

Carbon-Aware Global Routing In Path-Aware Networks

Jonghoon Kwon
ETH Zürich



Why CO₂-Awareness?

EU commission chief asks G20 to join global carbon pricing

Reuters

September 9, 2023 11:43 AM GMT+2 · Updated 5 days ago



Carbon accounting is going broad and granular. Are we ready?

by Ralf W. Seifert, Richard Markoff, Alexander Schmidt
Published 11 April 2023 in Supply chain · 8 min read



Europe is about to implement a major change in the reporting standards and requirements for carbon as part of the European Green Deal. These changes will require more companies to account for their carbon footprints over a broader scope and in greater granular detail. The authors explore the implications of this major policy shift.



VOXEU COLUMN CLIMATE CHANGE ENVIRONMENT EU POLICIES

The economic effects of carbon pricing

Diego Känzig, Maximilian Konradt / 12 Aug 2023

Carbon pricing policies are critical tools to mitigate the effects of climate change. This column examines the impact of European carbon pricing policies on the economy, contrasting the common carbon market with national carbon taxes. The authors find that



Ursula von der Leyen gestures during a joint press statement with Philippine President Ferdinand Marcos Jr. at the Malacanang Presidential Palace in Manila, Philippines, July 31, 2023. Aaron Favila/POOL via Getty Images

Reuters) - The European Commission president asked G20 leaders on Tuesday to set up global carbon pricing.

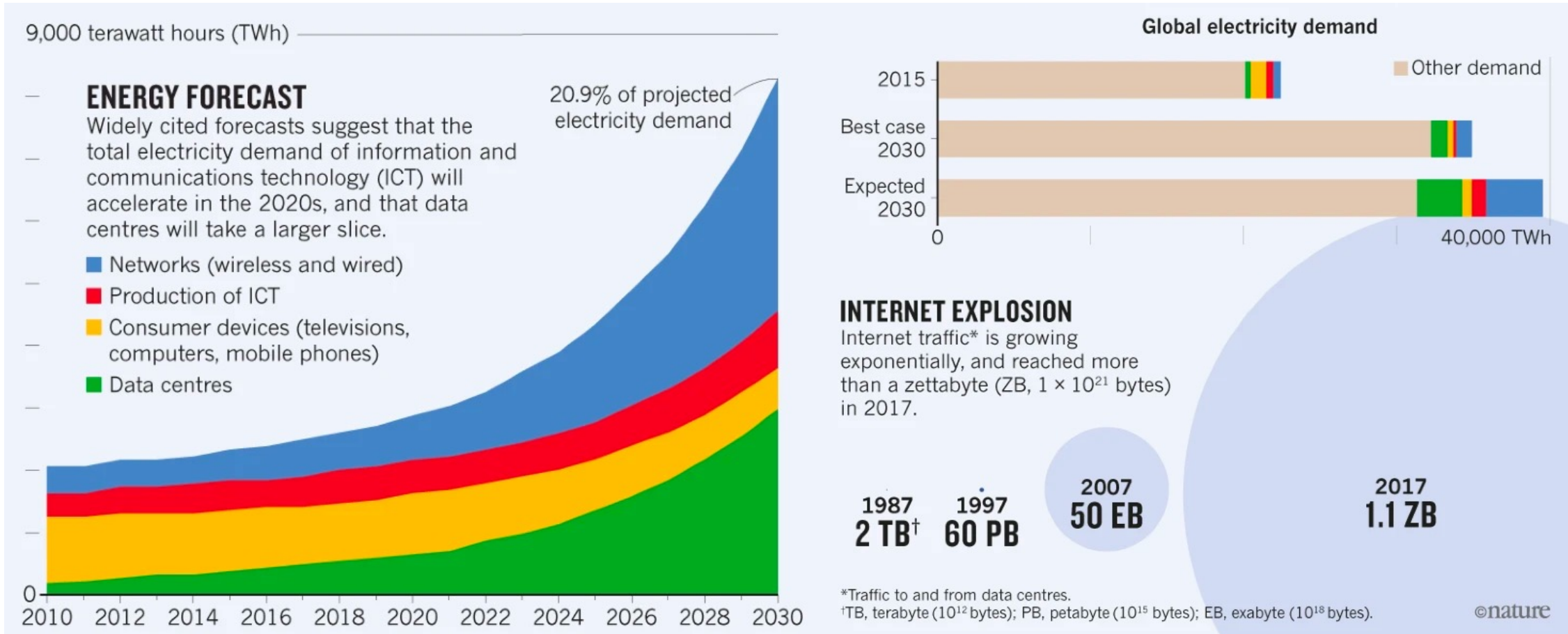
...ing a price on carbon to help meet their climate goals in the form of a tax, such as a carbon trading (ETS), or cap-and-trade, system.

An email with attachment
is account for **50g** of CO₂

<source: ictfootprint.eu>



ICT Carbon Footprint



<Source: nature.com>

Is It Possible in Today's Internet?

ISPs select inter-domain paths



Endpoints have no control over paths



No means of carbon transparency

Carbon-Aware Networking?

- Path transparency



Carbon-Aware Networking?

- Path transparency
- Carbon intensity estimation



Carbon-Aware Networking?

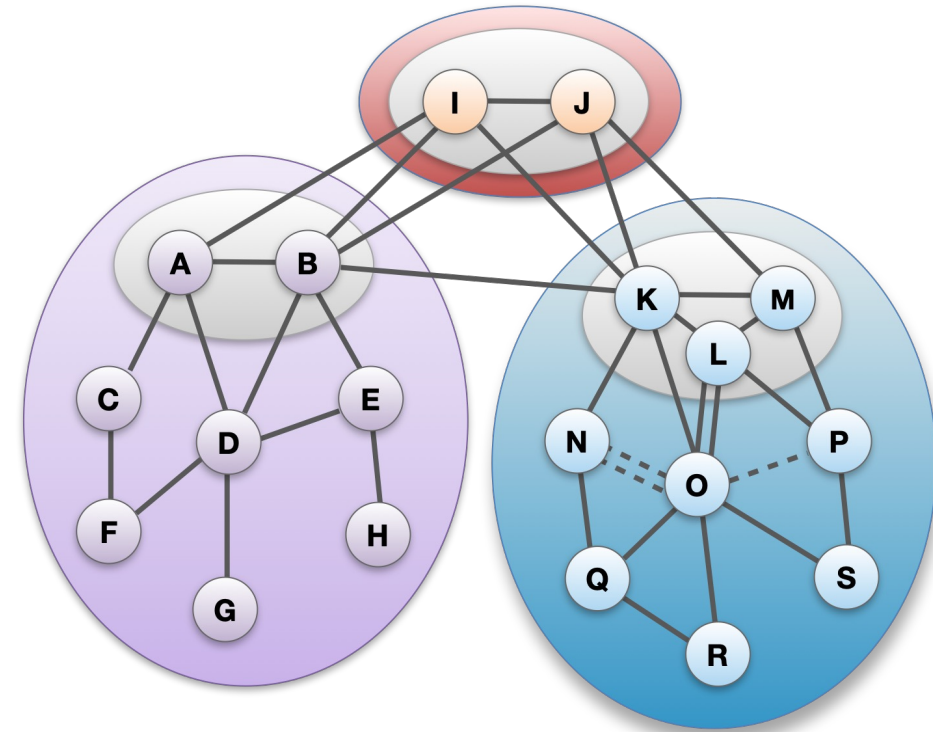
- Path transparency
- Carbon intensity estimation
- Endpoint path control



Already Possible with The Future Internet Architecture



- Path-based Network Architecture



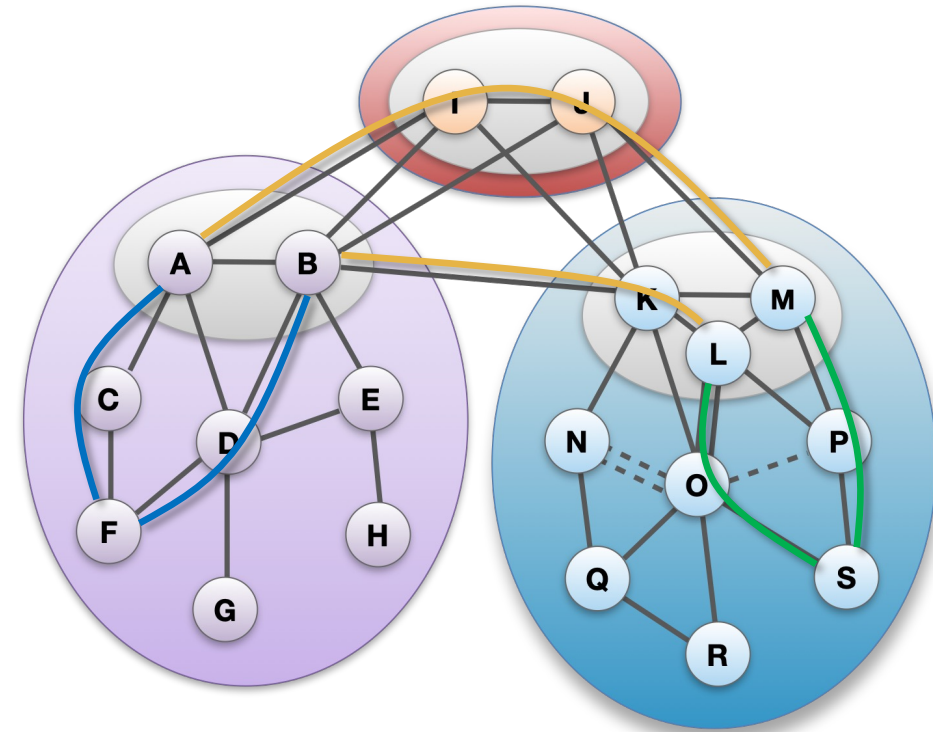
Already Possible with The Future Internet Architecture



- Path-based Network Architecture

Control Plane - Routing

- ❖ **Constructs** and **Disseminates**
Path Segments



Already Possible with The Future Internet Architecture



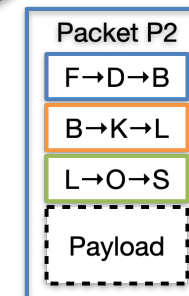
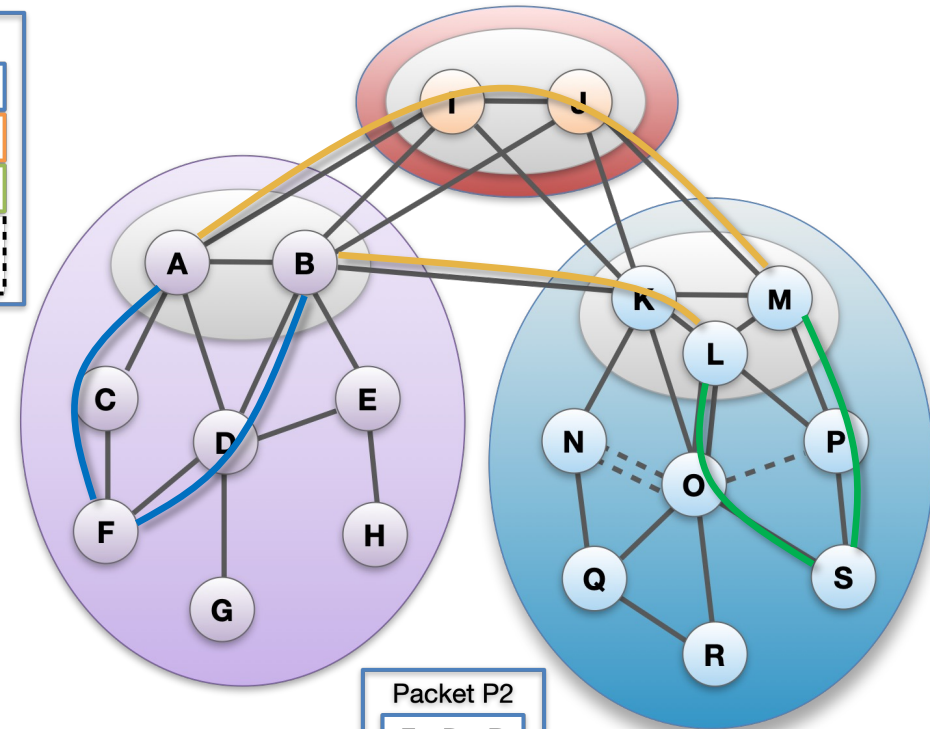
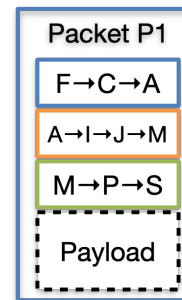
- Path-based Network Architecture

Control Plane - Routing

- ❖ **Constructs** and **Disseminates** Path Segments

Data Plane - Packet forwarding

- ❖ **Combine** Path Segments to Path
- ❖ Packets contain Path
- ❖ Routers forward packets based on Path
- ▶ Simple routers, stateless operation



