Energy-Efficient Networks under Coordinated and Uncoordinated Sleeping Approaches

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***Abstract*—Wired IP networks handle the bulk of today's communication. These networks are built with over-provisioning and redundancy of devices to support critical activities. However, the activities can vary significantly, resulting in unused network online waste of power. In this study, we examine two existing power-saving approaches for wired IP networks: *i) uncoordinated sleeping* and *(ii) coordinated sleeping*. The uncoordinated and coordinated sleeping algorithms investigated are respectively Energy Efficient Ethernet (EEE) and Energy-Aware Routing (EAR) for green OSPF. In addition, we investigate the combination of coordinated and uncoordinated sleeping algorithms, EEE and EAR for green OSPF. The energy performance of the two algorithms and their combination is evaluated in two networks of different dimensions under varying traffic loads.**

The investigation shows that EEE, EAR for green OSPF and the combination significantly reduce the energy consumption of a network. However, the highest peak of energy conservation is achieved when EAR for green OSPF is activated in an EEE network during lower traffic load periods and deactivated during high traffic load periods.
Keywords: power, coordinated, uncoordinated, EEE, EAR for green OSPF

I. Introduction

The energy consumption of wired IP networks is becoming a major concern within the communication systems research community. This is witnessed by an increasing number of studies aiming at reducing electrical energy in network devices. The research field dealing with energy efficiency in communication systems and networks is referred to as green networking. The research categories within this field range from hardware virtualization, interface proxying, design of energy-aware applications and infrastructures, and adaptive link rate (ALR) [1]. In this study, we focus on ALR and energy-aware infrastructure.

ALR for a typical Ethernet link is a well-studied category. It is based on two power management techniques: rate switching and sleeping mode. Rate switching dynamically adapts Ethernet link data rates according to utilization [2], [3]. This technique was never implemented due to lack of a faster data rate switching mechanism. Sleeping mode puts the physical link into low-power sleep mode between frame transmissions. When frames arrives at the output port and need to be transmitted, the link is resumed to active mode [4] [5]. Sleeping mode has been standardized under the name IEEE 802.3az Energy-Efficient Ethernet (EEE) also called low power idle (LPI). Currently, there are a number of IEEE 802.3az EEE compliant network devices. These devices include, for example, access switches Cisco Catalyst 4500E series, D-LInk DGS-1100 series and Juniper EX4300-32F series as well as interface cards Intel 82579LM Gigabit Ethernet and Intel Ethernet Controller I350.

Energy-aware Infrastructure is accomplished by either redesigning the network architecture so that devices collaborate and share knowledge about the network energy management state or by embedding energy awareness to routing protocols through integration of power metrics [1]. With energy-aware routing (EAR) protocols, the energy consumption of a network can be reduced by aggregating packets and rerouting through specific paths allowing some links to be completely switched off [6].

In general, to reduce the power consumption of an IP network, the network devices or components of the network devices must be put in low-power sleep mode [7]. For a typical Ethernet link, there are two distinct types of low-power sleep mode: LPI and deep sleeping mode. In LPI, the link is idle and consumes the minimal amount of energy. A link in deep sleeping mode is completely switched off; the power consumption in this mode is null.

In order to allow that links transition to low-power sleep mode efficiently and faster, two sleeping approaches were developed, namely coordinated sleeping and uncoordinated sleeping. Coordinated sleeping is a network-wide approach used by routing protocols to reroute traffic during low load periods, allowing some links to be put into deep sleeping mode [7]. Uncoordinated sleeping is a link-layer-based approach where local information is used to sleep an interface [7]. ALR sleep mode algorithm is based on an uncoordinated sleeping approach while EAR algorithms are based on coordinated sleeping approaches.

Although, there are many studies attempting to minimize the power consumption of wired IP networks, most of these studies investigate algorithms that are based either on coordinated sleeping approaches or uncoordinated sleeping approaches. There are almost no studies that combine these sleeping approaches. Therefore, it is yet unclear how much power saving can be achieved through the implementation of the combination of these two sleeping approaches in a network.

In this paper, we investigate the performance in term of the power consumption of two sleeping approaches: uncoordinated sleeping and coordinated sleeping approaches. The uncoordinated sleeping algorithm selected for our investigation is IEEE 802.3az EEE [8], [9] and the coordinated sleeping algorithm is EAR for green Open Shortest Path First (OSPF) [6]. In addition, we perform the combination of the two algorithms, EEE and EAR for green OSPF. We design analytical models to estimate the energy consumption of a wired IP network under EEE, EAR for green OSPF and their combination.

