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A survey on green routing protocols using sleep-scheduling in wired networks

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ABSTRACT

Over recent years, green communications have been proposed as an emerging strategy to reduce the Carbon footprint produced by the networking sector. It consists in using different software and hardware techniques allowing to minimize the energy consumption of network components. A significant amount of energy saving can be obtained by switching redundant or unused network components to inactive mode, referred to as sleep-scheduling. To achieve this, the routing algorithm should aggregate traffic flows over a subset of network routers and their links, allowing other components to be switched off. The objective of this paper is to present a holistic survey on existing sleep-scheduling based green routing protocols in wired networks. First, we propose a classification of main properties of sleep-scheduling based green routing protocols and use the proposed classification to categorize and describe the existing literature. Moreover, we provide a comprehensive comparison of existing green routing protocols and determine the main characteristics, assets and issues of each proposal. In addition, we identify and classify the main metrics for evaluating and comparing the efficiency of green routing protocols using sleep-scheduling. Finally, we identify the open issues and key guidelines towards an ideal green routing protocol for wired networks.

1. Introduction

Over recent years, green communications have been emerged as an important area of concern for communication research and industrial communities. It relates to any hardware or software technique allowing to reduce the energy consumption of Information and Communication Technology (ICT) sector. The relevance of this trend turns back to its impact on environmental pollution and economic cost. Indeed, recent studies estimated that the ICT is responsible for up to 10% of the global CO2 emissions, while its contribution is doubled from the year 2006 to the year 2011 (Beloglazov et al., 2011; Webb, 2008; Global Action Plan Report, 2007). An important amount of ICT energy is reported to be consumed in network components, reaching between 30–37% of Green Houses Gases (GHG) produced by the ICT sector (Webb, 2008; Gartner, 2007). Consequently, an important effort is required to reduce the energy consumption of networking environments.

Nowadays, network resources including bandwidth, processing power and memory are oversized to handle high traffic loads, with only 30–40% of utilization in low traffic periods (Nedevschi et al., 2008; Guichard et al., 2005; Adelin, 2010; Gupta and Singh, 2003). Consequently, an important energy saving can be obtained by switching off extra components during low traffic conditions (Bianzino et al., 2012; Eyupoglu and Aydin, 2015). To achieve this, the routing algorithm should aggregate traffic flows over a subset of network routers and their links, allowing other components to be switched off. In this paper, the technique of switching off extra components is designated as *sleep-scheduling*, while the routing algorithm using this technique to provide the network with green features is referred to as *sleep-scheduling based green routing protocol*. Due to the significant amount of energy conserved through sleep-scheduling, this paper mainly focuses on sleep-scheduling based green routing protocols.

Since the green communications' tentative has been launched, a number of sleep-scheduling based green routing protocols has been proposed by the research community (Cianfrani, 2010; Cianfrani et al., 2012; Amaldi et al., 2011; Bianzino et al., 2012; Cuomo et al., 2011; Shen et al., 2012). However, to the best of our knowledge, a holistic survey on works overviewing recent advances in sleep-scheduling based green routing in wired networks has not existed so far. To address the aforementioned shortage in current literature, we present a comprehensive survey on sleep-scheduling based green routing protocols. Moreover, we propose a classification on green properties highlighting different characteristics of existing proposals. Based on this

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classification, we identify the main advantages and issues of existing green routing proposals and compare them qualitatively based on their main features. Due to the relevant impact of quantitative evaluation and comparison towards an ideal solution, we also identify and classify the main numerical metrics for evaluating and comparing the efficiency of sleep-scheduling based green routing protocols. Finally, we raise a set of open issues and propose key guidelines towards an ideal solution.

The reminder of this paper is organized as follows. Section 2 provides background and related topics. Section 3 reports main related surveys relevant to the present study. Section 4 presents our proposed classification of main green properties. Section 5 surveys general green routing protocols using sleep-scheduling. Section 6 describes the main existing MPLS-based and SDN-based proposals. In addition, it presents existing protocols considering inter-domain routing aspects to optimize the network performance and the energy gain of sleep-scheduling decisions. Section 7 presents a classification on the identified metrics for evaluating and comparing the efficiency of green routing protocols using sleep-scheduling. Section 8 presents a qualitative comparison of surveyed literature and outlines some open issues and guidelines towards an optimal green solution. Finally, Section 9 concludes the paper.

2. Background

In this section, we determine the scope and main terminologies of the paper, providing a clear definition of the employed key terms and some highly related topics.

2.1. Green communications

Green communications consist in an emerging approach to respond to the increasing economic cost and environmental pollution produced by the ICT industry. In 2007, the ICT sector was estimated to be responsible for about 10% of total energy consumption in UK (ITWales, 2007). Other estimations showed that the Italian Telecom consumed about 1% of its total energy consumption in 2006, which was increased 7.95% and 12.08% with respect to the years 2005 and 2004 (Bianco et al., 2007; Telecom Italia Website; British Telecom Group, 2009). Due to the increasing network usage and further requirements for network infrastructures, the contribution of ICT sector in GHG emissions is expected to increase significantly in next years. Global e-Sustainability Initiative (GeSI) estimated that network infrastructures will emit about 350 million tons of CO_2 in 2020 (Global e-Sustainability Initiative). As illustrated in Fig. 1, the CO_2 emissions of telecommunications devices (e.g. routers, switches) are estimated to increase from 12–22% in 2020 compared to 2002. Consequently, an important deal of attention should be concentrated on reducing the energy consumption of networking components.

Due to this importance, we carried out an extensive literature study on mechanisms applicable to reduce the energy consumption of networking components. Identified approaches can be classified in four categories, as described in the following:

- *Re-engineering*: The aim of this approach is to use more energy-efficient hardware components for network architectures, especially through reducing the internal complexity of elements (Chabarek et al., 2008; Ceuppens et al., 2008).
- *Interface proxying*: This approach consists in switching an inactive end device to the sleep/standby state and delegating the processing of its background traffic either locally to the low-energy processor onboard of the NIC of the same device, or to an external entity (Jimeno and Christensen, 2007; Sabhanatarajan and Gordon-Ross, 2008; Agarwal et al., 2009).
- *Power-proportional* or *Adaptive Link Rate (ALR)*: In this approach, the Ethernet link capacity is adapted with its local current flow load (Bilal et al., 2013). For instance, several transmission rates are predefined for each link and the more appropriate one is adaptively set according to the current traffic (Gunaratne et al., 2005, 2008; Gunaratne and Christensen, 2006).
- *Sleep-scheduling*: This approach consists in switching off some unnecessary network components (node or link) to preserve the energy consumed for keeping them awake during inactive periods (Bolla et al., 2011; Bianzino et al., 2012; Sarigiannidis et al., 2015).

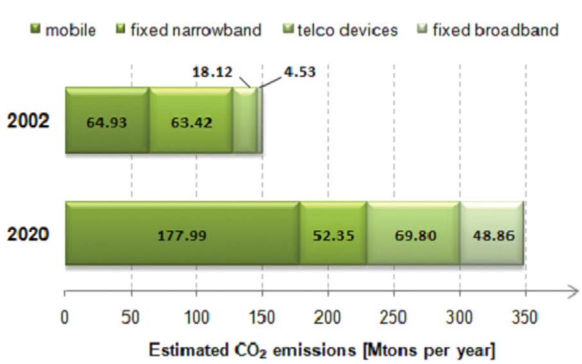

Fig. 1. GeSI estimation on GHG emission (Global e-Sustainibility Initiative).

Although the re-engineering approach can increase the hardware energy efficiency of individual network components, other green approaches are required to optimize the effective utilization of such devices. In this regard, the interface proxying suffers from its restriction to end devices, ignoring the components of the core network as the main sources of permanent and extensive energy consumption. Besides, the management complexity of the power-proportional approach is an obstacle to its wide development (Meisner et al., 2009; Wierman et al., 2009). Moreover, recent studies show that the amount of energy conservation obtained by the power-proportional approach is significantly lower than the one obtained by the sleep-scheduling technique (Nedevschi et al., 2008). Consequently, in the present survey, we mainly emphasize on green routing protocols using sleep-scheduling. In the following, the principles of IP routing and its relation to sleep-scheduling are described.

2.2. Routing protocol

A routing protocol specifies how routers exchange routing information with each other, enabling them to determine routes between any two nodes on a computer network. As a result of receiving a routing packet, the router updates its routing table to indicate an appropriate next hop for any destination. Due to the large scale of today's Internet, its management is undertaken by different administrative domains, called Autonomous Systems (AS). Each AS may use a different routing protocol, which can be Routing Information Protocol (RIP) (Malkin, 1998), Open Shortest Path First (OSPF) (Moy, 1998) or Intermediate System to Intermediate System (IS-IS) (Oran, 1990). The routing protocol executed inside an AS is called *intra-domain* (*interior*) *routing* protocol. OSPF, as the most common interior routing protocol, broadcasts Link State Advertisement (LSA) messages to whole the network to provide any router with information of link states of other routers. LSA reports connectivity information of the router and may also carry Quality of Service (QoS) information such as its link utilization or bandwidth, just to mention a few. Based on the received LSAs from other nodes, each router constructs the network topology as a weighted graph. The weight represents the cost of a link which is equal to 1 when the default hop count metric is considered. The well-known shortest path algorithm is then executed on the constructed graph to find a tree of shortest paths to any destination, with itself as root.

In addition to the interior routing protocol, an *inter-domain* (*exterior*) *routing* protocol is also required to route between different ASs, ensuring end-to-end data transmissions. Border Gateway Protocol

(BGP) is the commonly used exterior routing protocol which determines the ordered set of ASs towards the end destination based on administrative network policies. However, the path from the entry point inside an AS (called Ingress Router (IgR)) to the exit point relaying to the next AS (called Egress Router (EgR)) is determined by the interior routing protocol.

It is worth mentioning that a component sleep-scheduling may affect the current routes, forcing the routing protocol to find other paths avoiding that component. As a result, the shortest paths length may be increased and the network may be congested due to the load aggregation over a subset of network components.

To avoid this negative impact, the management of sleep-scheduling decisions should be performed by the routing protocol, considering a trade-off between energy saving and network performance. In this regard, traffic engineering and QoS routing concepts can be utilized, as described in the next subsection. In addition, the inter-related impact of the resulted intra-domain traffic changes on the inter-domain routing should be taken into consideration. This latter, which is unfortunately ignored in most existing literature, is discussed in Section 6.1.

