Carbon Footprints on Inter-Domain Paths: Uncovering CO_2 Tracks on Global Networks

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Abstract

In the years after signing the Paris agreement, corporations have been experiencing increasing pressure to monitor and reduce their carbon footprint. Nevertheless, the information and communication technology sector lacks an effective tool for monitoring and optimizing the carbon footprint of data transmissions over the public Internet.

In this work, we propose a carbon-footprint transparency system based on a path-aware Internet architecture that enables endpoints to monitor the carbon footprint of their inter-domain communications, and optimize it through carbon-aware path selection. Furthermore, we show by means of simulations that in a realistic inter-domain topology, 85% of traffic sources could reduce the carbon footprint of their outbound inter-domain traffic by at least 50% through carbon-aware path selection.

1 Introduction

In the face of growing concerns regarding climate change, companies are experiencing increasing pressure to measure and reduce their carbon footprint, i.e., the amount of CO_2 emissions they are responsible for. This pressure originates not only from governmental regulation, but also from investors who are reallocating their investments towards sustainable companies. For example, BlackRock, the world's largest asset manager [75], only invests in companies that have committed to a "net-zero" emission target by 2050, creating a strong incentive to reduce corporate carbon footprints.

This pressure applies also to the information and communication technology (ICT) sector, which has raised significant concerns regarding its aggravating impact on climate change—given its current 2.7% share of global CO_2 emissions [45] and the expected significant increase in its power consumption by 2030 [4, 6]. Hence, monitoring and reducing the CO_2 emissions from ICT use is increasingly relevant for enterprises.

Among various part of ICT, networks are responsible for around 13% of energy consumption [4], a third of which is attributable to backbone (core) networks[1] [32]. Consequently, backbone networks on average cause 4% of ICT CO_2 emissions. However, the carbon intensity of data transmission over different backbone paths at different times can vary significantly as a consequence of 1) path diversity in the densely connected Internet backbone, 2) the wide geographical expansion of backbone networks, and 3) the significant temporal and spatial variations in the carbon intensity of power grids [12, 40, 44, 67]. For example, the inter-domain topology in Fig. 1 offers path P2, which is fully powered by solar-generated electricity and thus has lower carbon intensity than paths P1, P3, and P4, which are at least partially powered by emission-intensive coal energy.

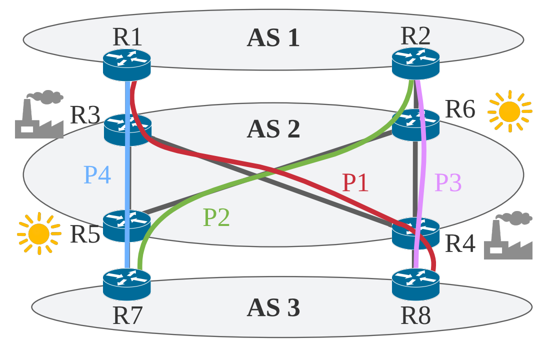


Figure 1: Inter-domain paths differ in the carbon emissions associated with data transmission, and carbon-aware path selection can leverage these differences to reduce the carbon-footprint of senders.

Such a variation in carbon intensity of backbone paths provides an opportunity to reduce the carbon footprint of traffic sources and the overall carbon emissions of backbone networks by sending traffic over paths with lower carbon intensities. However, to the best of our knowledge there is currently no effective means of leveraging this carbon intensity variations among multiple domains in the Internet backbone to reduce transmission-related CO_2 emissions. This is mainly

[1] We use the term backbone instead of core to make it distinguishable from core ASes in SCION terminology.

due to the limited knowledge about inter-domain paths (i.e., lack of path transparency), and limited control and flexibility on inter-domain paths (i.e., lack of control).

Zilberman et al. [79] have recently introduced carbon-aware networking (including backbone networks) as a high potential research area. They elaborate on main challenges and requirements of achieving carbon-aware networking and draw research directions for the future work. One of the important research directions they introduce is “carbon-intelligent routing", i.e., to leverage the difference between the carbon intensity of network paths to reduce carbon emissions.

One promising approach to achieve carbon-intelligent routing in backbone networks is to leverage the path-awareness provided by path-aware network architectures to make endpoints aware of the carbon emissions of backbone paths and let them select paths accordingly. As environmentally conscientious customers probably prefer greener network paths, such a system allows (greener) ISPs to attract traffic from conscientious customers by providing carbon-intensity information about inter-domain paths.

While an exciting prospect, such environmentally conscious path selection can only be implemented in practice if its technical prerequisites are established. Concretely, we identify three important research challenges that must be addressed to enable carbon-aware routing: (1) estimating carbon intensity of inter-domain paths, (2) scalably disseminating this information to all endpoints, and (3) enabling endpoints to select the greenest paths.

First, the carbon intensity of network paths must be characterized in a quantitative, accurate and reliable manner. This characterization is complex because the carbon intensity of a network path is highly variable and depends on the location of all devices on the path, their real-time traffic, and their electricity mix, which in turn depends on the daytime and the weather conditions. Hence, the estimation of path carbon intensity involves the elaborate methods of carbon-footprint assessment (as practiced by climate certification companies such as South Pole [63] or GHG Protocol [28]).

Second, the carbon-intensity information of paths must be disseminated across the Internet. Two challenges arise in designing such a dissemination scheme. On the one hand, the carbon intensity of a path is variable such that dissemination must be rapid enough to provide endpoints with up-to-date carbon-intensity information. On the other hand, such rapid dissemination must be scalable in terms of communication and computation cost for participating nodes.

Third, endpoints must be provided with the technical means for selecting paths based on CO_2 information, i.e., the control plane must provide endpoints with multiple paths along with their carbon-intensity information, and the data plane must guarantee to send traffic on the selected path. In large networks with massively interconnected nodes, disseminating all existing paths is impractical; hence, the carbon intensity of paths must be taken into account in path discovery. Moreover, endpoints require a calculus for trading off environmental path properties against conventional performance metrics of a path (such as latency or bandwidth), otherwise performance may be severely impacted to save a negligible amount of carbon emission.

In this paper, we undertake a first exploration of the design challenges associated with carbon-aware path selection. In particular, we devise (1) approaches for uncovering the carbon intensity of inter-domain paths by ISP measurements, (2) a system for communicating path carbon intensity to endpoints, and (3) an algorithm for optimizing carbon intensity of inter-domain paths.

To concretize our proposals, we apply them to the SCION next-generation architecture [10, 42, 49, 59, 77], which has experienced growing real-world deployment over the past few years. Importantly, however, the principles of carbon-aware path selection are compatible with any other path-aware Internet architecture that allows path-property advertisement and endpoint path selection.