This study is original and the main contribution is the investigation of how combining or implementing EAR for green OSPF in a EEE network will reduce the energy consumption of a network during lower traffic load periods while EEE will perform better in a network under high traffic load. In a loaded network, EAR for OSPF increases not only the length of some paths but also the utilization of the links shared by multiple connections, this behavior leads to higher power consumption. A smart mechanism to automatically activate and deactivate EAR for green OSPF in an EEE network according to network traffic conditions can greatly improve network energy conservation.

This paper is organized as follows. In section II, we present related work. In section III, we briefly describe uncoordinated and coordinated sleeping based algorithms: EEE and EAR for green OSPF. In section IV, we describe the combination of uncoordinated and coordinated sleeping strategies. In section V, we design the power consumption estimation analytical models. Section VI evaluates the energy performance of the algorithms followed by the conclusions in section VII.

II. Related Work

Putting components of network devices in low-power sleeping mode has been envisioned as the appropriate method of reducing power consumption of IP networks [7]. This is achieved using either uncoordinated sleeping or coordinated sleeping algorithms. Uncoordinated sleeping is a mature research field, the most known algorithms in this set of approaches are ALR using rate switching and EEE. Rate switching is designed to operate under standard data rates, from 10 Mbps to 10 Gbps. The decision to transition between data rates depends on the implementation policies. The authors of [2] proposed a buffer occupancy policy termed dual threshold (DTP) and a Ethernet link utilization policy. DTP suffered from switch oscillations; thus, to minimize the oscillations and maximize energy gain, a third policy named dual utilization threshold was investigated in [3]. The authors of [10] redefined the model proposed in [3] by adding the rate switching times and the NIC buffer size as a new metric.

IEEE 802.3az EEE is already an available standard [5]. IEEE 802.3az EEE specifies a new power saving mode for Ethernet link called LPI. This mode is activated during idle periods between packets. The authors of [8], [9] investigated mechanisms to enter LPI mode efficiently with minimum packets delays and maximum power saving. The authors of [10] designed and evaluated a Dynamic Ethernet Link Shutdown (DELS) algorithm. The algorithm uses buffer occupancy and monitors the behavior of previous packet arrival times and a configurable maximum bounded delay to make sleeping decisions.

The studies of coordinated sleeping approaches include [11] where the authors formulate EAR as an optimization problem and numerically solve the problem to evaluate the achievable energy saving. They showed that the trade off between green networking optimization and performance does not necessarily hold. The authors of [6] proposed an EAR algorithm based on OSPF routing protocol which consists of re-usage of short path tree by routers. Using this algorithm they were able to reduce power consumption by 50%. The authors of [12] proposed an enhancement of EAR for green OSPF presented in [6] by introducing a new mechanism of Shortest Path Tree (SPT) exportation called *move* for a two layers IP-over-WDM network where the IP logical topology is mapped onto a WDM network of fiber links.

III. EEE and EAR for Green OSPF

A. Energy Efficient Ethernet

IEEE 802.3az Energy Efficient Ethernet (EEE) is a recent IEEE standard resulting from enhancement of Ethernet Interfaces [5]. The IEEE 802.3az EEE specifies a new power saving state for Ethernet physical interfaces (PHY) called LPI. LPI defines periods over which no data is transmitted. During these periods, short signals are periodically transmitted to refresh the receiver state to keep the link alive. Although, the power consumption of LPI depends on the physical link, LPI consumes the minimum amount of power around one tenth of the power under normal operations [8], [9]. Since during LPI, the Ethernet interface can not send nor receive traffic, IEEE 802.3az EEE defines a mechanism to transition the interface between LPI and the normal mode also called active mode [9]. The transitions between the modes are triggered based on uncoordinated sleeping approaches. In active mode, the components of the transceivers of the Ethernet interfaces on both ends of the link are operative and ready to transmit and receive data. Thereby, the power consumption of the active mode is the maximum defined for the concrete Ethernet PHY. Figure 1 shows an IEEE 802.3az EEE network interface. As illustrated, the IPL is the periods in which no transmission is required and active mode is data transmission periods.

The power consumption of an EEE based Ethernet link between nodes i and j, $l_{i,j}$, depends on the utilization of the link and is given by equation (1) [9].

$$\bar{P}_{i,j} = \rho_{off} P_{i,j}^{off} + \rho_{tra} P_{i,j} + \rho_{on} P_{i,j}, \tag{1}$$

where $P_{i,j}$ is the power in active mode; $P_{i,j}^{off}$ is the power in LPI mode; and ρ_{off}, ρ_{tra} and ρ_{on} are the utilization factors representing, respectively, the fractions of time in which the link is sleeping, transitioning between modes and awake [9].

