Green Placement of Data Centers over Optical Networks for Minimizing Carbon Emissions

Renjie Zhang[1], Wei Wang[1], Yanran Xiao[1], Liyazhou Hu[2], Yajie Li[1], Yongli Zhao[1], Jie Zhang[1]
[1]School of Electronics Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]Macau University of Science and Technology, Macau 999078, China
jie.zhang@bupt.edu.cn

***Abstract*—This paper proposes a low-carbon data center placement model based on integer linear programming to reduce carbon emissions. Simulations show the model can effectively reduce carbon emissions while meeting the latency and power constraints.**

***Keywords*—Cloud computing, DC placement, carbon emission**

I. INTRODUCTION

Over the past few decades, as information and communication technology (ICT) has flourished, Internet-based applications have profoundly impacted the lives of individuals across the globe. While we enjoy the convenience of global network information, it has also brought significant impacts on the environment, leading us to re-examine the dual nature of information technology. Studies have shown that as of 2015, the energy consumed by the ICT industry accounted for 1% of the world's total energy consumption, surpassing even the energy consumption of some small countries. It is projected that by 2030, the energy consumption of the ICT industry will reach 7% [1]. With an increasing number of internet companies utilizing cloud computing, cloud service providers are deploying a large number of data centers(DC) to provide computing services, resulting in high energy consumption and significant carbon emissions. As a result, several countries have implemented laws and regulations to penalize DCs based on their carbon emissions [2].

To reduce carbon emissions, employing clean and renewable green energy sources (e.g., wind, hydro, and solar power) is a promising solution. As green energies are typically produced in specific geographical locations, placing DCs in areas with abundant green energy is an effective way to reduce carbon emissions. Several studies have proposed different approaches, such as considering different response times, availability levels, consistency times, and green energy geographical location when selecting DC locations to reduce construction costs [3, 4]. Y. Wu and et al., proposed a multi-objective optimization-based solutions to balance brown energy consumption and cost in cloud network placement and addition scenarios. Most of the work related to deploying DCs has been focused on reducing the construction costs, but our main objective is to minimize the carbon footprint of the entire network. When considering business operations, people usually take into account the network's latency, availability, and consistency, but few people consider that power generation efficiency in green regions is not infinite. Therefore, we take into account both the business's latency requirements and the power generation efficiency of the region to achieve a low-carbon deployment of DCs.

In this paper, with the aim to minimize carbon emissions, we formulate an ILP model to place DCs while considering network delay and the power supply constraints of candidate locations. We solve the model and measure the network carbon emissions and service latency under different computational demands, carbon intensity, and power generation capacities in different regions. Simulation results show that when the latency constraint is 50ms and the electricity generation capacity is 1.9, our model can reduce carbon emissions by about 18%.

II. CLOUD DATA CENTER NETWORK MODEL

A. Cloud Service

In our cloud model, DCs can be deployed at each backbone node. Although local DC computation in each backbone city has advantages such as low latency, it does not consider the environmental impact of carbon emissions. Different regions have varying energy structures, and the power usage effectiveness (PUE) of different DCs also differ. Therefore, it is possible to place DCs to the regions with more abundant clean energy. Fig.1 illustrates the remove-service paradigm with DCs placed at clean-energy-abundant locations.

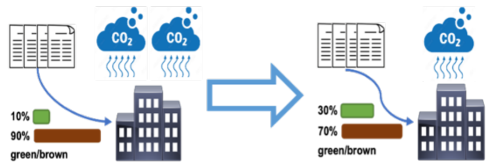

Fig. 1 brown DC vs. green DC

B. Carbon Emission Model

Given a set of DCs D, which are inter-connected with optical networks, the carbon emissions generated from each DC $d \in D$are related to three factors：

- M_d, refers to the number of standard racks, which is usually used to measure the datacenter capacity, in DC d. Each DC needs to be large enough to handle all the computational tasks that are assigned to it within the network.
- PUE_d, refers to the energy efficiency of DC d, and it is calculated by dividing the total DC energy consumption by the IT equipment energy consumption.
- CI_d, Carbon intensity of DC d. It is calculated based on the proportion of energy sources, and it's used to describe the amount of carbon emissions produced per unit of energy consumption in a given region.

The total amount of carbon emissions produced by all the DCs is as Eqn. (1):

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$$E = k\sum_{d\in D}\frac{M_d * CI_d}{PUE_d} \quad (1)$$

Fig. 2 delay constraint

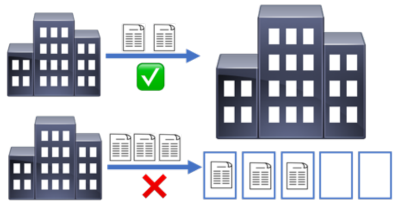
Fig. 3 electricity generation capacity constraint

III. Problem Formulations

A. Problem Statement

Given a set of network nodes, the computation demand from each network node, the carbon intensity, the PUE, and the power generation capacity of each node, we determine the size of DCs deployed at each node and the amount of computation demand that needs to be offloaded between each node pair, and the objective is to minimize carbon emissions generated by the entire DCnetworks.