To evaluate our carbon-transparency system, we also aim to quantify the extent to which carbon-aware path selection redistributes traffic on paths with low carbon intensity. However, such an evaluation is notoriously hard, exactly because the carbon intensity of paths in today’s Internet is not transparent. This intransparency complicates computing the exact carbon-footprint reduction that carbon-aware path selection can bring in today’s Internet. To investigate the effects of carbon-aware path selection, we therefore first extract a large and realistic inter-domain topology from publicly available data sets that plausibly reflects environmentally relevant characteristics of today’s Internet, and simulate carbon-aware path selection in this topology. In our simulation on such a realistic inter-domain topology, we show that our carbon-transparency system can reduce the carbon footprint of 90% of end-to-end communications compared to BGP path discovery, introducing at least a 50% reduction for half of the communications. Furthermore, by modeling the inter-domain traffic in such a topology, we show that by selecting the greenest paths, 85% of ASes can reduce the carbon footprint of their outbound inter-domain traffic by at least 50%.

These estimates, while only constituting a first step, highlight the promise of carbon-aware path selection to support the global effort against climate change.

2 Background

Path-aware Internet architectures provide a promising opportunity to achieve monitoring and regulating the carbon footprint from Internet communication. Furthermore, to allow a meaningful optimization across multiple criteria, including carbon intensity, providing a wide range inter-domain paths by the control plane is essential. To achieve such optimizations, such an architecture must assure that packets actually take the exact path as selected by the sender. As an example for such an architecture, SCION can help concretize the principles of carbon-aware inter-domain networking throughout this paper, although these principles could be applied to other architectures as well. As SCION is in production use in several ISPs [42], the concepts presented in this paper can be readily implemented. In this section, we provide an overview of the SCION Internet architecture, and describe how researchers analyze the energy consumption of the Internet.

2.1 SCION

Here, we present the SCION features that are directly relevant for the remainder of the paper; a comprehensive description of the architecture can be found in dedicated works [48].

2.1.1 Control plane

To provide isolation and scalability, autonomous systems (ASes) in SCION are grouped in *isolation domains* (ISDs). In each ISD, a set of well-connected *core ASes* administers the intra-ISD path discovery and provides the remaining non-core ASes with connectivity to other ISDs.

The SCION control plane constructs path segments through the *beaconing* process, which proceeds as follows. In each AS, the *beacon service* initiates *path-segment construction beacons* (PCBs), and/or extends and propagates received PCBs to other ASes. The beaconing process is conducted on two hierarchy levels: (1) *core beaconing* among all core ASes in all ISDs, and (2) *intra-ISD beaconing* within each ISD.

Each PCB contains multiple *AS entries* with information about each AS hop on the path as well as their signatures. Along other fields, each AS entry contains a *StaticInfoExtension* field [25] which can be used to convey information about the AS hop in an authenticated manner (in our context: carbon-intensity information). After receiving PCBs from other ASes, the beacon service at each AS extracts their path segments and registers them to the *path service*, so endpoints can fetch them and include them in packet headers.

To construct a complete path to a destination AS, endpoints ask the path service in their AS for necessary path segments. To resolve each query, the local path service may need to query remote path services at other ASes. The path service may provide endpoints with a variety of path segments, enabling endpoints to compose paths according to their optimality criteria.

2.1.2 Data plane

Each SCION packet contains its inter-domain forwarding path in its header, which consists of multiple path segments. Each segment contains forwarding instructions (e.g., ingress and egress interfaces of inter-domain links connecting neighboring ASes) that are executed by border routers during packet forwarding. Hence, traffic follows the path selected by the source host.

2.2 The Internet's energy consumption

As the CO_2 emission of the Internet is a result of its energy consumption, we provide an overview of the Internet model that is commonly used for analyzing the energy consumption of different parts of the Internet.

Internet model To analyze the energy consumption of the Internet, researchers divide it into access, metro/edge, and core networks [32, 33, 57].

The core network provides global inter-domain connectivity between all networks in the Internet. Therefore, estimating the energy consumption of inter-domain communications requires understanding the core network structure.

Core network The core network is an optical multi-layer network (also: IP-over-WDM network) consisting of two layers: (1) the Internet Protocol / Multiprotocol Label Switching (IP/MPLS) layer, and (2) the optical or the wavelength-division multiplexed (WDM) layer [2, 31].

In the IP/MPLS layer, core routers, such as the Cisco CRS [18] series or Juniper PTX-series [38], perform layer-3 routing and forwarding. Every core router has three main building blocks [31]: (1) the basic node, containing chassis, switching fabrics, routing engine, internal cooling equipment, and power supply, (2) line cards, containing the forwarding engine, and (3) port cards, providing physical connection to the optical layer, and an interface between the Ethernet layer (layer 2) and the IP/MPLS layer (layer 3).

The WDM layer (also: optical layer) provides a broadband physical connection between core routers. This layer consists of numerous types of optical devices such as transceivers, transponders, muxponders, WDM terminal systems, optical switches (OADMs, OXCs), optical line amplifiers (OLAs), and regenerators [31].

Estimating energy consumption of the Internet

Numerous studies estimate the energy consumption of the Internet (or parts of it), where the methodologies can be categorized in bottom-up, top-down, or model-based approaches.

Bottom-up approaches Bottom-up approaches generalize the energy-intensity values obtained through direct measurement of selected network devices. The study conducted by Coroama et al. falls into this category [21].

Top-down approaches In top-down approaches, researchers divide the total energy consumption of a network by the amount of traffic transited by the network over a particular time period. Studies conducted by Koomey et al. [41], Taylor et al. [66], Weber et al. [74], Lanzisera et al. [43], and Andrae et al. [5] are examples of top-down approaches.

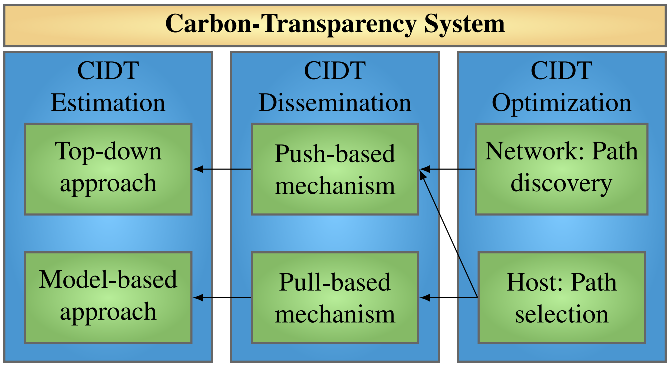


Figure 2: Overview of carbon-transparency system. An arrow from component A to component B indicates that component A relies on data generated/transferred by component B.

Model-based approaches Model-based approaches rely on modelling parts of the Internet based on network-design principles, and on energy-consumption information of device vendors in order to find the total energy consumption of specific Internet parts. Baliga et al. [8, 9], Vishwanath et al. [72], and Hinton et al. [32] propose model-based approaches to estimate the energy consumption of the Internet.

3 Carbon-Aware Inter-Domain Communication

To realize carbon-aware inter-domain communication, we design a system capable of measuring long-term and instantaneous carbon intensity of inter-domain paths, disseminating this information in a scalable fashion, and optimizing path carbon intensity via a carbon-aware routing algorithm. The overview of our system is depicted in Fig. 2. We discuss the three pillars of our carbon-transparency system in Section 3.1 (estimation of path carbon intensity), Section 3.2 (dissemination of carbon-intensity information), and Section 3.3 (finding paths with low carbon intensity).