2.3. Traffic engineering and quality of service routing

Traffic engineering (TE) is defined as performance evaluation and performance optimization of operational IP networks (Awduche et al., 1999), performed through the measurement, characterization, modeling, and control of Internet traffic (Awduche et al. 1999; Awduche, 1999). Due to the paramount role of traffic routing in the network performance, the control and optimization of the routing process is one of the most distinctive functions performed by Internet traffic engineering (Awduche et al., 2002). From this view, the aim of TE is "to put the traffic where the network bandwidth is available" (Lee and Mukherjee, 2004). However, TE mechanisms should cope with nowadays applications which require other QoS guarantees (e.g. end-to-end delay, jitter, or packet loss ratio) in addition to bandwidth requirements. This latter is referred to as *QoS routing*, in which the path to be used by a flow is selected based on the QoS requirements of the flow. The QoS extension of OSPF, as the more common used routing protocol, finds shortest paths based on only one QoS measure (e.g. delay). However, in generalized QoS routing, a set of QoS constraints including traffic attributes, network constraints, and policy restrictions may be required to be satisfied. The generalized QoS routing, also referred to as *constraint-based routing*, can be considered as a multi-constrained path (MCP) problem, which is NP-complete (Mieghem et al., 2003; Garey and Johnson, 1979).

Generally, two approaches exist to solve the MCP problem. In the first approach, one of the QoS constraints is used to calculate the shortest paths, on which all other QoS constraints are then checked (Iwata et al., 1996). If all constraints are satisfied, the calculated shortest paths are kept. Otherwise, another QoS constraint is examined according to the explained process. The second approach consists in combining QoS parameters as a single link weight and then executing the well-defined shortest path algorithm based on these combined weights (Jaffe, 1984).

3. Related surveys

A number of comprehensive surveys on routing protocols and Internet traffic engineering has been already provided in the literature. Mainly, routing protocols in wired and wireless networks are summarized in Boukerche et al. (2011), Goyal and Tripathy (2012), Patil and Biradar (2012), Tang and Liu (2011), Levis et al. (2009). In Awduche et al., (2011) the authors described the general issues and principles of Internet traffic engineering. A holistic overview of QoS/constraint-based routing and routing optimizations for Internet traffic engineering are respectively provided in Mieghem et al. (2003) and Wang et al. (2008).

Although the energy-efficient and sleep-scheduling based routing protocols have been already overviewed in wireless networks (Wang and Xiao, 2006; Bangash et al., 2014; Kumar and Chauhan, 2011; Baby and Jacob, 2013; Jones and Sivalingam, 2001; Soua and Minet, 2011; Feng et al., 2013; Carrano et al., 2014; Wu and Zhang, 2015), a survey dedicated to wired environments has not been provided so far.

In Bianzino et al. (2012), a general survey of the work focusing on green networking research in wired networks is provided. The authors used the employed energy-aware strategy to classify existing efforts into adaptive link rate, interface proxying, energy-aware application and energy-aware infrastructure categories. The adaptive link rate and interface proxying categories follow the same definition as presented in Section 2.1. The energy-aware application category proposes modifications in user-level applications or kernel-level network stack according to the varying load imposed by applications. The energy-aware infrastructure comprises approaches using collaborative decision with a wider knowledge of the entire system state to improve the amount of energy saving. Especially, some general sleep-scheduling based routing protocols up to year 2011 are enumerated in this category. Compared to this work, our paper provides a specialized and comprehensive study of existing sleep-scheduling based energy-aware infrastructure approaches. In addition, we propose a classification of green properties and compare the characteristics and features of existing proposals.

A survey on wired green communications using adaptive link rate is presented in Bilal et al. (2013). The paper overviews recent ALR solutions employed for fast modification and negotiation of the link data rates, as well as the ALR policies used for controlling the link rate switching.

In Bolla et al. (2011), a survey of green networking research in wired networks is presented. The authors first characterize the sources of energy waste in computer networks and then classify existing green approaches into re-engineering, adaptive link rate and sleep/standby categories. Based on this classification, green approaches on different type of networks or network components are presented. Compared to our survey, the sleep/standby category does not include sleep-scheduling based routing and mainly focuses on sleeping individual components according to the current local load.

A recent survey on techniques and solutions dealt to improve the energy efficiency of computing and network resources is provided in Orgerie et al. (2014). The paper categorizes the existing approaches by node level and network level. In the node level, re-engineering, shutdown and adaptive link rate techniques are identified. The shutdown technique refers to the interface proxying at end devices. In the network level, some coordinated techniques including energy-efficient network protocols, clean-state approaches and energy-aware frameworks are considered. With respect to this paper, our work presents a deep and dedicated survey on routing protocols using sleep-scheduling to conserve the energy at the network level.

In Dharmaweera et al. (2014), a review on power-efficient solutions in backbone networks is provided. The existing approaches are classified in four categories, namely re-engineering, traffic engineering, power-aware networking and adaptive link rate. In traffic engineering category, traffic grooming schemes are developed. The power-aware networking category describes works which switch network devices between different operating states to achieve a global energy conservation. Compared to this paper, our survey can be considered as a dedicated study on the power-aware networking category. In addition, we propose a holistic classification of green properties considered by sleep-scheduling approaches and outline their comparative pros and cons, open issues and future directions using this classification.

Finally, a recent review on energy-efficient approaches for the Internet protocol stack is presented in Cengiz and Dag (2015). The existing energy efficiency mechanisms are classified based on the targeted layer of TCP/IP protocol suite. Compared to this survey, we focus on the network layer and present a comprehensive survey specialized on sleep-scheduling based approaches in wired networks.

Table 1
Green properties classification.

Category	Description	Possible values
Type of sleep-scheduled component	Type of components selected for sleep-scheduling	Nodes, links, or both
Decision structure	Whether the sleep-scheduling decisions are carried out by distributed or centralized controllers	Centralized or distributed
Network traffic awareness	The availability and type of network traffic knowledge for sleep-scheduling decisions	Traffic-unaware, off-line traffic-aware, on-line traffic-aware
QoS awareness	The QoS parameters considered by sleep-scheduling decisions	QoS-unaware, QoS-aware using MLU, paths length, delay or a combination of these parameters

4. Green properties classification

In this section, we classify relevant properties of existing green routing protocols using sleep-scheduling. Four classes of green properties have been identified, namely type of sleep-scheduled component, decision structure, network traffic awareness and QoS awareness. In the following, we describe each identified category of green properties and outline its importance to green routing. Table 1 summarizes the green properties classification.

4.1. Type of sleep-scheduled component

Sleep-scheduling green routing protocols can be classified based on the type of components targeted for sleep-scheduling, i.e. nodes, links or both of these components.

The choice of sleeping components' type depends on whether the network topology includes *access* (*edge*) or/and *backbone* (*core*) nodes. An access node designates a node providing an entry point to the core network. Obviously, such nodes can not be switched off since their absence breaks the network access of some users. Consequently, green routing protocols in which all nodes are considered as access routers can only switch the links to the sleep mode.

Backbone nodes are core routers acting as intermediate nodes in the routing process. Usually, a sufficient number of backbone nodes are installed in the network to ensure a smooth data delivery in high traffic loads. Consequently, in low traffic situations, some of core routers can be switched off without an important impact on quality constraints of data traffics. Obviously, green routing protocols switching off core nodes can achieve higher energy conservation since nodes and all of their respective links are switched off. However, the energy optimization obtained by switching off individual links still remains interesting, with links consuming more than 40% of the total network power consumption in an Internet Service Provider (ISP) (Chiaraviglio et al., 2012).

4.2. Decision structure

Sleep-scheduling green routing protocols can be classified based on whether the sleep-scheduling decision is carried out in a distributed or centralized manner. *Centralized* sleep-scheduling based green routing protocols use a *central controller* in charge of selecting sleeping network components.

Compared to the centralized approach, *distributed* proposals do not dispose any central controller. Consequently, the sleep-scheduling related decisions are carried out in a distributed manner by all or a subset of network elements, referred to as *distributed controllers*. The latter category benefits from the service availability and single point of failure avoidance, while the decision convergence between distributed controllers should be carefully guaranteed.

4.3. Network traffic awareness

The network traffic is one of the paramount factors for sleep-scheduling decisions. On the one hand, switching some network components to the sleep mode in high traffic loads may result in a congestion collapse in remained topology and affect the QoS constraints of the data traffic. On the other hand, some traffic-dependent QoS parameters (e.g. delay) may be affected due to the further load on remained topology, even in congestion-free situations.

We classify sleep-scheduling based green routing protocols based on their awareness on network traffic into three categories, as described in the following:

- *Traffic-unaware algorithms:* This category ignores the network traffic in selection of sleeping components. Consequently, the only concern of traffic-unaware algorithms resides on keeping the reachability of network destinations.
- *Off-line traffic-aware algorithms:* This category includes works considering a predefined network traffic matrix in sleep-scheduling decisions. Such an off-line information may not be appropriate for today's indeterministic and dynamic networks in which nodes and links may join or leave randomly, affecting the traffic in the entire network. In addition, it can not reflect the network traffic change following a node/link add or removal decided by the sleep-scheduling algorithm.
- *On-line traffic-aware algorithms:* This category considers current traffic in sleep-scheduling decisions. Obviously, an on-line traffic information represents more realistic input for green protocols since the inter-related impact of sleep-scheduling decisions on network traffic can be taken into consideration. However, a network traffic monitoring mechanism is required to provide a correct view on the network load state while minimal amount of extra overhead is generated.

4.4. QoS awareness

The QoS is one of the major factors for sleep-scheduling decisions. Indeed, the sleep-scheduling of a component may affect the current routes, forcing the routing protocol to find other paths avoiding that component. This latter may result in longer paths length and lower QoS performance for data packets. In addition, the traffic will be aggregated over a subset of network components, increasing the Maximum Link Utilization (MLU) and degrading the QoS performance. Recent studies reported that an energy saving of 15% may result in 1% increase in links utilization (Yin Zhangs Abilene TM). Consequently, a green routing algorithm should consider the trade-off between energy saving and QoS performance, caring of parameters such as shortest paths length, link utilization, packet delay or a combination of these parameters.

5. Green routing protocols using sleep-scheduling

As mentioned, the sleep-scheduling approaches can switch off some underutilized devices in order to more energy conservation. In this regard, finding a minimum connected subgraph of network topology is an objective that should satisfy the network performance metrics. Obviously, there exists a trade off between energy conservation and network performance. Therefore, the optimal version of sleep-scheduling approaches is modeled by Integer Linear Programming (ILP) and the complexity of it is NP- complete (Qi Li et al., 2014). In the following, we formulate the problem of sleep-scheduling based energy-efficient approaches using ILP formulation.

