Carbon-Aware
Global Routing in Path-Aware Networks

Seyedali Tabaeiaghdaei
Simon Scherrer
Jonghoon Kwon
Adrian Perrig
ETH Zurich

e-Energy 2023, Orlando
What is Carbon-Aware Global Routing?

Enable Internet path selection based on carbon information.
What is Carbon-Aware Global Routing?
What is Carbon-Aware Global Routing?

- NW 1
- 100% NW 2
- 50% + 50% NW 3B
- 100% NW 3A
- 100% NW 3C
- NW 4
What is Carbon-Aware Global Routing?

Enable Internet path selection based on carbon information.
What is Carbon-Aware Global Routing?

Carbon-Aware Global Routing:
Enable Internet path selection based on carbon information

NW 1
NW 2
NW 3A
NW 3B
NW 3C
NW 4
Our contribution: Carbon-Aware Global Routing with CIRo

We present **CIRo** (Carbon-Aware Inter-Domain Routing, based on Path-Aware Networking):
Our contribution: Carbon-Aware Global Routing with CIRo

We present **CIRo** (Carbon-Aware Inter-Domain Routing, based on Path-Aware Networking):

**Carbon-Intensity Forecasting**

Model for carbon intensity of Internet paths

**Carbon-Footprint Impact Analysis**

Simulation on data-backed large-scale topology

**Impact Analysis: Carbon Footprint**

25% 50% 75% 100%

Carbon-Footprint Reduction by CIRo compared to Carbon Footprint under BGP

Cumulative Share of networks (CDF)
Our contribution: Carbon-Aware Global Routing with CIRo

We present CIRo (Carbon-Aware Inter-Domain Routing, based on Path-Aware Networking):

Carbon-Intensity Forecasting
Model for carbon intensity of Internet paths

Carbon-Information Dissemination
System for timely communication of forecasts
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**Carbon-Intensity Forecasting: Device Power Profile**
- **Capacity**
  - Total power consumption [W]
  - Traffic volume [bps]
  - Idle power consumption
  - Variable power consumption
  - Marginal energy intensity [W/bps]

**Amortized idle energy intensity [W/bps]**

**Use for forecast? Requires traffic prediction!**

**Minimum amortized idle energy intensity**

**Carbon-Footprint Reduction by CIRo**
Compared to Carbon Footprint under BGP

**Impact Analysis: Carbon Footprint**
Cumulative Share (%)

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Our contribution: Carbon-Aware Global Routing with CIRo

We present **CIRo** (Carbon-Aware Inter-Domain Routing, based on Path-Aware Networking):

### Carbon-Intensity Forecasting
Model for carbon intensity of Internet paths

### Carbon-Information Dissemination
System for timely communication of forecasts

### Carbon-Footprint Impact Analysis
Simulation on data-backed large-scale topology

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**Carbon-Intensity Forecasting:** Device Power Profile

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Total power consumption [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 bps</td>
<td></td>
</tr>
</tbody>
</table>

**Traffic Volume [bps]:**

<table>
<thead>
<tr>
<th>Idle power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable power consumption</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Amortized idle energy intensity</td>
</tr>
<tr>
<td></td>
<td>Idle power consumption</td>
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</tbody>
</table>

**Use for forecast?** Requires traffic prediction!

**Minimum amortized idle energy intensity:**

<table>
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<tr>
<th>Capacity [W/bps]</th>
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</thead>
<tbody>
<tr>
<td>Idle power consumption</td>
</tr>
</tbody>
</table>

**Carbon-Footprint Reduction by CIRo**

**Impact Analysis:**

- 25%
- 50%
- 75%
- 100%

Cumulative Share of networks (CDF)
Carbon-Intensity Forecasting: What Is the Purpose of Forecasts?

100% Wind

NW 3A

100%

NW 1

100%

NW 2

50% Wind + 50% Power Plant

NW 3B

100%

NW 3C

100%

NW 4

Enabled by Path-Aware Networking

Carbon information in announcements: Network-specific carbon-intensity forecasts

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Carbon-Intensity Forecasting: What Is the Purpose of Forecasts?

