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Eco-sustainable routing in optical networks

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Abstract It is quite easy to foresee that in the next years, the future generation ultra-high speed network infrastructures and equipments will be no longer constrained only by their pure transport capacity, but also by their energy consumption costs and environmental effects. In particular, large network infrastructures are now widely recognized to play a fundamental role in the emission of greenhouse gases in the atmosphere, significantly affecting the environmental sustainability of new evolutions in network architectures as well as technological developments in communication devices. In this paper, a novel eco-sustainable routing and wavelength assignment algorithm, based on shortest path routing with an adaptive link weighting function relying on an extension of the OSPF-TE protocol to convey carbon footprint information, has been proposed to decrease the network ecological impact while balancing the traffic load and maintaining acceptable connection-blocking rate. The trade-off between load balancing and carbon footprint is also analyzed to evaluate the effectiveness of the proposed strategy within the context of a real world network.

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1 Introduction

The energy consumption of network infrastructures has recently attracted interest from the research community. Current network devices (routers, switches, line cards, signal regenerators, optical amplifiers, etc.) have reached huge bandwidth capacity, but their development has not been compensated at the same rate as for their energy consumption [2,19], and only limited benefits have been achieved, e.g., through local strategies for energy-efficient networking [17]. It has been estimated that network infrastructures alone consume 22 GW of electrical power corresponding to more than 1 % of the worldwide production of electrical energy, with a growth rate of 12 % per year [5], further stressing the need for energy-efficient and environment-saving solutions. Nevertheless, the energy consumption is not the only dimension to consider when evaluating the ecological impact of a network. The production of energy may often have an adverse effect on the environment that can be viewed as a measure of human demand on the Earth's ecosystems, also referred to as the anthropogenic ecological footprint. It has been recently estimated to be equivalent to 1.5 planet Earth's [28]—in other words, humanity uses ecological resources 1.5 times as fast as the planet Earth can renew them. Simply stated, humanity's demands exceed the planet's capacity to sustain us. As a part of the ecological footprint, the carbon footprint measures the total set of greenhouse gases (GHG) emitted by the network infrastructure. Smart grid power distribution networks enable the flexible interconnection of green renewable energy sources with dirty fossil fuel-based energy sources, providing the energy consumers with real-time information of the energy source that is currently powering them, together with the capability of dynamically switching between the available options. The availability of an interface between the optical networks and the smart grid will enable the communication between the two control planes, opening a new opportunity in telecommunication networks. The GMPLS network control plane can be aware of the current carbon footprint of the network elements (NE) and can route the connections through green NEs in order to minimize their emissions and greatly reduce the associated ecological footprint [21]. Nonetheless, optimizing only the carbon footprint may lead to increased connection-blocking rates. For this reason, in this paper, the previous work [26] is extended by adding a tunable load balancing factor to the routing decision process in order to decrease the carbon footprint while keeping the connection-blocking rate at the desired level. The resulting RWA scheme has the inherent capability of exploiting the presence of renewable energy sources when dynamically building WDM-based virtual topologies on the underlying physical network. This possibility can be exploited in order to establish the paths in such a way that the use of dirty energy sources and hence the global carbon footprint of the whole network is minimized, while keeping an acceptable blocking rate. Since the availability of green energy sources varies with natural phenomena (sunlight, wind, tide, etc.) in an often unpredictable way, multiple simulation experiments, aiming at verifying the effectiveness of the proposed approach, have been conducted in a dynamic environment with the energy sources availability changing at different time scales. Based on the achieved results, we envision that such approach can open the door to new promising network management and engineering strategies with the capability of driving the change toward a more sustainable generation of communication infrastructures.

2 Backgrounds

This section briefly introduces some of the basic concepts that will be useful to better explain the proposed approach and defines the basic building blocks that are necessary to understand the involved scenario and the fundamental ideas and choices behind it.

