Energy Aware Routing based on Energy Characterization of Devices: Solutions and Analysis

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***Abstract*—The paper[1] copes with the reduction of network power consumption by the definition of new routing algorithms, able to take into account the energy consumed by the network devices. In particular, based on the power consumption characterization of the network devices obtained using the Energy Profile (EP) concept, the paper presents the analysis of the exact solution of the Energy Aware Routing (EAR) problem solved with a Mixed Integer Programming solver. The analysis is aimed at evaluating the impact on the performance of three relevant aspects of the problem: the approximation of the actual EP, the traffic load and the topology of the network. Furthermore, the paper proposes a heuristic solution of the EAR, denoted as Dijkstra-based Power Aware Routing Algorithm (DPRA), defined in order to cope with the complexity of the exact solution.**

I. INTRODUCTION

Today, energy consumption is one of the key issues for the future life. The Internet is rapidly becoming a major consumer of power, with significant economic and environmental impacts. For example, in Italy, Telecom Italia is the second largest consumer of electricity after the National Railway system [1], consuming more than 2 TWh. In Japan, the power consumption of the network infrastructure is predicted to be 103.3 TWh/year in 2025 [2]. In US, the network infrastructure require between 5 and 24 TWh/year [3]. Considering that energy cost is constantly growing, it is not surprising that communication operators and equipment vendors are trying to reduce the power consumption of network.

Recent works on Green Networks have defined the energy aware problems and (in some cases) solutions on three relevant aspects of a network: the *system design*, the *routing design* and the *network design*. The system design problem consists in energy efficient mechanisms implemented in network equipments, examples of these works are Adaptive Link Rate (ALR) [4] and Low-Power Idle (LPI) [5]. The routing design consists in methods to achieve further energy savings by means of appropriate flow routing strategy [6], whereas the network design problem is based on the idea of dynamically shutting down nodes and links when these resources are not strictly necessary (e.g. resources overprovisioned for fault protection) [7].

Our work is focused on the Energy Aware Routing (EAR), which consists in taking routing and traffic-engineering decisions to minimize the overall energy consumption of a network. In this paper, we have carried out extensive and accurate analysis of an EAR problem formulated in [6] by using a state-of-the-art branch-and-cut solver for Mixed Integer Programming (MIP) and a new heuristic algorithm denoted as Dijkstra-based Power Aware Routing Algorithm (DPRA). The analysis is focused on the evaluation of the potential power savings offered by these algorithms in different load and topology conditions. Furthermore, we evaluate the impact of the approximation of the actual power behavior of the network equipments on the performance of the algorithms.

The paper is structured as follows. Section II introduces the problem statement and the proposed algorithm. Section III presents the simulations settings and discusses results. Finally, conclusions are drawn in Section IV.

II. PROBLEM STATEMENT

The concept of Energy Profile (EP), presented in [6], permits the characterization of the energy consumption of a network equipment in function of its traffic throughput. Taking into account this characterization, the authors of [6] presented the idea of the Energy Profile Aware Routing (EPAR), which consists in the minimization of the overall energy consumption based on the EP of network devices and the actual traffic load. The model is described in the following subsection, while in the successive one the proposed heuristic, developed taking into account the EPAR model, is presented.

A. Energy Profile Aware Routing (EPAR)

Given a network modeled as a directed graph $G(V,E)$, where V is the set of nodes and E the set of links (to note that for each couple of nodes we consider two different directed links uv and vu), and indicating with D the traffic matrix, where each element, d_{sd}, represents the traffic demand from s to d, the EPAR problem can be formulated as follows:

$$\text{minimize} \sum_{v\in V} EP_{v,T(v)} \tag{1}$$

subject to

$$\begin{aligned} &\sum_{v\in V} f^{sd}_{sv} - \sum_{v\in V} f^{sd}_{vs} = d_{sd} \qquad \sum_{v\in V} f^{sd}_{dv} - \sum_{v\in V} f^{sd}_{vd} = -d_{sd} \\ &\sum_{v\in V} f^{sd}_{uv} - \sum_{v\in V} f^{sd}_{vu} = 0 \qquad \forall u \in V\setminus\{s,d\} \qquad \forall sd\in D \end{aligned} \tag{2}$$