- NW 1
- NW 2
- NW 3A
- NW 3B
- NW 3C
- NW 4

Carbon Intensity = Carbon Emission / Transmitted Data

Enabled by Path-Aware Networking!

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Carbon-Intensity Forecasting: What Is the Purpose of Forecasts?

100% \[\text{NW 3A}\] \[\text{NW 3A} \rightarrow \text{NW 4}\]

50% \[\text{NW 3B}\] \[\text{NW 3B} \rightarrow \text{NW 4}\]

100% \[\text{NW 3C}\] \[\text{NW 3C} \rightarrow \text{NW 4}\]

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Carbon-Intensity Forecasting: What Is the Purpose of Forecasts?

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Carbon-Intensity Forecasting: What Is the Purpose of Forecasts?

Carbon information in announcements: Network-specific carbon-intensity forecasts

Carbon Intensity = \( \frac{\text{Carbon Emission}}{\text{Transmitted Data}} \)

Enabled by Path-Aware Networking!
Carbon-Intensity Forecasting: What Is the Purpose of Forecasts?

- **NW 1**: 100%
- **NW 2**: 100%
- **NW 3B**: 50% + 50%
- **NW 3A**: 100%
- **NW 3C**: 100%
- **NW 4**: 100%

Enabled by Path-Aware Networking!
Carbon-Intensity Forecasting: Network-Specific Carbon Intensity
Carbon-Intensity Forecasting: Network-Specific Carbon Intensity
Carbon-Intensity Forecasting: Network-Specific Carbon Intensity
Carbon-Intensity Forecasting: Network-Specific Carbon Intensity

- Interface
- Intra-NW path
- Devices

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Carbon-Intensity Forecasting: Device-Specific Carbon-Intensity

\[
\text{Carbon Intensity of Data Transmission} = \frac{\text{Carbon Emission}}{\text{Transmitted Data}}
\]
Carbon-Intensity Forecasting: Device-Specific Carbon-Intensity

\[
\text{Carbon Intensity of Data Transmission} = \frac{\text{Carbon Emission}}{\text{Transmitted Data}} = \frac{\text{Carbon Emission}}{\text{Consumed Electricity}} \cdot \frac{\text{Consumed Electricity}}{\text{Transmitted Data}}
\]
Carbon Intensity of Data Transmission = \frac{\text{Carbon Emission}}{\text{Transmitted Data}}

= \frac{\text{Carbon Emission}}{\text{Consumed Electricity}} \cdot \frac{\text{Consumed Electricity}}{\text{Transmitted Data}}

\text{① Carbon Intensity of Electricity}
Carbon-Intensity Forecasting: Device-Specific Carbon-Intensity

Carbon Intensity of Data Transmission = \frac{\text{Carbon Emission}}{\text{Transmitted Data}}

= \frac{\text{Carbon Emission}}{\text{Consumed Electricity}} \cdot \frac{\text{Consumed Electricity}}{\text{Transmitted Data}}

① Carbon Intensity of Electricity

Device Location
Carbon-Intensity Forecasting: Device-Specific Carbon-Intensity

\[
\text{Carbon Intensity of Data Transmission} = \frac{\text{Carbon Emission}}{\text{Transmitted Data}} = \frac{\text{Carbon Emission}}{\text{Consumed Electricity}} \cdot \frac{\text{Consumed Electricity}}{\text{Transmitted Data}}
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① Carbon Intensity of Electricity

Device Location ⊕ Electricity-Grid Forecast

(Source: electricitymaps.com)
Carbon-Intensity Forecasting: Device-Specific Carbon-Intensity

Carbon Intensity of Data Transmission = \frac{\text{Carbon Emission}}{\text{Transmitted Data}}

= \frac{\text{Carbon Emission}}{\text{Consumed Electricity}} \cdot \frac{\text{Consumed Electricity}}{\text{Transmitted Data}}