B. Input

V, a set of nodes
C_v, computation demand of node v
PUE_v, average PUE at node v
CI_v, carbon intensity at node v
P_v, electricity generation capacity at node v
D_{pq}, delay from node p to q
m, the computation capability in each standard rack
k, the energy consumption of each standard rack
T, latency threshold for inter-datacenter offloading

C. Variables

M_v, number of standard racks allocated to node v
T_{pq}, standard racks for transferring from node p to q

D. Objective:

$$\text{Minimize } k\sum_{v\in V}\frac{M_v * CI_v}{PUE_v} \quad (2)$$

E. Constraints:

$$C_v/\text{m} + \sum_{m\in V} T_{mv} - \sum_{m\in V} T_{vm} < M_v(\ \forall v \in \text{V}) \quad (3)$$

$$M_v \geq 0 \ \ \forall v \in V \quad (4)$$

$$T_{pq} \geq 0 \ \ \forall p, q \in V \quad (5)$$

$$D_{pq} \leq \text{delay} \ \ \forall p, q \in T_{pq} \quad (6)$$

$$M_v * \text{k} < \text{P}_\text{v} \ \ \forall v \in V \quad (7)$$

Eqn. (3) dictates that the amount of computation capacity of the placed DC for each node must be more than the assigned workload. Eqn3. (4) and (5) enforce that the number of placed standard racks in a DC and the amount of inter-node offloaded computation demand must be positive. Eqn. (6) ensures that the computation demand must not be offloaded to a node, which exceeds the delay threshold, as shown in Fig.2. Eqn. (7) ensures that the power consumption of each DC must not exceed the power generation capacity, as shown in Fig.3.

IV. Evaluation and Numerical Results

We use the NSFNET network topology for simulation, and the PUE values of the nodes are shown in Table I. For the carbon intensity of nodes, we refer to the data on the electricity maps website [6], and for the delay between nodes, we refer to the data on the Wonder Network website [7].

TABLE I PUE and CI(carbon intensity) Value on NSFNET

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PUE	1.85	1.75	2.03	1.82	2.2	1.74	1.71	1.7	2.03	1.71	1.7	1.65	1.8	1.7
CI	24	301	301	674	455	206	321	578	361	395	390	280	361	361

A. The impact of computing demand

Fig.4 compares the carbon emissions generated by DC nodes. In general, the overall carbon emission increases as the offered computation workload increases. This is as expected because more computation demand means higher energy consumption. When latency constraints were set to 1 ms and 10 ms, network-wide carbon emissions increased linearly with computation demand, as computational tasks could only be served locally under low latency thresholds. However, when latency constraints were relaxed to 30 ms or higher, network carbon emissions are reduced.

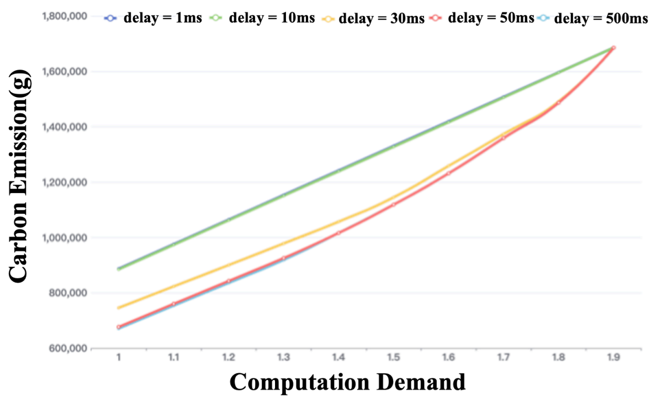

Fig. 4 Carbon emission vs. Computation demand

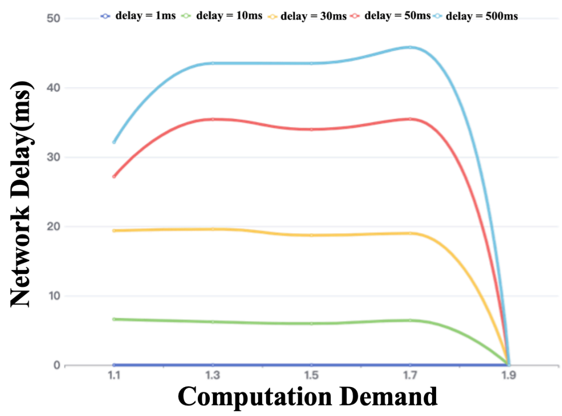

Fig. 5 Network delay vs. Computation demand

Fig.5 compares the service latency that is caused by cross-node offloading. When latency constraints were set to 1 ms, 10 ms, and 30 ms, network-induced latency remained stable below the specified latency limit. However, when latency constraints were expanded to 50 ms or higher, latency showed an increasing trend, as DCs with high carbon intensity transferred their computation tasks to low-carbon intensity DCs, thereby increasing network latency.