2.1 Operating with multiple energy sources

Since the electrical energy needed to power network devices is not directly present in nature, it has to be derived from primary energy sources, directly available in nature. A wide variety of primary energy sources can be employed to produce the electrical energy required by telecommunication equipment, ranging from the legacy fossil-based fuels (carbon, oil, gas, etc.) to the alternative energy sources such as nuclear and renewable energy (solar, wind, geothermal, tide, etc.). Fossil-based sources are usually burned to produce energy, by emitting large quantities of GHG (mainly carbon dioxide, CO_2) in the atmosphere, thus contributing to global warming and pollution, whereas nuclear energy, although it does not emit significant quantities of CO_2, cannot be considered as a *clean* source due to its high adverse ecological effects, nor *renewable* since its fuels (mainly uranium and plutonium) are available only in limited quantities. Energy sources have different environmental impacts in terms, e.g., of the GHG emitted in the atmosphere (coal power plants), working noises (e.g., wind turbines), disruption of natural phenomena (e.g., hydro-electrical plants) and have different energy costs even varying in time (e.g., nightly produced nuclear energy is usually cheap). Renewable sources are usually referred to as "green" since they do not emit GHG in the atmosphere during their use (with almost the only exception of biomasses, which do emit CO_2, but it is partially compensated by the carbon dioxide absorbed during the plants growth). Furthermore, they regenerate themselves on a relatively small time scale, becoming virtually inexhaustible, and are beneficial over their entire life-cycle [13]. For this reason, eco-sustainable networking practices are being investigated in order to lower the ecological footprint of modern communication infrastructures. These practice may leverage the information and options for dynamic choice of power supply provided by next-generation smart grid interfaces in order to adaptively route network connection on equipment preferably powered by renewable sources. In such a way, energy-related information such as voltage, frequency, real and reactive power usage and power supply type can be imported at the network control plane layer to influence routing decisions according to properly crafted energy-management strategies (i.e., containment of GHG emissions).

2.2 The MPLS/GMPLS paradigm

Multi-protocol label switching (MPLS) is the currently the best available solution to provide enhanced traffic engineering facilities within backbone networks. The non-generalized version of MPLS implements an overlay label-stacked infrastructure on a traditional IP network. The reservation of communication resources and a fine-grained control on the routing dynamics is supported through the pre-determination of explicit label-switched paths. Such paths are based on tunnels or virtual pseudo-link abstractions, which implement end-to-end connections throughout the network. A label-switched path or LSP identifies and end-to-end traffic flow characterized by specific network management or traffic engineering constraints (e.g., minimum available bandwidth or latency, jitter etc.) where all the packets are tagged by a unique common label. This has the effect of creating virtual network topologies by decoupling the physical IP network layout from the logical-traffic engineered one. Traditional IP routing is therefore suspended for all the packets injected into a tunnel and hence entering the MPLS domain. Packets are switched based on their outermost label/tag until they remain in the MPLS domain and do not exit from the tunnel or virtual interconnection. Furthermore, label switching is extremely more flexible and effective, in terms of performance, than traditional IP destination-based routing.

The generalized version of MPLS (GMPLS) extends the MPLS traffic engineering and network management capabilities to the optical network environment, by generalizing the concept of label from the tag-switching to the wavelength switching domain, where every frequency/lambda can be mapped into a label in the packet-switched domain. Unlike in the case of traditional labels, in the optical domain there is no need of marking the data inside a virtual end-to-end optical path with a specific tag, since the label value is implicit in the fact that the data is being transported within the agreed wavelength band. Thus, a generalized label/lambda switched path may consist in the composition of some label-switched segments, typically located on the network edge, in correspondence of the two logical channel endpoints, and a pure optical switched path, or *lightpath*, carved onto a common wavelength across the network core.

GMPLS supports enhanced control plane capabilities for many kind of interfaces, including packet-switched, wavelength-switched, fiber-switched or TDM-capable ones, providing enough flexibility to enable the seamless migration of traffic from the electronic domain on the network edge to pure photonics within the network backbone. For these reasons, GMPLS is considered the control plane solution of choice for next-generation optical wavelength switches (WXC or OXCs) and optical service routers (OSR). This concept originated from the observation that from the perspective of control semantics, a GMPLS integrates label and lambda-switching capabilities into a single converged control plane, with only some minimal restriction due to the specific forwarding-plane features of the different technologies involved. From the forwarding-plane perspective, label-switching nodes manage packets according to the explicit label they carry whereas lambda-switching nodes properly manage wavelengths implicitly bearing their associated label. However, since the analog of a label in the optical domain is a wavelength there is no label merging or stacking capability in the optical domain.