The network topology can modeled as a directed graph $G = (N, L)$, where N is the set of network nodes and L is the set of network links. Let $p = |N|$ and $q = |L|$ be the number of network nodes and links, respectively. The average amount of traffic flowing from source node $s \in N$ to destination node $d \in N$ is presented by t^{sd} and $f_{ij}^{sd} \in [0, t^{sd}]$ is the amount of t^{sd} that is flowed by link (i,j). Therefore, f_{ij} denotes the total amount of flow on link (i,j) with capacity C_{ij}. According to this definitions, the following ILP formulation presents the trade off between energy conservation and network performance.

$$\text{Minimize:} \quad E_{tot} = \sum_{i=1}^{p}\sum_{j=1}^{p} y_{ij}E_{ij} + \sum_{i=1}^{p} x_i E_i \tag{1}$$

$$\text{Subject to:} \quad \sum_{j=1}^{p} f_{ij}^{sd} - \sum_{j=1}^{p} f_{ji}^{sd} = \begin{cases} t^{sd} & \forall\ s, d, i = s \\ -t^{sd} & \forall\ s, d, i = d \\ 0 & \forall\ s, d, i \neq s, d \end{cases} \tag{2}$$

$$f_{ij} = \sum_{s=1}^{p}\sum_{d=1}^{p} f_{ij}^{sd} \quad \forall\ i, j \tag{3}$$

$$f_{ij} \leq \alpha C_{ij} y_{ij} \quad \forall\ i, j \tag{4}$$

$$\sum_{j=1}^{p} y_{ij} + \sum_{j=1}^{p} y_{ji} \leq x_i \quad \forall\ i \tag{5}$$

Eq. (1) minimizes the total energy consumption of the active network devices. Where, E_{tot}, E_{ij}, and E_i designate the energy consumption of the network, link (i,j) and node i, respectively. The binary variable $y_{ij} \in \{0, 1\}$ $(i, j \in N)$ is 1 if the link (i,j) is powered on. Similarly, the binary variable $x_i \in \{0, 1\}$ $(i \in N)$ is 1 if the node i is powered on. Eq. (2) presents the classical flow conservation constraints (Cormen et al., 2001). Eq. (3) computes the total flow on each link. Constraint (4) limits the amount of link load that should be smaller than the predefined maximum utilization α. Finally, Eq. (5) specifies that a node can be powered off only if all its respective links are switched off.

In the following, we present an overview of main green routing protocols using sleep-scheduling. The surveyed works are classified based on their network traffic awareness property. For each green routing protocol, its other green properties, key characteristics and relevant features are described. Moreover, we identify the main pros and cons of each protocol in order to determine the open issues which can be addressed by the research community to converge to an optimal green solution. Fig. 2 illustrates the classification of existing sleep-scheduling protocols using the identified green properties.

It is worth mentioning that the description of some proposals specialized for a particular context are postponed to the next section. These proposals are illustrated by an asterisk (*) in Fig. 2 and include MPLS-based, SDN-based and inter-domain aware sleep-scheduling based green routing protocols.

5.1. Traffic-unaware algorithms

In the following, we describe main traffic-unaware green routing protocols, namely d-EAR (Cianfrani, 2010), EAR (Cianfrani et al., 2011), ESOL (Cuomo et al., 2011) and STB (Matsuura, 2013) algorithms.

d-EAR. The Energy-Aware Routing (d-EAR) (Cianfrani, 2010) is a traffic-unaware algorithm in which nodes are categorized in importer (IR) and exporter (ER) routers. This protocol uses the shortest path of only exporter nodes to allow switching off the links on the shortest path of non-exporters. d-EAR proceeds by the execution of three consecutive phases:

- In *ER selection phase*, nodes are assigned the role of exporter or importer routers. An *exporter router* is the one using its own shortest path tree (SPT) in routing process, while an *importer router* uses the SPT of its neighbor ER, called the *modified path tree* (MPT). In this way, some links on the original SPTs of importer nodes may be discharged and can hence be switched off to conserve energy. Since the MPT of an importer does not differ significantly from its original optimal shortest path, the QoS constraints can be preserved in some extend. However, the selected exporter routers and their number can affect the amount of energy conservation and network performance. The authors propose to use a distributed ER selector which assigns the ER role to a set of non-neighbor routers with the highest degree. Such selected ERs allow switching off further links in the network as they have more number of importer neighbors executing the MPT.
- In *MPT evaluation phase*, the classical Dijkstra algorithm (Dijkstra, 1959) is executed in order to extract the links employed by ERs. Since importer routers use same paths as their ER neighbors, links not placed on the ERs' shortest path can all be switched off. This process is depicted in Fig. 3.
- In *routing path optimization phase*, routers recompute SPTs using Dijkstra algorithm run on the remained topology.

Briefly, the d-EAR algorithm is an energy-efficient algorithm in which all routers use the shortest path of exporter routers in order to switch off discharged links. The main advantage of d-EAR is that the number of ERs can be set based on the trade-off between the desired energy saving and network performance. However, the d-EAR algorithm ignores the current network traffic which may overload the remained topology.

EAR. The Energy Aware Routing (EAR) (Cianfrani et al., 2011) is an extension of d-EAR algorithm which find optimal exporter routers to maximize the amount of energy saving. To achieve this, the network topology is modeled as a weighted directed graph $G(V, E)$, where V is the set of routers and E is the set of directed edges between routers. Each link within the graph denotes a potential exportation, linking an

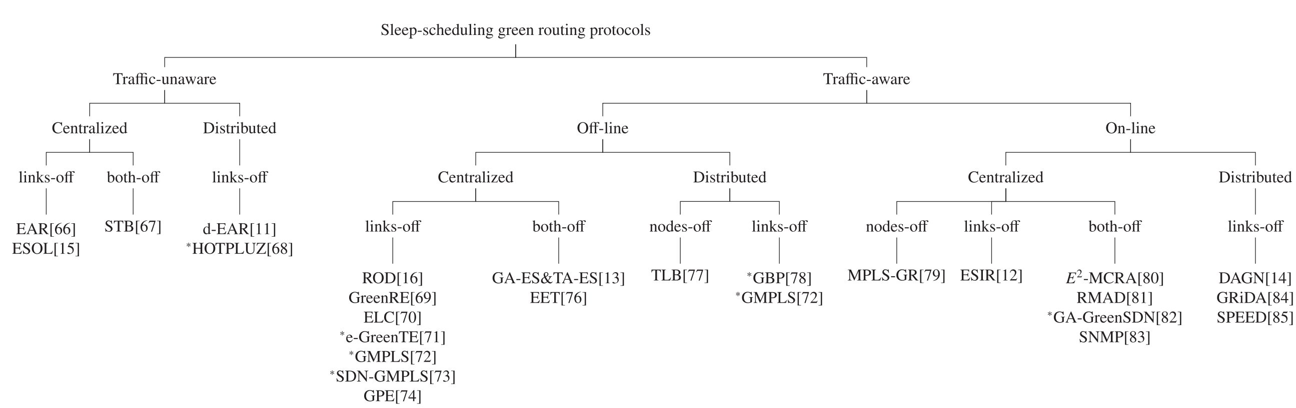

Fig. 2. Classification of sleep-scheduling based green routing protocols.

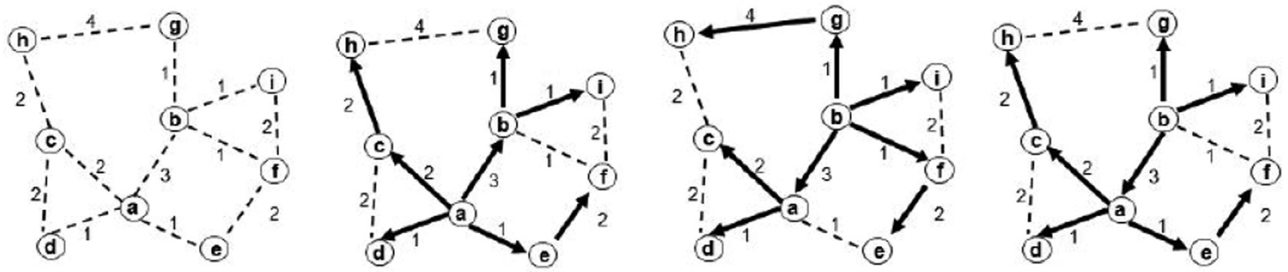

Fig. 3. d-EAR algorithm (a) Initial weighed network graph (b) SPT computed by "a" (c) SPT computed by "b" (d) MPT evaluation by "b" using "a" as its ER (Cianfrani, 2010).

importer node to its respective exporter, referred to as a *move*. The objective is to find the maximum compatible set of moves (MCM), where (i) a node assigned as importer node cannot be the importer or exporter of a next exportation, and (ii) a node assigned as exporter node cannot be the importer of a next exportation. Upon the selection of the maximum compatible set of moves, the selected importer routers can power down the links not situated on the exporters' SPTs. As the selected MCM is the one with the maximum set of moves, the number of exporters is maximized. Consequently, further importer routers can be assigned to an exporter, resulting in further links switch-off. Authors show that the MCM selection can be considered more complex than the maximum clique problem which is itself NP-hard (Miller et al., 1972). In order to solve this problem, EAR proposed a Max-Compatibility heuristic for selection of the maximum number of compatible moves. In the first step, the proposed solution selects one move with maximum compatibility with others. Then, a move limiting less other reminded moves is selected iteratively until no further move is possible.

To conclude, the EAR algorithm uses a move concept to optimize the selection of exporter routers and lead to further energy conservation. The main asset of EAR is that it does not significantly change the length of SPTs compared to classical Dijkstra algorithm. However, the proposed strategy is executed by a centralized controller and without considering the current traffic constraints. Indeed, even the traffic switching to near optimal shortest paths may cause important congestion on transiting links.

ESOL. The Energy Saving based on Occurrence of Links (ESOL) (Cuomo et al., 2011) is an energy-efficient algorithm that switches off links used by fewer number of SPTs.

The ESOL algorithm models the network topology as an undirected graph. For each link, an occurrence parameter is defined which consists in the number of shortest paths using that link. The links with the smallest occurrence are switched off if the network connectivity is not violated by that link removal. After each link switch-off, the occurrence of links is recalculated for next iteration. The authors present four different algorithms to identify this set of links, as described in the following.

- In *basic-ESOL* (b-ESOL) algorithm, all of unidirectional links in the network topology are sorted in non-decreasing order of their occurrences in the network shortest paths. The b-ESOL algorithm will then switch off links from ordered list until the residual network remains connected.
- The *fast-ESOL* (*f*-ESOL) algorithm switches off all links with an occurrence less than a given threshold. The algorithm will decrease the threshold value if the sleep-scheduling of all links fitting to that threshold will result in network disconnection. The main issue of this algorithm is that links with an occurrence more than the selected threshold are not switched off even if their absence does not impact on the network connectivity. In order to address this problem, the following optimization algorithms are proposed.
- The (*f*+*b*)-*ESOL* algorithm cascadely executes f-ESOL and b-ESOL to switch off further links. The network graph obtained by f-ESOL execution is employed as the input of b-ESOL to turn off those links with occurrence more than the threshold used by f-ESOL.
- The (*f*×2)-*ESOL* algorithm applies f-ESOL in cascade two times, allowing to switch off another portion of links remained active after the first f-ESOL run.

To sum up, the ESOL algorithm is an energy-efficient algorithm switching off low occurrent links in the shortest path trees. Although a higher amount of energy saving can be obtained by ESOL, the network performance constraints may not be guarantied since MLU and current traffic load are not considered. Moreover, as the proposed ESOL is designed based on a central controller, the resulted performance will highly depend on the timeness and overhead of the sleep-scheduling enforcement mechanism.

