Low-Carbon Routing Algorithms For Cloud Computing Services in IP-over-WDM Networks

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***Abstract*—Energy consumption in telecommunication networks keeps growing rapidly, mainly due to emergence of new Cloud Computing (CC) services that need to be supported by large data centers that consume a huge amount of energy and, in turn, cause the emission of enormous quantity of CO_2. Given the decreasing availability of fossil fuels and the raising concern about global warming, research is now focusing on novel "low-carbon" telecom solutions. E.g., based on today telecom technologies, data centers can be located near renewable energy plants and data can then be effectively transferred to these locations via reconfigurable optical networks, based on the principle that data can be moved more efficiently than electricity. This paper focuses on how to dynamically route on-demand optical circuits that are established to transfer energy-intensive data processing towards data centers powered with renewable energy. Our main contribution consists in devising two routing algorithms for connections supporting CC services, aimed at minimizing the CO_2 emissions of data centers by following the current availability of renewable energy (Sun and Wind). The trade-off with energy consumption for the transport equipments is also considered. The results show that relevant reductions, up to about 30% in CO_2 emissions can be achieved using our approaches compared to baseline shortest-path-based routing strategies, paying off only a marginal increase in terms of network blocking probability.**

I. Introduction

Information and Communication Technology (ICT) industry is rapidly developing worldwide . Meanwhile, also carbon emission from ICT industry is increasingly growing. Ref. [1] shows that the ICT industry is responsible for 2% of the world's CO_2 emission and, based on 2009 data, ICT consumes about 8% of total electricity worldwide. Energy consumption of telecom networks, which represent a significant part of ICT, is also growing due to the never ceasing increase of traffic. In particular the power consumption of *Data Centers* (DCs) is rapidly increasing fueled by the growth of data-intensive applications such as *Cloud Computing* (CC) services.

ICT has been recognized as the key to a low-carbon economy and it has been estimated that ICT could reduce CO_2 emissions in other sectors of approximately five times as much as the ICT's own emissions and deliver about 1/3 of the expected total abatements in 2020 [2]. Recently, significant research efforts have addressed the reduction of energy consumption of telecommunications networks, and specifically optical core networks which are the major focus of this work (see e.g., [3], [4]). Only few works so far have directly addressed the issue of directly minimizing CO_2 emissions (which is a different target than minimizing overall energy consumption, especially when renewable energies come to play) in the design and operation of an optical network. Authors in [5] propose an approach to reduce CO_2 emissions in IP over WDM networks (with or without data centers) by using renewable networks. They develop a Linear Programming (LP) model for a network design that minimizes CO_2 emissions (low-carbon design) and propose a heuristic to increase renewable energy utilization. The main contribution of [6] is the formulation and the comparison of several energy-aware static RWA strategies for WDM networks where optical devices can be powered either by renewable or legacy energy sources. Note that various research projects in the last years have been investigating how to utilize renewable energies in the telecom network infrastructure. One of the most relevant is the GreenStar Network (GSN) project [7]; one of the goals of the GSN project is to create technology and standards for reducing the carbon footprint of telecom network and a test-bed based on CANARIE network, which includes solar, wind and geothermic energy-powered nodes, has been already successfully demonstrated.

In this paper, we focus on reducing the CO_2 emissions of DCs in IP over WDM networks. First, we model the power consumption of IP-over-WDM networks that contain DCs (that process Cloud Computing requests) powered by renewable energy sources (wind and solar energy) by providing simple formulas to derive the energy consumption of different types of CC services and to perform a realistic dimensioning of capacity of renewable energy plants. Then, we propose and evaluate new routing strategies, designed to route optical connection supporting (aggregation of) CC service requests, that are able to follow the the current availability of renewable energy and consequently to reduce the CO_2 emissions, without affecting other performance metrics such as blocking probability or delay. Note that, in order to move this huge amount of data towards (usually) remote locations, the energy consumption for the data transfer arises and it may neutralize all the savings in terms of CO_2 emissions coming from using renewable energy. So our algorithms are designed to carefully address the trade-off between the energy consumption of data transport and the energy consumption to process the CC request inside DCs. As a main difference from other works (such as [5])

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where static traffic is simulated, we consider here a dynamic traffic scenario. Results show that our approach can achieve significant reduction in CO_2 emissions, up to about 30%.