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$$\sum_{sd\in D} f_{uv}^{sd} \leq C_{uv}^{L} \quad \forall uv \in E \tag{3}$$

$$T(v) \leq C_{v}^{N} \quad \forall v \in V \tag{4}$$

Equation (1) is the *Objective Function* to minimize, where $EP_{v,T(v)}$ is the energy consumption of the node v at the traffic throughput $T(v)$. The traffic throughput of node v can be calculated as follows:

$$T(v) = \sum_{u\in V}\sum_{sd\in D} f_{uv}^{sd} + \sum_{\substack{sd\in D\\ s=v}} d_{sd} \tag{5}$$

where f_{uv}^{sd} is the amount of traffic demand between s and d that flows through the link uv. Equations (2) are the classical *Flow Conservation Constrains,* while equation (3) forces the traffic flowing in link uv to be smaller than the link capacity C_{uv}^{L}. Equation (4) limits the load of node v to the node capacity C_{v}^{N}. The EPAR problem can be solved by means of a MIP solver such as CPLEX [8]. Nevertheless, high-performance mathematical programming solvers are expansive for economic, computational resource and time aspects. Whereupon, we have studied an heuristic denoted as Dijkstra-based Power-aware Routing Algorithm (DPRA).

B. Dijkstra-based Power-aware Routing Algorithm (DPRA)

The DPRA consists in the partitioning in small quantities, δ, of the traffic demand sd, and in the calculation of the minimum power consumption path for δ taking into account the resources already allocated in the network. This procedure is recursively executed for all couples of nodes, and until all the traffic demands reported in the traffic matrix D are allocated. At each iteration, the proposed heuristic associates at each oriented link a cost equal to the increase of the power consumption of the destination node. This parameter is calculated taking into account the δ, the traffic allocated on the considered link, and the EP of the destination node. Then, the Dijkstra's algorithm is used to compute the minimum cost path. The pseudo-code of the proposed DPRA is shown in the Algorithm 1.

Algorithm 1 Dijkstra-based Power-aware Routing Algorithm

```
Given: $G(V,E)$, $C_l$, $C_n$, and $D$
 1: Set $\delta_0$, $T^{CI}(v) = \sum_{u\in V} d_{vu}\ \forall v \in V$, and $d_{sd}^{RES} = d_{sd}\ \forall sd \in D$
 2: repeat
 3:     Select randomly a couple $sd$ such that $d_{sd}^{RES} > 0$
 4:     Set $\delta$
 5:     Calculate cost $w_{uv}\ \forall uv \in E$
 6:     Calculate $C_{v}^{MAX}\ \forall v \in V$ and $C_{uv}^{MAX}\ \forall uv \in E$
 7:     Delete links and nodes that do not satisfy maximum utilizations
 8:     Run Dijkstra's algorithm between $s$ and $d$ with cost $w_{uv}$
 9:     Update $T^{CI}(v) += \delta\ \forall v \in P_{sd}^{CI}$ and $d_{sd}^{RES} -= \delta$
10: until $d_{sd}^{RES} == 0 \quad \forall sd \in D$
```

After the initialization (steps 1), DPRA begins the iterations and selects sd, then δ is set as shown in Algorithm 2. Note that the choice of parameter δ_0 is a trade off between accuracy and simulation time. At step 5, the cost of the link $uv\ \forall uv \in E$ is calculated as follows:

$$w_{uv} = EP_{v,T^{CI}(v)+\delta} - EP_{v,T^{CI}(v)} \tag{6}$$

where $T^{CI}(v)$ is the traffic throughput of node v at the current iteration.