Regarding the dissemination of path-specific carbon-intensity information, our system ensures scalability and accuracy by combining a push-based mechanism (cf. Section 3.2.1) with a pull-based mechanism (cf. Section 3.2.2). The push-based mechanism proactively advertises the long-term carbon intensity of dozens of inter-domain paths, calculated by a top-down approach (cf. Section 3.1.1), helping network nodes to discover greener paths and endpoints to select greener paths. As the long-term carbon-intensity information is not highly variable, there is no need to advertise it frequently, ensuring the scalability of the push-based mechanism. The pull-based mechanism, on the other hand, follows a probing approach and provides accurate instantaneous information about the carbon intensity of a single path, calculated by a model-based approach (cf. Section 3.1.2), enabling accurate carbon-footprint accounting of inter-domain communications at endpoints. This mechanism ensures scalability by providing information about a single path (or a few paths at the path selection stage, cf. Section 3.3).

The *novelty* of the top-down and model-based approaches we propose in this paper in comparison to already existing approaches (e.g., the ones mentioned in Section 2) is three fold: 1) our approaches estimate the CO_2 emission while other approaches estimate electricity consumption, 2) our approaches estimate CO_2 on a *per path* basis, while others try to estimate the electricity consumption of the whole network, and 3) we try to estimate the intensity of CO_2 per amount of traffic, while others try to estimate the whole electricity consumption.

As SCION provides endpoints with a wide range of fine-grained inter-domain paths (i.e., at the level of inter-domain interfaces of the outgoing and incoming border routers of two neighboring ASes), and ensures that packets are forwarded on the paths selected by the sender, it provides a concrete foundation for carbon-aware inter-domain communications on which we establish our system.

3.1 Estimating path carbon intensity

Every inter-domain path in the core network is a sequence of network devices (i.e., core routers and optical devices), each consuming energy to process and forward data to the next device on the path and resulting in some amount of CO_2 emission depending on the carbon intensity of the used electricity mix. Therefore, we introduce the concept of path-specific *carbon intensity of data transmission (CIDT)*, corresponding to the sum of CIDTs of all constituent devices. Importantly, computing CIDT does not require that paths are specified at the level of devices, which would require revealing intra-domain topologies and would therefore be considered undesirable. Instead, CIDT can also be computed as a sum of the aggregate carbon intensity of all *intra-domain* paths in a full path, i.e., the intra-domain path starting from the ingress interface of an AS and ending at the egress interface of the same AS. To be precise, the full-path CIDT should also include the CIDT of inter-AS links; however, since these links are usually short, we assume their CIDT to be negligible. Therefore,

$$CIDT_{path} = \sum_{AS \in AS\ path} CIDT_{AS,[ing,eg]} \tag{1}$$

where $[ing, eg]$ denotes an intra-domain path between the inter-domain interfaces of an on-path AS. The source endpoint figures as ingress interface to the source AS, and the destination endpoint as egress interface of the destination AS.

While the path-specific CIDT can be straightforwardly derived from CIDTs of intra-AS paths, these intra-AS CIDT values are challenging to calculate. In particular, an intra-AS path contains a specific composition of devices, each of which may be powered with a different energy mix, may have a different energy efficiency, and may have a different relationship between load and energy consumption (e.g., due to idle power consumption). In the following sections, we propose two complementary approaches that enable ASes to estimate the CIDT of intra-domain paths, namely a model-based approach and a top-down approach. The complementary approaches serve two different purposes in enabling carbon-aware path selection: The top-down approach yields an estimate of long-term carbon intensity, where this estimate is propagated through a push-based mechanism within path-segment construction beacons (PCBs) in SCION, enabling endpoints to select the greenest paths; the model-based approach yields an accurate estimate of instantaneous carbon intensity, where this estimate is retrieved by endpoints on request through a pull-based approach, enabling accurate carbon-footprint accounting at endpoints (cf. Section 3.2).

3.1.1 Top-down approach

In this approach, an AS computes the *average* CIDT of its intra-domain paths using the whole CO_2 emission $CE_{AS,t}$ of the AS during a time interval t.

$CE_{AS,t}$ is equal to the sum of CO_2 emissions the AS is responsible for at all its points of presence ($CE_{PoP,t}$). The CO_2 emission at each PoP is the production of the AS's energy consumption at that PoP during the time interval ($E_{PoP,t}$), which can be inferred from electricity bills, and the carbon intensity of the electricity mix at the PoP (CI_{PoP}), which can be inferred from electricity contracts. Therefore,

$$CE_{AS,t} = \sum_{PoP \in AS\ PoPs} CI_{PoP} E_{PoP,t}. \tag{2}$$

Using $CE_{AS,t}$, we define the epxected CIDT *per kilometer distance* of the AS during a time interval t ($CIDT^{\text{km}}_{AS,t}$) as

$$CIDT^{\text{km}}_{AS,t} := \frac{CE_{AS,t}}{\sum_{i,j \in interfaces} v_{[i,j],t} \cdot d_{[i,j]}}, \tag{3}$$

where $v_{[i,j],t}$ is the traffic volume transited between the interface pair $[i,j]$ during t, and $d_{[i,j]}$ is the great circle distance between the same interface pair. Similarly, we define the CIDT of the AS during t as

$$CIDT_{AS,t} := \frac{CE_{AS,t}}{\sum_{i,j \in interfaces} v_{[i,j],t}}. \tag{4}$$

We therefore approximate the CIDT of a path between an interface pair during t ($CIDT_{[ing,eg],t}$) as a function of $CIDT^{\text{km}}_{AS,t}$, $CIDT_{AS,t}$, and $d_{[ing,eg]}$ since the farther the two interfaces are, the more devices are on the path between them, thus the larger the CIDT of the path is. However, this relation is not necessarily linear, especially for short distances [21], where the actual CIDT of the path is considerably larger than the value approximated by the distance. Hence,

$$CIDT_{[ing,eg],t} := \begin{cases} CIDT^{\text{km}}_{AS,t} \cdot d_{[ing,eg]}, & \text{if } CIDT^{\text{km}}_{AS,t} \cdot d_{[ing,eg]} > CIDT_{AS,t} \\ CIDT_{AS,t} & \text{otherwise,} \end{cases} \tag{5}$$

meaning that we assume the carbon intensity of any path within an AS to be at least equal to the CIDT of the whole AS, providing a CIDT approximation for short-distance paths. However, using Eq. (5) may result in the sum of CO_2 emissions of all paths being greater than the CO_2 emission of the whole AS ($CE_{AS,t}$), which we address by normalizing the calculated CIDTs for every path to $CE_{AS,t}$:

$$CIDT^{normalized}_{[ing,eg],t} := \frac{CE_{AS,t} \cdot CIDT_{[ing,eg],t}}{\sum_{i,j \in interfaces} v_{[i,j],t} \cdot CIDT_{[i,j],t}}. \tag{6}$$

Since intra-domain traffic also contributes to the CO_2 emission of an AS, we generalize Eqs. (3), (4), (5) and (6) to all networks within an AS. In that case, $v_{[i,j],t}$ is the traffic volume transited between a pair of networks within an AS during t, and $d_{[i,j]}$ is the great circle distance between them.

