Computer Networks 78 (2015) 26–41

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Freezing forwarding functionality to make the network greener

Marco Polverini [a], Antonio Cianfrani [a,*], Angelo Coiro [a], Marco Listanti [a], Roberto Bruschi [b]

[a] DIET Department, Sapienza University of Rome, Via Eudossiana, 18, 00184 Rome, Italy
[b] CNIT, Research Unit of the University of Genoa, Via all'Opera Pia 13, Genova 16129, Italy

A R T I C L E   I N F O

Article history:
Received 28 February 2014
Received in revised form 23 September 2014
Accepted 1 October 2014
Available online 7 January 2015

Keywords:
Green networks
Energy aware routing
Table lookup bypass

A B S T R A C T

This work proposes a novel approach to reduce the power consumption of IP routers: freezing the forwarding engine of routers line-cards. In fact, recent studies showed that about 60% of the power consumption of a line-card is wasted to lookup the routing table during packet forwarding process. We first define the proposed approach, called Freezing Forwarding Functionality (F^3). Then, we provide an ILP formulation of the energy minimization problem under F^3 *mode* and define a heuristic algorithm, referred to as Green Backbone Algorithm (GBA), to solve the problem in large networks. The performance of GBA is evaluated under different traffic scenarios in real ISP network topologies, and a comparison with the ILP solution is carried out for small networks. Results show that: (i) GBA performance, in terms of number of nodes in F^3 *mode*, are very close to optimal ILP solution ones; (ii) a large energy saving (up to 80% of nodes in F^3 *mode*) is obtained in large networks during low traffic hours; (iii) a limited impact on paths length increase is achieved.

1. Introduction

The reduction of energy consumption of IP networks has been a fertile research topic in recent years. Green networking aims at reversing the principle that the network power consumption be constant even though traffic varies over the time. Many techniques have been proposed to adapt the network consumption to the actual traffic load. The most widely used strategy is to put in low-power *standby mode* a subset of routers and/or line cards according to traffic load variation [1] and to wake them up only if necessary. These mechanisms have to be supported by traffic engineering techniques [2,3] able to modify network paths so that links or routers to be put in standby mode can be bypassed. It has to be noted that they also need a modification or an adaptation of currently adopted routing protocols, for instance, enhancements of routing protocols as OSPF are under study [4]. Most of these studies exclusively concentrates on links since it is practically infeasible to put in standby an entire node. In fact, in principle, if a whole router were put in standby, it would not be able to receive, to process and to forward packets any more. Consequently, it would be virtually removed from the network topology.

This paper faces the problem of defining a low-power state for nodes, avoiding the virtual removal of them from the network. The idea is to define a router state, called *Freezing Forwarding Functionality* (F^3), able to obtain a significant energy saving, comparable to the case of complete "router standby", and, at the same time, able to limit the impact on network performance, stability, and reliability levels. This objective is achieved by introducing a mechanism aiming at bypassing lookup operations in router line-cards. This choice is supported by the consideration that these operations are the most power hungry [5] and a considerable energy saving can be obtained through their deactivation.

A preliminary work on the definition of a low-power state for nodes was presented in [6], where the authors describe several theoretical states for network nodes.

* Corresponding author.
E-mail address: cianfrani@diet.uniroma1.it (A. Cianfrani).

http://dx.doi.org/10.1016/j.comnet.2014.10.034
1389-1286/

Starting from the “bridged local” operation mode proposed in [6], we defined the “router standby” solution [7], taking into account real router implementation components. This work is an evolution of [7], since: (i) the F^3 mode of operation is defined, providing a more accurate evaluation of the internal architecture of IP routers; (ii) a novel formulation of the energy saving routing problem when F^3 state is available, with the specific constraints of IP routing, such as the destination-based forwarding mechanism and the shortest path routing policy, is proposed; (iii) an improved heuristic algorithm, to be applied in real network cases, is defined and evaluated.