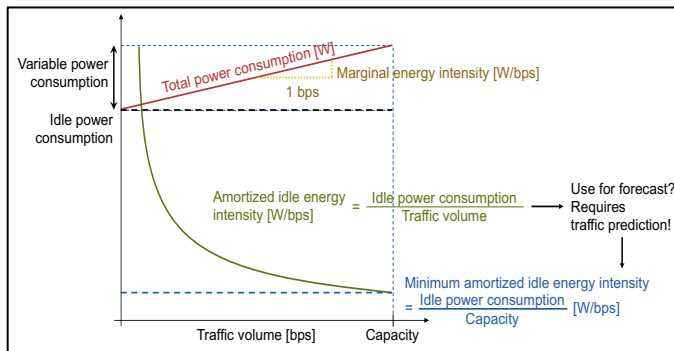
Carbon-Aware Inter-Domain Routing



- CIRo: Carbon-Aware Inter-Domain Routing based on Path-Aware Networking

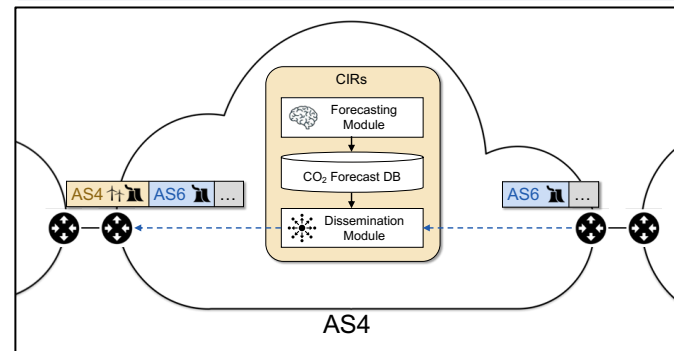
Carbon-Intensity Forecasting

Model for carbon intensity of Internet paths



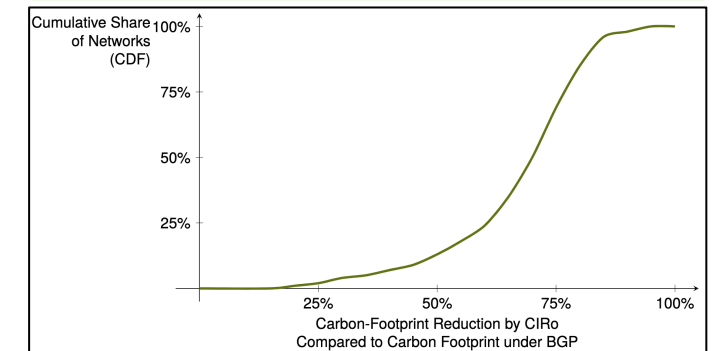
Carbon-Information Dissemination

System for timely communication of forecasts



Carbon-Footprint Impact Analysis

Simulation on data-backed large-scale topology



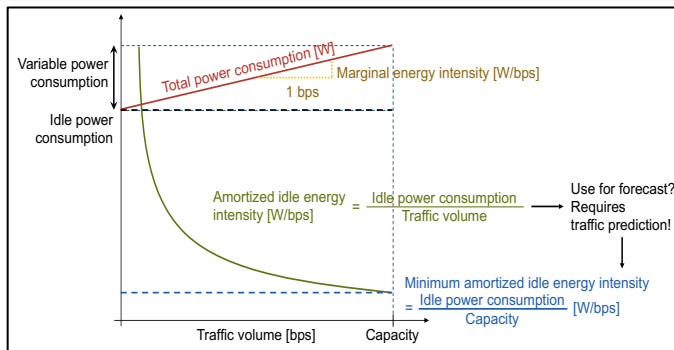
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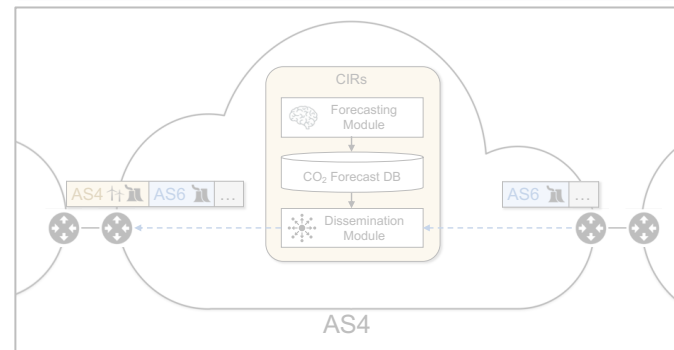
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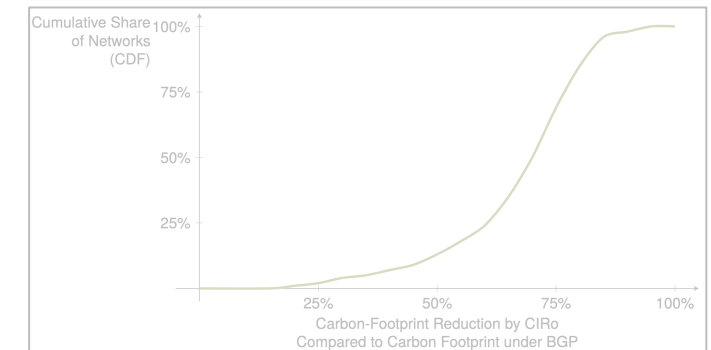
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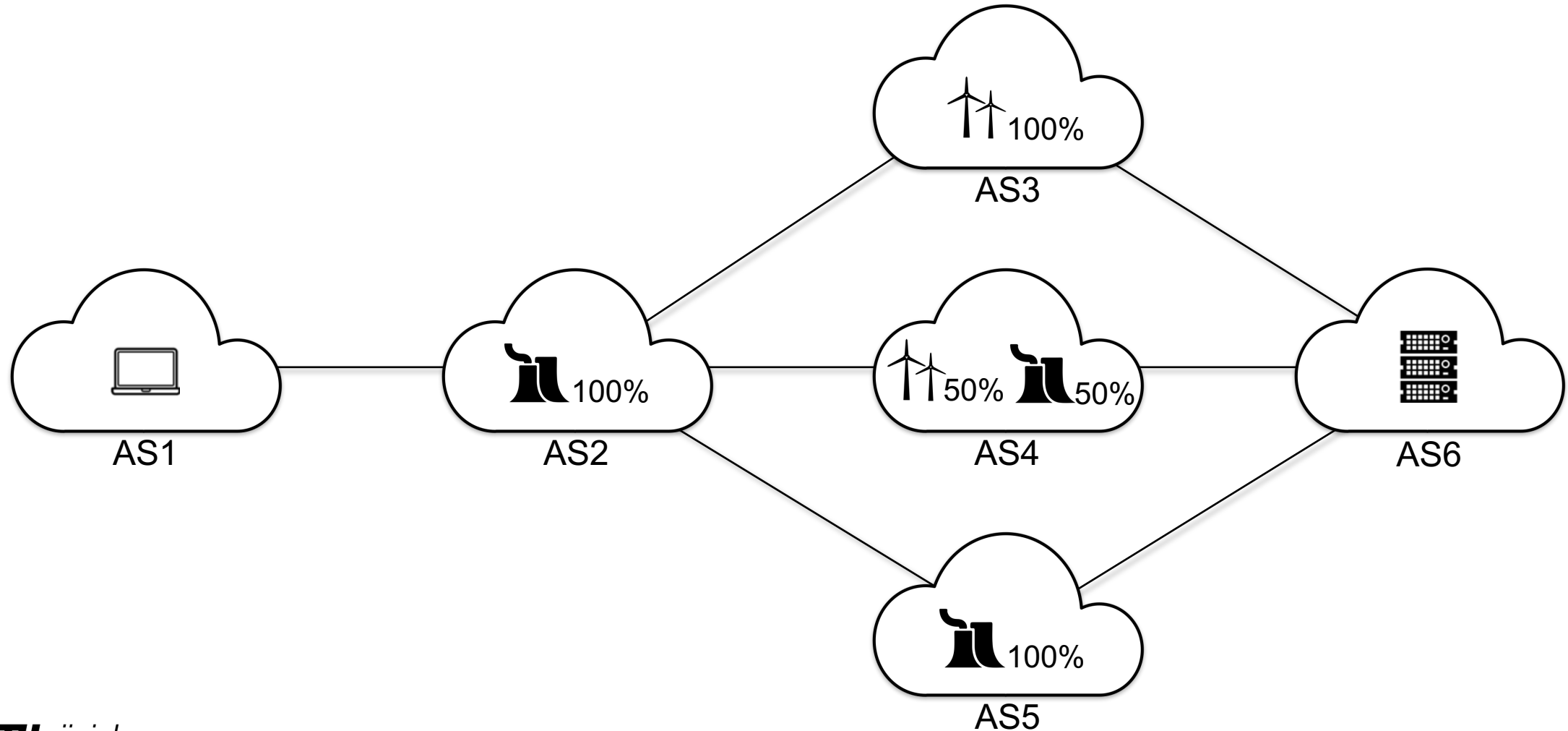