GMPLS specifically encompasses all the control plane issues related to the management of the above overlay infrastructure, mainly centered around selecting the best path (or set of paths) for the transport of traffic across the network, according to specific traffic engineering constraint. This activity implies neighbor node and network resource discovery as well as acquisition, dissemination and management of topology and status information. Path selection, is clearly the most critical issue in the design and implementation of control planes for GMPLS-based transport networks.

Each node within the GMPLS domain maintains a topology view as a representation of the status of each resource (network element or communication link). The link status may include the total number of active channels, the number of allocated channels, and the bandwidth available on them, whereas the network element status may include the type of energy source, as well as the carbon footprint or energy consumption information. Conventional link-state interior routing protocols such as OSPF or ISIS, properly extended to transport all the needed traffic engineering information in the GMPLS environment, are specifically responsible for the reliable advertisement of the network topology and of the available bandwidth and wavelength resources within the whole domain. Information are exchanged on a periodical basis or are triggered by a topology change.

In the optical domain, since each lightpath contains a large volume of bandwidth, optical topology change (including setup/teardown and local optimization of the optical path) is not as frequent as that of the electrical domain.

Therefore, optical parameters, such as the OXC status and fiber channel usage, need not to be exchanged on a periodic basis. Instead, such exchange can be done based on an event-driven basis, e.g., when an optical path is set up or torn down or when a broken fiber is detected. Therefore, these optical parameters could be included and transmitted in a separate type of link-state update packet.

Effective signaling protocols and facilities are also needed to exchange control messages during the setup and deletion of paths, to reserve free network resources, and to distribute label or lambda information. Suitable signaling protocols for the GMPLS control plane include RSVP [29] and CR-LDP [3]. Both protocols perform signaling on a hop-by-hop basis, with RSVP reserving resources in the backward direction (destination-initiated reservation), and CR-LDP reserving resources in the forward direction (source-initiated reservation). Both RSVP and CR-LDP may be used to reserve a single wavelength for a lightpath if the wavelength is known in advance (i.e., it has been determined at the path selection time together with the route from source to destination, according to a dynamic, combined RWA model). However, these protocols may also be modified to incorporate wavelength selection into the reservation process.

3 An eco-sustainable RWA framework

We present an integrated eco-sustainable single-stage RWA scheme that operates online, by running at each request of a dedicated connection with specific user requirements (typically bandwidth capacity) between two network nodes, with the goal of minimizing the environmental impact (carbon footprint) of the resulting wavelength routing architecture while keeping into account also the other traditional carrier's performance objectives (optimizing resource usage, reducing operating costs, etc.). We make the assumption that each connection is bidirectional and consists in a specific set of traffic flows that cannot be split between multiple paths. A connection can be routed on one or more (concatenated) fiber links between its source and destination nodes, with sufficient available wavelength capacity, resulting into a dedicated logical circuit or "*lightpath*" built upon a single wavelength. Allocation of wavelengths on the optical links on a lightpath takes place according to a circuit switched model where the same wavelength resource is assigned to each end-to-end circuit for its entire duration (continuity constraint). By using totally optical devices such as amplifiers and transparent wavelength switches, these lightpaths can span more than one fiber strand, remaining entirely optical from end to end, and avoiding, as possible, the use of any intermediate regeneration device converting the signals from the optical to the electronic domain and vice-versa.

3.1 The network model

The WDM network is modeled as an undirected graph $G = (V, E)$, with the nodes $v \in V$ being the optical cross-connects (OXC) or routers (OSR), each characterized by a specific carbon footprint e_v (depending on the energy source powering it), and the edges E representing the optical connections between site pairs, composed by a single fiber with length l_{uv}, supporting a maximum number $\lambda_{uv}^{\max}$ of wavelength channels, where $\lambda_{uv}^{\text{busy}}$ of them are currently busy. The generic ith optical amplifier device located on the fiber link connecting nodes (u, v) is characterized by a specific carbon footprint $e_i^{(u,v)}$. Each device (nodes and fibers) in the network is assigned to an energy source from Table 1, and the energy sources availability is changed on a prefixed time basis.