1. Carbon Intensity of Electricity

2. Energy Intensity of Data Transmission

(Source: electricitymaps.com)
Carbon-Intensity Forecasting: Device-Specific Carbon-Intensity

Carbon Intensity of Data Transmission

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\text{Carbon Intensity of Data Transmission} = \frac{\text{Carbon Emission}}{\text{Transmitted Data}} = \frac{\text{Carbon Emission}}{\text{Consumed Electricity}} \cdot \frac{\text{Consumed Electricity}}{\text{Transmitted Data}}
\]

① Carbon Intensity of Electricity

② Energy Intensity of Data Transmission

Device Location ⊕ Electricity-Grid Forecast

Device Power Profile

(Source: electricitymaps.com)
Carbon-Intensity Forecasting: Device Power Profile

Total power consumption [W]

Traffic volume [bps]  Capacity

Amortized idle energy intensity [W/bps] = \frac{\text{Idle power consumption}}{\text{Traffic volume}}

Use for forecast?

Requires traffic prediction!

Minimum amortized idle energy intensity = \frac{\text{Idle power consumption}}{\text{Capacity}}
Carbon-Intensity Forecasting: Device Power Profile

Total power consumption [W]

Variable power consumption
Idle power consumption

Traffic volume [bps]  
Capacity

Marginal energy intensity [W/bps]
Amortized idle energy intensity [W/bps] = Idle power consumption / Traffic volume

Use for forecast? Requires traffic prediction!

Minimum amortized idle energy intensity = Idle power consumption / Capacity
Carbon-Intensity Forecasting: Device Power Profile

Variable power consumption

Idle power consumption

Total power consumption [W]

Marginal energy intensity [W/bps]

Traffic volume [bps]

Capacity

Amortized idle energy intensity [W/bps] = Idle power consumption / Traffic volume

Use for forecast? Requires traffic prediction!

Minimum amortized idle energy intensity = Idle power consumption / Capacity
Carbon-Intensity Forecasting: Device Power Profile

- Total power consumption [W]
- Variable power consumption
- Idle power consumption
- Marginal energy intensity [W/bps]
- Amortized idle energy intensity [W/bps] = Idle power consumption / Traffic volume
- Use for forecast? Requires traffic prediction!

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Carbon-Intensity Forecasting: Device Power Profile

Total power consumption [W]

Marginal energy intensity [W/bps]

Idle power consumption

Variable power consumption

Amortized idle energy intensity [W/bps] = 

Idle power consumption

Traffic volume

Traffic volume [bps]

Capacity

Requires traffic prediction!
Carbon-Intensity Forecasting: Device Power Profile

**idle power consumption**

- **Idle power consumption**
- **Variable power consumption**

**Use for forecast?** Requires traffic prediction!

**Amortized idle energy intensity [W/bps]**

\[
\text{Amortized idle energy intensity} = \frac{\text{Idle power consumption}}{\text{Traffic volume}}
\]

**Total power consumption [W]**

**Marginal energy intensity [W/bps]**

- **1 bps**

**Minimum amortized idle energy intensity**

\[
\text{Minimum amortized idle energy intensity} = \frac{\text{Idle power consumption}}{\text{Capacity}}
\]
Carbon-Intensity Forecasting: Device Power Profile

Total power consumption [W] = Idle power consumption + Variable power consumption

Marginal energy intensity [W/bps] = Idle power consumption / Traffic volume

Amortized idle energy intensity [W/bps] = Idle power consumption / Capacity

Use for forecast? Requires traffic prediction!

Minimum amortized idle energy intensity [W/bps] = Idle power consumption / Capacity
Carbon-Intensity Forecasting: Device Power Profile

Total power consumption [W]

Marginal energy intensity [W/bps]

Idle power consumption

Variable power consumption

Traffic volume [bps]

Capacity

Amortized idle energy intensity [W/bps] = \frac{\text{Idle power consumption}}{\text{Traffic volume}}

Use for forecast? Requires traffic prediction!