STB. Steiner Tree Based (STB) (Matsuura, 2013) is a green routing algorithm that uses a Steiner tree to discover the minimum subgraph ensuring the connectivity of edge nodes. The links and core nodes not involved on the created subgraph can hence be switched off to minimize the energy consumption.

The STB algorithm models the network topology as a graph composed of edge and core routers and their respective links. It then switches off links and nodes according to the following phases:

- In the *Steiner tree creation* phase, a Steiner tree is used to find the minimum connected subgraph of edge nodes. The discovered subgraph includes all edge nodes of the network as well as a subset of its core routers necessary to ensure the connection between edge nodes. The mentioned Steiner tree is created by the well-known BBMC algorithm (Matsuura).
- In the *point-to-point (P2P) connection creation* phase, P2P routes among all the edge nodes and their length are calculated using the subgraph created in the previous step.
- Finally, in the *bypass route search* phase, the calculated paths length is compared against a predefined threshold. The original shortest path is added to the Steiner tree to substitute large hop-count routes.

To summarize, STB is a refinement algorithm that adds required links to the Steiner tree of edge nodes in order to minimize the path length along with energy conservation. The main advantage of STB is that it switches off both nodes and links leading to more energy saving. However, the STB algorithm depends on central controller and not consider current traffic flows. Finally, the algorithm may cause degrading the QoS performance of data packets since it does not consider the network traffic and data QoS requirements.

5.2. Off-line traffic-aware algorithms

In the following, we describe main green routing protocols using a predefined traffic matrix for sleep-scheduling decisions. The identified protocols in this category include GA-ES (Amaldi et al., 2011), TA-ES (Amaldi et al., 2011), EET (Lai et al., 2011), GreenRE (Giroire et al., 2012), ROD (Shen et al., 2012), TLB (Listanti et al., 2013), ELC (Chiaraviglio et al., 2013), LiSOA-LiWOT (Obinna Okonor and Wang, 2014) and GPE (Luca Chiaraviglio et al., 2015) algorithms.

GA-ES & TA-ES. Amaldi et al. (2011) proposed two heuristic off-line algorithms to switch off nodes and links, namely the Greedy Algorithm for Energy Saving (GA-ES) and the Two-stage Algorithm for Energy Saving (TA-ES). These algorithms consider the network topology as a directed graph composed of both core and edge nodes.

GA-ES algorithm consists in placing nodes and links in two separate sorted lists. The sorting is performed based on the priority a node/link has for being switched off, i.e. the node/link whose absence seems to engender a minimal impact on the network current topology or traffic is placed on top of the list. This latter is defined by a sorting criterion, which could be Least-Link, Least-Flow or Sum-of-Weights for the nodes, and Least-Flow (LF) or Traffic-Engineering for the links (Amaldi et al., 2011; Chiaraviglio et al., 2009). The Least-Link designates the node degree (number of a node's incident links), indicating the topology change caused by the node switch-off. Compared to Least-Link, Least-Flow measures the total amount of traffic flowing through the node (or link). The Sum-of-Weights criterion considers the overall impact of the node switch-off on the network performance by summing the weight of active links of the router. The Traffic Engineering follows the same objective as the Sum-Of-Weights but for a single link. Since the node sleep-scheduling results in a more significant energy conservation than a single link, the node switch-off is prioritized in the GA-ES algorithm. For a given node/link in the list, the switching off decision depends on the capability of the residual network topology to support the traffic matrix while the maximum link utilization is not exceeded. GA-ES proceeds until all the node/link list's elements have been tested. As shown in Fig. 4, *TA-ES* performs in two stages. In the first stage, a minimum topology satisfying the network traffic matrix is discovered, resulting in powering down the highest number of network components without taking the MLU into account. This stage is carried out using the capacitated multi-commodity minimum cost flow (CMCF) approximation algorithm (Ghamlouche et al., 2003). In the second stage, if the MLU is exceeded ($U_{max} < \alpha(0 \le \alpha \le 100)$), the original traffic matrix is augmented, multiplying it by a fixed γ parameter, incremented for each unfeasible iteration by 0.1. The first stage is then reiterated using the new increased traffic matrix. The TA-ES algorithm terminates when a minimal topology respecting the MLU is found.

To recapitalize, GA-ES and TA-ES algorithms provide heuristic off-line solutions to economize energy consumption of a network composed of core and edge routers. The main advantage of these proposals consists in switching off both links and nodes, leading to further energy conservation. However, they suffer from their dependence on a pre-defined traffic matrix, which is not available in real network environments. Moreover, they do not consider the current network traffic, which may result in critical performance degradation of transiting flows.

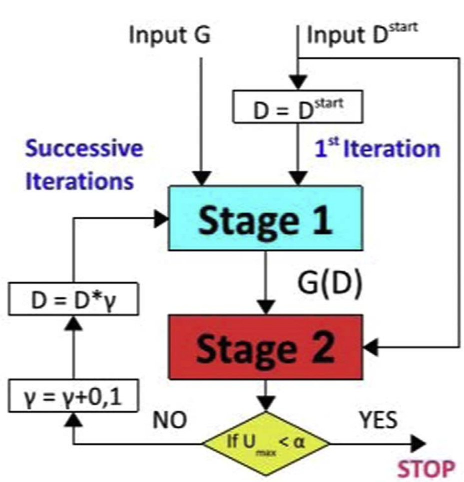

Fig. 4. TA-ES flow chart (Amaldi et al., 2011).

EET. The Energy Efficient Algorithm (EET) (Lai et al., 2011) is a heuristic algorithm which switches off both links and nodes to improve energy consumption of the entire network. EET models the network topology as a graph composed of both backbone and access nodes. The aim of EET algorithm is to elect some of backbone routers and links for sleep-scheduling. The EET algorithm proceeds in two consecutive phases. In the first phase, the backbone routers with low traffic flow are powered off considering the MLU constraint. In the second phase, the minimum number of links required to guarantee the connectivity of the residual network is selected to be kept awake using the Minimum Spanning Tree (MST) algorithm (Cormen et al., 2001). However, since this process may lead to violate the MLU constraint, the links with the high energy efficiency are added to MST one-by-one until the MLU constraint is satisfied.

To summarize, the EET algorithm keeps awake the minimum connected graph of high energy-efficient backbone routers to which it adds some links with high energy efficiency to satisfy the MLU constraint. The main advantage of the EET algorithm is that it switches off both links and nodes, leading to more energy saving. However, EET depends on a central controller and is not adapted to the current flow.

GreenRE. Green Redundancy Elimination (GreenRE) (Giroire et al., 2012) is an off-line traffic-aware algorithm that switches off low traffic links and uses the data redundancy elimination (RE) to avoid resulted congestion. All routers are assumed to be equipped by a data redundancy elimination feature or a WAN Optimization Controller (WOC), reducing extra data in traffic transmissions (BlueCoat: WAN Optimization; Grevers and Christner, 2007).

The network topology is modeled as a directed graph and the set of traffic requests is represented as the required bandwidth from two adjacent nodes.

GreenRE algorithm begins with running the well-known shortest path algorithm. Based on selected shortest paths, the amount of traffic flowing through network links can be computed using the predefined traffic matrix. The links to be switched off and the RE-enabled routers are then determined based on following criteria:

1. The links sorted in non-decreasing order of their utilization are one-by-one selected for sleeping down if their absence does not impact on network connectivity.
2. If links removal results in congestion, RE-routers are activated one-by-one until the problem is elevated.

A comparative example of routing with RE and without RE is shown in Fig. 5.

To summarize, the GreenRE algorithm switches off maximum possible links and uses data redundancy elimination technique to provide a green solution for routing protocols. The algorithm assumes the existence of RE-enabled routers, which can be highly interesting when most data in the network contain heavy extra information. However, it dependence on RE-enabled routers questions its wide industrial utilization by current ISPs. Moreover, GreenRE uses a central controller and off-line traffic matrix, which are not applicable choices in real environments.

ROD. The Routing On Demand (ROD) (Shen et al., 2012) algorithm switches off extra links in the network using a Multiple Commodity Flows (MCF) problem formulation (Cormen et al., 2001) with a weighted function based on both energy consumption and network performance.

ROD models the network topology as a directed graph. The aim of this algorithm is to discover a configuration of network topology in which the total maximum link utilization and energy consumption is minimized. This selected configuration is then used to assign *optimal link weights* so that the shortest path algorithm excludes links beyond the selected configuration. Consequently, such extra links can be switched off without any important impact on network performance.

To achieve this, the ROD algorithm relaxes the energy consumption

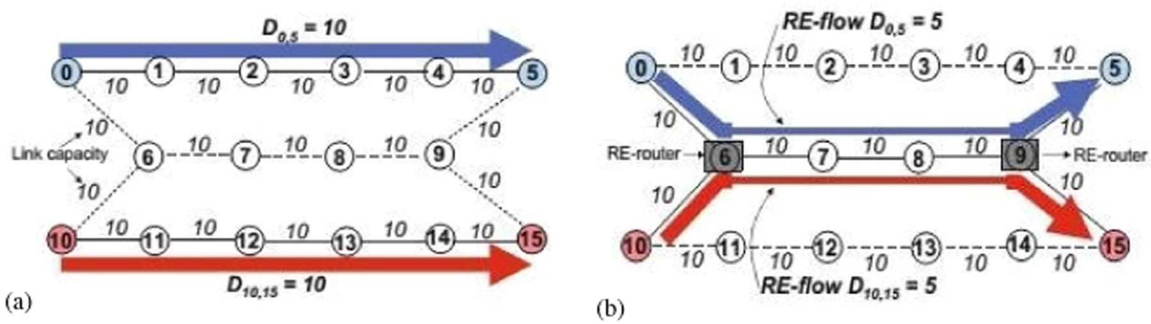

Fig. 5. GreenRE (a) without RE-routers and (b) with RE-routers (Giroire et al., 2012).

by the maximum flow. The maximum flow and maximum utilization on link ij are respectively defined by f_{ij} and $\max f_{ij}/C_{ij}$, where C_{ij} is the link capacity. The ROD algorithm merges maximum link utilization and energy consumption as follows:

$$minimize \quad \Theta \max_{(i,j)\in E} \frac{f_{ij}}{C_{ij}} + \sum_{(i,j)\in E} f_{ij} \tag{6}$$

where Θ is a *green factor* defining the importance of MLU in multi-objective optimization problem.

To conclude, ROD consists in a green algorithm which switches off network links considering a trade-off between energy consumption and network performance. The main advantage of this mechanism is that the obtained energy saving will not be in despite of network traffic performance. However, its centralized and off-line nature is not consistent for real underlying networks.