The active mode includes the time to wake up the link, t_w, the data transmission time, and the time to sleep, t_s. Two algorithms have been adopted to wake up a link: *(i) Frame transmission (FT)* and *(ii) Burst transmission (BT)* also called *Packet coalescing* [8], [9].

When frame transmission is configured, packets are sent to the outgoing link immediately after their arrival at the output queue. In contrast, in burst transmission, the packets are queued and sent to the outgoing link after a specific period of time, t_{max}, or after a number of output queued packets is reached, q_w. Burst transmission improves power saving compared to frame transmission at the expense of increasing packet delays. Frame Transmission provides better QoS at the expense of power saving [8], [9].

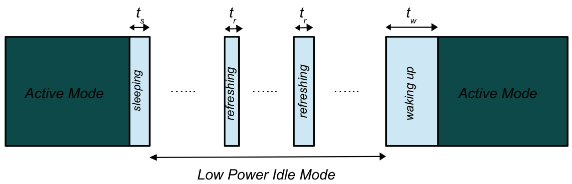

Figure 1: EEE model

B. EAR for Green OSPF

Energy-aware routing (EAR) is a process of embedding energy awareness to routing protocols through integration of power metrics [11], [6], [13]. With EAR, packets are aggregated and rerouted through specific paths allowing some links to be completely switched off. These links are considered to be in deep sleeping mode. In this mode, the power consumption is null. The remaining links in the network continue to operate in active mode consuming the amount of power defined by the Ethernet physical interface. EAR implements coordinated sleeping approach.

In this work, we focus on the EAR for Green OSPF [6]. EAR for green OSPF is an algorithm compatible with classic OSPF. It is a three-phase algorithm. The first phase selects a set of routers called Exporter Routers (ER). ERs compute their shortest path tree (SPT) based on Dijkstra algorithm, just like in the regular OSPF. The second phase, referred to as Modified Path Tree (MPT) evaluation, identifies links that can be powered off. To accomplish this, the algorithm determines the second set of routers called Importer Routers (IRs). IRs import the SPTs of the associated ERs, compute the MPT, and power off links not in MPTs. An ER can be associated to a number of IRs, but an IR is only associated to one ER. ER and IR are neighbor routers. The other routers, outside the neighborhood, are referred to as neutral routers (NRs). NRs compute their SPT based on classic OSPF. The third and last phase builds the routing tables based on the residual network. The residual network is the logical topology obtained by putting redundant links in deep sleeping mode. It is comprised of the set of active links connecting all the routers. The last phase ensures that the network is stable and loop free.

IV. The Combination of Uncoordinated and Coordinated Sleeping Approaches

To investigate the energy saving of the combination of uncoordinated and coordinated sleeping approaches, we selected and combined IEEE 8032.3az EEE from uncoordinated sleeping approach and EAR for OSPF from coordinated sleeping approach.

To implement the combination, we build an EEE network, a network where all links are EEE links and the power consumption depends on the traffic load, see subsection III-A. Then, we activate EAR for green OSPF on the EEE network. Once EAR for green OSPF is activated, see subsection III-B, a number of Ethernet links is put in deep sleeping mode. The remaining Ethernet links build a new logical network topology, the so-called residual network. The links in the residual network comply with EEE. The minimal number of links that a residual network can have and guarantees connectivity of the nodes is $n-1$, where n is the number of nodes.

V. Energy Efficiency Estimation Models

A. Energy Efficiency of EEE

The power consumption of the links of an EEE network depends on the traffic load as well as on the number of links traversed by traffic. The links traversed by traffic are determined by the routing protocol in use in the network.

The total power consumption of the links of an EEE network is given by:

$$P_{total} = \sum_{l_{i,j} \in E} \bar{P_{i,j}}, \tag{2}$$

where $l_{i,j}$ is the link between node i and j, E is the set of all links in the network, and $\bar{P}_{i,j}$ is the power consumption of $l_{i,j}$ given in equation (1).

B. Energy Efficiency of EAR for Green OSPF

The EAR power saving depends on the number of links in deep sleeping mode. The higher the number of links in deep sleeping mode, more power saving is achieved. On the other hand, to put a greater number of redundant links in the deep sleeping mode as possible, there should be an effective strategy to select and set exporter routers. The authors of [6] proposed the degree of connectivity as the rule for the exporter selection. The rule states that routers with higher degree of connectivity have priority to become exporters.