The rest of the paper is structured as follows. Section II briefs the energy model for the IP-over-WDM network, the Cloud Computing services and the dimensioning of power plants based on renewable energies that power the DCs. Two routing algorithms for CO_2-reduction are introduced in Section III. Section IV elaborates on the study cases and test networks of this research; then simulation results are presented and analyzed. Finally, the paper is concluded in Section V.

II. Services and Energy Models

In this section we describe the model evaluating the energy consumption of CC services and we perform a simple dimensioning for wind and solar power plants, that will be useful for our numerical considerations in Sect. IV.

A. The Cloud services Energy Model

In our simplified model for CC services, every connection request coming from users is a Cloud request. We consider three cloud services: Storage as a Service (S_taaS), Processing as a Service ($PaaS$) and Software as a Service ($SaaS$) [8]; then, for different type of services, we calculate the power consumption necessary to processing the request inside a data center for every single connection at 10 Gbit/s, deriving our analysis from [8]. We focus in the following description on the $PaaS$ case. In the cloud, there are servers that are used for computationally intensive tasks. Data for computationally intensive tasks are uploaded to a cloud service, and the completed output is returned to the user. As an example of these task, we model the converting and compressing of a video file. We are only interested in power consumption of the computational server, so the per-user energy consumption (watt hours) of the processing service is $E_{proc} = 1.5 \cdot T_{proc} \cdot P_{ps,SR}$, where $P_{ps,SR}$ is the power consumption of the server (355 W), and T_{proc} is the average number of hours it takes to perform one encoding. A factor of 1.5 is included in the second term to account for the energy consumed to cool the computation servers, as well as other overheads. Let us consider the processing of a 2.5-h DVD-sized video stored in MPEG-2 (8.54 GB, i.e., 68.32 Gb) and encoding it into the H.264 (MPEG-4 Part 10) format. According to the measurements in [8], the encoding performed by a server of such a 68.32 Gb video file takes 1.25 h. We can say that encoding 10 Gb (i.e., the amount of data delivered in one second by a 10-Gbps lightpath, as in our following simulations) would take 0.183 h. Substituting the values in the above equation we obtain $E_{proc} \approx 100$ Watthour and then multiplied for connection's holding time will give the total energy consumption. We have considered similar models for S_taaS and $SaaS$ obtaining respectively power consumption of 1.41 and 27 Watt.

B. The Renewable Energy Model

Another important aspect of our study is the dimensioning of renewable energy sources. We need to power some of the DCs in the IP-over-WDM network by using renewable energy in order to reduce the CO_2 emissions. The main problem of renewable energy is that its generation is subject to relevant variability during the day (and along the seasons) depending mainly on weather conditions. Indeed, this is the main reason why routing algorithms which can follow the daily distribution of renewable energy are needed.

As shown in Sect. II-A, the power consumption for the processing to the load of a single connection in a DC is about 100 Watt. So, considering an average arrival rate of 180 arrival per second (the maximum used in our simulations), we need $120 conn/s \cdot 100 W/conn \cdot 60 s/min \cdot 60 min/h \cdot 24 h/day$ equals to 1 GigaWatt (GW)/day to supply enough power to support the power request in our study case. The entire power request is then divided into the number of "green" data centers connected to the network. In our case the number of "green" data centers is 3 so each data center needs about 300 MW.

<u>Solar energy plant</u>. We assume here that the DC is powered by a solar farm using parabolic troughs technology. The solar energy power available to a data center is shown in Fig. 1a. As the output power of solar energy sources varies in different hours of the day, we use the profile in [5]. The solar energy output is non-zero from 6:00 to 22:00 and the maximum output power occurs at 12:00.

<u>Wind energy plant</u>. We assume here that a DC is by a wind farm using wind turbines. The wind energy power available to a data center is shown in Fig. 1b. Wind presents more variability compared with the sun and it is quite difficult to predict. So the wind-intensity profile used in our numerical experiments follows an arbitrary profile. In practice this profile would differ according to seasons, geographical position, weather conditions, etc. Note that geographical location of data centers has impact on the generated renewable energy, so we have actually considered that different DCs can be located in different time zones of the network.