Algorithm 2 Set δ

```
if $d_{sd}^{RES} \geq \delta_0$ then
    $\delta = \delta_0$
else
    $\delta = d_{sd}^{RES}$
end if
```

Afterwards, the maximum resources available at each node, C_{v}^{MAX}, and at each link, C_{uv}^{MAX}, are calculated as explained in Algorithms 3 and 4. In particular, C_{v}^{MAX} is calculated taking into account the amount of traffic directed to the considered node v. In order to avoid that the algorithm could be blocked for lacking of resources at the receiving node, resources of node v must be reserved. Similarly, resources should be reserved in the link uv. In particular, in order to avoid the blocking of the algorithm for lacking of resources, three different cases should be considered (obviously when $uv = sd$, we do not need to reserve resources):

- when u is the source of the traffic demand, we should permit the reception of the traffic having v as destination; to this aim we allocate to each link attached to the node v an equal share of the amount of traffic transmitted to it;
- when v is the destination of the traffic demand, we should permit the transmission of the traffic generated by u; also in this case, we allocate to each link attached to the node u an equal share of the total traffic generated in u;
- when uv is an intermediate link of the traffic demand d_{sd}, we should allocate the resources needed for the reception of the other traffic having v as destination and those necessary for the transmission of the other traffic having u as source; in both cases, we assume that the whole traffic is uniformly distributed among the links attached to the node.

The next step consists in deleting (or equivalently in setting the cost to ∞) the nodes and the links that have not enough resources to participate to the next allocation process carried out by means of the Dijkstra's algorithm. In particular, defining $A^{CI}(uv)$ as the amount of traffic allocated on the link uv until the current iteration, the link uv is deleted from the graph iff $A^{CI}(uv) + \delta > C_{uv}^{MAX}$. Similarly, the node u is deleted iff $T^{CI}(u) + \delta > C_{u}^{MAX}$.

At the step 8, Dijkstra's algorithm runs using the costs w_{uv}, then the $T^{CI}(v)$ and d_{sd}^{RES} values are consequently updated (P_{sd}^{CI} is the set of nodes belonging to the path from s to d). Then, after the update of the variables $T^{CI}(v)$ and d_{sd}^{RES}, the algorithm returns to step 3 until $d_{sd}^{RES} = 0 \quad \forall sd \in D$.

The computational complexity of DPRA is about $\frac{|V|\cdot(|V|-1)}{2}\left\lceil\frac{\sum_{sd\in D} d_{sd}}{\delta_0}\right\rceil \times O(|E| + |V|\log|V|)$, where $|V|$ is

Algorithm 3 Calculate $C_v^{MAX}\ \forall v \in V$

```
if $v = d$ then
    $C_v^{MAX} = C_v^N$
else
    $C_v^{MAX} = C_v^N - \sum_{i \in V} d_{iv}^{RES}$
end if
```

Algorithm 4 Calculate $C_{uv}^{MAX}\ \forall uv \in E$

```
if $u = s$ and $v = d$ then
    $C_{uv}^{MAX} = C_{uv}^L$
else if $u = s$ and $v \neq d$ then
    $C_{uv}^{MAX} = C_{uv}^L - \frac{\sum_{i \in V} d_{iv}^{RES}}{deg(v)}$
else if $u \neq s$ and $v = d$ then
    $C_{uv}^{MAX} = C_{uv}^L - \frac{\sum_{i \in V} d_{ui}^{RES}}{deg(u)}$
else
    $C_{uv}^{MAX} = C_{uv}^L - \frac{\sum_{i \in V} d_{iv}^{RES}}{deg(v)} - \frac{\sum_{\substack{i \in V \\ i \neq v}} d_{ui}^{RES}}{deg(u)}$
end if
```

the number of nodes, $|E|$ is the number of links, and $O(|E| + |V| \log |V|)$ is the computational complexity of the efficient implementation of the Dijkstra's algorithm [9]

III. Performance Analysis

In the following we investigate the power savings provided by the EPAR and the proposed DPRA, in different traffic load and topological conditions.