TLB. Table Lookup Bypass (TLB) (Listanti et al., 2013) is an off-line algorithm which freezes the forwarding engine of some line cards, transmitting incoming packets towards a single predetermined outgoing interface. The TLB algorithm is inspired from recent studies reporting that about 90% of the total energy consumed by a router relates to its Line Cards (LCs) (Aleksic, 2009). Since the Forwarding Engine (FE) spends about 60% of the total LCs power consumption of a router, an important energy conservation can be achieved through bypassing the Table Lookup (TL) process for packet forwarding (Aleksic, 2009). Consequently, the TLB algorithm performs the aforementioned energy optimization by forwarding the incoming packets towards a predetermined next-hop router. While this process can result in inappropriate packet routing, the TLB assumes that the network performance will not be violated in low traffic conditions.

The TLB algorithm changes the network topology graph by adding an extra link between any two nodes with a common intermediate node. This extra link reflects the table lookup bypass potential of the intermediate node, where the cost related to FE of the intermediate node is excluded. An ILP formulation (Cormen et al., 2001) is then executed on the created network topology to extract a minimum topology satisfying links' bandwidth and MLU constraints for the predefined traffic matrix. Finally, the resulted topology is used to switch some nodes to the sleep mode or to the TLB state. In order to reduce the complexity that TLB imposes by augmenting the topology, an extended version of TLB (*e*-TLB) is proposed which uses a genetic algorithm to enable some routers with TLB states in a near optimal manner (Coiro et al., 2014).

To recapitulate, TLB algorithm provides an off-line energy saving solution based on bypassing the table lookup process in order to freeze the forwarding engine of some line cards. The main asset of this method resides in its independence from a central controller, avoiding the central point of failure problem. However, the use of a predefined traffic matrix renders the algorithm inapplicable in indeterministic network scenarios. Consequently, the efficiency of the proposed solution will highly depend on the degree of conformity between the predefined traffic matrix and the current transiting traffic. Finally, as no heuristic optimization is proposed for the NP-hard ILP problem (Cormen et al., 2001), the algorithm can be only applied on small experimental networks.

ELC. Energy efficient algorithm with Limited Configurations (ELC) (Chiaraviglio et al., 2013) limits the number of sleep-scheduling process executions during a day in order to avoid frequent changes in network topology. The ELC algorithm models the network topology as an undirected graph with N nodes and L links, where the average node degree is assumed to be K. In each time interval, the algorithm can potentially switch off a fraction $p \in [0, 1]$ of network links, resulting in an average node degree of $k' = K(1 - p)$ (Albert and Barabasi, 2001). In order to ensure the QoS requirements, the value of p is estimated based on the network connectivity, average link utilization, and increase of the shortest paths. The aim of this algorithm is to select G time intervals within a day while the maximum number of links can be switched off considering QoS demands and traffic matrix.

To achieve this, consider $[\tau_i, \tau_{i+1}]$ as the time interval during which the configuration i is applied. $p(\tau_i)$ is a fraction of links that put in sleep mode in configuration i. The energy consumption, $E'_{TOT}(G)$, obtained in a given combination of G time intervals can be modeled as:

$$E_{'TOT}(G) = N\frac{K}{2}\mathcal{P}_L \sum_{i=0}^{G} (\tau_{i+1} - \tau_i)(1 - p(\tau_i)) \tag{7}$$

where $\mathcal{P}_L$ is the energy consumption of a single link. Therefore, the energy saving $S(G)$ resulted from a given combination of G can be estimated as:

$$S(G) = 1 - \frac{E_{'TOT}(G)}{E_{TOT}} \tag{8}$$

where $E_{TOT} = N\frac{K}{2}\mathcal{P}_L T$ denotes the energy consumed by the original active topology over the total time T.

The aim of this algorithm is to find a combination $(\tau_1^*, \tau_2^*, \ldots, \tau_G^*)$ that maximizes $S(G)$. This latter can be computed by solving the equation $\frac{dS(G)}{d\tau} = 0$.

Briefly, the ELC algorithm finds G time intervals within a day to switch off maximum fraction of links satisfying QoS demands and traffic matrix. This algorithm avoids topology changes during high traffic periods to provide transiting packets with their demanded QoS constraints. However, its dependence on a predefined traffic matrix and a central controller makes it inappropriate for real network environments.

LiSOA-LiWOT. In Obinna Okonor and Wang (2014), two complementary Link Sleep Optimization Algorithm (LiSOA) and Link Wake-up Optimization Technique (LiWOT) are proposed to manage devices' state according to network traffic load using off-line traffic matrix.

Network links are classified as *stub* and *transit*. A stub link denotes a link used only by one router in OSPF shortest paths and hence does not carry traffic originated from others. Other links are referred to as transit links. LiSOA respectively switches off low utilized stub links in ascending order of utilization and then transit links, if the MLU constraint remains satisfied. During the network operation, LiWOT re-switches on stub links in decreasing order of traffic load generated by their source if any congestion is occurred. If the congestion is not resolved, the transit links are also added in the next step.

To summarize, the LiSOA-LiWOT proposal uses a central controller to switch off some underutilized links based on off-line traffic matrix. The main asset of this proposal is that the load variable nature of network is considered through the LiWOT mechanism. However, the conditions for re-adaptation of network configuration after a return to low traffic condition is not discussed. In addition, the impact of energy saving on sensitive QoS performance measures such as delay and shortest paths length can not be guaranteed.

GPE. The Green Partial Exportation (GPE) is an off-line extension of EAR algorithm, which uses a greedy method to switch off network links in both directions considering the MLU constraint (Luca Chiaraviglio et al., 2015). GPE is designed especially to consider the hardware constraint of real networking devices which does not allow a link switch-off only in one direction.

To achieve this, GPE defines a move as a candidate link for switching off in both directions, given a specific exporter for each direction. For each move, a partial exportation concept is derived from the complete exportation defined in EAR. This later consists in original SPT for paths not using the switched-off link and the exporter's shortest paths for others. The objective is to find the maximum compatible set of moves, where a move should not lead to switch off any link on the shortest paths resulted from any other move. Similar to EAR, Max-Compatibility algorithm is used to select the maximum number of compatible moves satisfying the MLU constraint.

To conclude, GPE uses the partial exportation concept to switch off some network links based on the MLU constraint using a predefined traffic matrix. This algorithm depends on a central controller. The proposed solution suffers from its high complexity due to its MCM selection phase. Consequently, it can not be applied in large scale networks.

5.3. On-line traffic-aware algorithms

In the following, we describe main green routing protocols considering the current traffic in sleep-scheduling decisions. This category includes DAGN (Bianzino et al., 2012), EISR (Cianfrani et al., 2012), GRiDA (Bianzino et al., 2012), E^2-MCRA (Avallone and Ventre, 2012), SNMP (Antonio Capone et al, 2013), RMAD (Oda et al., 2013) and SPEED (Qi Li et al., 2014) algorithms.

DAGN. Distributed Algorithms for Green IP Networks (DAGN) (Bianzino et al., 2012) is a distributed algorithm which switches off links according to the network state. DAGN estimates the network state using the Link State Advertisements (LSAs) of OSPF which announce the connected links along with their load state (if the link load is below a MLU threshold or not). Based on this information, each node computes the network load and connectivity to determine if the network is operating in a normal or abnormal state. The node can then decide to switch off or on some of its links using the following rules:

- If the network is in a normal state, the least loaded link or the most power hungry link is switched off.
- If the network is in an abnormal state, the last link entering to the sleep state or the sleeping link closer to the congestion point is re-switched on.

To summarize, DAGN is a green algorithm that switches links' state based on the underlying network. The main advantage of DAGN is that it is an on-line and distributed algorithm which self-adapts according to the network state. An important issue of DAGN is that it may switch its links' state even for transitory network conditions, which can result in cascade topology changes and increase the time and energy complexity.

ESIR. As mentioned, the EAR algorithm does not consider the current traffic and QoS constraints for MCM selection. In order to address this shortcoming, ESIR (Cianfrani et al., 2012) proposes an optimization of EAR, in which the MLU constraint is verified on the current traffic before the selection of each move. The performance comparison of EAR and ESIR shows that the number of links switched off in the ESIR algorithm is close to the one obtained by the EAR solution for a MLU of 50%.

GRiDA. The GReen Distributed Algorithm (GRiDA) (Bianzino et al., 2012) uses a distributed on-line approach to switch off some links in network topology.

For each node, the GRiDA algorithm determines all possible configurations of the node's links, each one obtained by switching off one or more incident links. For each configuration, the node computes a utility function defining the sum of energy consumption and penalty (or performance degradation) imposed to the network if that configuration is selected. The objective is to find a configuration with minimum utility. The penalty of a configuration is initially calculated by summing the penalty of its links which is set to 0 if the link is not used in SPTs and is inversely proportional to the node degree, otherwise. After initialization, the penalty is increased by a predetermined value if that configuration results in congestion or disconnection in the network. The potential disconnection resulted from a configuration is predetermined based on current network topology, while the congestion is evaluated based on the outcome of the last exploitation of that configuration. This latter is determined through the received LSA reports on the previous configuration.

Briefly, in GRiDA algorithm, each node selects its links' configuration based on current network topology and QoS constraints evaluated through network congestion. GRiDA profits from its distributed and on-line nature and uses a learning approach to punish or encourage last decisions. However, GRiDA considers only the local outcome of its decision, while the configuration change of a node may cause congestion in a remote area. This latter may lead to the configuration change of remote nodes, while these nodes are not responsible for the imposed congestion. Consequently, a coordination technique is required to monitor the remote outcome of a configuration.

E^2-MCRA. The Energy Efficient Multi-Constrained Routing Algorithm (E^2-MCRA) (Bianzino et al., 2012) is an incremental mechanism that starts with a small topology and then adds the minimal number of nodes and links required to service incoming flow requests.

In the E^2-MCRA algorithm, the network topology is modeled by a graph in which $(m + 1)$ QoS constraints, including bandwidth and m other additive measures (e.g., delay, jitter), are assigned to each link. Upon the reception of a flow request, the algorithm should find the shortest path with the minimal number of sleeping nodes and links which satisfies all QoS constraints of the flow. The shortest path with additive QoS constraints problem, called MCOP (Multi-Constrained Optimal Path), is largely investigated in the literature (Korkmaz and Krunz, 2001; Van Mieghem and Kuipers, 2004; Xue et al., 2007), for which many heuristics have been already proposed to overcome its NP-complete complexity (Korkmaz and Krunz, 1998; Kuipers et al., 2002; Yuan, 2002; Xue et al., 2008). For each flow request, E^2-MCRA finds a shortest path on the residual topology that satisfies the QoS constraints, if any, and $m + 1$ other QoS-satisfying paths which can comprise any of network devices independently of theirs current on or off status. After finding these feasible paths, the E^2-MCRA algorithm selects the path which further fits to QoS constraints and uses the minimal number of sleeping links and nodes.