III. Algorithms for CO_2 Emissions Reduction

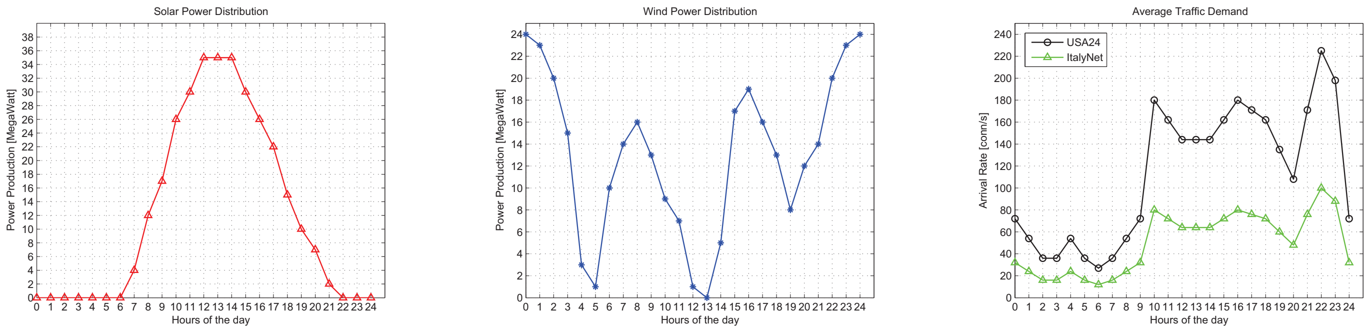
A. Problem definition

We consider the problem of routing dynamic connection requests in IP-over-WDM network architectures, considering renewable-energy powered DCs. Each connection request has to be mapped over an optical circuit (or lightpath) and must be served by a DC that have to process the CC-service requests. The problem can be stated as follows. Given:

- Dynamic connection requests to be established;
- Physical topology and number of wavelength per fiber;
- Current network state (information on existing lightpaths, number of used wavelengths);
- Number of data centers *k*, their position and their daily renewable-energy availability;
- Power consumption parameters: p_p processing power ,P_k current available renewable power, P_t transport power.

The goal is to determine:

- The route that minimizes the CO_2 emissions (promoting renewable-energy utilization);



(a) Solar Power (b) Wind Power (c) Traffic Profile

Fig. 1. Renewable Energy Distribution and Average Traffic Demand during the day

- The data center chosen to process the user's request.

Physical topology is described by a graph $G = (V, E, C, \lambda)$, where V is a the set of nodes, E the set of edges, C is the wavelength-channel capacity and λ is number of wavelengths on the link; the connection requests follow a given traffic profile and for each connection $c = \langle s, B, t_h \rangle$, s is the starting time, B is the requested bandwidth and t_h is the holding time. Besides these, each algorithm may need specific parameters such as the threshold T, a pair of weights (α, β).

Note that power consumption comes from: 1. transport power[1], needed to move traffic, 2. processing power at the DCs. While transport energy is always from not renewable sources (i.e., "brown" energy), processing energy can be either green (when renewable energy sources are active) or brown (when renewable sources are either inactive or not present).

B. Anycast Routing

In an IP-over-WDM network with DCs supporting CC services, each node is a possible source of a CC request and each DC is a possible destination where the connection can be processed, i.e. we assume that the contents that users want to access are replicated inside all the DCs. Consequently, an *Anycast Routing* [10] problem arises. In fact, in a Cloud scenario, a user's interest typically lies in successful job execution and not in the exact location and network route used. Anycast routing specifically enables users to transmit data for processing and service delivery, without assigning an explicit destination that can be anyone among a set of nodes associated to the DCs. To solve the anycast routing problem and transform it into an unicast routing problem we introduce in our work an anycast abstraction of the topology. From a routing perspective, all the network nodes A_j that host a DC are connected to an additional virtual anycast node A, called *Dummy Node*, as depicted in Fig. 2. Each user will then route towards the Dummy Node, i.e. the virtual destination,

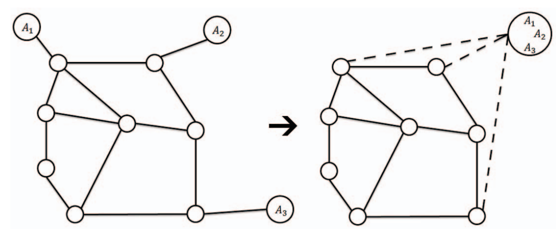


Fig. 2. Physical network topology VS Logical network topology

while the actual destination will be the last DC traversed before reaching the dummy node. In the following, the graph originating from the combination of the original graph, the dummy node and the so called anycast links (that connect DCs to the dummy node and have no bandwidth limitations) will be referred to as "auxiliary graph".