A weighting function c_{uv}, whose value is dynamically determined, is associated with each link (u, v), representing the cost of using the link from both the carbon footprint and resource usage perspectives. In particular, the last point implies ensuring a balanced usage of all the available network communication resources, in order to avoid the saturation of some more critical links that risk to become real bottlenecks in the overall network infrastructure. A lightpath $\pi_i = \{(s, x_1), \ldots (x_n, d)\}$ is then defined as an end-to-end single-wavelength channel, carved onto a set of optical edges connecting the source s and destination d by passing through the intermediate nodes $\{x_1 \ldots x_n\}$.

Given a set of end-to-end connection requests C, the fundamental goal of an RWA problem is determining a virtual topology, built on a set of lightpaths that are able to satisfy all the request in C by exhausting the minimum number of fiber links on the graph G by reducing as much as possible both the carbon footprint and network usage unbalancing, such that the maximum number of requests can be simultaneously satisfied. The set of connection requests C can be known in advance, which is referred to as the static (off-line) RWA problem, or the traffic matrix can be built as the connection requests arrive (without prior knowledge), which is referred to as the dynamic (on-line) RWA problem. The static RWA problem can be solved off-line, by using exact techniques such as integer linear programming (ILP), which find an optimal solution accommodating all the connection requests. In the dynamic RWA problem, instead, since the set of connection requests is not known a priori, each connection request has to be routed on-line, as it arrives, basing its choice according to the current state of the network, trying to balance the network resources in order to not compromise future connection requests. The problem formulation is the same in both cases (static and dynamic), but the solution changes provided the different visibility on the traffic matrix C. The aforementioned virtual topology can be modeled as a set of lightpaths $\Pi = \{\pi_1, \ldots, \pi_n\}$, with $n \leq |C|$ where each lightpath $\pi_i \in \Pi$ serves a specific connection request $c_i \in C$. Thus, the behavior of the entire RWA framework can be described by a surjective mapping function:

$$\rho : C \mapsto \Pi \quad \text{where} \quad \forall \pi \in \Pi, \exists\, c \in C \mid \rho(c) = \pi, \qquad (1)$$

in which, a path in Π is assigned to the connection requests in C. The static RWA problem is known to be NP-complete [6], i.e., when the instance of the problem increases (in size of the network, $|G|$, and number of connection requests, $|C|$), the problem soon becomes intractable. Since we are interested in modeling real case networks, we focus on the dynamic case, for which we employ a Dijkstra-based online RWA algorithm which calculates (in polynomial time) the routes for the incoming connection requests taking into account both the load balancing and the specific energy sources powering the network elements.

3.2 The cost function

Routing is implemented in the proposed eco-sustainable RWA scheme by using a single-stage constrained shortest path Dijkstra algorithm, enforcing during its operations the wavelength continuity constraint and based on the edge weighting cost function introduced in Sect. 3.1 and defined in the following. Wavelength assignment is performed by iterating path selections on multiple wavelengths (e.g., by using a fist-fit wavelength selection strategy) according to a progressive construction schema. In order to reduce the carbon footprint while not disrupting the network connection acceptance rate, the edge cost function c_{uv} (that will be used by our Dijkstra-based RWA scheme) must be defined as a

Table 1 Mean energy sources emissions [1]