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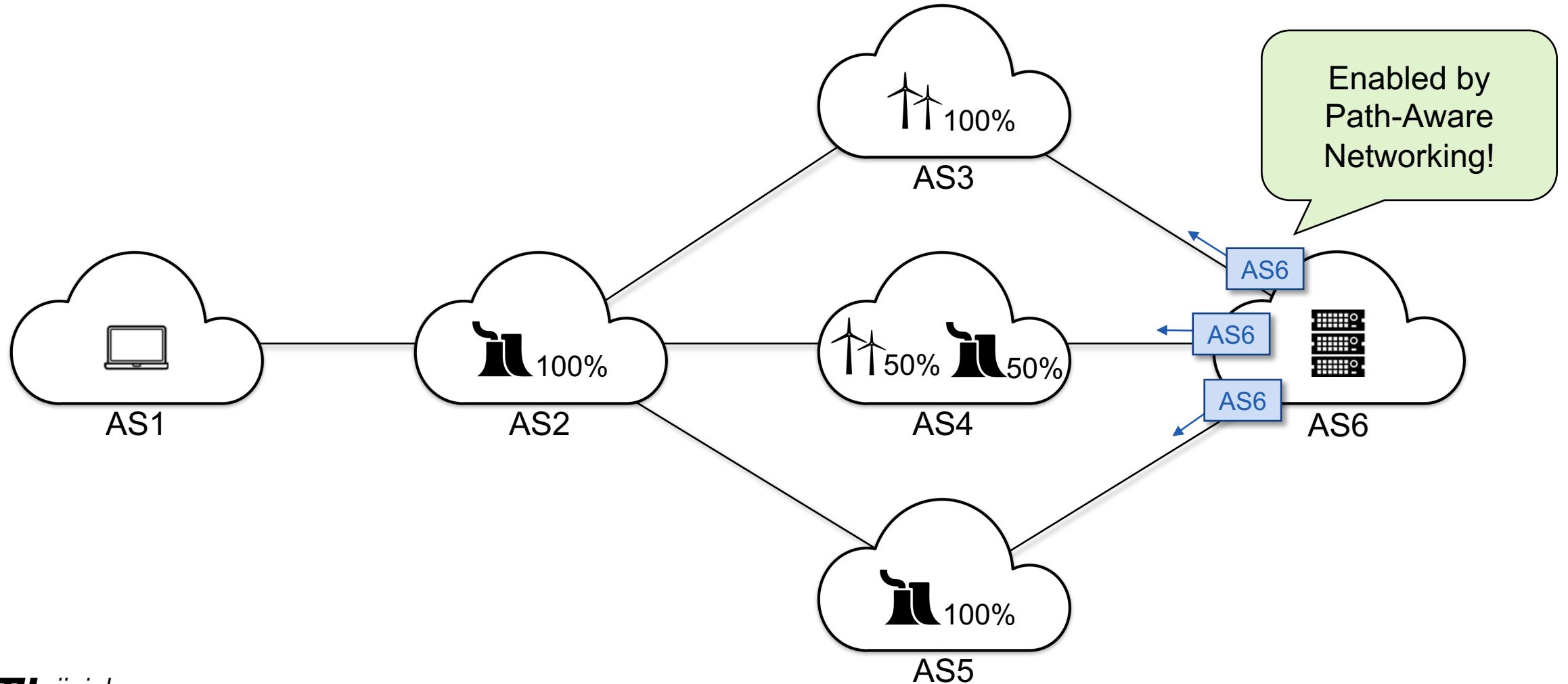
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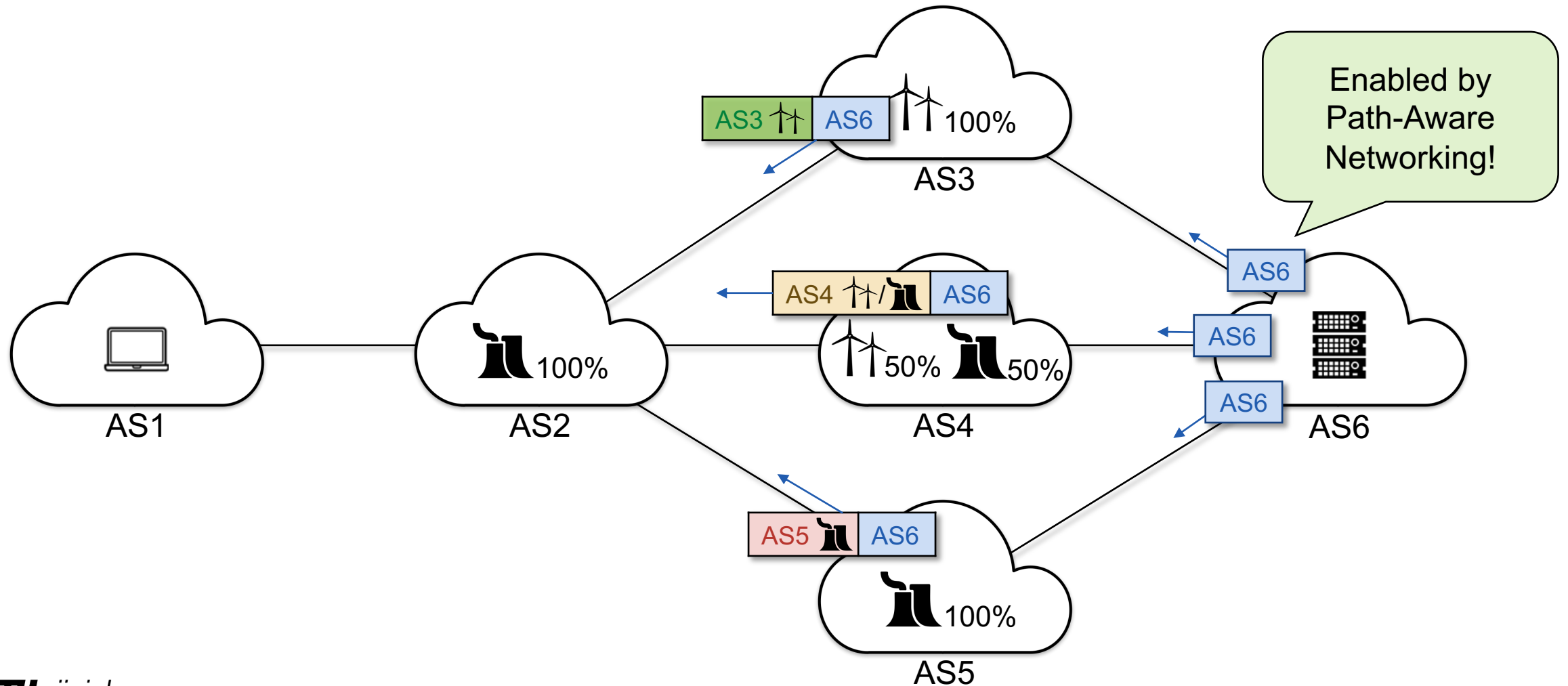
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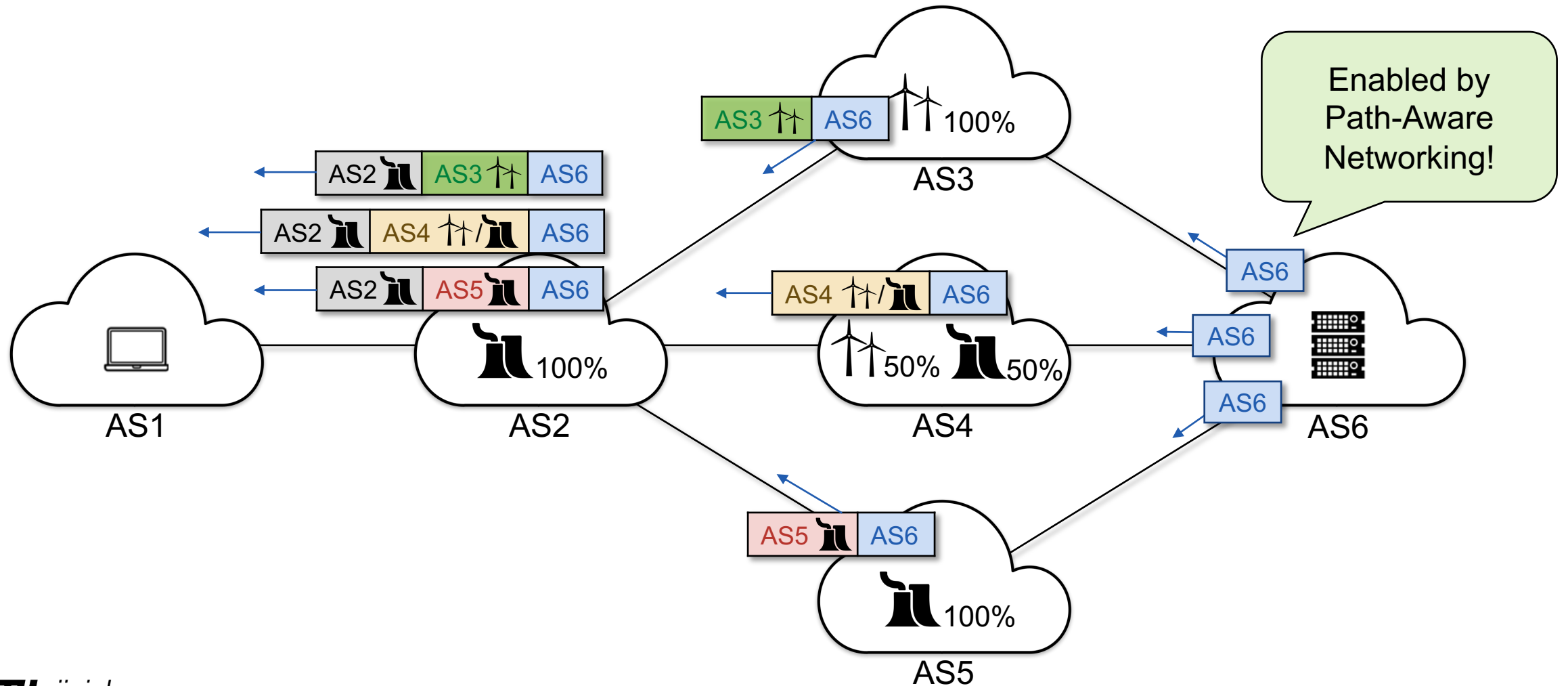
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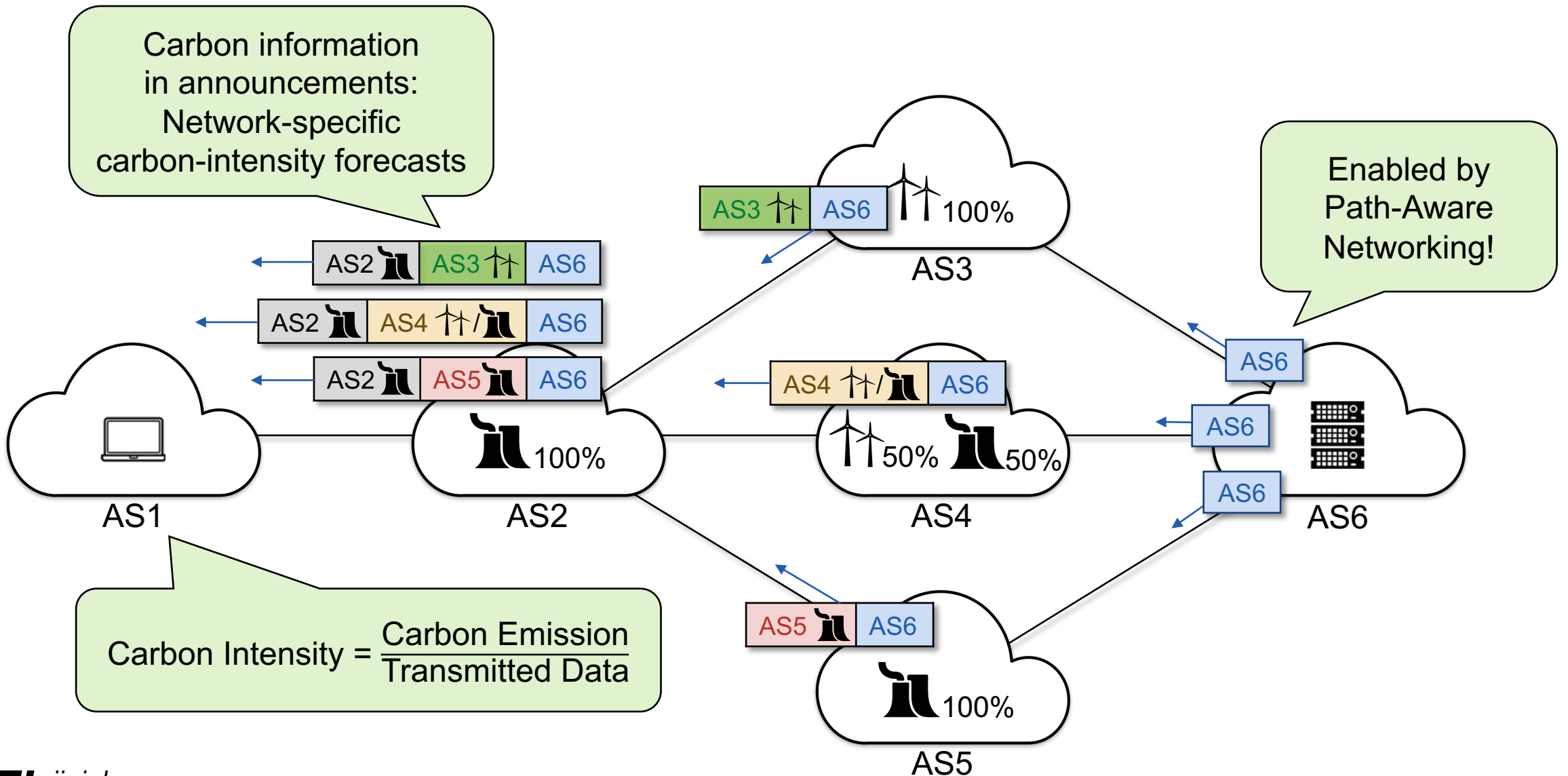
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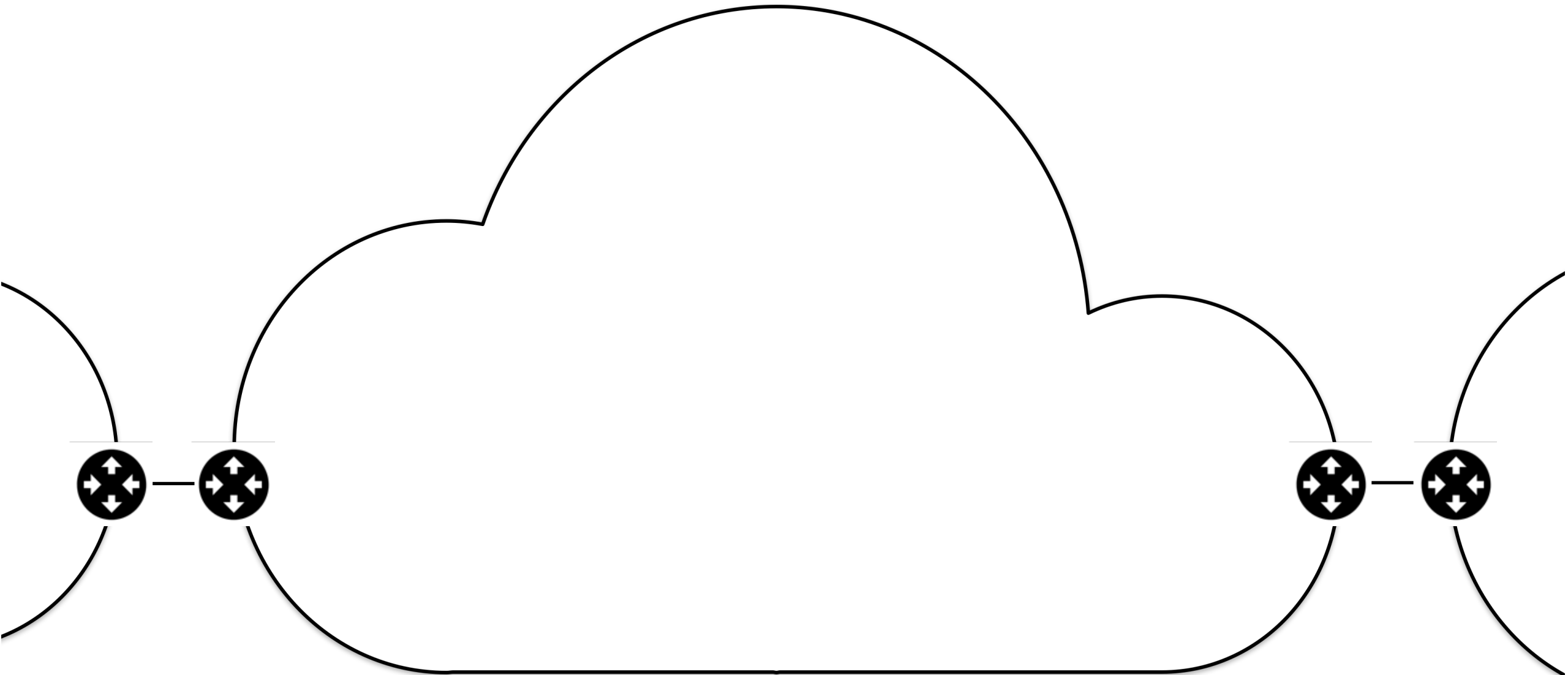
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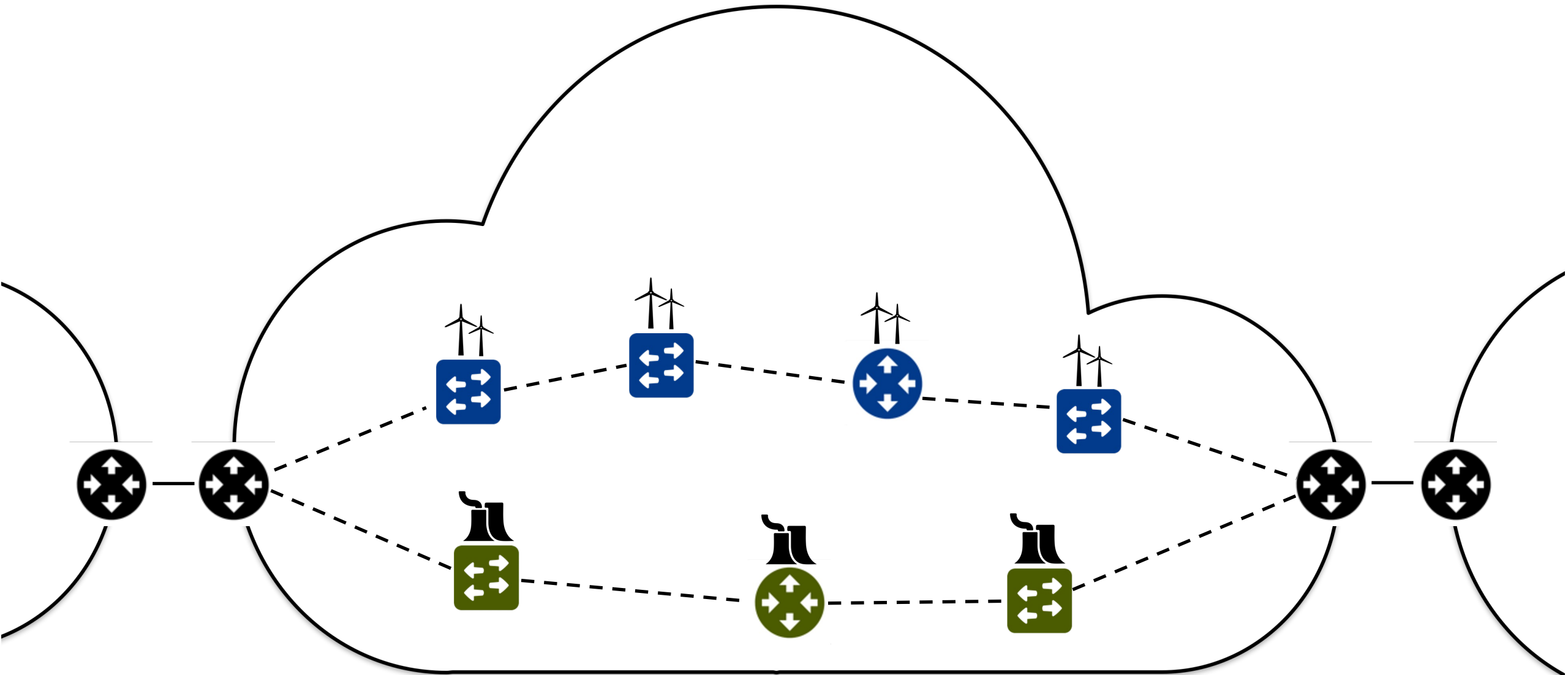
Carbon Intensity Forecasting