A. Simulations settings

The simulation scenario considered in the analysis is the European core topology taken from [10], given by the Nobel 2 project. The network, shown in Figure 1, is composed by 28 nodes and 41 links.

Each node represents a core router; we assume the use of the Juniper T1600 core router, having a total throughput capacity of 1600Gb/s and a power consumption of 8352W [11]; thus all nodes of the networks have the same EP. Consequently, referring to the models previously described, we assume a node capacity $C_v^N = 1600 Gb/s\ \forall v \in V$ and a link capacity $C_{uv}^L = 600 Gb/s\ \forall uv \in E$. The traffic matrix D is obtained by the data file "Nobel-2 directed graph" downloaded from [10]; the file contains the measured traffic for each couple of nodes sd of the considered network scenario (we assume that the reported values are Gb/s). The amount of traffic demand is of 1898 Gb/s, distributed among 378 active pairs (i.e. couples of nodes, sd with $d_{sd} > 0$). The mean traffic demand of an active pair is of about 5 Gb/s; then the parameter δ of the DPRA is set to the 2% of the mean traffic demand, i.e. to 0.1 Gb/s. This value of δ permits to achieve a good trade-off between performance and computation time.

Concerning the EP curve, we focused our attention on the *Cubic* EP since it represents the state-of-art of circuit-level energy-efficiency mechanisms [6]. In particular, the Cubic EP is the energy behavior of network equipments that use energy savings techniques such as dynamic voltage and dynamic frequency scaling (DVS-DFS), which permit energy consumption to scale with resource requirements.

Fig. 1. European core topology considered in the simulation study

In order to solve the EPAR problem, we considered three different linear approximations of the Cubic EP. The first one approximates the Cubic curve with 20 segments; this will be denoted as *20seg*. The second approximation considers four segments and will be denoted as *4seg*. The edges of the segments has been chosen taking into account the values of the ECR Initiative™ [12], which requires to measure the power consumption at 0%, 10%, 30%, 50%, and 100% of the total throughput capacity. Finally, we consider the approximation based on only two segments (denoted as *2seg*), which has been used in the simulation analysis of EPAR discussed in [6]. The used approximations of the Cubic EP are depicted in Figure 2.

The performance parameter considered in the comparison of the EPAR and DPRA is the power savings of these algorithms with respect to the Shortest Path Routing (SPR). The power savings are defined as follows:

$$Power\ Savings_A = \frac{Power_{SPR} - Power_A}{Power_{SPR}} \times 100 \qquad (7)$$

where the subscript A indicates the algorithm considered in the analysis (i.e EPAR or DPRA). The SPR is calculated by means of CPLEX, which is set to find the minimum hop paths between two nodes taking into account the constraints on the link and node capacity.

The study is carried out considering two different aspects of the network: the load and the topology. In particular, in order to evaluate the impact of the load on the algorithm performance,

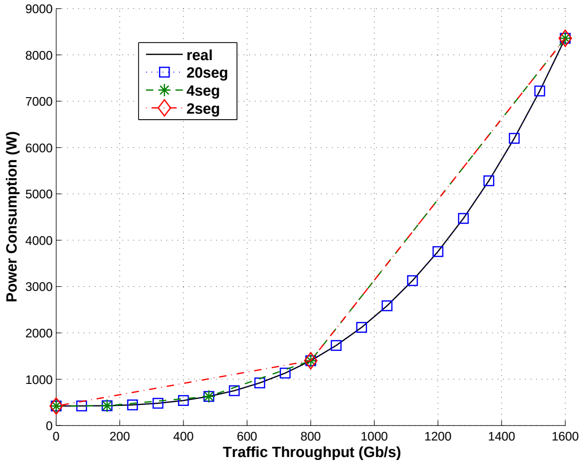


Fig. 2. Cubic EP and its linear approximations

we define the following parameter, denoted as Traffic Load (TL),

$$TL = \frac{1}{N} \cdot \sum_{u \in V} \frac{\sum_{v \in V} d_{uv}}{C_u^N}. \quad (8)$$

The *TL* represents the average fraction of the maximum capacity that a node should reserve for transmitting the locally generated traffic. Obviously, when the traffic load of a node is equal to 1, the node has not resources for forwarding or receiving traffic produced by others. The traffic load of the reference traffic matrix is 0.084. In order to vary the traffic load, we have multiplied the reference traffic matrix downloaded from [10], by diverse values.