Energy source	Mean CO_2 emissions (grams per kWh)
Solar, wind, tide, hydro-electrical	0
Nuclear	20
Geothermal	107
Biomasses	180
Natural gas	370
Fuel	880
Coal	980

linear combination of the energy source emissions e_{uv} and the wavelength occupancy ratio ℓ_{uv}:

$$c_{uv} = \alpha \cdot e_{uv} + (1 - \alpha) \cdot \ell_{uv}, \quad (2)$$

where ℓ_{uv} is the number of busy wavelengths over the number of maximum available wavelengths of the fiber link (u, v):

$$\ell_{uv} = \lambda_{uv}^{\text{busy}} / \lambda_{uv}^{\max}, \quad (3)$$

and e_{uv} is the carbon cost function assigned to link (u, v):

$$e_{uv} = \frac{e_u}{n_u} + \frac{e_v}{n_v} + \sum_{i=1}^{\lfloor l_{uv}/\Lambda \rfloor} e_i^{(u,v)}, \quad (4)$$

in which e_u and e_v are the carbon footprints of nodes u and v (values from Table 1) scaled by their nodal degrees n_u, n_v, and $e_i^{(u,v)}$ is the carbon footprint of the optical amplifiers on link (u, v), whose number is given by the length l_{uv} of the fiber link (u, v) divided by the maximum allowed length $\Lambda = 80$ km the optical signal can travel without need of optical amplification.

All the variable parameters are scaled into the interval [0, 1] in order to be comparable with each other. The parameter α, with $0 \leq \alpha \leq 1$, is the weighting factor between the load balancing and the carbon cost function (*greenness*) of edge (u, v), which is used to bias their relative weights in the calculation of the edge cost. Note that the more a link is "dirty" and loaded, the higher its cost is, and vice-versa. The carbon footprint E_{sd}^P of a lightpath P from source node s to destination node d is measured as the sum of the carbon footprints of the NEs traversed in the lightpath:

$$E_{\text{sd}}^P = \sum_{(u,v) \in P} e_{uv}. \quad (5)$$

Note that the edge cost function is recalculated each time a new connection is routed into the network or a new update of the energy sources is received. Therefore, the weights of the edges given by Eq. (2) will vary according to their instantaneous occupancy ratio (load balancing) and current carbon footprint ("greenness"). In this way, each connection request will be routed by selecting the lowest carbon footprint or the best load balancing path or a mix of the two, as defined by the value of the parameter α. It is worth noting that the weighting function reported in Eq. (2) has all the four desirable properties defined in [16] as the basic requirements for an optimal edge metric, which can be resumed as follows: the edge cost has to be inversely proportional to both the (1) residual and (2) the maximum capacities of the edge; (3) an edge with no residual capacity must have an infinite cost (obtained by temporarily removing the edge from the network); (4) two fibers with the same occupancy ratio ℓ_{uv} but different characteristics (length and type of energy sources) should have different costs.

3.3 OSPF-TE extensions

The proposed RWA scheme requires the existence, at the network control plane level, of the basic routing and signaling services, operating in a fully distributed way to support interworking between the nodes that cooperate to the construction of the virtual topology satisfying, as possible, the users' connection requests. This implies providing a link-state advertisement protocol, needed to synchronize the nodes' network views by transporting the link status information (including carbon footprint-related ones) to every participant, as well as a signaling mechanism to be used for the reservation and establishment of paths.

For example, the available routing (e.g., OSPF-TE) and signaling (e.g., RSVP-TE) protocols within the GMPLS traffic engineering framework may be properly extended to include energy-related information such as the carbon footprint associated with nodes and the type of energy source currently used for powering them. In detail, to obtain the information needed in the cost function reported in the Eq. (2), an extension to the OSPF-TE link-state routing protocol [12] is necessary. Opaque Link-State Advertisements [7] (LSAs) for the OSPF protocol are used for implementing the proposed extensions. New TLVs (Type, Length, Value) fields are added directly to the Traffic Engineering extensions for OSPF-TE (Traffic Engineering LSA, opaque type=1) according to an agile implementation (the detailed explanation of each field of the TE LSA can be found in [14]). The *Type* field (16 bits) contains the ID of the newly defined entry (32768, which is the first available one) and the *Length* field (16-bits) specifies the extension of the *Value* field (in octets), which are contained in the payload of LSAs. As illustrated in Table 2, the Value field identifies the energy source that is currently powering the device. The proposed TE LSAs will be flooded

Table 2 Sub-TLVs for TE LSA

Type	Length	Value
32768	4 octets	CO_2 emissions (from Table 1)

Fig. 1 The cost 266 case study topology used in simulations

over the whole network on a fixed time basis, disseminating the energy source information.