Network-Specific Carbon Intensity



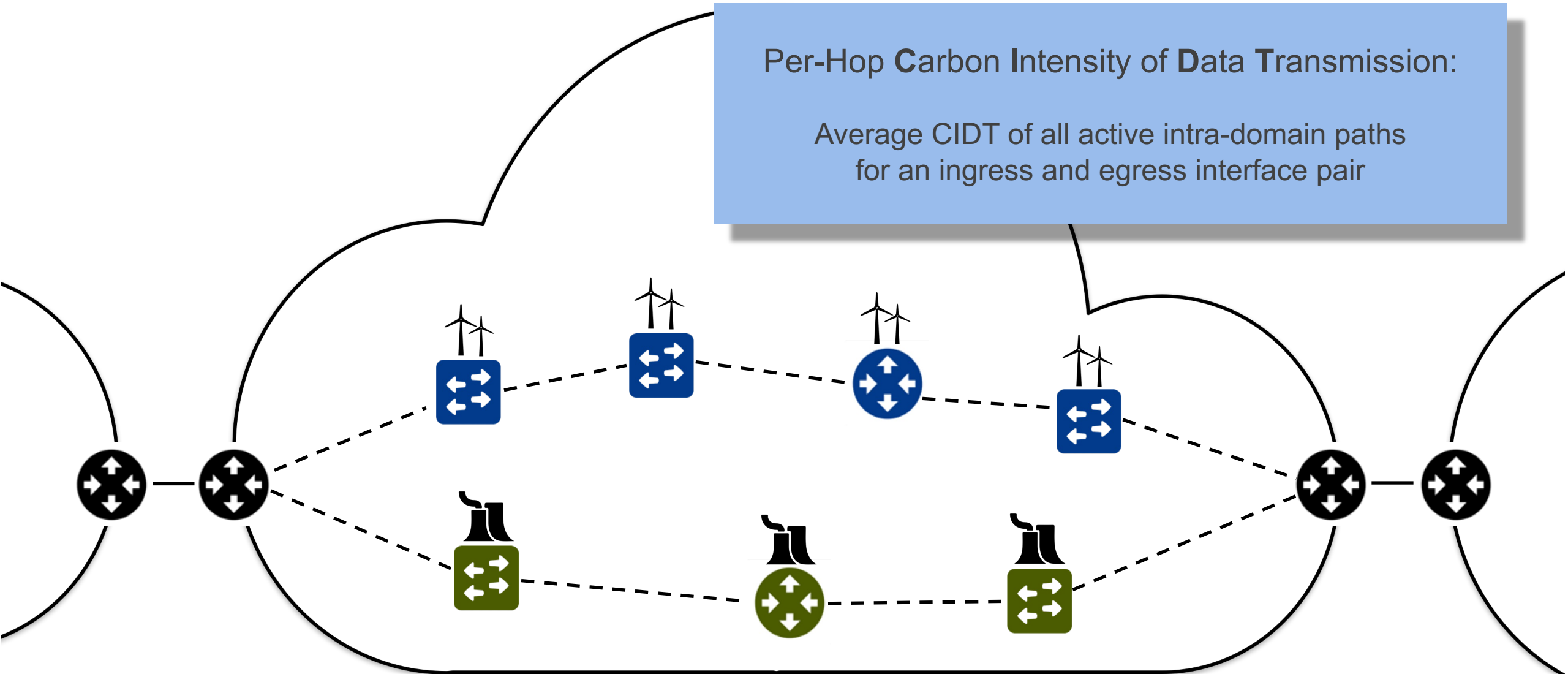
Network-Specific Carbon Intensity



Network-Specific Carbon Intensity

Per-Hop Carbon Intensity of Data Transmission:

Average CIDT of all active intra-domain paths
for an ingress and egress interface pair



Device-Specific Carbon Intensity

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

Device-Specific Carbon Intensity

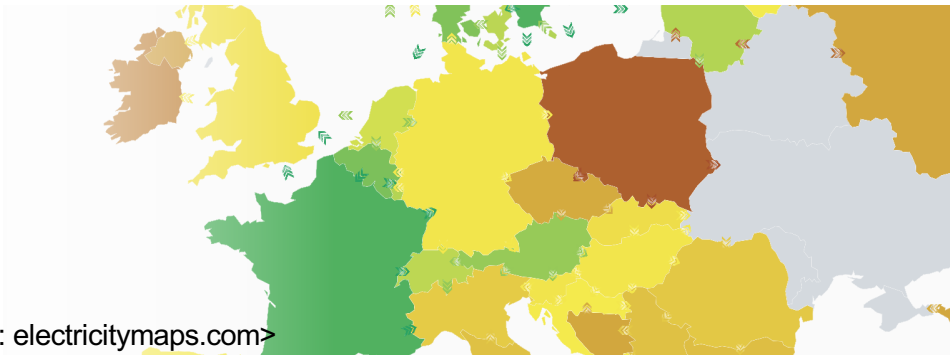
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① Carbon-Intensity of Electricity

Device Location ⊕ Electricity-Grid Forecast



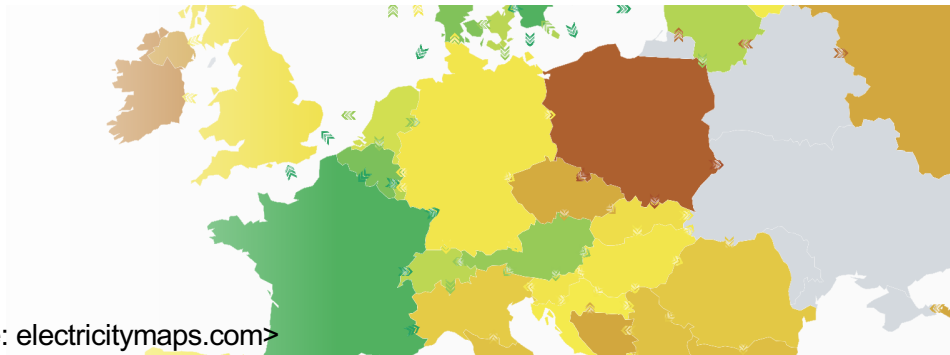
<source: electricitymaps.com>

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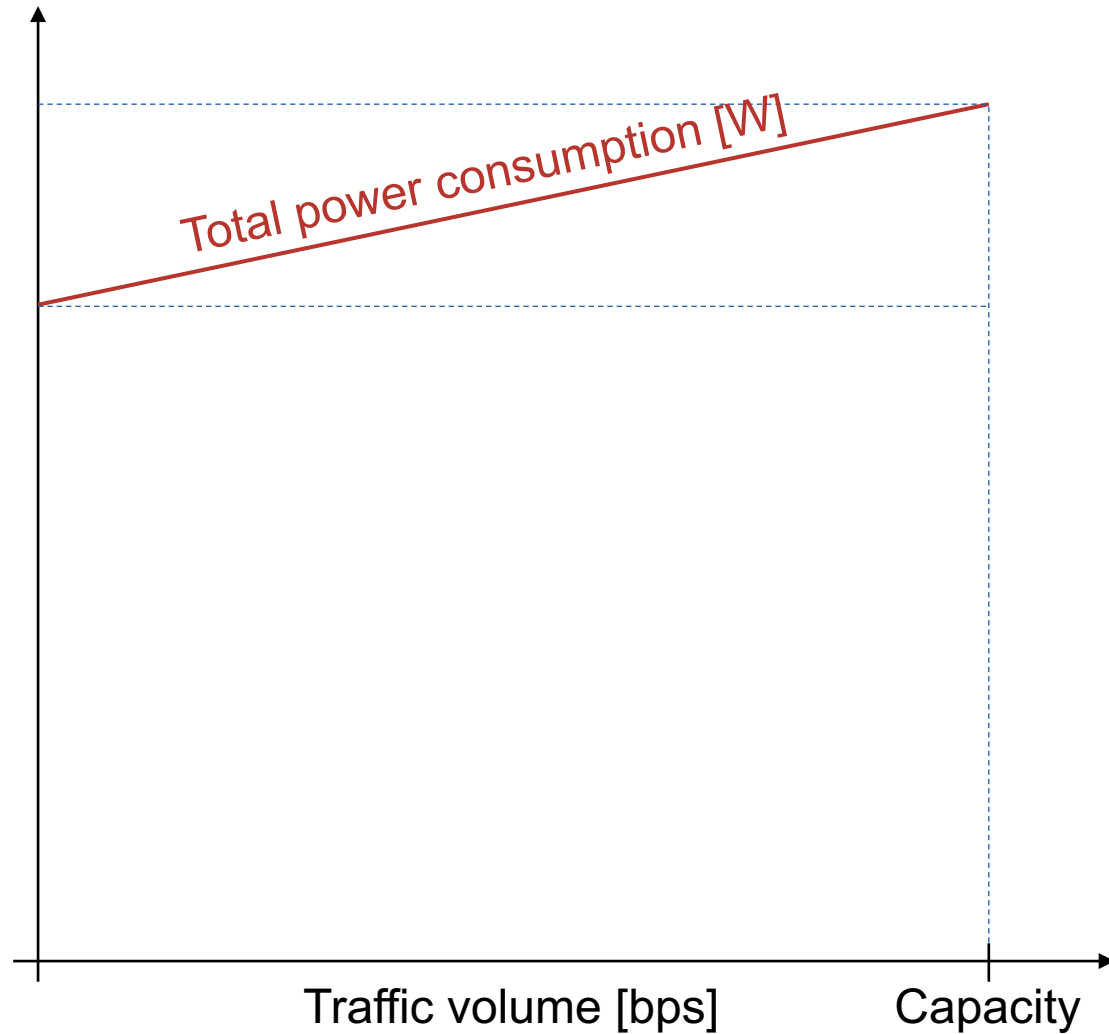


② Energy-Intensity of Data Transmission

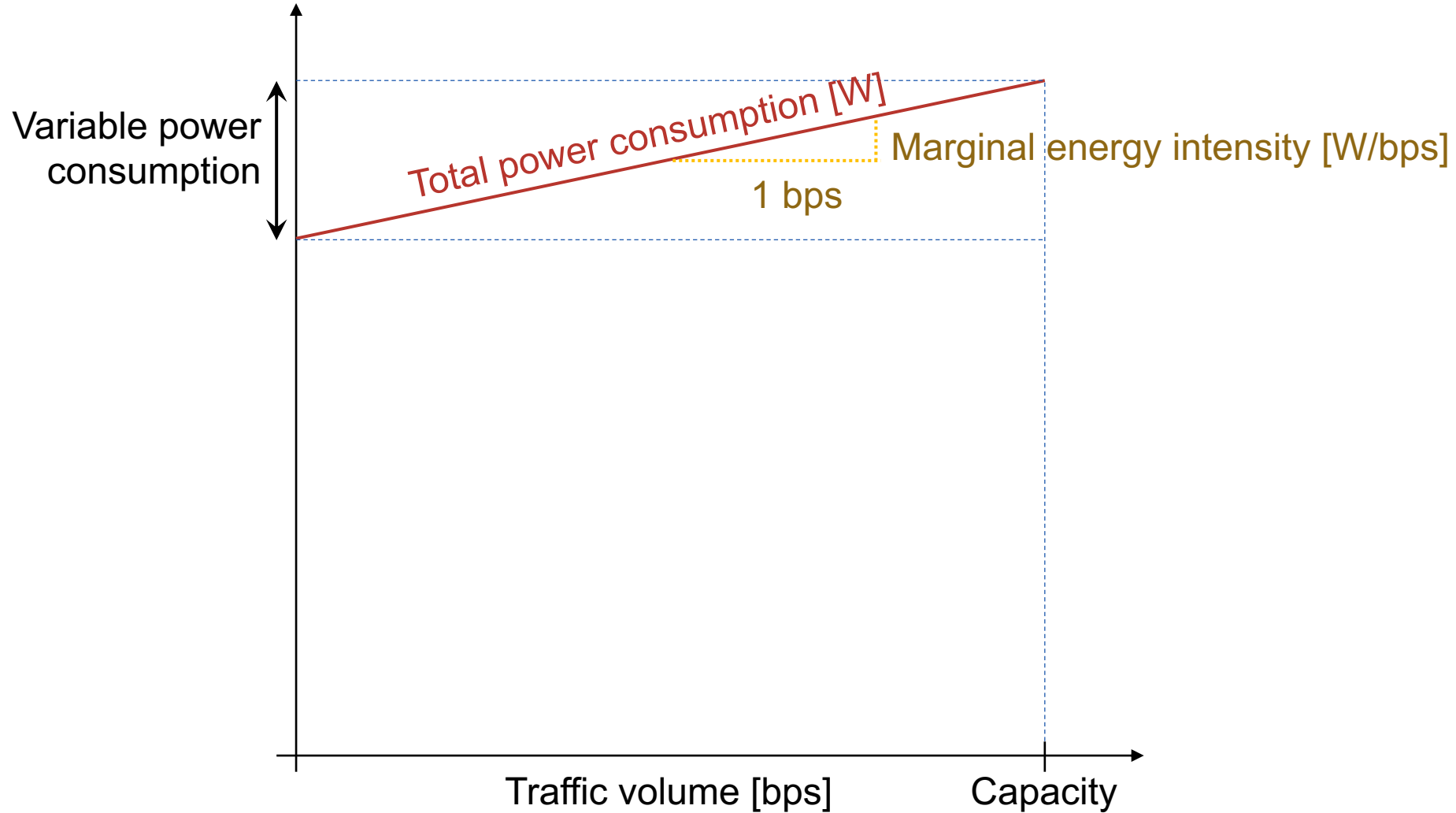
Device Power Profile

Mode	Current [mA]	Power Consumption [mW]		Grade
		@ 1.8 V	@ 3.6 V	
Power Down	700 nA	< 1.26 uW	< 2.52 uW	A
CPU Active	4.1	7.38	14.76	B
Receiving	6	10.8	21.6	C
Transmitting	14.5	26.1	52.2	D
CPU Active + TX	18.6	33.48	66.96	E