C. SWEAR

The first proposed algorithm is called Sun-And-Wind Energy Routing (SWEAR). SWEAR is designed to promote the choice of a renewable-energy powered data center (end-node), based on its current renewable-energy availability; it also attempts to perform load balancing on network links. In brief, the algorithm compares two candidate paths: the one with lowest transport-power consumption (i.e., minimal power needed to transport the data) and the one with maximum usage of renewable energy. If the increase in transport power of the second option is compensated by the utilization of renewable energy, the second option is chosen.

D. GEAR

The second proposed algorithm is called Green-Energy-Aware Routing (GEAR). The aim of GEAR is to directly find the path with the lowest non-renewable (brown) energy consumption. GEAR assigns as weights of a transport link the transport power, and as weight of the anycast link the current brown power of the DC traversed by the link. In this case, it is enough to apply the shortest path routing algorithm to obtain the "minimum brown power" path.

For both algorithms, we assume that information regarding current available renewable power at the end-nodes is always available for the routing algorithms, carried by a routing

[1] The transport power P_t of a single connection is calculated as described in [9], considering an *Opaque* IPoWDM network architecture, so:

$$P_t = 2 \cdot (H-1) \cdot P_{tr} + H \cdot P_0 + 2 \cdot P_{SR}$$

where H is the hop number, P_{tr}=18.25W, P_0=1.5W, and P_{SR}=16.25W are the power consumptions of transponders, OXC node and short-reach interfaces.

Algorithm 1 - SWEAR

Input: $G = (V, E, C, \lambda)$, $c = \langle s, B, t_h \rangle$, k, P_k, T, (α, β), p_p
Output: Path with maximum usage of renewable energy considering a trade-off with transport energy. The DC chosen to process the user's request.

1) Build auxiliary graph $G' = (V, E)$ with transport links and anycast links.
2) Weight assignment for transport links: check the load on transport links (Load Balancing phase):
   a. for every transport link, calculate $L_{xy} = \dfrac{(\lambda - \lambda_{xy})}{\lambda}$, where λ_{xy} is the number of free wavelengths;
   b. if $L_{xy} > T$, then the weight assigned to transport link is $c_{xy} = \alpha L_{xy}$;
   c. else: the weight assigned to the link is $c_{xy} = 1$.
3) Weight assignment for anycast links: verify which DC among the k DCs has enough renewable energy to process the connection and assign weights consequently:
   a. calculate the threshold S, as the product of the holding time t_h and the processing energy consumption of the connection p_p, hence $S = p_p \cdot t_h$;
   b. if $P_k < S$ then the weight of the anycast link is $d_{kd} = M \cdot p_p$, with M is a large number;
   c. else: assign the weight $d_{kd} = \beta \dfrac{(P_k^h - P_k)}{P_k^h}$, i.e., the energy utilized by the DC, normalized to the starting available energy at hour h.
4) Once weights have been assigned according to step 2 and 3:
   a. calculate the shortest path l_g and the transport energy cost t_g for the connection;
   b. assign value 1 to all the weights in G': $c_{xy} = 1$ and $d_{kd} = 1$ for all the links;
   c. calculate the shortest path l_s and the transport energy cost t_s for the connection;
5) Compare the two paths:
   a. calculate $\Delta_t = t_g - t_s$, as the difference between the two transport energy cost;
   b. if Δ_t is lower than the threshold S, choose path l_g;
   c. else: choose path l_s.
6) If at least one path exists, set up the new lightpath and update network's status. Else block the connection and exit.