4 Discussions of the results

The cost function and the proposed OSPF-TE extension have been implemented in the event-driven simulator OPNET [15]. Simulations have been performed on the European network COST266 [11] case study topology, shown in Fig. 1, with 37 nodes and 55 bidirectional links, each with 64 wavelengths.

Label-switched path (LSP) connection requests are generated as a Poisson process, with exponentially distributed connection duration. Simulation results are generated with 95 % confidence interval and 20 prime numbers were taken as random seeds. The mean value of the connections duration is 6 h, with mean inter-arrival time of 30 min. The total traffic load is given by the connection duration and inter-arrival rate, and is maintained at a fixed value of 12 Erlangs per node. In the simulation model, a first fit algorithm is applied for the wavelength assignment.

In order to model the variation in time of the energy sources, we adopted a totally random model. This choice is motivated by the fact that the availability of the renewable sources of energy is a not always easily predictable phenomenon (especially in the case of wind and tide, but also the energy production of ground-installed solar panels can be affected by clouds, pollution and other atmospheric phenomena). Furthermore, since several distributed sources of energy can be available in smart grids, the energy that powers the network equipment can proceed from any of the currently available sources. Therefore, in order to not depend on some specific forecast model predicting the availability of renewable energy sources, and assuming a smart grid power distribution network, we modeled the variation in time of the energy sources as a random function, assigning to the network elements a random energy source at fixed time intervals (3, 6, 12 and 24 h), in an effort to keep the model as general as possible. Each time energy sources change, a new update of the power source information (TE LSA) is originated and flooded between neighbors using the proposed OSPF-TE extension. The new carbon footprint is updated in each LSA database and thus used for routing calculation according to Eq. (2).

Simulation runtime was set to 30 days, during which the carbon footprint, hop count and blocking probability of the connections were monitored. While we are mainly interested in the reduction in carbon footprint, the hop count and blocking probability metrics give also us very useful information about, respectively, the network resources usage (in terms of load balancing) effectiveness and lightpath complexity degree (depending on their length), clearly depicting the trade-off between our eco-sustainability objective and the more traditional network management practices.

The average carbon footprint per connection of the proposed eco-sustainable (indicated in figures as EE: energy-efficient) RWA scheme, namely *EE actual cost of path*, is plotted in Fig. 2 against different values of the power change interval. The *EE promising cost of path* represents what would be the cost of paths if the energy sources would not change during the whole connections lifetime, actually providing a lower bound for the cost of path of the proposed RWA algorithm. The carbon footprint of the shortest path algorithm (SP) is reported as a comparison. The SP algorithm is unaware of the energy sources and no LSA advertisements are propagated to neighbors when the energy sources change. This results in an almost constant carbon footprint of connections as a consequence of the routing always over the shortest paths. On the other hand, the EE algorithm presents

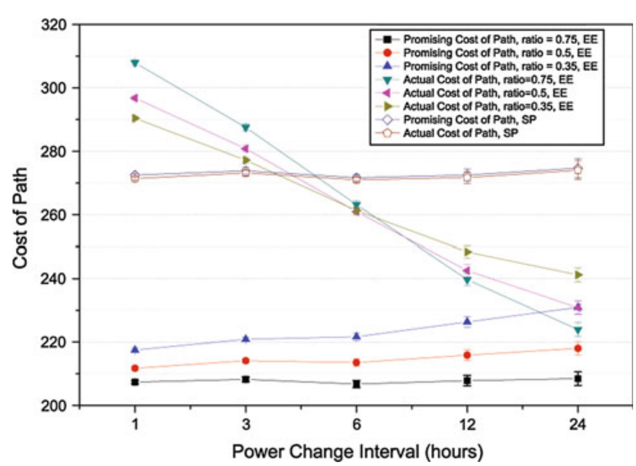

Fig. 2 Average cost of path (carbon footprint)