Minimum amortized idle energy intensity [W/bps] = \frac{\text{Idle power consumption}}{\text{Capacity}}

1 bps
Carbon-Intensity Forecasting: Summary

Carbon intensity of devices

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Carbon intensity of intra-network paths

What is Carbon-Aware Global Routing?

Enable Internet path selection based on carbon information

Goal:
Avoid responsibility for emission on high-carbon paths
Carbon-Intensity Forecasting: Summary

Carbon intensity of devices

Carbon intensity of intra-network paths
Carbon-Intensity Forecasting: Summary

Carbon intensity of devices

Carbon intensity of intra-network paths

Carbon intensity of network with respect to interface pair
Carbon-Intensity Forecasting: Summary

Carbon intensity of devices

Carbon intensity of intra-network paths

Carbon intensity of network with respect to interface pair

Carbon intensity of Internet path
Our contribution: Carbon-Aware Global Routing with CIRo

We present CIRo (Carbon-Aware Inter-Domain Routing, based on Path-Aware Networking):

Carbon-Intensity Forecasting
Model for carbon intensity of Internet paths

Carbon-Information Dissemination
System for timely communication of forecasts

Carbon-Footprint Impact Analysis
Simulation on data-backed large-scale topology

Impact Analysis: Carbon Footprint
Cumulative Share of networks (CDF)
Carbon-Information Dissemination: System Overview
Carbon-Information Dissemination: System Overview

NW 2

NW 3B

NW 4

I1

I2

NW 4

...
Carbon-Information Dissemination: System Overview
Carbon-Information Dissemination: System Overview

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Carbon-Intensity Forecast DB
Dissemination Module

NW 2 → I1 → NW 3B → I2 → NW 4
Carbon-Information Dissemination: System Overview

- **NW 2** to **I1**
- **Carbon-Intensity Forecast DB**
- **Dissemination Module**
- **NW 3B**
- **NW 3B** to **NW 4**
- **Path Service**
- **I2** to **NW 4**

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Carbon-Information Dissemination: System Overview

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Carbon-Intensity Forecast DB
Dissemination Module
Path Service

NW 2 I1 NW 3B I2 NW 4

NW 3B NW 4
Carbon-Information Dissemination: System Overview

Dissemination Module

Carbon-Intensity Forecast DB

Path Service

NW 2 → I1

NW 3B

NW 4 → I2
Carbon-Intensity Forecast DB

Dissemination Module

Path Service

NW 3B

NW 4

NW 2

NW 3B

NW 4

I1

I2

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Carbon-Information Dissemination: System Overview

- **Dissemination Module**
  - **Carbon-Intensity Forecast DB**
  - **Path Service**

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Our contribution: Carbon-Aware Global Routing with CIRo

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Model for carbon intensity of Internet paths

**Carbon-Information Dissemination**
System for timely communication of forecasts

**Carbon-Footprint Impact Analysis**
Simulation on data-backed large-scale topology
Impact Analysis: Carbon-Footprint Impact ≠ Carbon-Emission Impact!

- **NW 1**: Switch to greener path continues to emit CO$_2$.

**Carbon-Intensity Forecasting: Device Power Profile**

|----------|-----------------------------|----------------------|------------------------|---------------------------|-----------------------------------|----------------------------------------|

- **Use for forecast?** Requires traffic prediction!
- **Minimum amortized idle energy intensity** = Idle power consumption / Traffic volume.

- **NW 3A**: 100%
- **NW 3B**: 50% + 50%
- **NW 3C**: 100%

**Endhost-associated carbon emission (carbon footprint)** is reduced, not overall carbon emission!
Impact Analysis: Carbon-Footprint Impact ≠ Carbon-Emission Impact!

Switch to greener path

NW 1

NW 2

NW 3A

NW 3B

NW 3C

NW 4
Impact Analysis: Carbon-Footprint Impact ≠ Carbon-Emission Impact!