Algorithm 2 - GEAR

Input: $G = (V, E, C, \lambda)$, $c = \langle s, B, t_h \rangle$, k, P_k, p_p, P_t
Output: Path with lowest non-renewable (brown) energy consumption. The DC chosen to process the user's request.

1) Build auxiliary graph $G' = (V, E)$.
2) Weight assignment for transport links: link weight is equal to transport power P_t.
3) Weight assignment for anycast links: verify which DC among the k DCs has enough renewable energy to process the connection and assign weights consequently:
   a. if renewable energy is enough to process the connection request, then assign zero cost;
   b. if renewable energy is not enough to process the connection request, then assign to link cost $(p_p - P_k) \cdot t_h$ which is the amount of non-renewable energy used to process the connection request;
   c. if no renewable energy is present, then assign to link cost $p_p \cdot t_h$, which is the non-renewable energy used to process the connection request.
4) Once weights are assigned as defined at step 2 and 3, calculate the shortest path.
5) If the chosen path exists, set up the new lightpath and update network status. Else block the connection and exit.

protocol, e.g., a modified version of OSPF-TE, or periodically collected in an centralized computing element, such as a PCE. The metacodes for SWEAR and GEAR are proposed in Algorithm 1 and 2 scheme.

IV. Illustrative Numerical Simulation Results

In this section we describe our case study and we show numerical simulation results. We consider two network topologies, the *USA24* and the *ItalyNet* [11]. In our simulation study Fig. 3 and *ItalyNet* consist of bidirectional links, with in-line erbium-doped fiber amplifiers (EDFAs) placed 80 km apart, each carrying data at a rate of 10 Gbits/s and 16 WDM channels. We assume that there is full wavelength conversion and no regeneration capability in the network. Connection arrivals follow a Poisson process with an arrival rate depicted in Fig.1c. The average arrival rate varies according to the time of the day according to the profile in Fig. 1c. Peak traffic is 220 arrival per second for the *USA24* and 100 arrival per second for *ItalyNet*. The average traffic demand between each node and a data center ranges from 120 Gb/s to 1 Tb/s and the

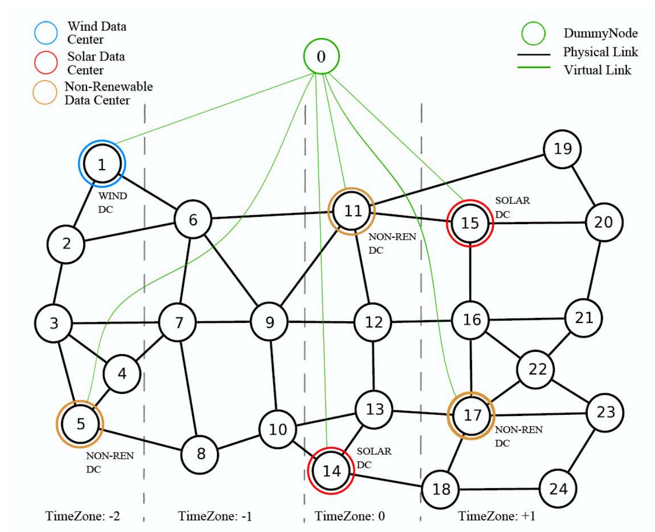
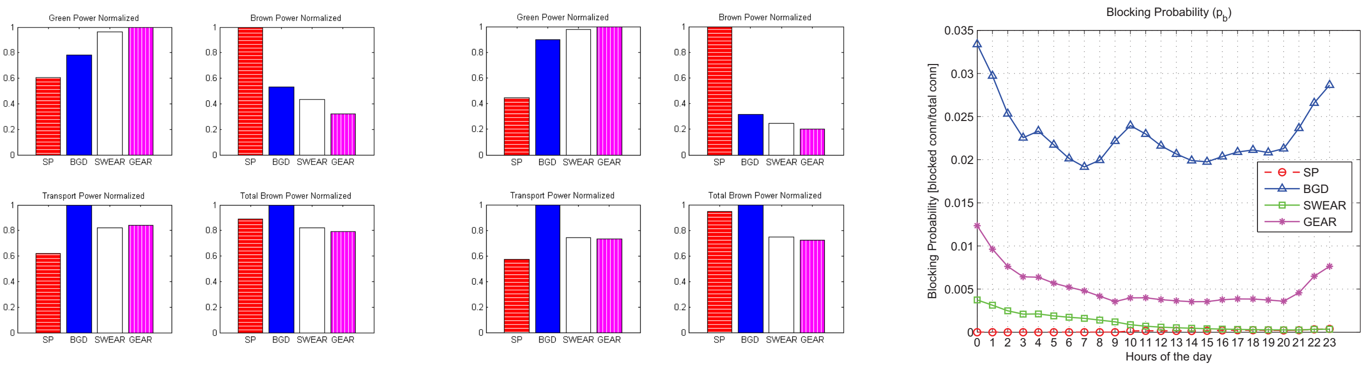


