking research community.

A. The Network Simulator NS2

NS2 is an open source network simulator for evaluating networks, protocols and topologies. It provides discrete event-based simulations including, among others, transport protocols, routing protocols, and multicast protocols over wired and wireless (local and satellite) networks[1]. The core is written in C++ and the provided simulation interface is in OTcl (an object-oriented extension of Tcl). So, the user describes a network topology and traffic using OTcl scripts.

Our module is integrated within NS2, and thus is written in C++. It defines energy properties for each network equipment and the energy model is implemented with the aim to obtain the energy consumption for each equipment and the overall consumption at each second.

B. The Energy Module

This NS2 module takes several experiment parameters as input data.An experiment is composed of four elements:

- a network topology (with link capacities and type for each equipment),
- network traffic (sources, destinations, type of traffic, rate profile, protocols),
- a scenario (beginning and end of the different traffic, failures, switching on and off of the network equipments and ports),
- real energy consumption values for the network equipments used in the topology: these values are included in the model detailed in the previous section to provide the overall consumption.

For example, for a router, the energy consumption values include the fix cost (power consumption of the chassis, the route processor module, etc.) and the variable costs (energy profile for each port depending on the link rate). From the variable costs, we compute the cost (in Joules) for a byte received or sent by an interface. This cost is used by the simulator to compute the overall consumption of the equipment.

The simulator is able to compute the energy consumed from the smallest possible network (2 end-host machines connected together) up to networks of thousands of nodes. This also implies the ability to choose the physical characteristics of hardware, and the bandwidth of a link and its latency.

The traffic between the network nodes is configurable: the user can choose where and when sending the packets, the packet sizes and characteristics and the used protocols. Any network usage can be simulated, like for example voice over IP, Peer-to-Peer networking or browsing the Internet.

In addition, our simulator is able to simulate the different technologies proposed to save energy in wired networks: it is able to change the link state (on and off) and rate, and to extinguish nodes and ports.

[1] *http://www.isi.edu/nsnam/ns/*

For a given experiment the simulator's outputs show the power consumption per node and per second. Thus, it provides the ability to compare different algorithms (routing or energy savings algorithms for example), different network architecture designs with different network components (different routers, switches, NICs, etc.) in terms of both energy consumption and performance.

IV. Scenario and simulations

To evaluate the ECOFEN simulator, we simulated different scenarios.

A. Comparison of Network Architectures

The first example uses the network depicted on Figure 3 with all the nodes (referred as the *full topology*) and secondly, without three router nodes (referred as the *minimal topology*). For both cases, each of the two clients downloads a big file from one of the servers. The servers send packets of 1500 bytes at regular intervals. The power consumption values used for this experiment are given on Figure 3. For each networked equipment, the simulator uses one value for the chassis and one value per interface (port or NIC) when working at full speed. The cost per octet is computed from this latter value.

The goal of this example is to compare in terms of energy consumption two different network architecture solutions for a given application. Table I presents the total energy consumed by the network by evaluating the two proposed topologies.

As expected, the minimal topology consumes less, since even idle nodes consume a lot of energy. Thus, energy management algorithms for networks can take advantage of this to switch off unused resources.

Scenario	Consumption (Watts)
Full topology	3971.5 W
Minimal Topology	2351.5 W

Table I
POWER CONSUMPTION FOR THE MINIMAL AND FULL TOPOLOGIES ON A BIG FILE DOWNLOAD SCENARIO BETWEEN CLIENTS AND SERVERS

B. Evaluation of the Dynamic Energy Cost of Traffic

The ECOFEN simulator allows to directly evaluate the cost of networks due to involved equipments. Moreover, this simulator can take into account traffic variations which imply power consumption variations.

Figure 5 presents the consumption of the Ethernet Card of node A on the topology presented on Figure 2. The traffic generated is a basic TCP flow sent by node A to node B. It uses TCP NewReno which is widely deployed on the Internet. This graph clearly illustrates the behavior of the window congestion of TCP.