As concerns the impact of the network topology on the algorithms performance, we consider two indexes of the graph theory: the average node degree and the node degree distribution. Starting from the considered topology, having an average degree of 2.90, we generate three new topologies applying one of the modifications reported in the following:

- *rand-add*: we randomly add links to the original topology to increase the average degree of one;
- *rand-add-2*: as *rand-add*, but with an increase of the average degree of two;
- *const*: we add and remove links in order to obtain a topology, where each node has a degree equal to 3.

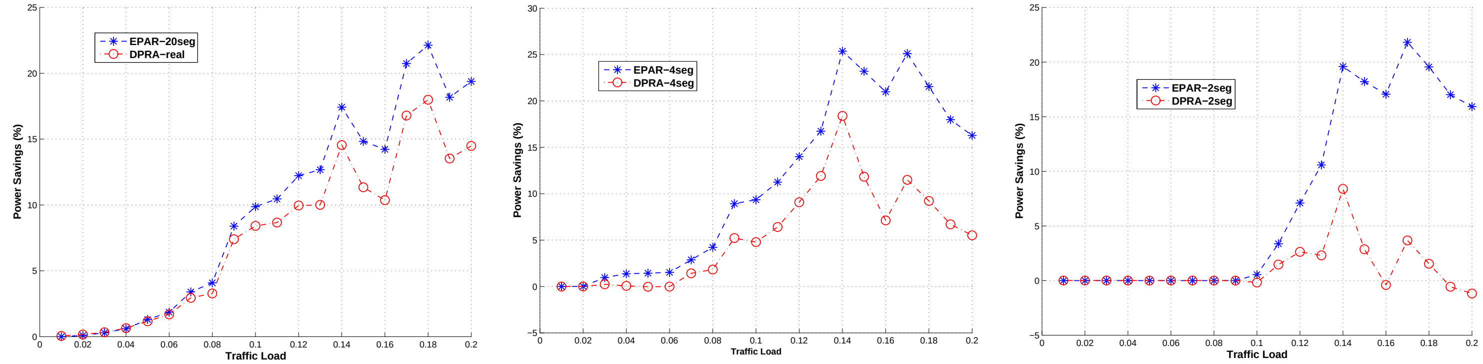
The procedure used to randomly add links consists in a first step of choosing randomly with uniform distribution a node of the network. Then, considering all neighbors not connected with the chosen node, we add a link towards the neighbor chosen randomly with a probability inversely proportional to the geographic distance.

B. Simulation Results

The discussion of the simulation results is organized in two subsections, depending on the considered aspect of the network features, i.e. traffic load and topology.

1) Traffic Load:

The power savings (in %) obtained considering the different approximations of the Cubic EP and for diverse traffic load values are summarized in Figure 3. A first observation regards the impact on the algorithm performance of the number of segments used to approximate the Cubic curve. In particular, when the number of segments is reduced, the power savings are lost for low values of traffic load. This conclusion is supported by the comparison of the Figure 3(a), where we observe about the 10% of power savings with the EPAR and a traffic load of 0.1, with the Figure 3(c), where no power saving is observed until a traffic load of 0.1. This behavior of the EPAR is due to the fact that until the TL assumes values that lead all the nodes to work in the first segment of the approximate EP, the EPAR solutions are the same as the SPR. This statement is supported by the results shown in [6], in the case of a network having the same linear EP; the simulation results demonstrated that in this condition, the minimization of the overall power consumption of the network leads to the same results of the shortest path routing. When the TL value leads to have network nodes working in diverse parts of the linear approximation of the Cubic EP (hence, in some cases characterized by different slopes), the minimization process of the EPAR induces a diverse distribution of the traffic with respect to the SPR, resulting into power savings. This observation explains the increase of the power savings with the TL and the absence of power savings for low values of TL. In particular, the length of the first segment of the approximating curve of the Cubic EP is directly correlated to the value of the TL where the power savings begin. This remark is supported by the Figure 3(b), where the power savings of the EPAR curve are higher than zero already after the third point. Indeed, in this case the length of the first segment of the approximating curve is less than $1/4$ of the *2seg* case, as shown in Figure 2. As concerns the DPRA performance, we can observe that the coarse approximation of the Cubic EP leads to the worsening of the performance with respect to the EPAR. In particular, in the *2seg* case, Figure 3(c) shows the lack of power savings when the DPRA is used. On the contrary, the performance of the DPRA and the EPAR are very close when we improve the approximation of the Cubic EP. It is relevant to note that, in the DPRA, the EP curve is considered in the calculation of the link costs w_{ij}; hence the utilization of the actual Cubic curve, i.e. without linear approximation, is not a problem and does not increase the complexity of the algorithm. On the contrary, the linear approximation of the Cubic EP is mandatory in the case of the EPAR; furthermore, the complexity of the EPAR algorithm increases with the number of segments used in the linear approximation. Table I reports the mean values and the 99% Confidence Interval (CI) of the time (in s) necessary for the two compared algorithms to produce the results, for two diverse traffic load values (we choose the most significative, i.e. near the conditions of the actual traffic matrix and one of the points where the power savings are high). The CIs are calculated taking into account the results of 100 different runs. The values reported in the table highlight that the DPRA running with the actual Cubic EP is about 3 times faster than the EPAR solved with the *20seg* approximation.



(a) Real (DPRA) and *20seg* approx. (EPAR) of Cubic EP

(b) *4seg* approximation of Cubic EP

(c) *2seg* approximation of Cubic EP

Fig. 3. Power savings as a function of the TL and the approximation of Cubic EP

TABLE I
COMPARISON OF THE COMPUTATION TIMES (IN S) AND THE 99% CI

	TL=0.1	TL=0.2
EPAR *(2seg)*	2.03 ± 0.01	3.41 ± 0.02
EPAR *(20seg)*	4.78 ± 0.03	6.73 ± 0.04
DPRA *(real Cubic EP)*	1.34 ± 0.04	2.71 ± 0.06

TABLE II
STANDARD DEVIATION OF LOAD OF EACH NETWORK NODE AFTER THE SPR (Gb/s)

original	rand-add	rand-add-2	const
433.15	298.36	270.28	241.93

Furthermore, the DPRA is faster than the EPAR also when the *2seg* approximation is considered.

2) Impact of Network Topology: For this analysis, we define the energy savings as $Energy\ Savings_A = Energy_{SPR} - Energy_A$, where $Energy_{SPR}$ is the energy consumed by the overall network when the SPR is used, and $Energy_A$ the energy consumed when the analyzed algorithm A, i.e. EPAR or DPRA, is considered. The results of the energy savings obtained with the diverse network topologies and for different traffic loads are reported in Figures 4 (EPAR algorithm with the *20seg* approximation of the Cubic EP) and 5 (DPRA algorithm with the real Cubic EP). In particular, comparing the *rand-add* and the *rand-add-2* in the Figure 4, we can deduce the reduction of the energy savings when the mean network degree increases. This result is due to the fact that when the mean network degree increases, the probability of finding alternative routes, more energetic efficient than the SPR path, decreases. As an example, in the boundary case of a complete meshed network, the link directly connecting the source and the destination is the shortest path, but also the only path with the lowest energy consumption; this path consumes only the energy at the transmitter/source node and at the receiver/destination node.