3.1.2 Model-based approach

In this approach, an AS estimates the CIDT of intra-domain paths within its AS as the sum of CIDTs of all devices on each path:

$$CIDT_{AS,[ing,eg]} = \sum_{D \in \mathcal{D}_{ing,eg}} CIDT_D = \sum_{D \in \mathcal{D}_{ing,eg}} CI_D \overline{E}_{D,\text{bit}}, \tag{7}$$

where $\mathcal{D}_{ing,eg}$ is the set of devices between ingress *ing* and egress *eg*, D denotes a network device on the path, which can be a core router (R), or an optical device (OD), CI_D denotes the carbon intensity of the device's electricity mix, and $\overline{E}_{D,\text{bit}}$ denotes the *expected* amount of consumed energy each bit is responsible for when it is processed by device D.

$\overline{E}_{D,\text{bit}}$ depends on three main factors [31]: (1) the energy consumption of the device (E_D), (2) the redundancy provisioning factor of the device ($\eta_{D,\text{rd}}$), which determines the number of redundant devices per on-path device, and (3) the power-usage effectiveness (PUE) [11], which is the ratio of total consumed energy to the useful consumed energy. The non-useful consumed energy is usually consumed by the external cooling and facilities [31], so we denote it by $\eta_{D,\text{c}}$.

The energy consumption of a network device (E_D) consists of: (1) the idle energy consumption ($E_{D,\text{idle}}$), (2) the dynamic per-bit energy consumption ($E_{D,\text{bit}}$), and (3) in case of a router, the dynamic per-packet energy consumption of the forwarding engine ($E^{\text{fwd}}_{R,\text{pkt}}$) consumed by line cards to perform forwarding actions on each packet [72]. Therefore,

$$E_D = E_{D,\text{idle}} + E_{D,\text{bit}} + R(D) \cdot E^{\text{fwd}}_{R,\text{pkt}}, \tag{8}$$

$$\text{where } R(D) := \begin{cases} 1, & \text{if } D \text{ is a router} \\ 0 & \text{otherwise (optical device).} \end{cases} \tag{9}$$

Given average packet size $\overline{S}_{D,\text{pkt}}$ and device-carried traffic load l_D (in bps), $\overline{E}_{D,\text{bit}}$ in one second as a function of $\overline{S}_{D,\text{pkt}}$ is:

$$\begin{aligned} \overline{E}_{D,\text{bit}}(\overline{S}_{D,\text{pkt}}) &:= \eta_{D,\text{c}} \left(\frac{\eta_{D,\text{rd}} E_{D,\text{idle}}}{l_D \times 1\,\text{s}} + E_{D,\text{bit}} + R(D) \frac{E^{\text{fwd}}_{R,\text{pkt}}}{\overline{S}_{D,\text{pkt}}} \right) \\ &= \eta_{D,\text{c}} \left(\frac{\eta_{D,\text{rd}} P_{D,\text{idle}}}{l_D} + E_{D,\text{bit}} + R(D) \frac{E^{\text{fwd}}_{R,\text{pkt}}}{\overline{S}_{D,\text{pkt}}} \right), \end{aligned} \tag{10}$$

where $P_{D,\text{idle}}$ is the device's idle power consumption. Note that a data bit is only responsible for the idle power consumption on redundant devices, and hence $\eta_{D,\text{rd}}$ is only multiplied by the $P_{D,\text{idle}}$ in Eq. (10).

By substituting Eq. (10) in Eq. (7), ASes can calculate the CIDT of the intra-domain paths between their inter-domain interfaces. Note that this approach assumes that an AS have information about the idle, per-bit, and per-packet power consumption of all its devices, as well as their locations and their electricity mix.

3.2 Disseminating carbon-intensity data

We design a carbon-intensity information dissemination system consisting of two mechanisms: (1) a push-based mechanism relying on path-segment construction beacons (PCBs) during the beaconing process, enabling carbon-aware path selection at endpoints, and (2) a pull-based mechanism using requests to path services of on-path ASes, enabling accurate carbon-footprint accounting for inter-domain communications at endpoints. Both mechanisms are jointly used in path selection in a hierarchical process described in the next section (cf. Section 3.3).

3.2.1 Push-based mechanism

To advertise long-term average CIDT values, an AS beacon service includes a `greenness_metadata` value in the `StaticInfoExtension` [25] of AS entry appended to the PCB whenever it disseminates a PCB to a neighboring AS over an egress interface. This metadata maps interface identifiers to the *average* CIDT values of paths between specified interfaces and the egress interface. These values are pre-computed using the top-down approach presented in Section 3.1.1 over a long time interval in the past (e.g., days to weeks). Note that since the model-based approach (cf. Section 3.1.2) gives a real-time estimate for paths' CIDT, its estimated values are not suitable for the relatively low-frequency dissemination by PCBs (i.e., with long periods in the order of minutes to hours).

In intra-ISD beaconing, the set of interfaces specified by `greenness_metadata` contains the ingress interface of the PCB and all interfaces connected to peering, customer, and core links of the AS, which are useful for estimating the CIDT of path-segment combinations and peering shortcuts. In core beaconing, however, the set of specified interfaces only contains the ingress interface of the PCB, if available.

3.2.2 Pull-based mechanism

To perform carbon-footprint accounting of their inter-domain communications, endpoints probe the *instantaneous* CIDT of paths they actively send traffic on. Since the carbon intensity of a path may vary quickly, such probing need to be repeated over time to provide acceptable accuracy. The frequency of such probing depends on the stability of previous measurements, i.e., the more stable the previous measurements are, the lower the measurement frequency is.

To probe the instantaneous CIDT of an inter-domain path, an endpoint sends a `get_instant_CIDT` request to the path service of the hosting AS, containing the inter-domain path and a `CIDT` field initially set to zero.

Upon receiving a `get_instant_CIDT` request, the path service of every on-path AS adds the instantaneous CIDT of the segment within its AS to the request's `CIDT` field, and forwards it to the path service of the next AS on the path. When the path service of the destination AS receives the request, it responds to the source endpoint with a message containing the CIDT of the end-to-end path. This instantaneous CIDT information is also cacheable for short periods.

To monitor the real-time CIDT of on-path intra-domain segments within their ASes, path services use the model-based approach provided in Section 3.1.2.

3.3 Discovery and selection of green paths

With push- and pull-based mechanisms in place, endpoints can select the greenest inter-domain paths, thus reducing the carbon footprint of their inter-domain communications.