To resume, E^2-MCRA finds a QoS-satisfying path for each flow request, so the minimal number of sleeping links and nodes needs to be re-switched on. The main advantage of the E^2-MCRA algorithm is that it considers the current network traffic, bandwidth and other data constraints to find a trade-off between the energy consumption and network QoS performance. However, the algorithm should be aware of the entire current topology including all nodes and links physically connected to the network. Whereas, this information may not be available since no LSA is received informing the physical existence of sleeping devices. Furthermore, E^2-MCRA requires a mechanism to force awakening remote sleeping network components, which can itself be energy demanding and generate extra traffic to the network. Finally, the proposed algorithm does not care of re-sleeping the network devices after the network is re-switched to lower traffic load.

SNMP. Simple Network Management Protocol (SNMP) is an on-line energy saving algorithm that switches off both links and nodes in low traffic periods (Antonio Capone et al., 2013). This algorithm selects a minimal topology among a set of predefined possible OSPF configurations to adapt to underlying network traffic.

Prior to green algorithm execution, SNMP considers a set of traffic matrices, each one representing a certain network traffic condition. For each traffic matrix, SNMP computes a number of appropriate subgraphs based on original network topology. During the network operation, SNMP switches the network configuration to a higher topology if MLU is higher than a predefined threshold and to a smaller topology in low utilization situation.

To conclude, the SNMP algorithm is an on-line and centralized green solution which dynamically selects a suitable OSPF configuration based on network utilization. SNMP can achieve further energy saving since it switches off both network links and nodes. However, the performance of the proposed solution depends on the number and accuracy of predefined traffic matrices. Obviously, higher number of traffic matrices can better represent possible network load conditions to the detriment of further complexity. Moreover, SNMP does not discuss how an appropriate subgraph is selected among OSPF configurations predefined for a specific load level.

RMAD. Routing for Minimization of Active Devices (RMAD) (Oda et al., 2013) is a centralized algorithm which dynamically adds required links and nodes to the initial small network topology in order to service an incoming flow arrival.

The RMAD algorithm considers the QoS constraints to find a path with minimal number of sleeping links. For each flow arrival, RMAD firstly calculates the set of paths satisfying the flow bandwidth. If such paths exist, the path with minimum number of sleeping links is selected. Otherwise, the algorithm selects the path with minimum MLU to approach the bandwidth required by the flow.

In order to increase the energy conservation of RMAD, *RMAD+* algorithm has been proposed, switching off nodes in addition to links. Moreover, RMAD+ considers the length of shortest path to conserve the overall performance of data flows. Indeed, among the paths satisfying the bandwidth, RMAD+ extracts paths with a length not more than the length of shortest path by a predetermined threshold. The path with minimum number of sleeping nodes is then selected. If more than one alternative exist, the path with minimum number of sleeping links is considered. Similar to RMAD, if no feasible path is found following the above criteria, the path with minimum MLU is selected.

To sum up, RMAD proposes an incremental on-line algorithm which augments the network topology with required links based on the QoS constraints of incoming flows. RMAD+ improves the energy saving obtained by RMAD through switching off both nodes and links. However, these schemes do not re-switch off currently on-devices after the network returns to lower traffic conditions. More importantly, RMAD variants depend on a central controller in charge of keeping track of the current network traffic and MLU, and enforcing sleep-scheduling decisions to network components. Such a central controller imposes extra traffic to the network.

SPEED. Safe and Practical Energy-Efficient Detour routing (SPEED) is an on-line energy saving approach to switch off under-utilized links (Qi Li et al., 2014).

In the first phase, the SPEED algorithm extracts the minimum spanning tree from the original topology. Then, the link to the primary next hop of a source node is added if the shortest paths lengths of that source exceed a given threshold. In the next phase, other primary next hops may be added to this topology to satisfy the MLU constraint.

To conclude, SPEED is an on-line and distributed algorithm that switches off underutilized network links. The main drawback of SPEED relates to its topology augmentation procedure which may result in adding an inappropriate next hop to the residual topology based on original topology.

6. Other green routing protocols using sleep-scheduling

In the previous section, we surveyed the IP-based and inter-domain unaware green routing protocols using sleep-scheduling. In order to provide a holistic survey, this section overviews the existing inter-domain aware and MPLS-based proposals. In addition, some recent works using the new Software Defined Networking (SDN) concept are presented. These subjects are respectively presented in following subsections.

6.1. Inter-domain aware proposals

A literature study does not yield a relevant progress in proposing inter-domain aware green routing protocols using sleep-scheduling.

Extended Green Traffic Engineering (*e*-GreenTE) (Shi and Zhang, 2014) consists in a centralized and off-line inter-domain aware green routing approach. In e-GreenTE, the network graph is augmented by extra links between border routers of two neighbor ASs and their corresponding traffic demands are reflected on the graph. The amount of traffic passing between IgR and EgR nodes are also added to the graph topology. Then, a Mixed Integer Programming (MIP) formulation is developed to maximize the total power conservation.

HOT Potato Low UtiliZation (HOTPLUZ) (Ruiz-Rivera et al., 2014) is a distributed and on-line traffic-aware algorithm which avoids the increase in BGP update messages caused by a green intra-domain routing protocol. This latter is resulted from imposed intra-domain traffic changes, which may cause the selection of a different EgR for destination prefixes. The proposed approach ensures the connection between IgR and their respective EgRs, while the maximum link load is minimized. Initially, HOTPLUZ computes the shortest IgR-EgR paths based on hop count. Then, each IgR determines the link costs based on the used bandwidth. These weights are then used by each IgR to determine and switch to a new least cost path to a corresponding EgR, if any.

6.2. MPLS-based proposals

Despite the differences between MPLS and IP routing, MPLS-based networks can also obtain some extend of energy conservation through sleep-scheduling. In this section, we present an overview of main green MPLS-based routing protocols using sleep-scheduling.

Green MPLS (GMPLS) (Cerutti et al., 2011) defines two centralized and distributed extensions for managing the sleep-scheduling in MPLS networks. In the centralized mode, an ILP formulation is used to switch some links to the sleep mode based on gathered network-wide information. In the distributed mode, each node decides to power off its links with less occurrence based on local information.

MPLS-based Green Routing (MPLS-GR) (Chu et al., 2011) is a centralized and off-line energy conservation algorithm using sleep-scheduling. The algorithm first sorts all routers based on the ascending order of the number of Label Switching Paths (LSPs) passing through them. In the next step, routers are switched to the sleep mode one by one from the top of the sorted list if the MLU constraint remains satisfied. After checking all of routers, the LSP minimizing MLU is set between each source and destination node.

Green Backup Paths (GBP) is a distributed and traffic-aware MPLS-based green algorithm using sleep-scheduling to save the energy consumption of backup paths (Francois et al., 2014). Backup paths are defined as pre-installed paths by network operators to protect against single link failures in backbone MPLS networks. In GBP, each router periodically reroutes traffic to power off the highest number of links based on local traffic conditions. GBP is performed based on off-line and online components. The off-line component calculates the primary paths based on the shortest path algorithm using delay metric. Moreover, it identifies the backup paths for each source/destination route. The online component is executed in each router and uses the local information about traffic flows to decide switching to alternative backup paths to save energy or/and minimize the MLU. The links not situated on selected paths are then switched off to conserve energy.

6.3. SDN-based proposals

Software Defined Networking is an emerging network architecture in which the complexity and intelligence of network components are delegated to dedicated devices (Kreutz et al., 2015). Its main objective is to centralize the management of network functions and to optimize the network performance using a wider knowledge of the network. SDN defines two separate data and control plans (Shenker, 2011; Hakiri et al., 2015). The control plan is implemented in a central controller which manages the functionalities of the data plan (e.g. routing). Therefore, network elements can be planned in simplex architecture and software functions of network components can be executed by the central controller. The communication between the data and control plan is performed through the OpenFlow protocol (McKeown et al., 2008).

The energy efficiency of the SDN architecture has been already investigated with regard to its various components (Assefa and Ozkasap, 2015). The existing proposals generally profit from the global knowledge of the central controller to provide the network with green features.

In Oda et al. (2013) and Wang et al. (2014) (GA-GreenSDN: Greedy Algorithm for Green SDN-based protocol), an incremental approach is used by the SDN architecture to propose a sleep-scheduling green IP routing protocol. In both these schemes, the central controller dynamically adds required links and nodes to the initial small network topology in order to service an incoming flow arrival and satisfy QoS constraints.

In Celenlioglu et al. (2014), a SDN-based approach for Green MPLS-based routing protocol (SDN-GMPLS) is presented. In this algorithm, the controller considers several Pre-established LSPs (PLSPs) between each ingress and egress pairs. In the PLSPs selection phase, the paths with more capacity than load are turned off in order to conserve energy.

6.4. Wireless-based proposals

There exist a lot of energy-efficient approaches in wireless networks (Ha et al., 2006; Feng et al., 2009, 2010; Shah and Bansode, 2016). Therefore, in this section, we discuss the main differences between energy-efficient routing protocols in wired and wireless networks and briefly explain some energy-efficient objectives and metrics in wireless networks.

Energy-efficient approaches in wired networks aim at reducing environmental pollution and economical cost. In this regards, the existence proposals temporarily reduce network resources including bandwidth, processing power and others in order to energy conservation in low traffic periods. Therefore, there exists a trade off between energy conservation and network performance in wired communications. However, reducing economical cost is the one point of energy-efficiency in wireless networks, the main objectives of it is quite different that we explain some of these differences in the following.

It is clear that each mobile device in wireless networks has limited only to a finite amount of battery supply. Therefore, the increasing of battery lifetime of devices is an objective of energy-efficient wireless networks. In addition, each wireless network (e.g. WSN) is composed of thousands of nodes, therefore it is important the design and component selection of each node in order to energy conservation and cost reduction (Ha et al., 2006). Moreover, according to broadcasting nature of the radio medium in wireless networks, an energy-efficient approach should consider this property and should prevent from collisions and interferences during transmission scheduling and energy saving (Bianzino et al., 2012). While, wired networks are collision-free.

In Glaropoulos (2015), the metrics of energy-efficiency in wireless networks are classified in four categories including *transmission cost*, *lifetime*, *duty-cycle ratio* and *delay overhead*. The objective of transmission cost is the minimization of transmission overhead in order to energy conservation. In lifetime metric, an energy-efficient approach considers and improves the network topology and routing mechanism to increase the lifetime of the wireless devices. In duty-cycling, wireless devices that do not participate in data transmission during one/more traffic periods, can be switched to sleep (IEEE Standard for Information Technology, 2006) or doze mode (IEEE Standard for Information Technology, 2012) in order to energy conservation. Therefore, each sleep device in duty-cycling is not able to receive data and data transmission is buffered until device waking up. Given that the data buffering may occur delay at intermediate nodes, the delay overhead metric quantifies the impact of duty-cycling on end-to-end delays.

7. Green evaluation metrics

An important step towards an ideal sleep-scheduling based green routing protocol is to be able to evaluate and compare the efficiency of existing green solutions. This latter can lead to identify the pros and cons of each approach and to propose an optimal solution taking the advantages of existing proposals while avoiding their shortcomings. In the following, we identify and classify the main metrics for evaluating and comparing the efficiency of green routing protocols using sleep-scheduling.