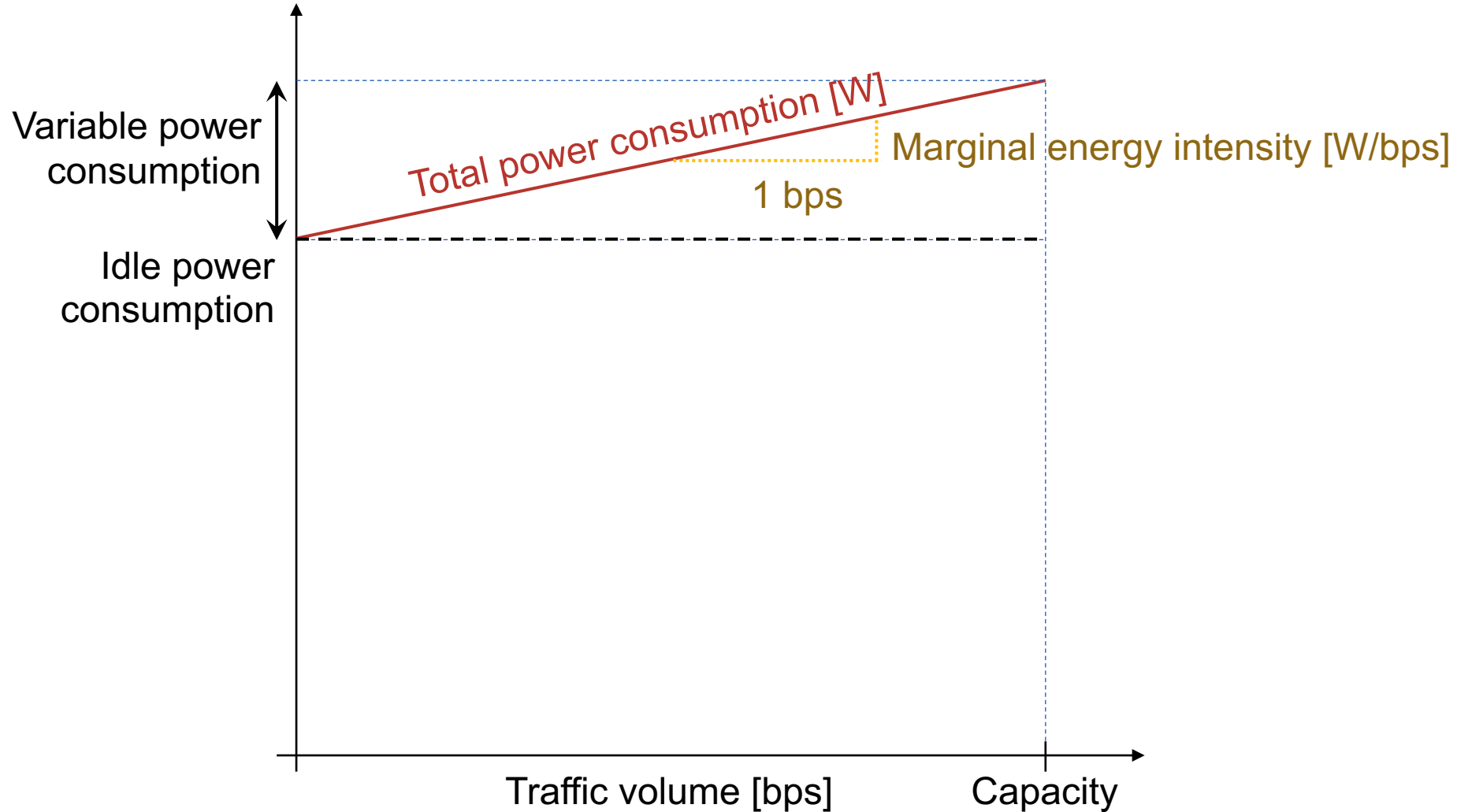
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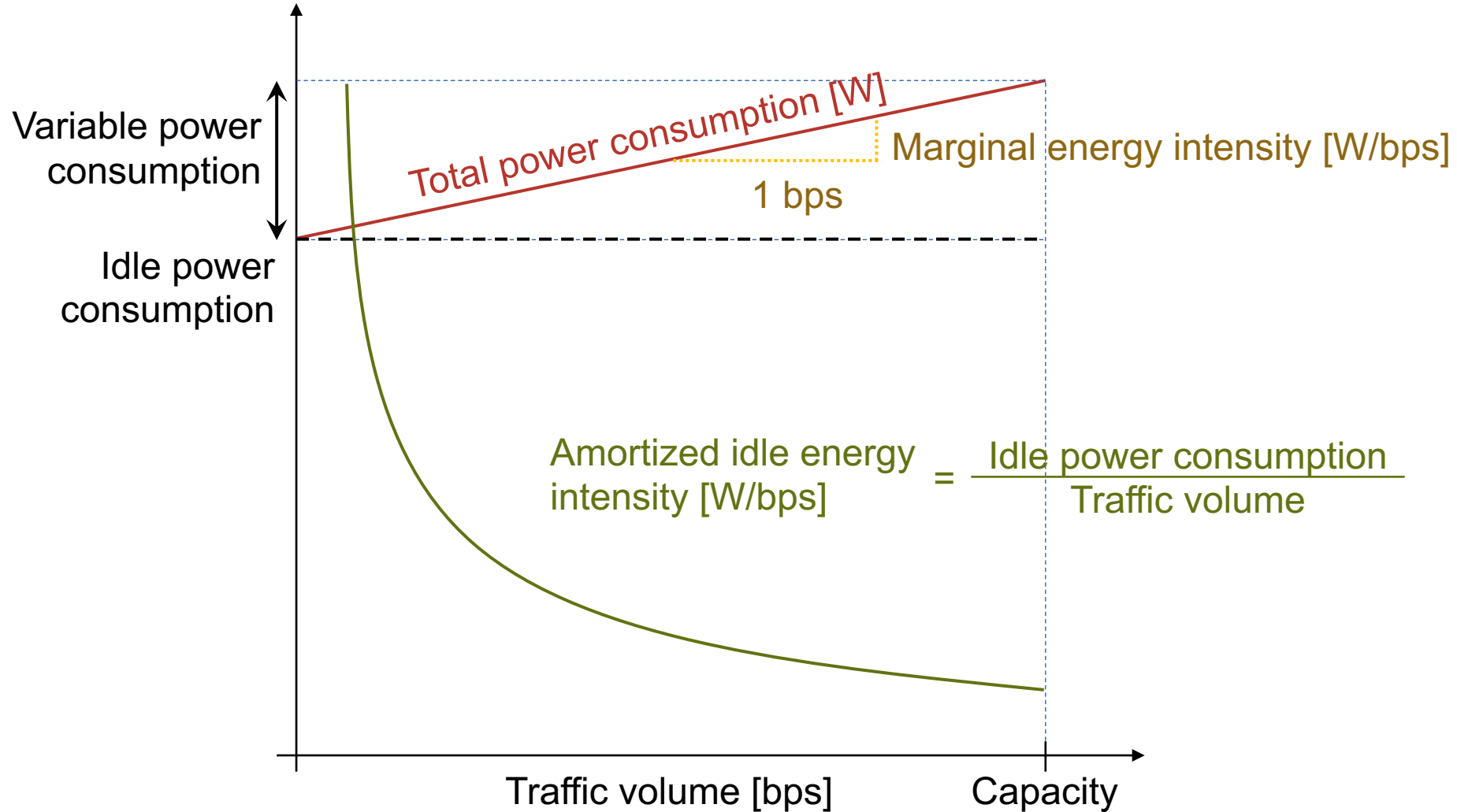
Device Power Profile



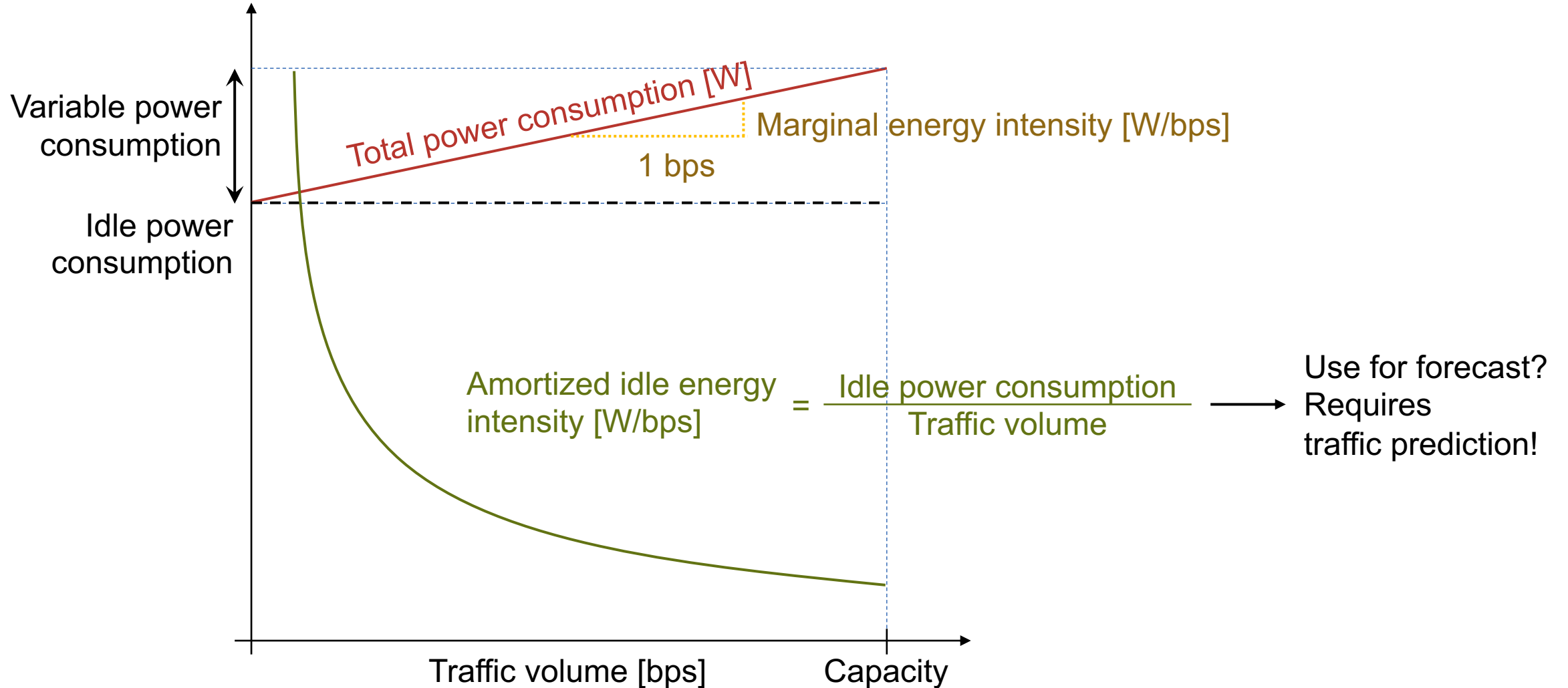
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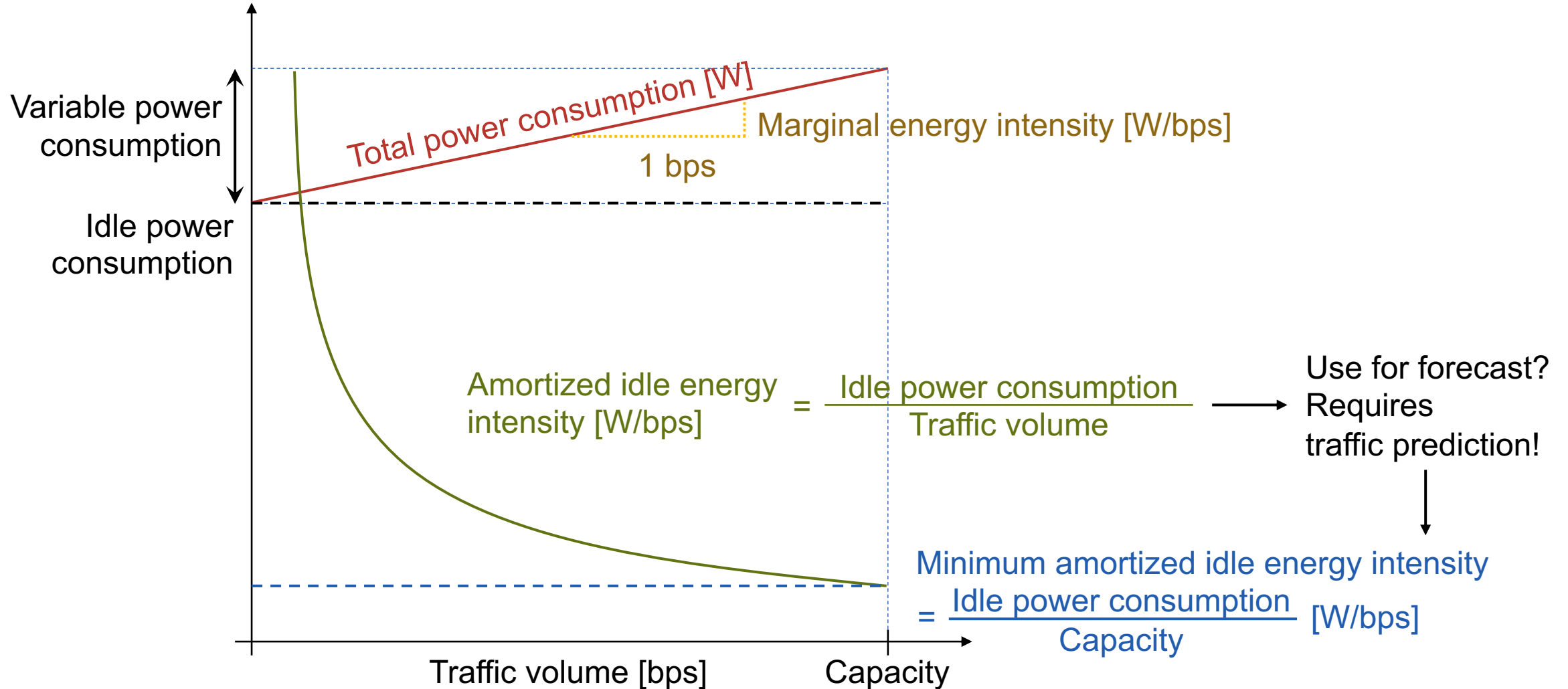
Device Power Profile