Our model proposes that a router can assume two modes of operation: *full mode* and F^3 *mode*. In *full mode*, all the router line cards operate normally; on the contrary, in F^3 *mode* the routing functionalities are frozen and router line-cards assume specific fixed configurations, making the router behave like a sort of multiplexer/de-multiplexer. With respect to energy saving mechanisms based on the standby approach, the main advantages of F^3 *mode* are: (i) a router in F^3 *mode* maintains its network presence, avoiding network connectivity problems and the reduced network reliability due to nodes disconnection; (ii) differently to the node standby approach, the F^3 *mode* can bring energy saving even in a network scenario where every router is source and/or destination of traffic.

The problem of finding the set of nodes to be put in F^3 *mode* that minimizes the network power consumption and meets routing requirements is modeled as an optimization problem. Moreover, in order to find an approximate solution of the above mentioned problem even in case of large networks, a heuristic algorithm, called *Green Backbone Algorithm* (GBA), is proposed. The solution of the aforementioned problem will allow the network to work in a highly dynamic way: the nodes kept in *full mode* will compose a reduced Elastic Backbone that increases or decreases its size according to the needs due to the traffic load.

Summarizing, the main contributions of the present paper can be summarized as follows:

- the proposition of a low-power mode of operation for routers, called F^3 *mode*, and its specification according to the architecture of the currently adopted routers hardware;
- the formalization of the energy minimization problem in case of F^3 *mode* taking into account the specific constraints of IP routing features;
- the definition of the Green Backbone Algorithm heuristic, able to solve the energy minimization problem in case of large networks and to outperform previously proposed heuristics.

The rest of the paper is organized as follows. In Section 2 the contribution of this work with respect to similar solutions already proposed in literature, is highlighted. In Section 3 a brief review of the energy consumption associated to router elements is presented. In Section 4 details of the F^3 *mode* of operation are given. Section 5 is devoted to the explanation of the topological and traffic requirements under the identification of a feasible network configuration. Then, a MILP formulation of the energy minimization problem is presented. Section 6 is focused on the presentation of GBA heuristic algorithm. Finally, results of the performance evaluation study are discussed in Section 7.

2. Previous works

In the last few years many works focused on the reduction of energy consumption in backbone networks [8]. Anyway only few of them are devoted to the definition of a low power state for the routers, considering the standby of links/line-cards as the only available option. The main reason of such a situation is that putting a whole device in standby state is equivalent to remove it from the network, with a considerable impact on network performance and reliability.

The first work focusing on the definition of a new low power state for routers, different from a simple shut down, was proposed by Kist and Aldraho in [6], where a theoretical analysis of operational modes for routers is provided. The authors define several low power states for a network node; among them the most interesting one is the “bridged local”, representing the starting idea of our work. The authors also define a MILP formulation for the detection of a minimal topology, i.e. the minimum number of active nodes to satisfy a specific traffic demand; the formulation is based on the node bypass transformation, leading to a new network topology with an higher number of nodes and links. Due to the high complexity of the MILP problem, in [9] the same authors provide two simple heuristics to find a feasible solution in a real network scenario. The heuristics differ for the sorting criterion used “to scan” the network nodes: (i) the Lightest Node First (LNF) uses a topology parameter, i.e. the node gravity; (ii) the Least Loaded Node (LLN) exploits the node traffic load. Both heuristics try to remove a node from the network following the nodes order, and use the Shortest Path algorithm for network paths computation; as detailed discussed in Section 7, the way to connect each “bridged local” node to the rest of the network is not clearly explained in the work.

Starting from the “bridged local” model in [6], we defined the more accurate “router standby” model [7], taking into account the real router implementation components, i.e. those regarding IP packets processing and routing. In the work we also provide a new heuristic solution for the energy minimization problem when router standby is available. The heuristic, based on the well-known Floyd-Warshall algorithm, is able to detect a subset of network nodes that must work in active state, while the “router standby” state can be enabled on the remaining ones; moreover the problem of detecting the active outgoing link of standby routers is deeply investigated by the introduction of a specific procedure, referred to as bandwidth reassignment phase.

In this work we introduce our low power state for routers, referred to as F^3 *mode*. We provide a new MILP formulation of the energy minimization problem w.r.t [6]: in particular we formulate the problem of detecting the maximum number of nodes to put in F^3 *mode*, maintaining the classical IP routing among active nodes,