B. The impact of carbon intensity

In Fig.6 and Fig.7, we compared the carbon intensity of DC nodes, the carbon emissions generated by the network, and the network latency under different latency constraints as the carbon intensity increases. It's clear from our analysis that changes in carbon intensity have a direct, linear impact on carbon emissions. However, we found that network latency remains unchanged under different carbon intensities.

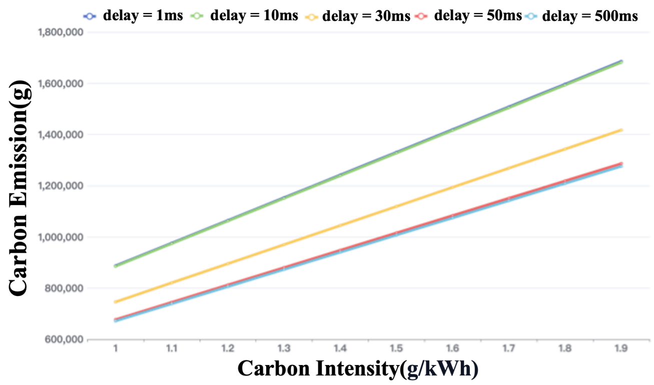

Fig. 6 Carbon emission vs. Carbon intensity

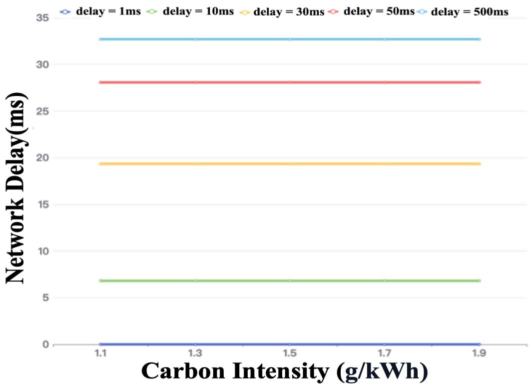

Fig. 7 Network delay vs. Carbon intensity

C. The impact of power generation capacity

Fig.8 compares the carbon emissions generated by DC nodes under different power generation capacities. When the latency constraint was set at 1 ms or 10 ms, there was no significant change in network carbon emissions as the DC node power consumption increased since all computation tasks were processed locally at the DC. However, when the latency constraint was increased to 30 ms or higher, we observed a significant reduction in carbon emissions.

Fig.9 compares the carbon emissions generated by DC nodes under different power generation capacities. When we set the latency constraints at 1 ms, 10 ms, and 30 ms, the network latency remained stable below the specified limit. However, when we increased the latency constraint to 50 ms or higher, we noticed a decreasing trend in network latency. This may seem counterintuitive because nodes with higher carbon intensity distribute computation demand to nodes with lower carbon intensity when their power consumption is only slightly higher than the computation demand. But as the power consumption of each node increases, nodes with higher carbon intensity only need to distribute their computation tasks to a few nodes with lower carbon intensity.

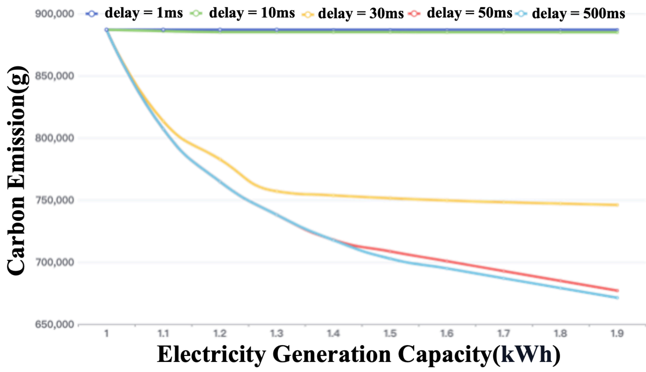

Fig. 8 Carbon emission vs. Electricity generation capacity

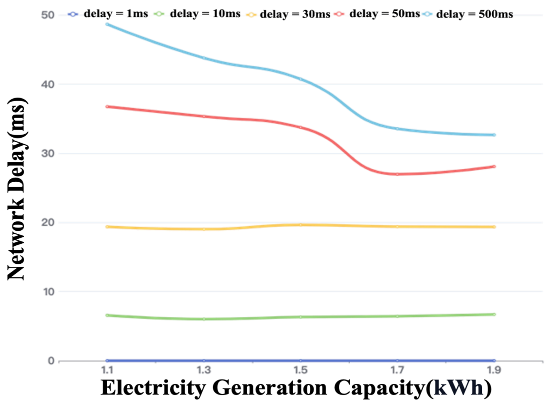

Fig. 9 Network delay vs. Electricity generation efficiency

V. CONCLUSION

In this paper, we develop an integer linear programming model for DC placement, with the aim to minimize the carbon emissions generated by DCs. We consider the latency constraints of network computation tasks and the power generation capacity of nodes in different regions to provide a solution with optimized carbon emissions. We investigate the effects of changes in computation demand, carbon intensity, and power generation capacity on network carbon emissions and the service latency. Results show that our approach can effectively reduce carbon emissions generated by DCs.

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