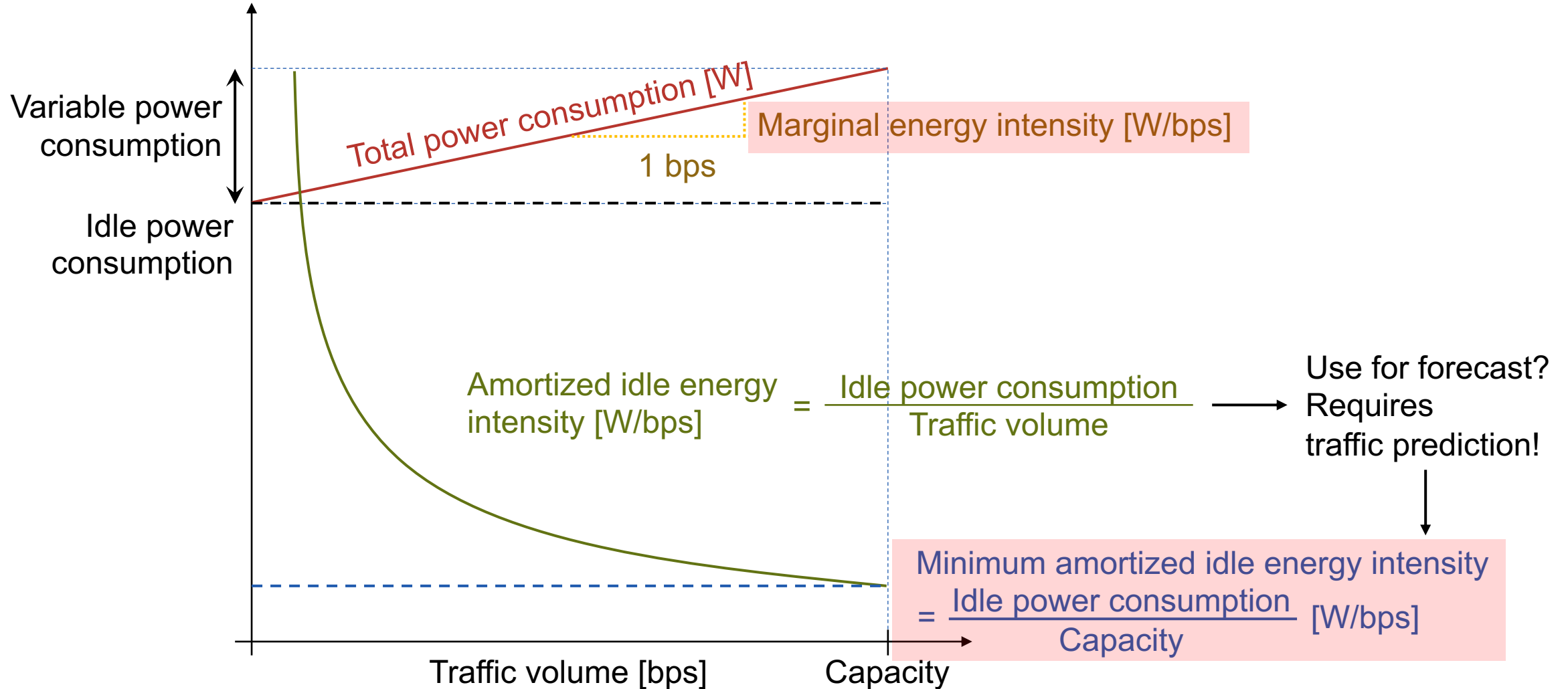
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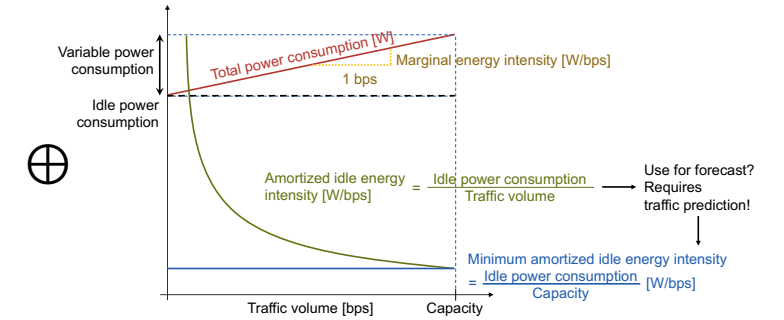
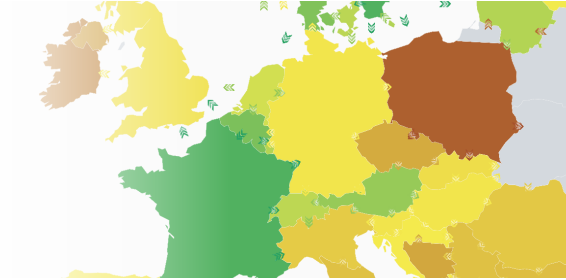


Device Power Profile



Carbon Intensity Forecasting: Summary

Carbon intensity of devices

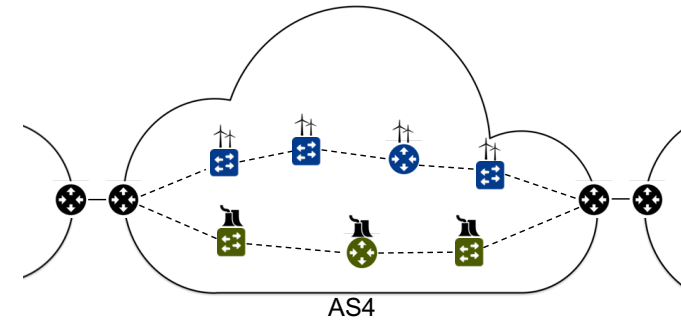
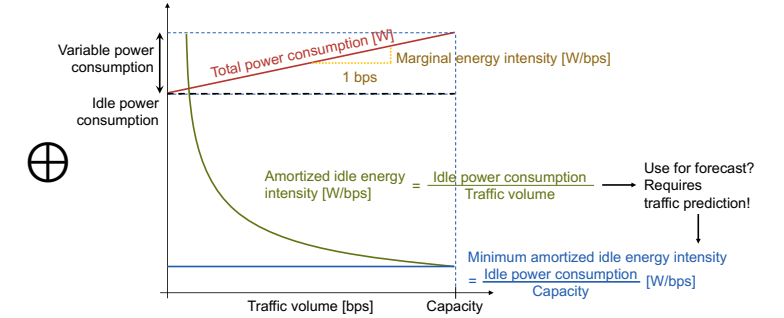
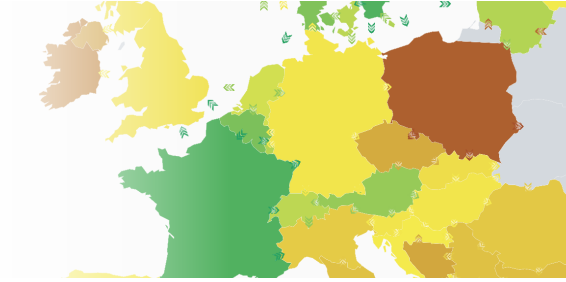


Carbon Intensity Forecasting: Summary

Carbon intensity of devices



Carbon intensity of intra-network paths



Carbon Intensity Forecasting: Summary

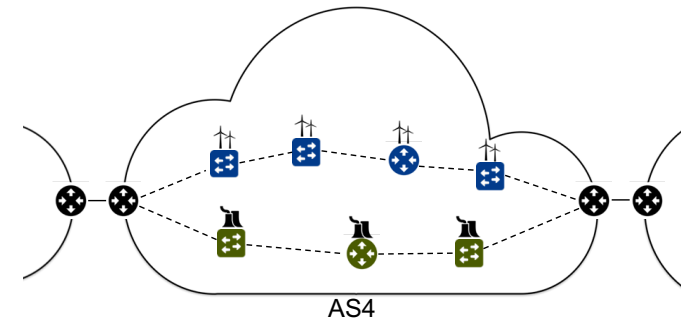
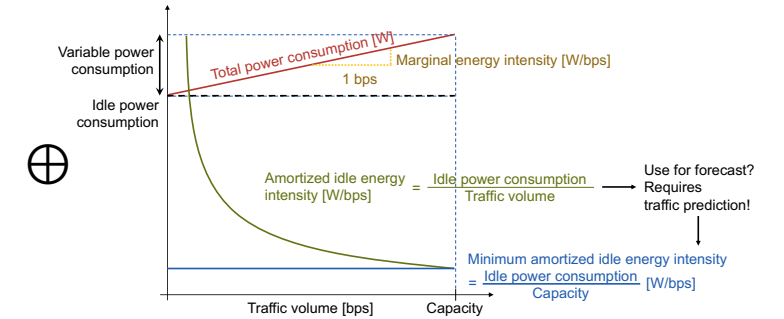
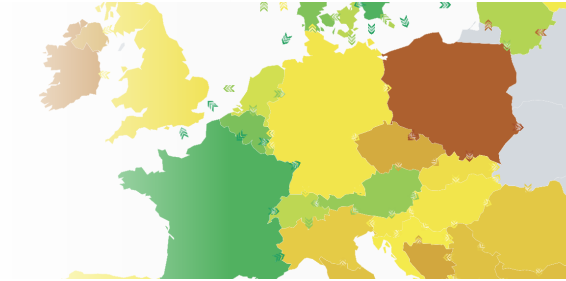
Carbon intensity of devices



Carbon intensity of intra-network paths



Carbon intensity of network with respect to interface pair



Carbon Intensity Forecasting: Summary

Carbon intensity of devices



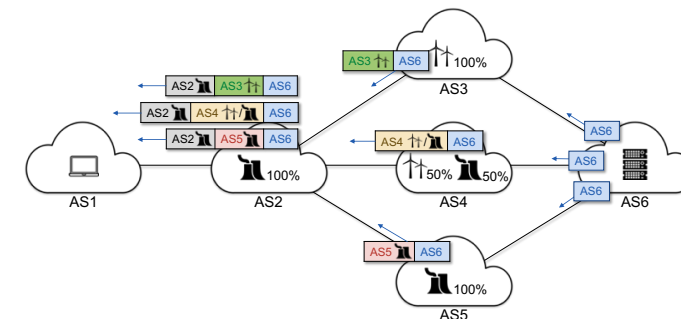
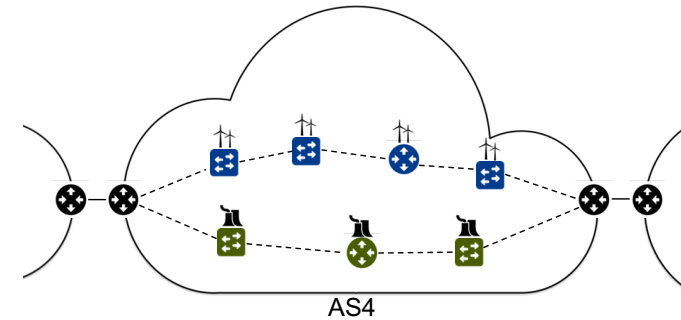
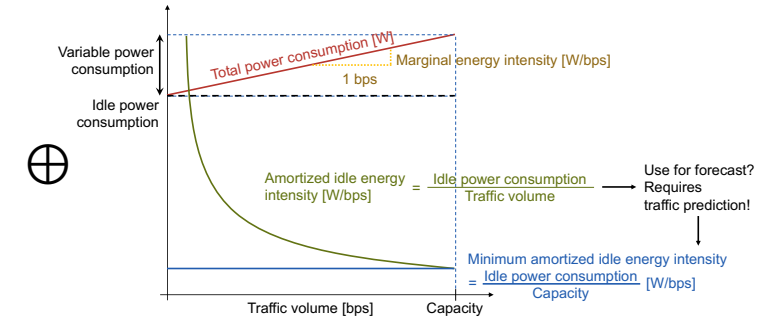
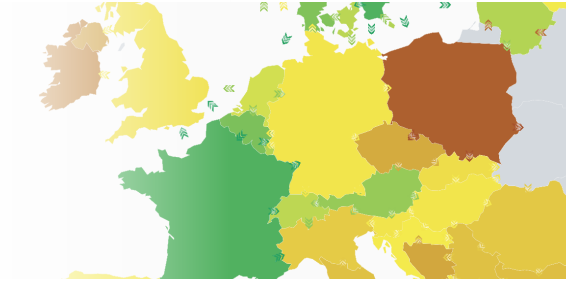
Carbon intensity of intra-network paths