As stated before, green routing protocols should consider a trade-off between energy saving and network performance. Consequently, we classify green evaluation metrics into *energy conservation* and *performance* metrics, as illustrated in Fig. 6. The energy conservation metrics evaluate the amount of energy saving obtained by the protocol. The main energy conservation metrics are described in the following:

- *Average ratio of sleep-scheduled links*: This metric consists in the percentage of switched-off links with respect to the maximum number of links that could be powered off. This latter can be obtained based on the minimum connectivity of network topology and is equal to $N - 1$, where N is the number of network topology nodes. The higher values of this metric indicate further energy conservation.
- *Average number of sleep-scheduled components*: This metric measures the number of links/nodes switched off by the green protocol.
- *Average power saving*: This metric evaluates the average amount of energy saved by switching off networking components.

The performance metrics measure the impact of sleep-scheduling on network performance. Some of these metrics aim at evaluating the network performance observed by data traffic following the green routing execution. Some other performance metrics measure the relative network performance compared to the classical routing. The main identified performance metrics are described in the following:

- *Average paths length*: This metric designates the average length of shortest paths on residual topology. This measure should not differ significantly from the original shortest paths.

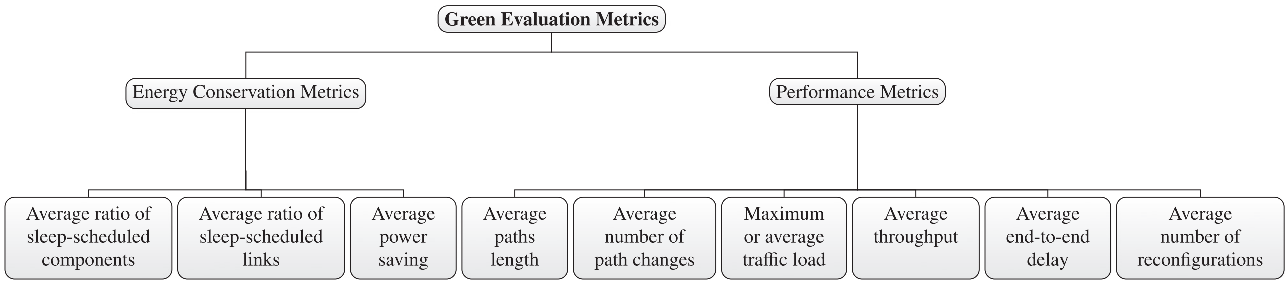

Fig. 6. Green evaluation metrics.

- *Average number of path changes*: This metric denotes the number of shortest paths changed compared to original shortest paths.
- *Average number of reconfigurations*: This metric denotes the average number of reconfigurations of a component (switching off or on) during network operation. This measure is expected to be as small as possible since frequent topology changes lead to extra load and network performance degradation.
- *Maximum or average traffic load*: This metric evaluates the amount of load on residual topology. This measure should not exceed a predefined congestion threshold.
- *Average throughput*: This metric consists in the number of data packets successfully delivered at the destination divided to the total number of data packets sent from the source.
- *Average end-to-end delay*: This metric evaluates the total transmission time of data packets from the source to the destination.

Table 2 summarizes the evaluation metrics used by existing sleep-scheduling based green routing protocols. As shown in the table, all existing works considered energy conservation metrics in some extent. Since all these metrics evaluate the same capability, the energy related study of existing works using only one of the identified energy conservation metrics can be considered sufficiently illustrative. As

Table 2
Green evaluation metrics used in surveyed literature.

Name of approach	Performance metrics	Energy conservation metrics
General approaches		
d-EAR (Cianfrani, 2010)	Average traffic load	Average ratio of sleep-scheduled links
EAR (Cianfrani et al., 2011)	—	Average ratio of sleep-scheduled links, Average power saving
STB (Matsuura, 2013)	Average paths length	Average number of sleep-scheduled components
ESOL (Cuomo et al., 2011)	Average paths length, Average traffic load	Average power saving
GA-ES & TA-ES (Amaldi et al., 2011)	Average traffic load	Average number of sleep-scheduled components
TLB (Listanti et al., 2013)	Average paths length	Average number of sleep-scheduled components, Average power saving
ROD (Shen et al., 2012)	Average traffic load	Average power saving
GreenRE (Giroire et al., 2012)	Average paths length	Average power saving
ELC (Chiaraviglio et al., 2013)	Average traffic load, Average paths length	Average power saving
EET (Lai et al., 2011)	—	Average number of sleep-scheduled components
LiSOA-LiWOT (Obinna Okonor and Wang, 2014)	Average traffic load	Average ratio of sleep-scheduled links
GPE (Luca Chiaraviglio et al., 2015)	Average end-to-end delay, Average number of path changes	Average ratio of sleep-scheduled links
GRiDA (Bianzino et al., 2012)	Average traffic load, Average number of reconfigurations	Average power saving
ESIR (Cianfrani et al., 2012)	Average paths length	Average power saving
DAGN (Bianzino et al., 2012)	Average traffic load, Average number of reconfigurations	Average power saving
E^2-MCRA (Avallone and Ventre, 2012)	Average throughput	Average number of sleep-scheduled components
SNMP (Antonio Capone et al, 2013)	Average traffic load	Average number of sleep-scheduled components
RMAD (Oda et al., 2013)	Average end-to-end delay	Average number of sleep-scheduled components
SPEED (Qi Li et al., 2014)	—	Average number of sleep-scheduled components, Average power saving
Inter-domain aware approaches		
e-GreenTE (Shi and Zhang, 2014)	—	Average power saving
HOTPLUZ (Ruiz-Rivera et al., 2014)	Average traffic load	Average power saving
MPLS-based approaches		
GMPLS (Cerutti et al., 2011)	Average traffic load	Average power saving
MPLS-GR (Chu et al, 2011)	—	Average power saving
GBP (Francois et al., 2014)	Average traffic load	Average power saving
SDN-based approaches		
GA-GreenSDN (Wang et al., 2014)	—	Average number of sleep-scheduled components
SDN-GMPLS (Celenlioglu et al., 2014)	Average traffic load	Average power saving

depicted in the table, existing works did not provide a relevant study regarding the performance metrics. Since each performance metric evaluates a specific network characteristic, the efficiency of these approaches can be validated only when a deep study of QoS performance of the network is performed.

8. Discussion and open issues

In this section, we compare the strengths and weaknesses of existing sleep-scheduling based green routing protocols, their open issues and the future directions towards a convergent green solution.

8.1. Comparison of existing proposals

In order to progress to a convergent green solution, there is a need to discuss how different proposals compare, which limitations of one proposal are addressed by the others and what is the best proposal for a given case. The comparison can be done either by comparing sleep-scheduling based green routing protocols regarding the results of quantitative measurements or with regard to their qualitative properties. Since the implementation of existing green protocols is not available, we use our identified green properties to compare qualitatively among existing proposals. Table 3 summarizes the main characteristics of existing literature with regard to different green properties. As all existing proposals have considered the connectivity constraint, this latter factor is not expressed in the table.

Based on the table, we can distinguish two *decremental* and *incremental* progress approaches for scheduling network components to sleep mode. In the decremental approach, network components within the original topology are switched off one-by-one considering network performance constraints. However, the incremental approach considers a small initial topology satisfying the connectivity constraint, to which some network components are then added in order to guarantee the network performance. Following this procedure, components not situated on the selected topology are switched to sleep mode.

Mainly, the following key points regarding green proposals using the **incremental** approach can be identified from the table:

- Incremental approaches aim at achieving the maximum energy conservation at first priority. Consequently, they start with a possible minimal topology and then add extra components in order to satisfy QoS constraints. In accordance with this perspective, all of existing incremental proposals switch off both network links and nodes which can lead to further energy conservation.
- Existing incremental proposals use different approaches to select the initial minimal topology. In this regard, STB and EET algorithms employ Steiner tree and minimum spanning tree, respectively. Flow-based methods, such as RMAD, E^2-MCRA and GA-GreenSDN, start with a topology composed of components on the shortest path of the first flow that requested to be routed to its destination.
- All the existing incremental approaches are based on a centralized decision structure. In flow-based methods, the controller of SDN architecture and the open-flow protocol can be employed to manage the sleep-scheduling procedure. However, for non SDN-based networks in which a central controller is not considered in the inherent architecture, a dedicated controller and communication protocol should be implemented for this purpose. This latter aspect is not addressed by the current literature.

The following key points can be identified for green proposals using the **decremental** approach:

- The main objective of the decremental approach is to prioritize the QoS performance of the network rather than the achieved energy conservation. Consequently, most of existing decremental proposals are aware of on-line traffic information (e.g. GRiDA, ESIR, DAGN, E^2-MCRA, SNMP, SPEED, HOTPLUZ and GBP) or off-line traffic characteristics (e.g. EET, GA-ES & TA-ES, ROD, GreenRE, TLB, ELC, LiSOA-LiWOT, GPE, e-GreenTE, GMPLS, MPLS-GR, and SDN-GMPLS). The traffic-aware decremental proposals consider performance metrics such as MLU, shortest paths length and congestion to guarantee smooth operation of the network.
- Existing decremental proposals switch off some network components based on single or multiple criteria. In GA-ES, TLB, ROD, GreenRE, DAGN, EET, LiSOA-LiWOT, GPE, GRiDA, ESIR, SNMP, SPEED, e-GreenTE, HOTPLUZ, GMPLS, MPLS-GR, GBP and SDN-GMPLS, the components are switched off based on their utilization, while d-EAR and EAR switch off links not situated on the shortest paths of any exporter node. ELC uses a combination of such parameters.
- Similar to incremental proposals, most of decremental approaches use a centralized decision structure. The distributed proposals are limited to d-EAR, TLB, GRiDA, DAGN, SNMP, SPEED, HOTPLUZ and GBP algorithms.
- In existing decremental approaches, EET, GA-ES & TA-ES and SNMP switch off both network links and nodes to achieve more energy conservation.

8.2. Open issues and future directions

In this section, we present the open issues of existing proposals and propose some new techniques towards the design of an ideal sleep-scheduling based green routing protocol. In order to provide a more consistent view, we separately address the open issues and future directions regarding each green property.

With regard to *targeted component* for sleep-scheduling, most of existing green proposals focus on switching off communication links. Since switching off nodes can lead to important amount of energy saving, we believe that the green community should orient its researches towards scheduling both links and nodes.

In order to optimize the cost of sleep-scheduling, the *decision structure* should be selected considering some key factors. In the following, we analyze existing literature based on their decision structure and propose some directions in this regard:

- Most of existing algorithms use a central controller for sleep-scheduling decisions. While such a centralized controller disposes of the holistic knowledge of the network and can lead to more convergent decisions, the amount of control overhead imposed to gather the global knowledge and to enforce remote decisions can be significant. Moreover, this approach suffers from the security issues and single point of failure problem. In the context of SDN architecture, in which the management is centralized in nature, the produced control overhead can be compensated by the gain obtained through optimizing other network functions using gathered information.
- The distributed approach should be preferred when the SDN architecture is not utilized or when the utility of the centralized decision does not surpass the imposed costs. In such a case, we believe that the distributed knowledge of the entire network topology available in link-state based routing protocols, such as OSPF, can be profited to extend a distributed version of the existing centralized solutions.