3.3.1 Green path selection at endpoints

Each endpoint selects the greenest path to a destination AS *hierarchically* in two steps: (1) it reduces the search space by selecting a small subset of all available paths with the lowest *average* CIDTs disseminated by the push-based mechanism via the `StaticInfoExtension` PCB field, then (2) it requests the *instantaneous* CIDT of the paths selected in the first step using the pull-based mechanism, and selects the one with the lowest instantaneous CIDT. An endpoint can also change the selected path during communication when observing a significant increase in the CIDT of the path.

3.3.2 Constructing green path segments

Selecting the set of greenest paths based on the average CIDT encoded in PCBs requires path services to return the greenest path segments to endpoints. Thus, algorithms for path-segment construction and registration at beacon services need to select paths according to their greenness; otherwise, finding the greenest path segments requires construing and registering all path segments, which overwhelms beacons servers in large and massively interconnected networks.

To construct the greenest path segments towards every origin AS, we propose a *green beaconing algorithm*, which is run by beacon services when disseminating PCBs to neighboring ASes. This algorithm stores the greenest received PCBs *per origin AS and ingress interface*, and constructs and disseminates the greenest PCB(s) *per origin AS and egress interface* by combining all stored PCBs *per origin AS* with all *egress interfaces*, and examining their CIDT. To compute the CIDT of the whole path from an origin AS to an egress interface, the algorithm adds the CIDT of the received PCB to the CIDT of the intra-domain path between the ingress interface of the PCB and the prospective egress interface using the top-down approach proposed in Section 3.1.1. We propose *per-interface* storage and construction of the greenest paths to provide endpoints with the greenest combination of inter-domain paths and the intra-domain access paths, which is beneficial in large ASes.

4 Evaluation

In this section, we evaluate the impact of the carbon-aware inter-domain communication on the carbon footprint of endpoints and investigate its prospective effects on the communication latency.

4.1 Evaluation methodology

To estimate the amount of carbon-footprint reduction enabled by carbon-aware path selection, we need to compute the difference between the CIDT of the greenest possible paths and the BGP-selected paths between every pair of ASes in a large-scale realistic inter-domain topology. Since the CIDT of paths in the current Internet is intransparent, we create a topology with estimates of path CIDT values by drawing from multiple datasets (see below). Then, we multiply the differences in path CIDT by the amount of traffic between every pair of ASes, where this traffic matrix is estimated using a realistic inter-domain traffic model.

4.1.1 Data sets

We rely on the following data sets:

- AS-Rel-Geo: *CAIDA AS relationship with geographic annotations data set* [14], containing 12,300 ASes, their relationships, and the geolocation of their interconnections (i.e., inter-domain interfaces).
- AS-Rel: *CAIDA AS relationships and customer cones data set* [13], containing the relationships of 73,300 ASes with their neighboring ASes, and their customer cones.
- ITDK: *CAIDA Internet Topology Data Kit data set* [15], containing the locations of 46 million routers as well as their degree and the ASes they belong to.
- Pfx2AS: *Routeviews prefix to AS mappings data set* [16], mapping every prefix in the global BGP routing table to its origin AS.
- IEA: IEA data set including the mix of electricity-production technologies used by each country [35]
- IPCC: IPCC data set including the average carbon intensity (gCO_2/kWh) of various electricity-production technologies [23]
- Tranco1M: The list of the 1 million most popular websites by Pochat et al. [50, 51]

4.1.2 Finding the greenest paths

Although SCION is currently deployed in multiple ASes and ISPs [42], the current deployment provides limited carbon-intensity diversity as most participant ASes reside in regions with similar electricity mixes, limiting the benefits of the carbon-aware path selection.

Therefore, we simulate the green-beaconing algorithm proposed in Section 3.3 using the ns-3-based [1] SCION beaconing simulator [42, 65] to construct the greenest inter-domain paths between every pair of ASes in a large-scale realistic topology extracted from the AS-Rel-Geo data set.

4.1.3 Topology

We assume a global SCION deployment with 200 ISDs and 10 core ASes per ISD [42], resulting in 2000 core ASes, which we assume to be the most-interconnected Tier-1 and Tier-2 ASes in today's Internet. We extract the topology of core ASes from the AS-Rel-Geo data set by iteratively removing the lowest-degree ASes from it. Since we limit our analysis to these 2000 core ASes, only the inter-ISD beaconing (core beaconing) has to be simulated, which helps make the simulation tractable. Moreover, since core beaconing is independent of the ISDs in which the core ASes reside, a focus on the core ASes allows to avoid splitting the set of ASes into ISDs, which would necessarily be arbitrary.

With this focused analysis, we obtain a lower bound on the possible emission savings. Still, our analysis likely captures most of the potential savings from carbon-aware path selection because core ASes are the main source of carbon-intensity diversity in the network given their massively interconnected network, and their spread across various regions.

4.1.4 Finding BGP paths

As not all ASes publish their routing tables, we simulate BGP using the SimBGP simulator [69] to find the BGP-selected paths between all AS pairs in the topology, and to produce emission results that can be compared to the simulation results for carbon-aware path selection. We assume that every border router of an AS is connected to a single route reflector in its own AS via iBGP, and to a single border router of the neighboring AS via eBGP. We also assume that all BGP speakers in an AS select the same AS-path to *all* prefixes of an origin AS. Therefore, announcing one prefix per origin AS suffices.

4.1.5 Estimating CIDT of intra-domain paths between interfaces

Although the real implementation of the PCB-based mechanism (cf. Section 3.2.1) would estimate the CIDT of intra-domain paths using the top-down approach (cf. Section 3.1.1 and Eq. (7)), we use the model-based approach (cf. Section 3.1.2) in simulations as it provides a more accurate estimation of how much CO_2 emission could be reduced by carbon-aware path selection.

However, the model-based approach requires the idle, per-bit, and per-packet energy consumption of all devices as well as their real-time traffic load (cf. Eq. (10)), which we do not have access to. Thus, we re-write Eq. (10) using a device's energy intensity ($I_{E,\text{bit}}$) defined as its maximum power consumption ($P_{D,\max}$) divided by its capacity ($C_{D,\text{bit}}$) in bps:

$$\overline{E}_{D,\text{bit}} = \eta_{D,\text{c}} \cdot \eta_{D,\text{rd}} \cdot \frac{P_{D,\max}}{C_{D,\text{bit}}} = \eta_{D,\text{c}} \cdot \eta_{D,\text{rd}} \cdot I_{E,\text{bit}}. \tag{11}$$

Table 1 shows the energy-efficiency values for typical IP-over-WDM devices [31] we use in our evaluation.

Furthermore, since finding the exact location and electricity mix of all devices on paths between interfaces is infeasible (especially regenerators and amplifiers), we assume that the carbon intensity of each device's electricity mix (CI_D) is equal to the average carbon intensity of its AS's electricity mix ($\overline{CI}_{AS}$). We compute $\overline{CI}_{AS}$ as the weighted average of electricity sectors' carbon intensities in all countries its routers are located in according to the ITDK data set, where each country's weight is the cumulative degree of all routers belonging to that AS and located in that country. For each country, we compute the carbon intensity of its electricity sector using its electricity resources mix available at the International Energy Agency (IEA) [34] web page, and the carbon intensity of each energy resource in Table 2.