Carbon intensity of network with respect to interface pair



Carbon intensity of Internet path

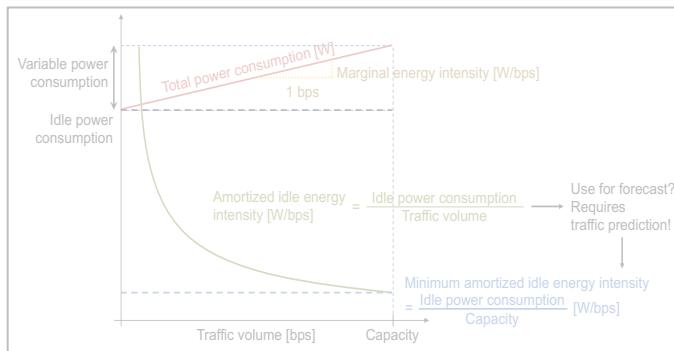


Carbon-Aware Inter-Domain Routing

- **CIRo**: Carbon-Aware Inter-Domain Routing based on Path-Aware Networking

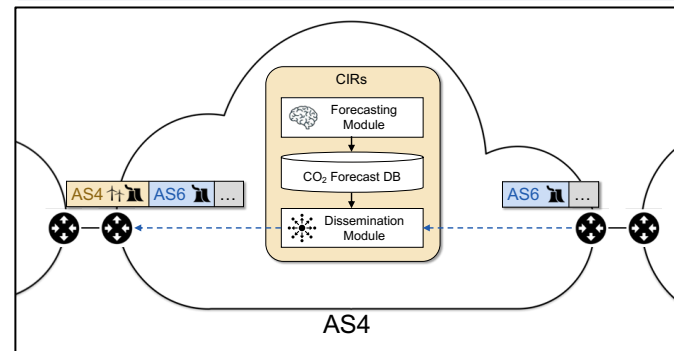
Carbon-Intensity Forecasting

Model for carbon intensity of Internet paths



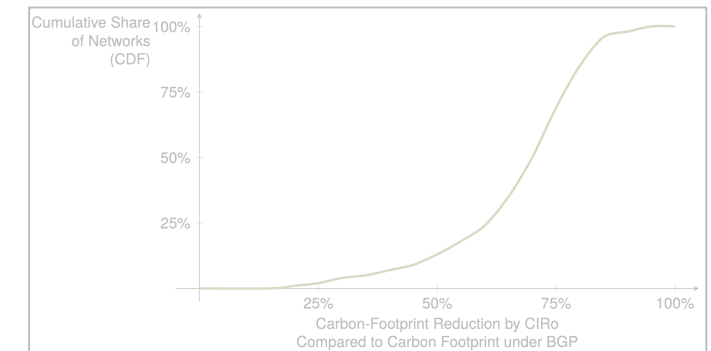
Carbon-Information Dissemination

System for timely communication of forecasts

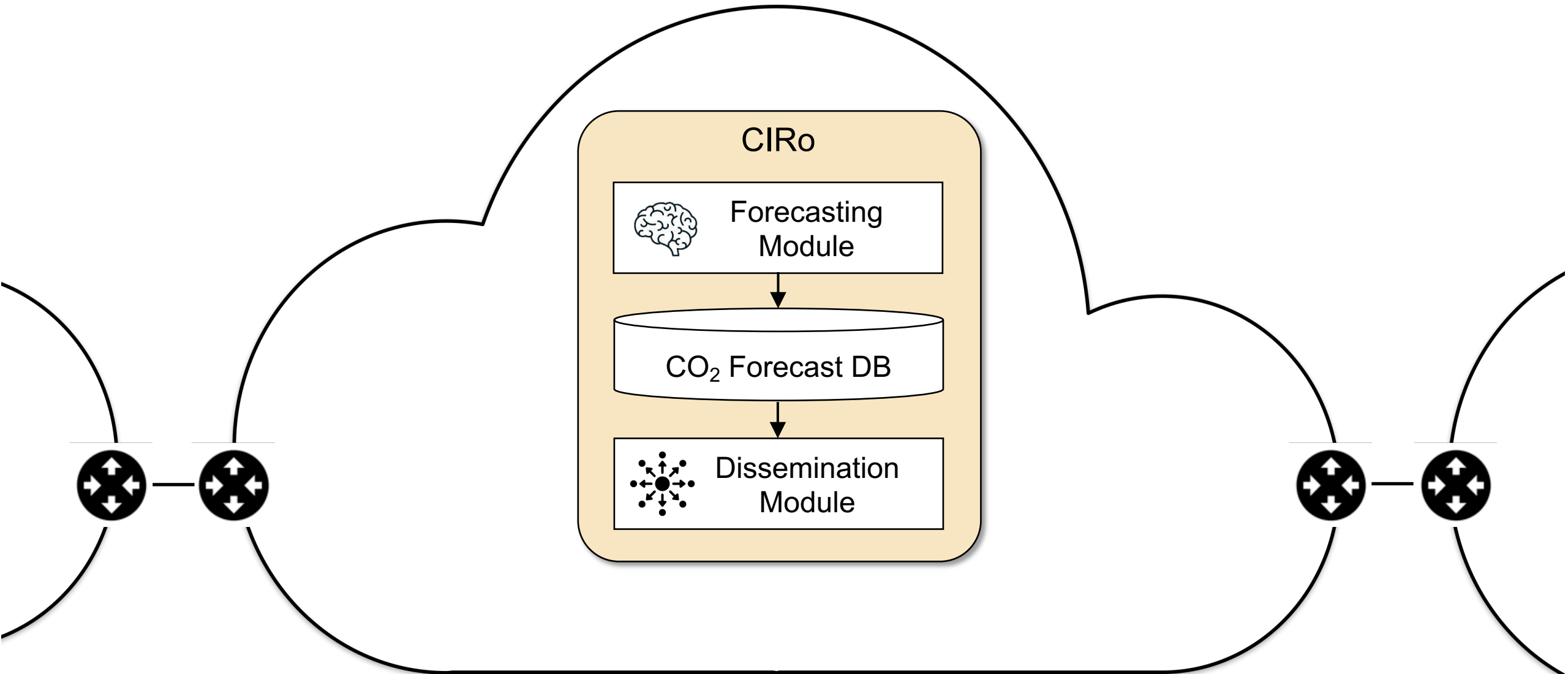


Carbon-Footprint Impact Analysis

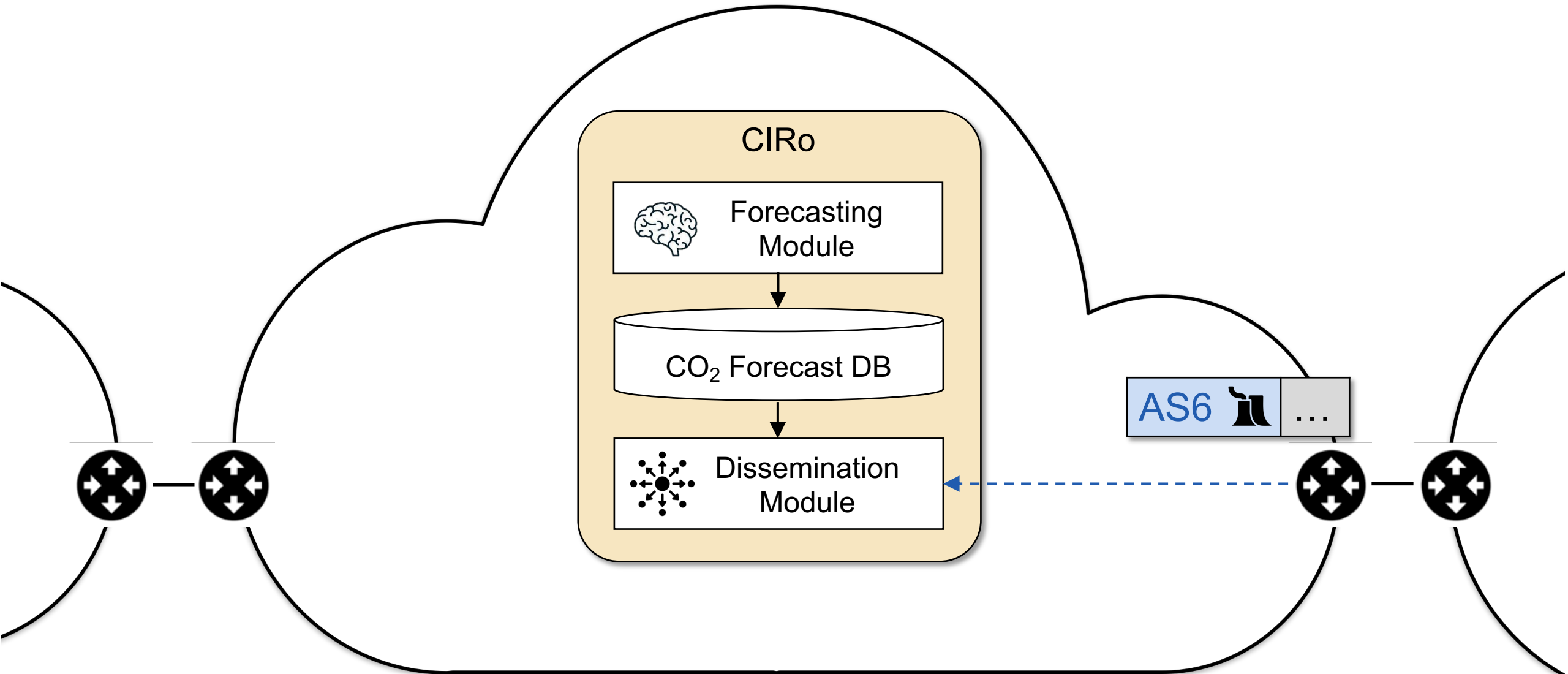
Simulation on data-backed large-scale topology



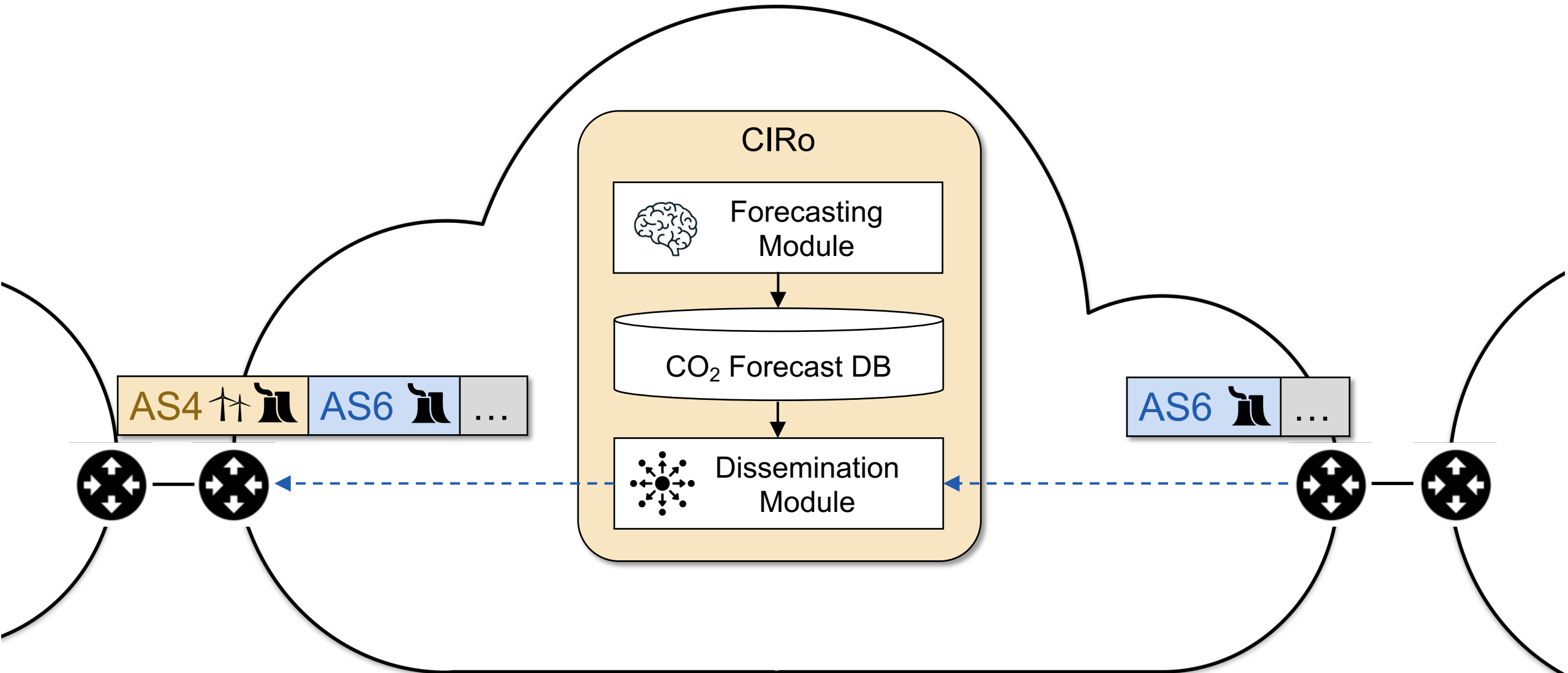
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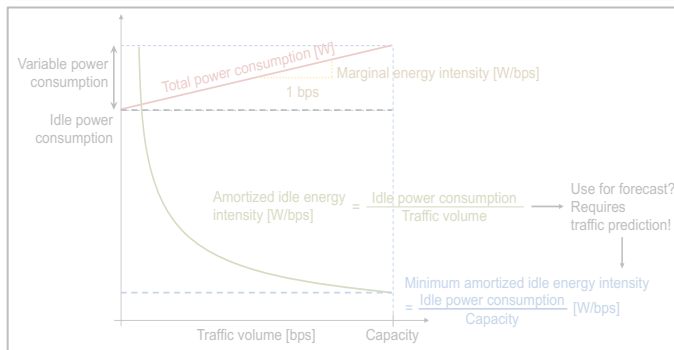