Switch to greener path

NW 1

NW 2

NW 3A

NW 3B

NW 3C

NW 4

Endhost-associated carbon emission (carbon footprint) is reduced, not overall carbon emission!

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Impact Analysis: Carbon-Footprint Impact ≠ Carbon-Emission Impact!

Switch to greener path

Endhost-associated carbon emission (carbon footprint) is reduced, not overall carbon emission!
Impact Analysis: Carbon Footprint (Simulation in CAIDA Core Topology)
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Cumulative Share of Networks (CDF)

Carbon-Footprint Reduction by CIRo Compared to Carbon Footprint under BGP
Impact Analysis: Carbon Footprint (Simulation in CAIDA Core Topology)

Cumulative Share of Networks (CDF)

Carbon-Footprint Reduction by CIRo Compared to Carbon Footprint under BGP

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Impact Analysis: Carbon Footprint (Simulation in CAIDA Core Topology)

50% of networks reduce their Internet carbon footprint by ≥ 70%!
Impact Analysis: Carbon Footprint (Simulation in CAIDA Core Topology)

50% of networks reduce their Internet carbon footprint by $\geq 70\%$!

Not actual emission savings!
Impact Analysis: How to Actually Reduce Emission?

- **NW 1**
  - 100%
- **NW 2**
  - 100%
- **NW 3B**
  - 50% + 50%
- **NW 3A**
  - 100%
- **NW 3C**
  - 100%
- **NW 4**

### Carbon-Intensity Forecasting: Device Power Profile

<table>
<thead>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= Idle power consumption / Traffic volume</td>
<td></td>
</tr>
</tbody>
</table>

Use for forecast? Requires traffic prediction!

Minimum amortized idle energy intensity = Idle power consumption / Capacity [W/bps]

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Impact Analysis: How to Actually Reduce Emission?

Switch to greener path

NW 1

NW 2

NW 3A

NW 3B

NW 3C

NW 4

Carbon-Intensity Forecasting: Device Power Profile

- Total power consumption [W]
- Traffic volume [bps]
- Idle power consumption
- Variable power consumption
- Marginal energy intensity [W/bps]
- Amortized idle energy intensity [W/bps] = (Idle power consumption / Traffic volume)

Requires traffic prediction!

Minimum amortized idle energy intensity = (Idle power consumption / Capacity) [W/bps]

Revenue loss

Adjust offer

100% + 50%
Impact Analysis: How to Actually Reduce Emission?

Switch to greener path

100%  
NW 3A

50% + 50%  
NW 3B

100%  
NW 3C

continues to emit CO₂!

NW 1

NW 2

NW 4

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Impact Analysis: How to Actually Reduce Emission?

Switch to greener path

Revenue loss

continues to emit CO₂!

NW 1

NW 2

NW 3B

NW 3A

NW 3C

NW 4

Carbon-Intensity Forecasting: Device Power Profile

Capacity

Total power consumption [W]

Traffic volume [bps]

Idle power consumption

Variable power consumption

Marginal energy intensity [W/bps]

Amortized idle energy intensity [W/bps] = Idle power consumption / Traffic volume

Use for forecast? Requires traffic prediction!

Minimum amortized idle energy intensity = Idle power consumption / Capacity [W/bps]

Revenue loss

100% 50% + 50% 100% 100% 50% 50% + 50% 100%
Impact Analysis: How to Actually Reduce Emission?

Switch to greener path

Revenue loss

Adjust offer

continues to emit CO$_2$!
Impact Analysis: How to Actually Reduce Emission?

Switch to greener path

NW 1

NW 2

NW 3A

NW 3B

NW 3C

NW 4

Revenue loss

Adjust offer

continues to emit CO$_2$!
Impact Analysis: How to Actually Reduce Emission?

Switch to greener path

100%  
NW 3A

50% + 50%  
NW 3B

100%  
NW 3C

continues to emit CO₂!