Table 1: Energy intensities of typical devices in IP and WDM layers [31].

Device type	Energy intensity (I_E in W/Gbps = J/Gbit)
Core router	10
WDM switch (OXC)	0.05
Trans/Mux -ponder	1.5
Amplifier	0.03
Regenerator	3

Table 2: 50^{th} percentile CO_2 emission of different energy resources. From Edenhofer's report at the International Panel on Climate Change (IPCC) [23].

Energy resource	Carbon intensity (gCO_2/kWh)
Coal	1001
Natural gas	469
Biomass	230
Solar	46
Geothermal	45
Nuclear	16
Wind	12
Hydroelectric	4

4.1.6 Finding intra-domain paths between interfaces.

For each AS in the topology extracted from the AS-Rel-Geo data set, we compute its device-level intra-domain paths between all its inter-domain interfaces. First, we select the representative router of every interface in each AS by looking up the ITDK data set for the AS's closest router to the interface that connects to the same neighboring AS as the interface connects to. If not available, we add a router at the interface's location. Then, we compute the shortest router-level path between every pair of border routers in each AS by running the Dijkstra algorithm [22] on the intra-domain topology of the AS in the ITDK data set. If we cannot find such a path, we assume that the number of routers is an increasing integer-valued step function of the distance between interfaces with the range of $\{1,2,3,4,5\}$ and steps at 1 km, 20 km, 100 km, and 1000 km distance.

Once the router-level intra-domain paths between any pair of interfaces are established, we add optical devices between consecutive routers. As each packet crosses every WDM switch, transponder, and muxponder once before entering a router and once after leaving it, we assume two of these devices per router on the path [31]. The number of amplifiers and regenerators, however, depends on the distance between consecutive routers. We assume one amplifier at each 80 km interval, and one regenerator at each 1500 km interval [31].

4.1.7 Traffic matrix synthesis

We need a global inter-domain traffic matrix to compute the global CO_2 emission reduction that carbon-aware path selection enables. In this work, we only consider HTTP(S) data and media streaming, and popular video streaming services as they contribute to 60% of Internet's traffic [55], and can be modelled plausibly.

We compute the global inter-domain traffic matrix for all ASes in the AS-Rel data set (almost all ASes in the Internet) using the model provided by Mikians et al. [46]. In this model, the amount of traffic from AS_i to AS_j is the sum of traffic sent from all users and servers in AS_i to all servers and users in AS_j for all application types:

$$T_{i,j} = \sum_{A \in applications} m_A \left(S_i p_i^A(j) + d_A S_j p_j^A(i) \right), \tag{12}$$

where $p_i^A(j)$ is the relative popularity of servers in AS_j for users in AS_i with respect to application A, S_i represents the size of an AS in the number of its IP addresses, d_A denotes the asymmetry factor for application A, which is the ratio of the response flow size to the request flow size for application A, and m_A scales the computed relative traffic for application A to its absolute real traffic volume.

Since $\log_{10} d_{http}$ falls into the range of $(0.4, 1.5)$ for HTTP(S) data and media [46], we assume $\log_{10} d_{http} = 1$. Furthermore, we assume the size of each AS to be its number of IPv4 addresses from the Pfx2AS data set, except Tier-1 ASes with no users and large CDNs with no users requesting a service. Moreover, $p_i^{http}(j)$ follows the Zipf distribution [80] with a slope of 1.2 [46]. For each source AS, we thus generate a vector of relative popularities from the Zipf distribution. Then, we assign the largest popularity values to the most popular destination ASes, and the remaining popularity values randomly to other ASes. We define the most popular ASes as the ASes whose hosted websites have the largest accumulated inverse ranks in the Tranco1M data set. We find the website to AS mappings using DNS queries, and the Pfx2AS data set. Once the matrix is computed, we scale it to the global HTTP(S) traffic, which is estimated to be 82 Exabytes per month [55, 64].

In addition to HTTP(s) traffic, we also include video traffic in the traffic matrix. For this video traffic, we consider Netflix, YouTube, and Amazon Prime Video, which are responsible for 15, 11.4, and 3.7 percent of total Internet traffic, respectively [55]. We construct the video traffic matrix by assuming that the amount of traffic any other AS receives from these services is proportional to its number of users in Pfx2AS data set, and these services receive negligible traffic from other ASes. Finally, we add the video traffic matrix to the HTTP(S) traffic matrix.

To construct the traffic matrix for the core topology of 2000 ASes used in our simulation, we assume that the amount of traffic between two core ASes is the sum of all traffic in the global traffic matrix between their customer cone ASes in the AS-Rel data set. If an AS is in the customer cones of multiple core ASes, its inbound and outbound traffic is evenly divided between its core AS providers.

Table 3: The amount of carbon-footprint reduction for the outbound inter-domain traffic (HTTP(S) and video streaming) of the most popular source core ASes.

Source AS (ASN)	Carbon footprint reduction (t/yr)	Relative carbon footprint reduction (%)	Core traffic (EB/yr)
Netflix (2906)	47,640	68	423
YouTube (36040)	43,032	55	326
Amazon (16509)	30,240	65	230
Cloudflare (13335)	28,728	79	147
Google (15169)	7536	69	57
Fastly (54113)	5520	57	55
Microsoft (8075)	4284	74	29
Incapsula (19551)	3876	76	22
All core ASes	210,564	66	2004

4.2 Results

Figure 3 shows CDFs of CIDT between all AS pairs using different types of paths: (1) the greenest path selected by the carbon-aware path selection, (2) the greenest BGP path among the ones selected by all source AS's border routers that are connected to the next AS on the selected BGP AS-path, (3) the average of all BGP paths selected by by all source AS's border routers that are connected to the next AS on the selected BGP AS-path, and (4) the average of the k-greenest paths selected by the carbon-aware path selection, where k is the number of BGP paths we consider between the same source and destination AS pair. According to this figure, the portion of AS pairs with a CIDT of more than 0.05 g/Gbit is negligible using the carbon-aware path selection while it is 20% using BGP. It also suggests that the carbon-aware path selection is capable of finding *multiple* paths with significantly lower CIDTs than the BGP paths. Figure 5c, depicting the CDF of CIDT difference between the greenest path and the greenest BGP path for all AS pairs, suggests that 90% of AS pairs would benefit from CIDT reduction through the carbon-aware path selection, which is at least 0.015 g/Gbit for half of them. Figure 5b, illustrating the CDF of the relative CIDT of the greenest path to the greenest BGP path for all AS pairs, demonstrates at least 50% CIDT reduction for half of AS pairs by the carbon-aware path selection.