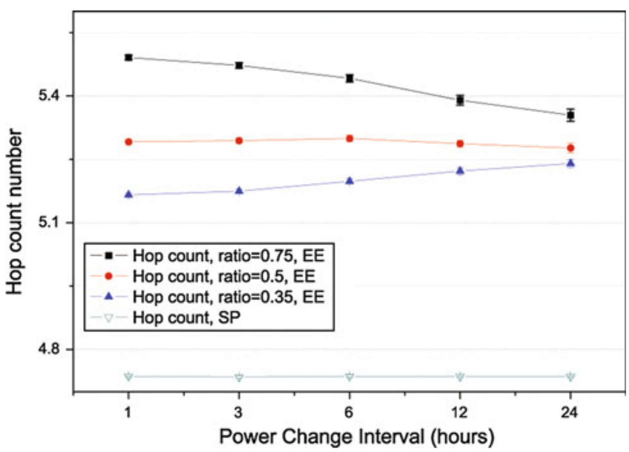

Fig. 3 Average hop count of lightpaths

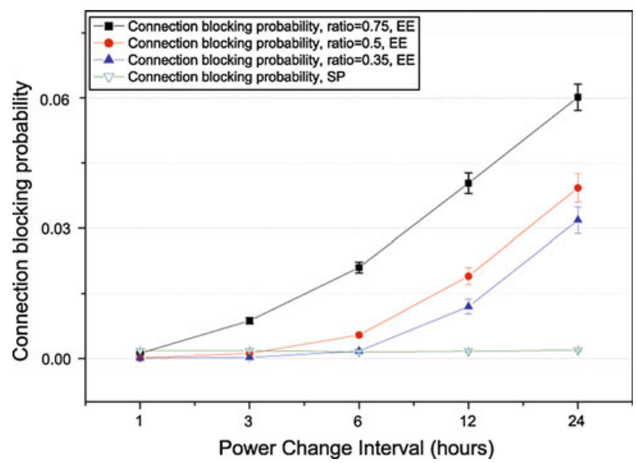

Fig. 4 Blocking probability of the connection requests

a high sensitivity to the power change interval, more prominent when greater importance is assigned to the energy factor ($\alpha = 0.75$); a more stable behavior is observed when the load balancing factor is privileged ($\alpha = 0.35$). Furthermore, the proposed algorithm routes the connections over longer paths than the SP algorithm, in an effort to both balance the load and achieve low carbon footprints (Fig. 3).

As a consequence, when the power change interval is shorter compared with the connections lifetime (i.e., energy sources change frequently, <6 h), the routing decisions taken by the proposed algorithm soon become sub-optimal, and the longer lightpaths result in higher carbon footprint. On the other hand, when the power change interval is longer than the connections lifetime (>6 h), the eco-sustainable routing decisions will maintain their optimality during the connections lifetime resulting in lower carbon footprint. When connections lifetime and power change interval have the same duration (6 h), the trade-off is slightly in favor of the eco-sustainable routing approach. For comparison, the lower bound for the carbon footprint of lightpaths is also plotted in Fig. 2 (namely, promising cost of path), in which the cost of paths is collected at connection setup time, and no change in the energy sources are produced during the connections lifetime. As it can be observed, the proposed RWA scheme approaches the theoretical limit when the power change interval is long enough with respect to the connections' lifetime (i.e., connections routing maintains its optimality throughout their lifetime).

The average connection-blocking rate of both the EE and the SP RWA schemes are plotted in Fig. 4.

The chosen traffic load (12 Erlangs per node) is low enough to allow the routing of almost all the connections over the shortest paths (SP), while routing on longer paths will consume more resources and may result in a nonzero blocking rate. When the carbon footprint is preferred with respect to the load balancing ($\alpha = 0.75$), the EE scheme presents an higher blocking probability, while giving more importance to load balancing ($\alpha = 0.35$) zeros the blocking rate when the power change interval is lower or equal to connections lifetime. When the energy sources change more frequently, the blocking rate increases, as a consequence of the lower impact of the energy sources in the edge cost function of Eq. (2). Results clearly show the trade-off between the carbon footprint and the connection-blocking rate of the EE scheme, indicating that benefits on the two dimensions are possible when the connections' lifetime and the power change interval have similar durations. If not, carbon footprint reduction is possible at the expense of connection-blocking rate (only when the power change interval is longer than the connections lifetime). Under appropriate conditions, the EE scheme can route the traffic passing through greener sources, thus reducing CO_2 emissions, while maintaining an acceptable blocking rate.