NW 1

NW 2

NW 4

Revenue loss

Adjust offer

50%  
NW 3B

100%  
NW 3C

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Carbon-Intensity Forecasting: Device Power Profile

Total power consumption [W]

Traffic volume [bps]

Idle power consumption

Variable power consumption

Marginal energy intensity [W/bps]

Amortized idle energy intensity [W/bps] = Idle power consumption / Traffic volume

Use for forecast? Requires traffic prediction!

Minimum amortized idle energy intensity = Idle power consumption / Capacity [W/bps]

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Revenue loss

Adjust offer

100%  
NW 3C

100%  
NW 3A

50%  
NW 3B

100%  
NW 3C

Continues to emit CO₂!
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**Carbon-Information Dissemination**

System for timely communication of forecasts

**Carbon-Footprint Impact Analysis**

Simulation on data-backed large-scale topology
Carbon-Information Dissemination: Why Trust Carbon Information?

Approach:
Certify carbon information by specialized and trusted certification authorities.
Carbon-Information Dissemination: Why Trust Carbon Information?

**Approach:** Certify carbon information by *specialized* and *trusted* certification authorities
Carbon-Information Dissemination: Why Trust Carbon Information?

**Approach:** Certify carbon information by *specialized* and *trusted* certification authorities.

- Carbon-Information Certification Authority
- Audit
- Electricity Provider Contracts
Carbon-Information Dissemination: Why Trust Carbon Information?

**Approach:** Certify carbon information by *specialized* and *trusted* certification authorities.
Carbon-Information Dissemination: Why Trust Carbon Information?

**Approach:** Certify carbon information by *specialized* and *trusted* certification authorities.

- **Carbon-Information Certification Authority**
- **Electricity Provider Contracts**
- **Network Equipment Specifications**
- **Intra-Network Forwarding**

Audit

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Carbon-Information Dissemination: Why Trust Carbon Information?

**Approach:** Certify carbon information by *specialized* and *trusted* certification authorities
Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

NW 1 — NW 2 — NW 3B — NW 4

NW 3A

100%

NW 3B

50% + 50%

NW 3C

100%
Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

NW 1 -> NW 2

NW 3A: 100%

NW 3B: 50% + 50%

NW 3C: 100%

NW 4

BGP: Announce a single path per destination
Pick greenest available path

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Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

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Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

NW 1

NW 2

NW 3A
NW 3A → NW 4

NW 3B
NW 3B → NW 4

NW 3C
NW 3C → NW 4

NW 4

BGP:
Announce a single path per destination
Pick greenest available path
Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

**BGP:** Announce a single path per destination

- NW 1
- NW 2
- NW 3A
- NW 3B
- NW 3C
- NW 4

100% 🌿 NW 3A

50% 🌿 + 50% 🌇 NW 3B

100% 🌇 NW 3C

NW 4

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Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

**BGP**: Announce a single path per destination

Pick greenest available path

- **NW 1**
- **NW 2**
- **NW 3A**
  - NW 3A → NW 4
- **NW 3B**
  - 50% + 50%
- **NW 3C**
  - 100%
- **NW 4**
  - NW 4
  - NW 4
  - NW 4
  - NW 4

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Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

**BGP:** Announce a single path per destination

- Pick greenest available path

NW 1

NW 2

NW 3A

NW 3B

NW 3C

NW 4

100%

50% + 50%

50%

100%
Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

Problem:
- Diverse optimality notions based on application and user
- Single-path propagation in BGP
  \[ \Rightarrow \]
  \[ \text{Single optimality notion satisfied at the same time} \]

Conflicting optimality notions
  \[ \Rightarrow \]
  \[ \text{Parallel BGP instances} \]
  \[ \Rightarrow \]
  \[ \text{Scalability problem!} \]

Greenest available path

NW 1

NW 2

NW 3A

NW 3B

NW 3C

NW 4
Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

Problem:
- Diverse optimality notions based on application and user
- Single-path propagation in BGP

\[ \Rightarrow \]
- Single optimality notion satisfied at the same time

Conflicting optimality notions
\[ \Rightarrow \]
- Parallel BGP instances
\[ \Rightarrow \]
- Scalability problem!
Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