Figure 5a illustrates the cumulative distribution of 2000 core ASes as the function of their annual relative carbon-footprint reduction for their outbound inter-domain traffic enabled by carbon-aware path selection. According to this

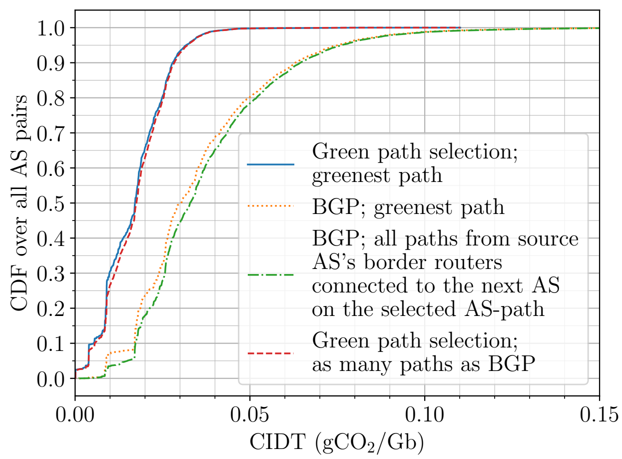


Figure 3: CDFs of CIDT for every AS pair, both for paths from green path selection and BGP.

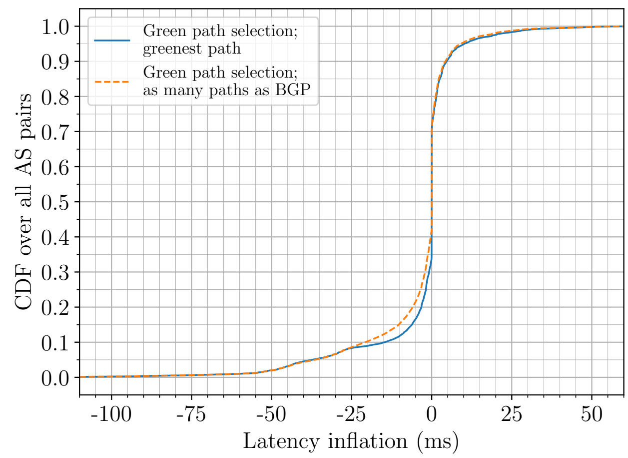


Figure 4: The cumulative distribution of core AS pairs as the function of latency inflation caused by selecting greener paths instead of BGP paths.

figure, more than 85% of core ASes could reduce the carbon footprint of their outbound inter-domain traffic by at least 50%. Note that this is not the actual CO_2 emission reduction resulting from carbon-aware path selection but is the amount of reduction in the CO_2 emission that the sender of the traffic is responsible for.

Table 3 demonstrates the annual carbon-footprint reduction for inter-domain traffic that the core ASes in the topology could benefit from through carbon-aware path selection, i.e., 66% equivalent of 210 kt CO_2 annually. Although the most popular ASes, i.e., the largest CDNs, would benefit from the most absolute carbon-footprint reductions, according to Figure 5a 85% of ASes could benefit from more than 50% reduction for their inter-domain traffic.

4.3 Discussion: impacts on the network

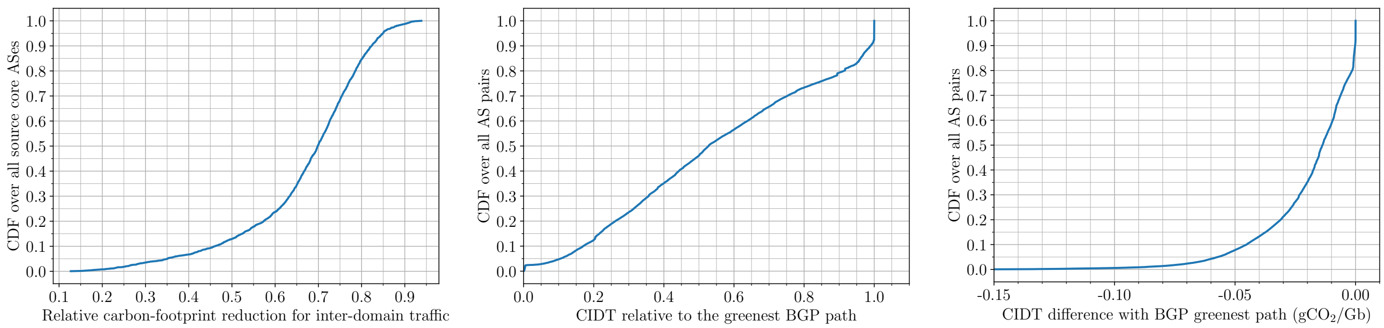
In this section, we discuss the prospective impacts of carbon-aware path selection on the network and communications quality.

Latency Figure 4 illustrates the CDFs of the inflated propagation delay with respect to BGP for (1) the greenest possible path, and (2) the k greenest paths between all AS pairs, where k is the number of source AS border routers that are connected to the first AS on the BGP-selected AS-path. We compute the propagation delay of an inter-domain path as the sum of the propagation delays of all AS hops, which in turn are approximated using the great circle latency between on-path border routers available in the CAIDA dataset. This is a lower bound for the actual latency, which on average underestimates by a factor of $\sim$1.5 [61].

According to Figure 4, carbon-aware path selection would *reduce* the propagation delay between almost 40% of AS pairs, where this reduction is more than 25 ms for 10% of the AS pairs. Furthermore, carbon-aware path selection introduces a propagation-delay inflation to only 25% of AS pairs. However, for only 10% of AS pairs, this inflation is more than 5 ms, and for only less than 1% of AS pairs, it is more than 50 ms. Moreover, this figure demonstrates that selecting multiple low-emission paths has almost the same impact on propagation delay as selecting the least carbon-intense path, providing endpoints with multiple low-emission and low-latency paths.

Therefore, optimizing inter-domain paths based on their carbon intensities does not introduce propagation-delay degradation but improves it in many cases. An explanation for this observation is that BGP selects paths based on commercial policies and AS-path length and not based on latency. On the other hand, since shorter paths contain fewer network devices, they consume less energy and emit less CO_2.

Congestion By enabling endpoints to optimize their communication paths based on carbon intensity, it is expected that numerous endpoints would select green paths towards any destination, raising concern regarding congestion on inter-domain paths. However, due to the vast diversity of existing paths in the Internet, there are numerous low-emission paths between any pair of ASes with almost the same carbon intensity as the greenest possible paths. Figure 3 confirms that finding multiple green paths between all AS pairs with carbon intensities as low as the greenest existing path is possible, especially when the routing infrastructure performs carbon-aware path optimization and provides endpoints with the set of greenest paths to any destination. Thus, endpoints have multiple choices to reduce the carbon footprint of their inter-domain communication, lowering the probability of congestion on the greenest possible path.



(a) The cumulative distribution of 2000 core ASes as the function of their annual relative carbon-footprint reduction for their outbound inter-domain traffic enabled by carbon-aware path selection.

(b) CDF of relative CIDT of the greenest possible path for an AS pair relative to the greenest BGP path.

(c) CDF of CIDT difference for every AS pair between the greenest possible path and the greenest BGP path.

Figure 5: Greenness comparison between carbon-aware path selection, and BGP.