Another important area of future research relates to *QoS awareness* of green protocols. As a green sleep-scheduling approach decreases the available network capacity, the QoS requirements may be violated. Therefore, the QoS parameters should be considered by sleep-scheduling decisions. In the following, key points and open issues in this field are presented:

- An ideal green solution should find a trade-off between energy saving and network performance. To this end, a green proposal

Table 3
Comparison of sleep-scheduling based green routing protocols.

Name of approach	Sleeping components	Decision structure	Traffic awareness	QoS awareness (used parameters)	Description
General approaches					
d-EAR (Cianfrani, 2010)	Links	Distributed	Unaware	Unaware	Selects a predefined number of exporter routers
EAR (Cianfrani et al., 2011)	Links	Centralized	Unaware	Unaware	Selects maximum compatible set of moves using exportation concept
STB (Matsuura, 2013)	Both	Centralized	Unaware	SPTs length	Creates a Steiner tree on edge nodes & adds some extra links to reduce paths length
ESOL (Cuomo et al., 2011)	Links	Centralized	Unaware	Unaware	Switches off low occurrent links in SPT.
GA-ES & TA-ES (Amaldi et al., 2011)	Both	Centralized	Off-line	MLU	Switches off nodes and then links based on their impact on network current topology or traffic, using an extended version of CMCF
TLB (Listanti et al., 2013)	Nodes	Distributed	Off-line	MLU	Activates the table lookup bypass for some routers
ROD (Shen et al., 2012)	Links	Centralized	Off-line	MLU	Keeps awake a configuration of network topology minimizing the MLU and energy consumption
GreenRE (Giroire et al., 2012)	Links	Centralized	Off-line	congestion	Switches off maximum number of links and enables some routers with redundancy elimination
ELC (Chiaraviglio et al., 2013)	Links	Centralized	Off-line	MLU & SPTs length	Finds G time intervals within a day to switch off maximum fraction of links satisfying QoS demands and traffic matrix
EET (Lai et al., 2011)	Both	Centralized	Off-line	MLU	Switches off nodes with low traffic flow & finds the MST on residual network topology to which necessary links is then added to satisfy the MLU
LiSOA-LiWOT (Obinna Okonor and Wang, 2014)	Links	Centralized	Off-line	MLU	Switches off maximum number of links based on increasing order of their utilization (first stub links then others). Then, some links are re-switched on in case of network congestion
GPE (Luca Chiaraviglio et al., 2015)	Links	Centralized	Off-line	MLU	Selects maximum compatible set of moves using partial exportation concept
GRiDA (Bianzino et al., 2012)	Links	Distributed	On-line	Local congestion	Keeps awake a configuration with minimal energy consumption and penalty (performance degradation)
ESIR (Cianfrani et al., 2012)	Links	Centralized	On-line	MLU	Selects maximum compatible set of moves satisfying the MLU considering the current load
DAGN (Bianzino et al., 2012)	Links	Distributed	On-line	MLU	In normal state of the network, the least loaded link or the most power hungry link is switched off. Otherwise, the last link entering to the sleep state or the sleeping link closer to the congestion point is re-switched on
E^2-MCRA (Avallone and Ventre, 2012)	Both	Centralized	On-line	MLU & others	Finds a QoS-satisfying path for each flow request, so the minimal number of sleeping links and nodes needs to be re-switched on
SNMP (Antonio Capone et al, 2013)	Both	Distributed	On-line	MLU	Selects a minimal OSPF configuration among a set of predefined topologies according to the current load
RMAD (Oda et al., 2013)	Both	Centralized	On-line	MLU & SPTs length	Starts with a small topology and adds extra links and nodes to service each incoming flow request using a path satisfying the flow bandwidth requirements with minimum number of sleeping links
SPEED (Qi Li et al., 2014)	Links	Distributed	On-line	MLU	Switches off underutilized links to primary next hops in the SPT and replaces them with other neighbors
Inter-domain aware approaches					
e-GreenTE (Shi and Zhang, 2014)	Links	Centralized	Off-line	MLU	Augments the graph topology by extra links and their traffic demands between border routers of two neighbor ASs and then formulates a MIP based on ILP of optimal green routing with MLU constraint
HOTPLUZ (Ruiz-Rivera et al., 2014)	Links	Distributed	On-line	MLU	Selects the shortest IgR-EgR path based on hop count and MLU constraint
MPLS-based approaches					
GMPLS (Cerutti et al., 2011)	Links	Both	Off-line	MLU	In the centralized mode, an ILP formulation is used to switch off some links based on network-wide information. In the distributed mode, each node powers off its less occurrent links based on local information
MPLS-GR (Chu et al., 2011)	Nodes	Centralized	Off-line	MLU	Sorts routers based on the ascending order of the number of LSPs passing through them. Then, routers are switched off one by one from the top of the sorted list if the MLU constraint remains satisfied
GBP (Francois et al., 2014)	Links	Distributed	On-line	MLU	Switches to alternative backup paths to minimize the energy and MLU. The links not situated on selected paths are then switched off
SDN-based approaches					
GA-GreenSDN (Wang et al., 2014)	Both	Centralized	On-line	Delay & MLU	The central controller dynamically adds required links and nodes to the initial small network topology to service an incoming flow arrival and satisfy QoS constraints
SDN-GMPLS (Celenlioglu et al., 2014)	Links	Centralized	Off-line	MLU	The central controller considers several PLSPs between each ingress and egress pairs and switches off paths with more capacity than load

requires some extent of traffic awareness to ensure the smooth performance of data packets delivery.

- Existing proposals use various parameters to ensure QoS constraints, including MLU, shortest paths length, bandwidth and congestion. Works based on MLU can limit the maximum link utilization of all network components. However, the overall performance on the entire path depends on other factors, e.g. the path length and the queue load of individual intermediary components. Consequently, we can conclude that works using network congestion instead of MLU are expected to result in better QoS performance.
- Approaches only considering the shortest paths length can not guarantee the QoS performance encountered on each network component over the path. In addition, bandwidth-based solutions, which implicitly ensure congestion-free paths, may not guarantee the selection of shortest paths and hence the overall performance can be degraded. Moreover, a path satisfying the required bandwidth of the flow may not be available in certain network conditions. Consequently, we believe that a combination of such parameters can lead to better outcomes.

As stated, the *network traffic awareness* is paramount to ensure QoS performance of the residual topology. Consequently, most of recent works focused on on-line or off-line traffic awareness. In the following, we extract main open issues regarding the traffic awareness property and propose some guidelines to overcome existing challenges:

- Although the off-line approach can reflect the network traffic status for deterministic networks, it is incapable to deterministically predict the traffic matrix for the entire network lifetime, specially for highly dynamic networks. In addition, proposals using off-line traffic awareness should care of network traffic changes following a node/link add or removal decided by the sleep-scheduling algorithm. It is worth mentioning that this latter requirement may impose some complexity to the algorithm.
- While the on-line traffic-aware approaches can benefit from up-to-date knowledge on the traffic status of the network, the monitoring of such on-line information is a complex task. More explicitly, the accuracy of the monitored information depends on the frequency of monitoring, which itself imposes extra cost to the network.
- To address the issues caused by both off-line and on-line approaches, we believe that some traffic prediction guidelines can be inferred from the combination of on-line and off-line traffic information. Moreover, the off-line traffic matrix can be employed occasionally in loaded network conditions in order to avoid the overhead of on-line traffic monitoring. Consequently, we suggest the green community to conduct the future researches towards combined approaches.

In addition to open issues extracted for each green property, existing proposals suffer from some *algorithmic deficiencies*. Mainly, existing proposals do not address the problem of determining the duration of sleep periods. In addition, any of existing proposals has not investigated the frequency of executing the green algorithm. Moreover, the complexity of green algorithm and the knowledge of inter-domain routing protocol are not considered in any existing proposals. In the following, we present main future directions in this regard:

- We believe that a dynamic mechanism should be designed to define the sleeping duration of a component considering current network traffic as well as future needs.
- The execution frequency of green algorithm should be defined through a cognitive mechanism which dynamically adjusts the execution interval or runs the algorithm upon an event raise according to the network conditions. Besides, this mechanism should care of the complexity and extra load imposed to the network by the algorithm. The transitory nature of some network events should be considered to avoid cascade re-switching between on and off states. In addition, the algorithm should consider the energy utility of sleep-scheduling decisions since the component state's change is itself power demanding.
- In order to maximize the amount of energy gain, the green algorithm should differentiate among different sleeping states (standby or power-off). While the power-off state can lead to further energy conservation compared to the standby mode, it consumes more time and energy for returning to the active state. Consequently, the green algorithm should select an appropriate sleeping state for each component based on its estimation on achieved energy gain considering the persistency of current network condition.
- None of existing green proposals combine the sleep-scheduling approach with the power-proportional technique. Since this latter can result in better QoS performance and energy consumption in the same time, we suggest to investigate on combined approaches.
- Since the inter-domain routing traffic can affect the efficiency of the green algorithm and vice versa, a great deal of attention should be focused to provide green algorithms with inter-domain awareness.

9. Conclusion

In this paper, we raised the importance of green communications in today and emerging networking area and surveyed the existing proposals in wired networks. We focused mainly on sleep-scheduling green approaches since a dominant source of energy waste is consumed during inactivity periods. The identified key characteristics of sleep-scheduling based green routing protocols were classified into four green properties, including the type of sleep-scheduled component, decision structure, network traffic awareness and QoS awareness. The existing protocols were presented based on their network traffic awareness as green property. For each protocol, we identified its key characteristics, relevant features and important drawbacks. In order to provide a holistic survey, MPLS-based, SDN-based and inter-domain aware green routing approaches were also presented. In addition, we identified a set of performance and energy related evaluation metrics to evaluate and compare the efficiency of green proposals. Moreover, we provided a qualitative comparison of surveyed proposals, highlighting the open issues and assets of each solution. This comparison leaded to a set of guidelines towards an ideal green protocol. Mainly, we highlighted the trade-off between the QoS performance of the network and the amount of gained energy conservation. Furthermore, we indicated that rather than considering an individual networking parameter (e.g. path length, MLU, congestion, bandwidth, etc.), a combination of these factors should be verified in order to satisfy the QoS requirements of data packets. In addition, the current traffic information should be taken into account, reflecting the inter-related impact of sleep-scheduling decisions and network traffic status. Moreover, we highlighted the advantage of distributed decision structure, especially for link-state routing protocols in which the information of the entire topology is already available. Finally, we raised the need for an adaptive algorithm that dynamically switches off/on nodes and links considering the QoS constraints and underlying network context.

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