**Problem:**
Diverse optimality notions based on application and user!

- Greenest available path
- Latency-optimal available path

100% NW 3A
50% + 50% NW 3B
100% NW 3C
50% NW 4

NW 1 → NW 2 → NW 3A → NW 4
NW 1 → NW 2 → NW 3B → NW 4
NW 1 → NW 2 → NW 3C → NW 4

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Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

**Problem:**
Diverse optimality notions based on application and user!

- Greenest available path
- Latency-optimal available path

Single-path propagation in BGP → Single optimality notion satisfied at the same time
Carbon-Aware Global Routing with Traditional Internet Routing (BGP)?

**Problem:**
Diverse optimality notions based on application and user!

- Greenest available path
- Latency-optimal available path

Single-path propagation in BGP
⇒ Single optimality notion satisfied at the same time

Conflicting optimality notions
⇒ Parallel BGP instances
⇒ Scalability problem!
Carbon-Aware Global Routing with Path-Aware Networking (PAN)

**Solution:**
Keep advertising *multiple* paths and let end-hosts select!

Greenest available path

Latency-optimal available path

---

NW 1

NW 2

NW 3A

NW 3B

NW 3C

NW 4
Carbon-Aware Global Routing with Path-Aware Networking (PAN)

Solution:
Keep advertising *multiple* paths and let end-hosts select!

Greenest available path

Latency-optimal available path

Enabled by emerging Path-Aware Networking (PAN) architectures

NW 1

NW 2

NW 3A

NW 3B

NW 3C

NW 4

100%

50% + 50%

100%

Network Security Group

Department of Computer Science

e-energy 2023
Impact Analysis: Overview of Approach

CAIDA
Internet Core
Topology
(AS Level +
Router Level)

Supplement
with Energy
and Carbon
Information

Simulate
Traditional
BGP Routing
(carbon-unaware)

Simulate
CIRo
(carbon-aware)

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CAIDA Internet Core Topology (AS Level + Router Level) -> Supplement with Energy and Carbon Information
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CAIDA Internet Core Topology (AS Level + Router Level) → Supplement with Energy and Carbon Information → Simulate Traditional BGP Routing (carbon-unaware) → BGP Paths
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- **CAIDA Internet Core Topology**
  (AS Level + Router Level)

- **Supplement with Energy and Carbon Information**

- **Simulate Traditional BGP Routing**
  (carbon-unaware)

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- **BGP Paths**

- **CIRo Paths**
Impact Analysis: Overview of Approach

- CAIDA Internet Core Topology (AS Level + Router Level)
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- Simulate CIRo (carbon-aware)

BGP Paths

CIRo Paths

Compare
Impact Analysis: Difference in Greenest Path
Impact Analysis: Difference in Greenest Path

Carbon-Intensity Reduction by Greenest CIRo Path Compared to Greenest BGP Path
Impact Analysis: Difference in Greenest Path

Cumulative Share of Network Pairs (CDF)

Carbon-Intensity Reduction by Greenest CIRo Path Compared to Greenest BGP Path
Impact Analysis: Difference in Greenest Path

Cumulative Share of Network Pairs (CDF)

Carbon-Intensity Reduction by Greenest CIRo Path Compared to Greenest BGP Path
Impact Analysis: Difference in Greenest Path

50% of network pairs gain a CIRo path that is $\geq 46\%$ greener than the greenest BGP path!
Impact Analysis: Carbon Intensity vs Latency
Impact Analysis: Carbon Intensity vs Latency

Latency of Greenest CIRe Path Compared to BGP Path
Impact Analysis: Carbon Intensity vs Latency

Cumulative Share of Network Pairs (CDF)

Latency of Greenest CIRo Path
Compared to BGP Path

100%
200%
300%
400%
25%
50%
75%
100%
For 50% of network pairs, greenest path has higher latency than BGP path.