Fig. 3. Network topology of USA24 network, consisting of 24 nodes and 43 bidirectional fiber links.

peak occurs at 22:00 in these traffic profiles. The duration of a connection is exponentially distributed with average duration time normalized to 1. Six data centers are deployed on the network: three of them are powered by renewable energy (node 1, 14 and 15 for Usa24 and 7, 15, 20 for ItalyNet) and three are powered by non-renewable energy (node 5, 11 and 17 for Usa24 and 1, 11, 13 for ItalyNet). Nodes with a DC connected can also work as a simple IP router.

Now we validate our proposed algorithms by using dynamic discrete-event based simulation. We contrast our proposed algorithms SWEAR and GEAR to a basic Shortest Path (SP) and another heuristic, Best Green Data Center (BGD), which always routes towards the data center with maximum renewable energy availability. For each algorithm we consider four energy metrics: *Green Power* and *Brown Power* are



(a) Results for USA24 network topology

(b) Results for ItalyNet network topology

(c) Blocking Probability for ItalyNet

Fig. 4. Normalized power contributions for the two different network topologies and Blocking Probability for ItalyNet topology

the renewable energy and non-renewable energy used for processing connections inside a DC, *Transport Power* is the power used during the transport and switching of the lightpath and *Total Brown Power* is the total non-renewable energy consumption, coming from the sum of *Brown Power* and *Transport Power*. Besides, we consider *blocking probability* as metric to evaluate the network performances.

In Fig. 4a and 4b we draw the normalized power consumption in the two topologies considering the four power contributions described above. We observe that SWEAR and GEAR can reduce the CO_2 emission up to 11% and 20% compared with SP in USA24 and up to 24% and 27% in ItalyNet network topology. These results come from two combined effects: our algorithms induce an increase of about 40% and 20% in Green power usage, compared to SP and BGD respectively for USA24 network and 55% and 10% in ItalyNet. On the other hand, SWEAR and GEAR reduce the Brown power consumption of 56% and 67% compared to SP and 25% compared to BGD in USA24 topology; in ItalyNet we have a reduction of about 75% and 16% respectively. So, as expected, Transport power increases for our algorithms compared to SP that routes with the shortest path and so the minimum transport power (increase of about 35% in USA24 and 21% in ItalyNet). Note that BGD, that routes directly connections to Green DCs without any concern about increasing transport energy, pays off an extremely high transport power, and it results in a very high Total Brown Power. In Fig. 4c we show the blocking probability p_b during the 24 hours of the day for all implemented algorithms in ItalyNet network topology; we note that BGD always forces the routing towards the "greenest" data center so it creates bottlenecks that raise the p_b values. We observe the lowest blocking with Shortest Path algorithm, but SWEAR and GEAR return very satisfactory blocking performance, especially in the case of SWEAR, that benefits of its load balancing phase.

In conclusion, fostering utilization of renewable resources through renewable-energy-aware routing is desirable, but care must be taken in avoiding an excessive increase of the average length of paths. The algorithms proposed in the paper have been demonstrated to address properly such trade-off.

V. Conclusions

We have proposed two routing algorithms, SWEAR and GEAR, to perform low-carbon routing of dynamic connections in IP-over-WDM architecture with data centers equipped with renewable energy plants. Simulation results show in our case study that compared to the Shortest Path and Best Green Data Center, our algorithms SWEAR and GEAR have reduced the CO_2 emission to serve traffic and process data by 25%–27% while maintaining blocking probability at an acceptable level. Areas of future work include the application of our algorithms for the more generic purpose of the stabilization of electrical grid.

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