Traffic oscillation Oscillation arises in load-adaptive path selection, where delayed information about path load entices end-points to switch paths, but then this shift causes high load on the newly selected path and a subsequent abandonment of that path [24, 56]. Therefore, such oscillation requires that the path attribute used as a selection criterion is changing in response to the selection of the path. In contrast to path load, path carbon intensity is generally no such responsive criterion and therefore is not likely to cause oscillation. However, we note that path selection based on carbon intensity may be combined with load-adaptive path selection to avoid congestion on green paths. The load-adaptive part of this multi-criteria strategy then needs to follow the guidelines for oscillation-free path selection developed in previous research [24, 39]. In any case, the risk of congestion on green paths should continually decrease as competitive pressure erodes the greenness differences between paths.

5 Related Work

Much work has studied how to reduce the carbon footprint of the ICT sector by either improving the energy efficiency of end devices and networks [3, 26, 36, 37, 47, 58, 60, 62, 73, 76], or increasing the utilization of available renewable energy resources [27, 53, 54, 68]. However, almost all these studies focus on either data centers, or intra-domain communications, and just Shi et al. [60] and Nafarieh et al. [47] take inter-domain communications into account, as we discuss below in more detail.

Green data centers A large body of research addresses ecological challenges in the area of data centers [29]: more energy-efficient software [37], better capacity planning for better resource utilization [62], improved energy management [26], better virtualization technologies [73], power-saving cooling systems [36], or simply using more renewable energy [53].

In a recent work, Radovanović et al. [52] propose a method to minimize the carbon footprint of computing among globally distributed data centers by temporally delaying flexible workloads. They achieve this goal by predicting the day-ahead carbon intensity and compution demands.

Carbon- or energy-aware networking Research conducted on green routing and traffic engineering falls into two main categories: they either make the network more energy-efficient or route packets through paths whose energy resources are green.

In a visionary paper, Gupta and Singh point out the energy utilization of Internet routers, and suggest energy savings by placing devices in sleep mode [30]. The principles laid by this work has been the foundations of much followup work in the next two decades, some of which we point out in the following paragraph.

Zhang et al. [76] propose a heuristic method to reduce energy by turning off as many line cards as possible and rerouting traffic to other underutilized links such that all traffic constraints are met. Vasic et al. [71] perform an energy optimization on real-world networks byoptimizing which network elements can be inactivated to save power, and which elements need to run to provide connectivity in case of network faults. They also perform traffic engineering optimizations within an ISP and demonstrate impressive savings while preserving network performance. Vasic and Kostic [70] propose Energy-Aware Traffic Engineering (EATe), to allocate traffic in an energy-optimal manner within an ISP. Andrews et al. [7] study network optimization from a theoretical perspective, with energy minimization as an objective. Chabarek et al. [17] show the potential for energy savings in operational networks. They study the power consumption of core and edge routers under different configurations. With these insights, they then optimize the energy consumption of the entire intra-domain network for a given traffic profile.

Among the studies also considering the CO_2 emissions into account, Van der Veldt et al. [68] propose a path provisioning method to reduce the CO_2 emission of communications in a national research and education network (NREN). Zhu et al. [78] develop an energy monitoring and routing component in OpenNaaS to perform energy-aware flow scheduling in data center networks. Aksanli et al. [3] design green energy-aware routing policies for wide area traffic between data centers. Ricciardi et al. [54] propose a method for routing and wavelength assignment formulation by taking every network node's carbon intensity into account. They solve this formulation using integer linear programming. Gattulli et al. [27] propose a CO_2 and energy-aware routing mechanism for intra-domain routing. They find two paths for each source and destination pair; one with routers whose energy resources have the lowest emission, and one with the lowest energy consumption. Then, they compare these paths and select the one with the lower emission. Schöndienst et al. [58] propose a heuristic algorithm for grooming traffic to shift the optical-electrical-optical conversions that are among the most power-hungry operations in IP backbone to nodes whose energy resources are green. Nafarieh et al. [47] proposed extensions for both OSPF-TE and BGP to propagate information about the emission of links on each path to routers inside and outside an AS.

Zilberman et al. pose the problem of carbon-aware networking and lay out promising directions and research challenges [79].

In July 2022, an effort for green networking was launched in the IETF [19, 20]. This indicates the increasing interest of the Internet standardization community for green technology. It is reassuring that many of the requirements outlined in these documents are addressed by our research.

The salient difference of our proposed work is that SCION's path-aware networking offers a decisive advantage by enabling inter-domain CO_2 transparency and energy optimization, without the constraints of operating in current intra-domain environments. In fact, our approaches are orthogonal and can be used in conjunction with most of the prior work.

Green inter-domain communication To the best of our knowledge, only two previous studies propose methods to reduce the carbon footprint of inter-domain communications. Shi et al. [60] extend the aforementioned traffic aggregation method [76] by taking into account the traffic between border routers of an AS. Thus, this work does not propose a global inter-domain method as ASes do not cooperate in green routing. Nafarieh et al. [47] propose extensions for OSPF-TE and BGP to propagate information about the emission of links on each path to routers inside and outside an AS. Using this information, each router selects the path with the minimum path emission to all other routers in its own AS, and each border router shares this information with the neighboring AS. During BGP route propagation, the emission of paths is accumulated in update messages, and used by multi-homed ASes to select the provider providing the greenest route. However, it provides very limited transparency and control over the carbon footprint of inter-domain communications compared to the present work.

6 Conclusion and Future Work

In this work, we propose an inter-domain carbon transparency system based on a path-aware Internet architecture. Our early results suggest that such a system would contribute to the mission to achieve a carbon-neutral Internet, by letting endpoints select greener inter-domain paths and incentivizing ISPs to deploy renewable electricity resources. Nonetheless, to accomplish this ambitious goal, additional work is needed, we present three broad directions

Economic effects of green routing From an economic perspective, it is central to predict the impact of carbon routing on the business performance of ISPs and on the competitive environment in the Internet, considering that ISPs might reduce their carbon footprint if they can thereby attract traffic. Fascinatingly, these competitive dynamics could result in a virtuous cycle, where ISPs compete for traffic shares by offering paths with ever-decreasing carbon intensity. However, to evaluate the plausibility of this scenario, modeling based on economics and game theory is needed.

Carbon trust roots Green path selection by endpoints could tempt malicious ASes to claim false carbon-intensity information to attract more traffic. Hence, carbon trust roots are needed to certify carbon-intensity information claimed by ISPs. The main challenges for these trust roots are: to estimate the carbon intensity of paths within ISPs, and to ensure that ISPs do not deviate from their certified carbon intensity after obtaining a certificate.

Green data centers and CDNs A path-aware Internet architecture also enables endpoints to select the data center providing a service or content. Therefore, providing carbon-intensity information of data centers in combination with information about communication paths enables endpoints to monitor and optimize the *total* carbon footprint of their requests, providing CO_2 optimization for computation-intensive *and* communication-intensive applications.

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