5 Related work

The need for greener networking infrastructures has been widely exploited in recent research efforts available in literature. The work presented in [4] proposes a new ECO-friendly distributed routing protocol based on OSPF that, in presence of limited loads, enables the routing of traffic through a small subset of routers, allowing unneeded routers to pass into sleep mode by reducing energy consumption and hence GHG emissions. Similarly, in [27] a new energy model based on the GMPLS framework is presented. It fosters power-efficient Green Photonic Networks through a routing algorithm delivering power reduction through a node hibernation approach. In [24], survivable IP/MPLS-over-WSON networks are designed to meet specific availability objectives considering single failures, and the benefits of the designed networks are evaluated from an economic perspective including power consumption and maintenance. Routing optimizations in dynamic GMPLS controlled optical networks, exploiting the use of green energy sources together with re-routing and load balancing factors has been presented in [25,26], where a trade-off between blocking probability and obtained CO_2 savings is studied. The works presented in [8,9] envision a low carbon emission IP over WDM network where renewable energy is used to reduce the CO_2 emissions by developing a linear programming model in order to minimize the non-renewable energy consumption of the network. Also in [23], mixed integer linear programming methods and heuristics are used to optimize the energy consumption of an IP over WDM transport network by switching off router ports, transponders and optical amplifiers. Other mathematical formulations based on integer linear programming are presented in [18] and [19], with the double objective of reducing both the energy consumption and the GHG emissions of network infrastructure by using multiple green and dirty energy sources. Since these formulations can be used to find an optimum solution of the offline RWA problem, these works give an upper bound for energy and GHG savings. The work presented in [20] exploits according to a more dynamic multi-stage approach the minimization of both energy consumption and GHG emission in wavelength-routed networks, providing dynamic sub-wavelength routing (grooming) facilities. Starting from a quite different perspective, the contribution reported in [10] focuses on how to dynamically route on-demand optical circuits that are established to transfer energy-intensive data processing toward data centers powered with renewable energy, by devising two routing algorithms aimed at minimizing the CO_2 emissions of data centers by following the current availability of renewable energy (sun and wind). Also in [22], a strategy for saving energy in high-density data center networks in a routing perspective is discussed. It is based on an energy-aware routing principle using as few network devices as possible to provide the routing service, with limited sacrifice on the network performance.

6 Conclusions

In this paper, we investigated the problem of reducing the carbon footprint in the future energy-aware wavelength-routed networks and presented a general framework for providing eco-sustainable routing in photonic networks built on the strengths of GMPLS for environmentally conscious dynamic path selection. Accordingly, we presented a single-stage wavelength routing algorithm aiming at placing the traffic into greener lightpaths, characterized by devices powered by renewable energy sources, while balancing the network traffic load, as possible. The implementation is made possible due to the development of smart grid power distribution networks and the proposed extension to the OSPF-TE protocol. Results show a reduction in the carbon footprint while maintaining low blocking rate when the power change interval is comparable or greater than the connections' lifetime, and a trade-off between the carbon footprint and the connection-blocking rate is shown.

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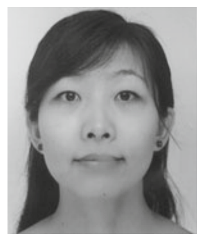

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Davide Careglio received the M.Sc. and Ph.D. degrees in telecommunications engineering both from the Technical University of Catalonia, BarcelonaTech (UPC), Barcelona, Spain, in 2000 and 2005, respectively, and the Laurea degree in electrical engineering from Politecnico di Torino, Turin, Italy, in 2001. He is currently an Associate Professor in the Department of Computer Architecture at UPC. Since 2000, he has been a Staff Member of the Advanced Broadband Communication Center. His research interests include networking protocols with emphasis on optical switching technologies, and algorithms and protocols for traffic engineering and QoS provisioning. He has participated in many European and national projects in the field of optical networking and green communication.

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