The reduction of the number of network links may lead to increased traffic load on the active links. This may negatively affect the level of quality; therefore it is advisable to use EAR for green OSPF during periods of lower traffic such as the nights. The active links, in a network using EAR alone, consume full power defined by the PHY.

The total power consumption of the links of a network running EAR for green OSPF is given by

$$P_{total} = \sum_{l_{i,j} \in E_r} P_{i,j}, \tag{3}$$

where $l_{i,j}$ is the link between node i and j, $P_{i,j}$ is the power consumption of $l_{i,j}$, and E_r is the set of links in the residual network.

C. Energy Efficiency of the combination of uncoordinated and coordinated sleeping approaches

The power consumption estimation model for the combination of uncoordinated and coordinated sleeping approaches is achieved through the application of EEE estimator given in equation (2) in the residual network built by activating EAR for green OSPF.

Thus, the total power consumption of the links of a network combining EEE and EAR for green OSPF is estimated by

$$P_{total} = \sum_{l_{i,j} \in E_r} \bar{P_{i,j}}, \qquad (4)$$

where $l_{i,j}$ is the link between node i and j, $\bar{P}_{i,j}$ is the power consumption of $l_{i,j}$ using uncoordinated sleeping strategy, EEE, given in equation (1) and E_r is the set of links in the residual network.

VI. Energy Efficiency Evaluation

A. Simulation set-up

The simulations were designed and conducted using an ns2 simulator [14]. We used two synthetic networks generated using Brite with Waxman's model [15], [16]. Network I consisted of 24 nodes and 43 links with an average degree of connectivity of 3.58. Network II, consisted of 250 nodes, 500 links with an average degree of connectivity of 3.6. Each link in both networks has a capacity of 10 Gbps and a constant OSPF cost equal to one.

In addition, we applied EAR for green OSPF to determine the links that could be put in deep sleeping mode in both networks and we obtained their corresponding residual networks, residual network I and II. The number of ERs of network I and II were respectively 5 and 30. This number of ERs of each network configuration corresponds to the maximum number ERs complying with the neighborhood requirement of exporters and importers of EAR for green OSPF algorithm described in section III-B. The requirement states that an ER may be associated to a number of IRs, but an IR is only associated to an ER. Furthermore, it is worth noting that the number of links that can be put in deep sleeping mode tend to converge to a constant when the number of ERs increases; therefore, the difference in the number of links in deep sleeping mode obtained with the largest numbers of ERs is small. Figure 2 shows the percentage of deep sleeping links as a function of ERs of network II. Residual network I is comprised of 26 active links corresponding to a reduction of 40% of links of network I. Residual network II is comprised of 250 active links corresponding to a reduction of 50% of links of Network II.

The configuration parameters of EEE were set to: time to sleep $t_s = 2.88\mu s$ and time to wake up $t_w = 4.48\mu s$. These configuration values are the same as in [8]. $P_{i,j}$ is the power consumption of a link $l_{i,j}$ in active mode and $P_{i,j}^{off}$ is the power consumption of the same link in LPI. In LPI mode, the power consumption of a link corresponds to 10% of the energy consumption of the same link in active mode, that is, $P_{i,j}^{off} = \frac{P_{i,j}}{10}$. In deep sleeping mode, the power consumption is zero.

B. Energy Saving Performance

To evaluate the energy saving performance of EEE, EAR for Green OSPF, and the combination of EEE and EAR for green OSPF, we implemented these algorithms on the network I and II described in subsection VI-A. To add traffic in these networks, we randomly set pairs of sender and receiver and started transmitting packets. The number of these pairs of nodes was gradually increased. The packet arrival rate follows Poisson distribution varying from 0 Gbps to 4 Gbps. The frame size was set to 1500 bytes. We ran each simulation for five minutes. Each simulation is repeated four times with different traffic generator seeds. The average power consumption is taken over all five runs.