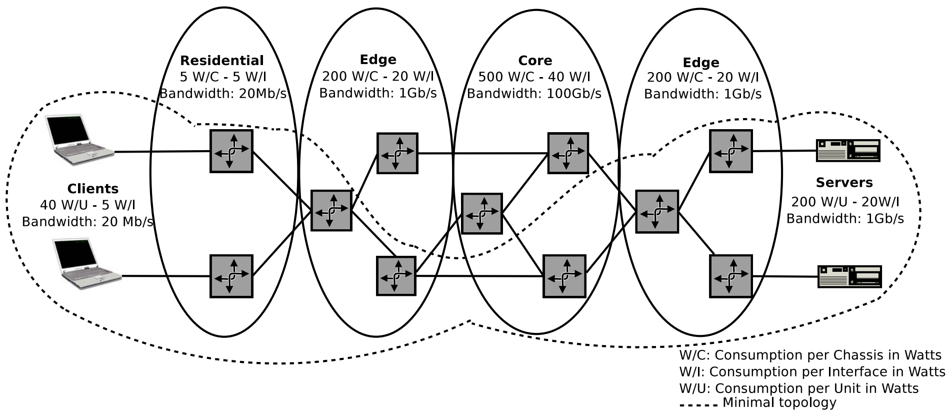

Figure 3. Full and minimal topologies for the client/server scenario

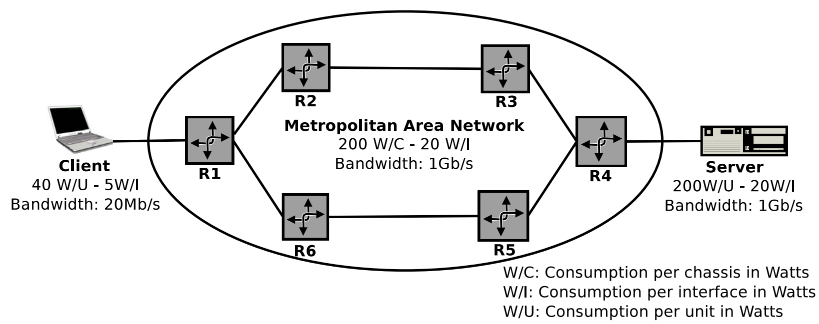

Figure 4. Topology of the metropolitan network with redundant routing equipments

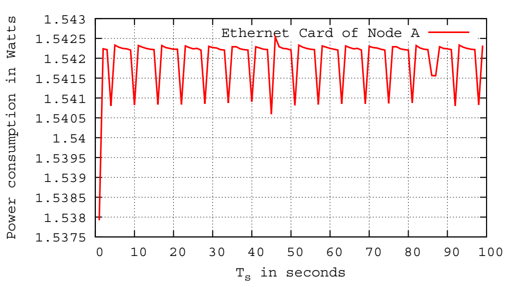

Figure 5. Power consumption of a 100Mbps Ethernet Card with a TCP flow

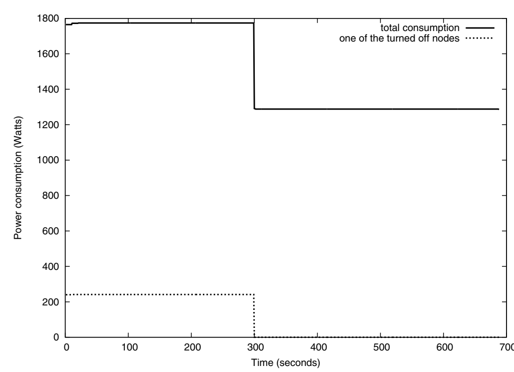

Figure 6. Power consumption of the network for the simulation of an energy management algorithm that turns off two nodes

C. Evaluation of Energy-Efficient Strategies

For the third example, the used topology is presented on Figure 4. The two upper nodes (R2 and R3) are turned off during the simulation at the 300th second with their interfaces and the interfaces they are linked with. Thus, from the 300th second, the overall system consumes less energy as shown on Figure 6. A rerouting algorithm is needed if the turned off path is switched on again.

This second example shows that this simulator, including basic energy saving techniques (on/off and rate adaptation), can be used to validate and compare new network energy management algorithms built on these basic techniques.

D. Evaluations on Large-Scale Networks

To show that this simulator can be used for computing energy consumption over large-scale networks, we simulate a hierarchical network consisting in 8 core routers, 52 edge routers, 52 access routers, 260 residential switches and 260 end-hosts. These nodes are connected between themselves with 1056 links. This network has been inspired by [17]. We simulate 130 TCP transfers between the end-host pairs (randomly chosen). The experiment lasts 100 seconds.The flows are chosen randomly and launched at different times to create an heterogeneous traffic: from 0 to 25 seconds, 30 TCP flows ; from 25 to 50 seconds, 90 TCP flows; from 50 to 75 seconds, 30 TCP flows, and from 75 to 100 seconds, 130 TCP flows.

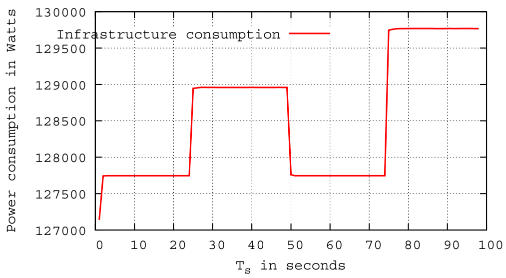

Figure 7. Power consumption of a network including 632 nodes and 1056 links

The total power consumption of this network is plotted on Figure 7. The energy dependence on traffic is highlighted with this graph. In proportion, it represents a small amount of energy. Indeed, like we have already explained the dynamic power consumption is small compared to the dynamic one.

V. Conclusions and Future Works

This paper presents ECOFEN, an End-to-End energy Cost mOdel and simulator For Evaluating power consumption in large-scale Networks. ECOFEN allows users to evaluate the power consumption of large scale networks by defining topologies, network equipments, traffic type and network protocols. ECOFEN has been designed to support energy leverages based on some advanced functionalities not yet largely available in networks (like dynamically switching on and off some equipments, adaptive link rate). This simulator should help network designers to simulate their proposed strategies on energy consumption reduction before deploying them at large scale.

The designed simulator is currently under finalization and will be made publicly available for the research community exploring energy issues in large scale networks. Some traffic plug-ins will be implemented in order to give more realism to observed traffic (like packet loss and jitter) and some real calibration values will be collected and injected in the simulator in order to include a collection of network equipments and devices (routers, interfaces, network cards) with realistic measured values.

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