Furthermore, the energy savings decrease when all the nodes of the network have the same degree. Indeed, in the figure we can observe the energy savings loss of the *const* scenario when compared with the *original* (both scenarios have similar mean network degree). The energy savings obtained with the *const* network topology are comparable with those achieved with the *rand-add-2*, although this last scenario has an higher network degree than the *const*. In order to explain this behavior, we analyze the load of each network node in the four topologies after the application of the simple SPR, in the case $TL = 0.2$. In particular, although the average load of each network node is almost equivalent (i.e. about 600 Gb/s), we observe a difference in terms of standard deviation of this parameter (see Table II) for the considered topologies. Comparing the values of the Table and the energy savings curves of Figure 4, we can conclude that the higher is the standard deviation of the load of a node after the application of the SPR the higher are the energy savings.

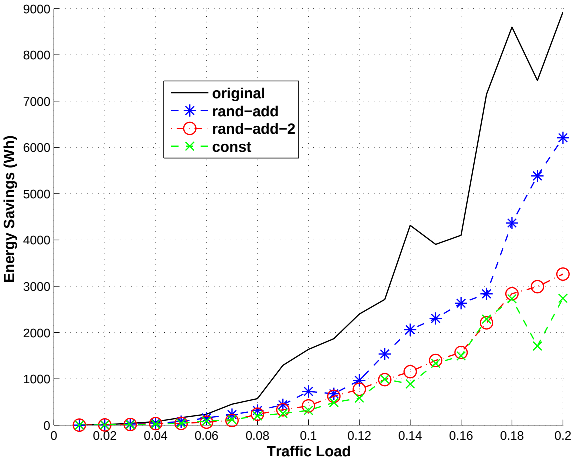


Fig. 4. Energy savings and network topology - EPAR Case

The results obtained with the DPRA algorithm, shown in Figure 5, lead to similar conclusions, although in this case the differences of the energy savings obtained with the diverse network topologies are less apparent.

IV. CONCLUSIONS

The simulation results shown in the paper highlight the ability of the proposed heuristic solution of the EAR problem, DPRA, in producing power savings comparable with the

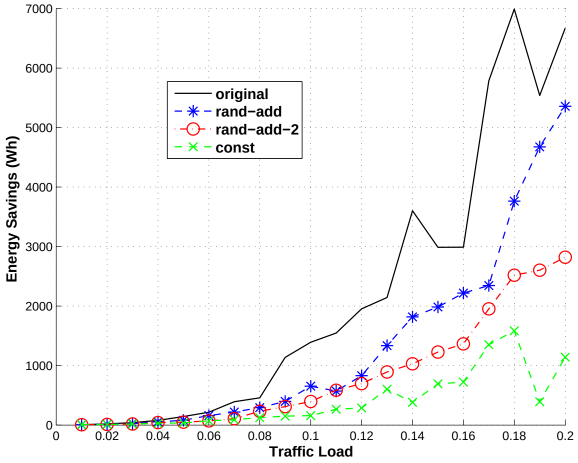


Fig. 5. Energy savings and network topology - DPRA Case

exact solution, EPAR, when the Cubic EP is considered. Furthermore, the EPAR solution shows the loss of energy savings when the Cubic EP is roughly approximated. It is relevant noting that in the EPAR case, the linear approximation of the Cubic EP is needed in order to reduce the computational complexity, whereas the proposed DPRA may work with the real Cubic EP and has a lower computational complexity.

Further, the simulation results show that, in order to achieve an adequate energy savings with respect to the SPR, the network traffic load should lead (in average) the nodes to work in a point of their EP where the rate of change is appreciable; the higher is the rate of change, the higher are the power savings obtained with the EPAR or the DPRA. Furthermore, in the same conditions of traffic load, the network topology can change the standard deviation of the load assigned to each node by the SPR; in this case, the simulation results point out that the higher is the standard deviation, the higher are the energy savings.

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