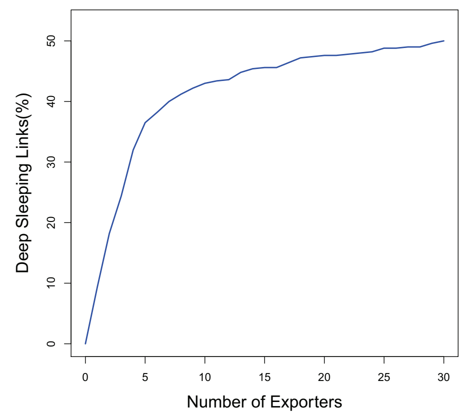

Figure 2: EAR Deep Sleeping Links

The traffic generation and transmission between nodes was interrupted as soon as some nodes of the residual network began experiencing packet dropping due to appearance of overloaded links. This interruption ensures that the performance of the energy saving algorithms are evaluated at the same level of traffic load for both the original and residual networks. From figures 3 and 4, one can see that the traffic generation and transmission was interrupted at 80 Gbps and 160 Gbps of load for network I and II respectively. Moreover, it is worth noting that at this traffic load level, it was already possible to infer the behavior of energy saving performance of the algorithms under investigation.

Figures 3 and 4 show respectively the percentage of power consumption of network I and II using the algorithms EEE, EAR for green OSPF and their combination in the figures denoted by EEE BT/FT+EAR. The three algorithms significantly reduce the amount of power consumption of wired IP network links. EAR depends exclusively on the number links in deep sleeping mode, showing a constant percentage of power consumption regardless of the traffic conditions. In figures 3 and 4, the EAR power consumption is denoted by EAR and corresponds to 40% and 50% of power saving for respectively network I and network II. *EAR max* denotes the power consumption of the network when the maximum power saving is reached. The *EAR max* of network I is 53.4%. The *EAR max* of network II is not shown in figure 4, as it is very close to EAR and equals to 49.8%.

We simulated EEE using the two wake-up algorithms: Burst Transmission (EEE BT) and Frame Transmission (EEE FT).

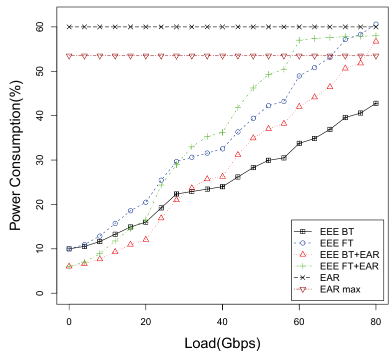

Figure 3: Links energy consumption of network I

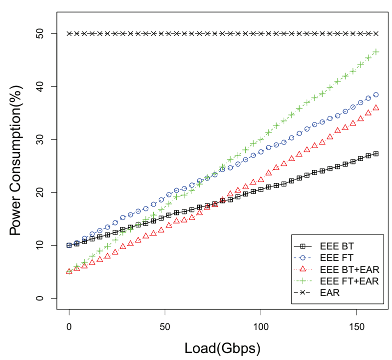

Figure 4: Links energy consumption of network II

EEE FT and the combination EEE FT + EAR show a steep rise of the energy consumption always above the BT counterpart. This behavior shows that FT consumes much more energy compared to BT. Analyzing EEE alone and the combination EEE+EAR, we conclude that EEE improves the energy saving when the network is loaded, while EEE+EAR energy saving is better when the traffic load is lower. Thereby, to exploit the most the energy saving approaches and improve significantly energy conservation in an EEE network with varying traffic demand, we propose the implementation of a smart mechanism to automatically activate EAR in an EEE network during periods of low traffic load and deactivate it during periods of higher traffic load. This mechanism could not only improve energy conservation but also ensure that the level of quality of service provision remains satisfactory. One can see that, the energy consumption of the combination EEE+EAR is upper bounded by EAR. Moreover, in a loaded network, the energy consumption of EEE+EAR is higher than that of EEE due to increase in the length of paths as well as link utilization.

VII. Conclusion

In this paper, we investigate the energy saving performance of two sleeping approaches in wired IP networks: uncoordinated and coordinated sleeping approaches. We use the energy saving algorithms EEE and EAR for green OSPF for uncoordinated and coordinated sleeping approaches respectively. In addition, we investigate the energy saving performance of the combination of EEE and EAR for green OSPF.

Based on analytical discussions and simulations, we find out that the maximum energy reduction can be achieved with a dynamic joint implementation of EEE and the combination of EEE and EAR for green OSPF. EEE should be configured with BT wake-up method. EAR for green OSPF should be deployed in an EEE network with the ability to activate and deactivate its operation automatically according to the traffic demand in the network. EAR for the green OSPF activation should be during lower traffic load periods and the deactivation during higher traffic load periods.

As further work, we will consider investigating mechanisms to determine the traffic levels where EAR for green OSPF should be activated and deactivated in an EEE network to improve significantly the energy saving of the links.

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