Carbon-Aware Inter-Domain Routing

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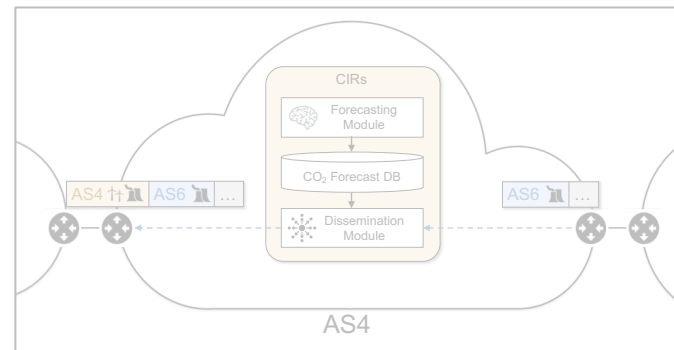
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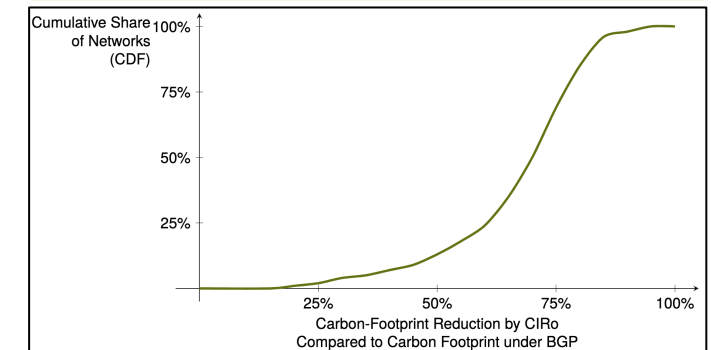
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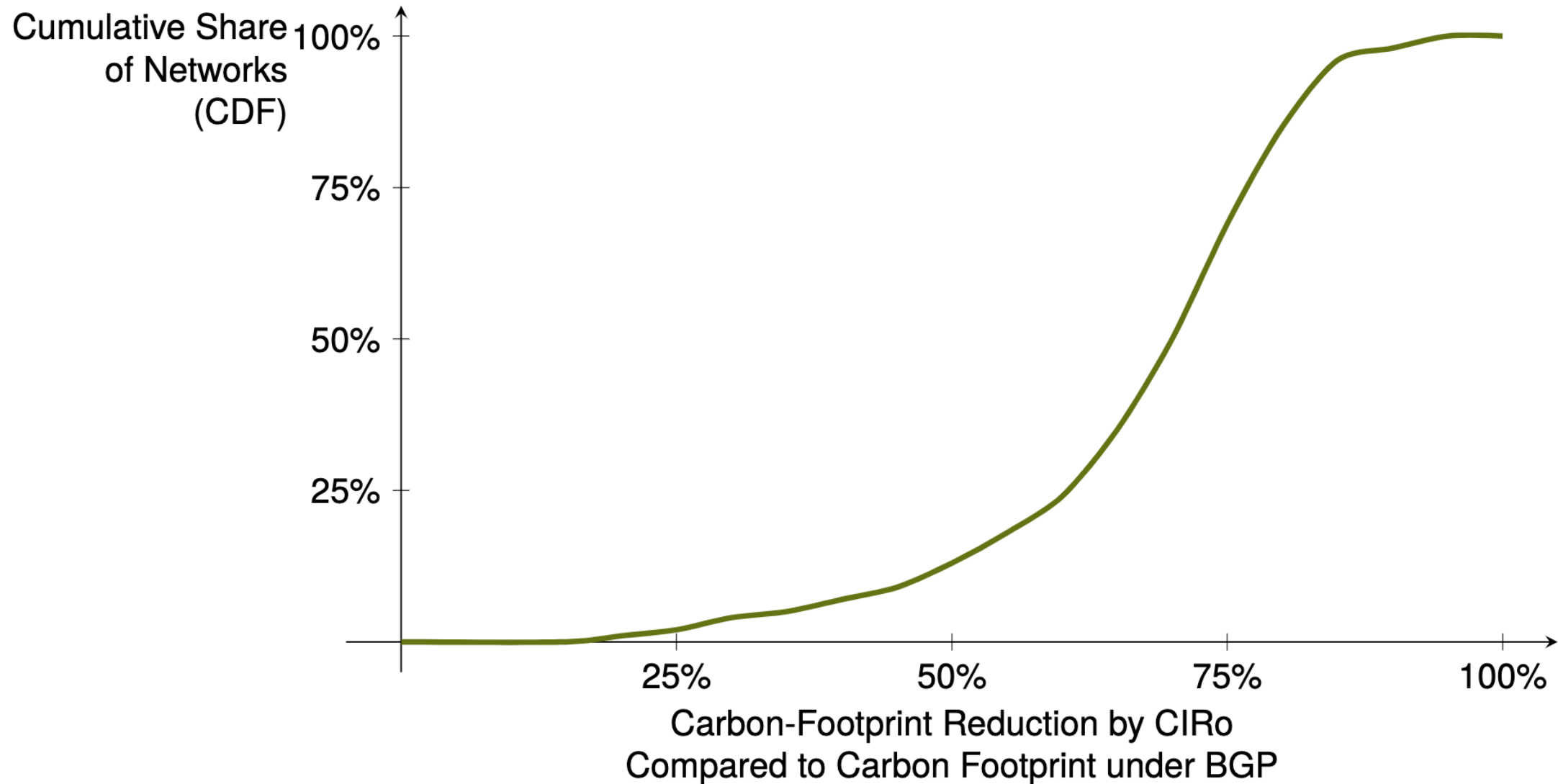


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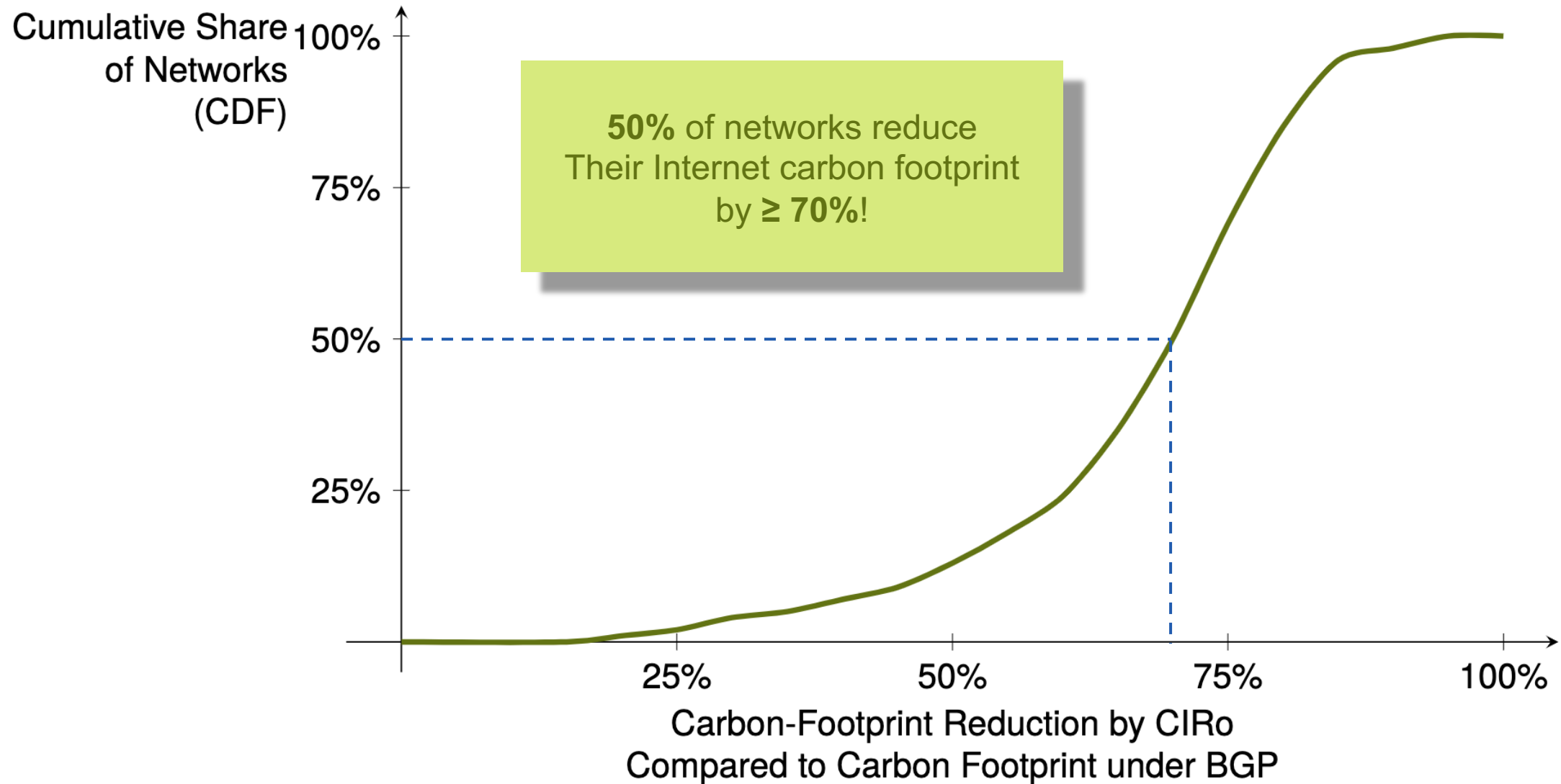
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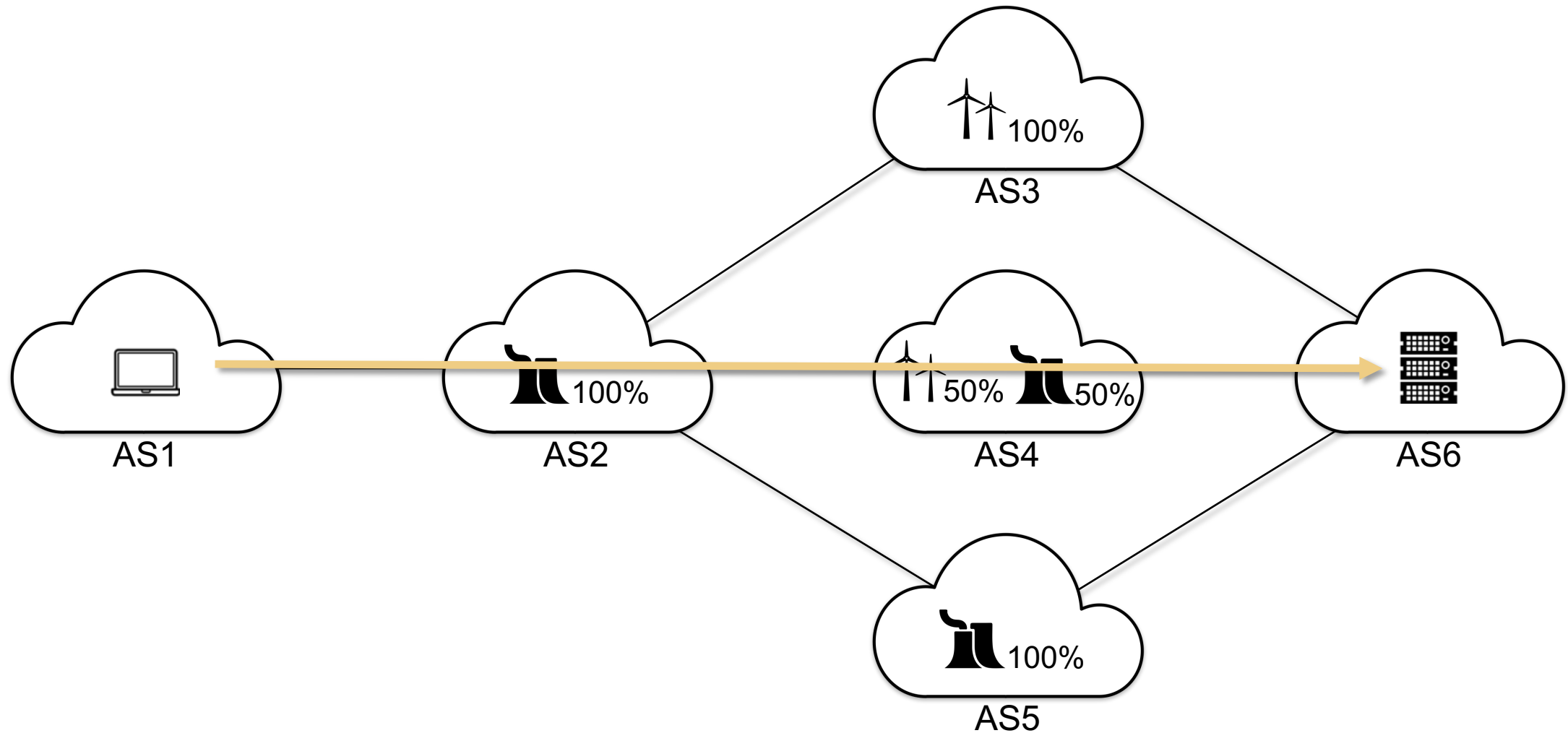
Carbon Footprint Simulation (CAIDA Core Topology)



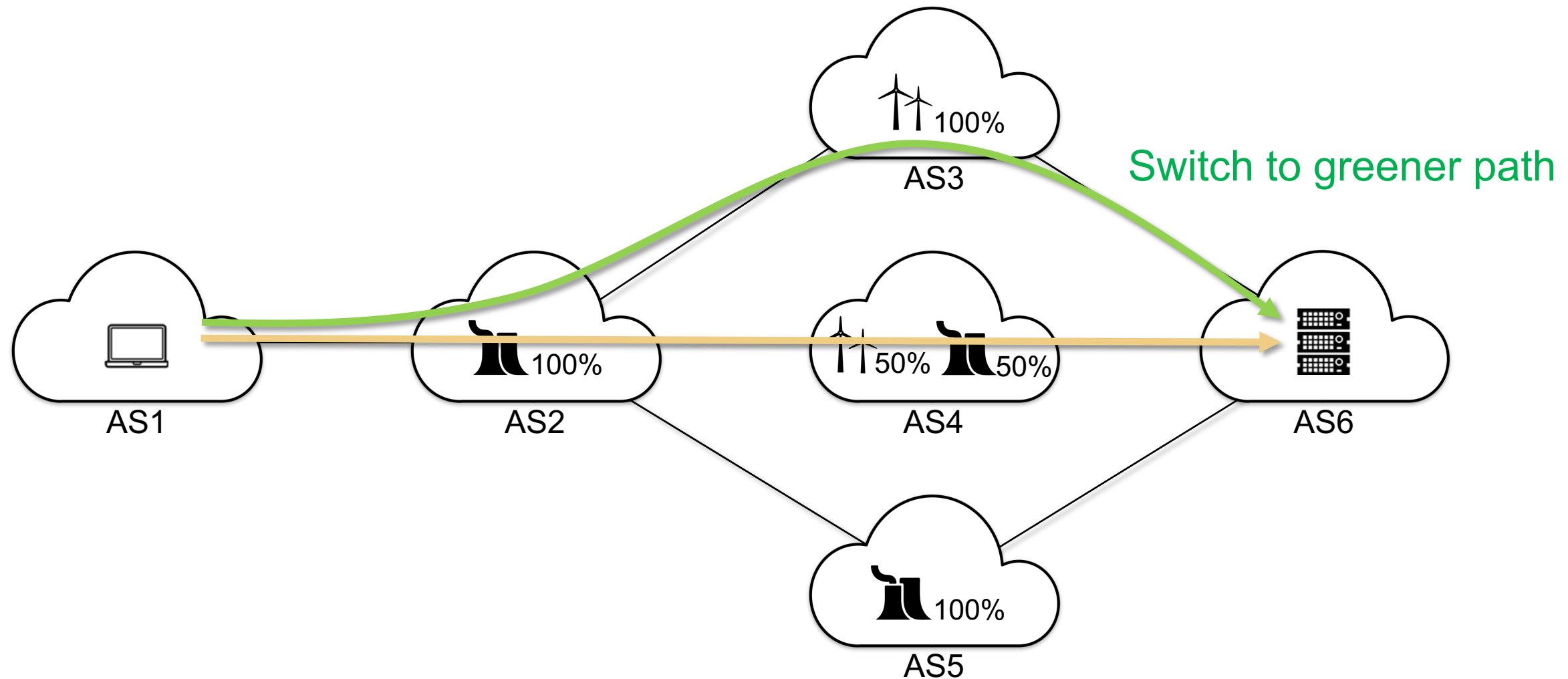
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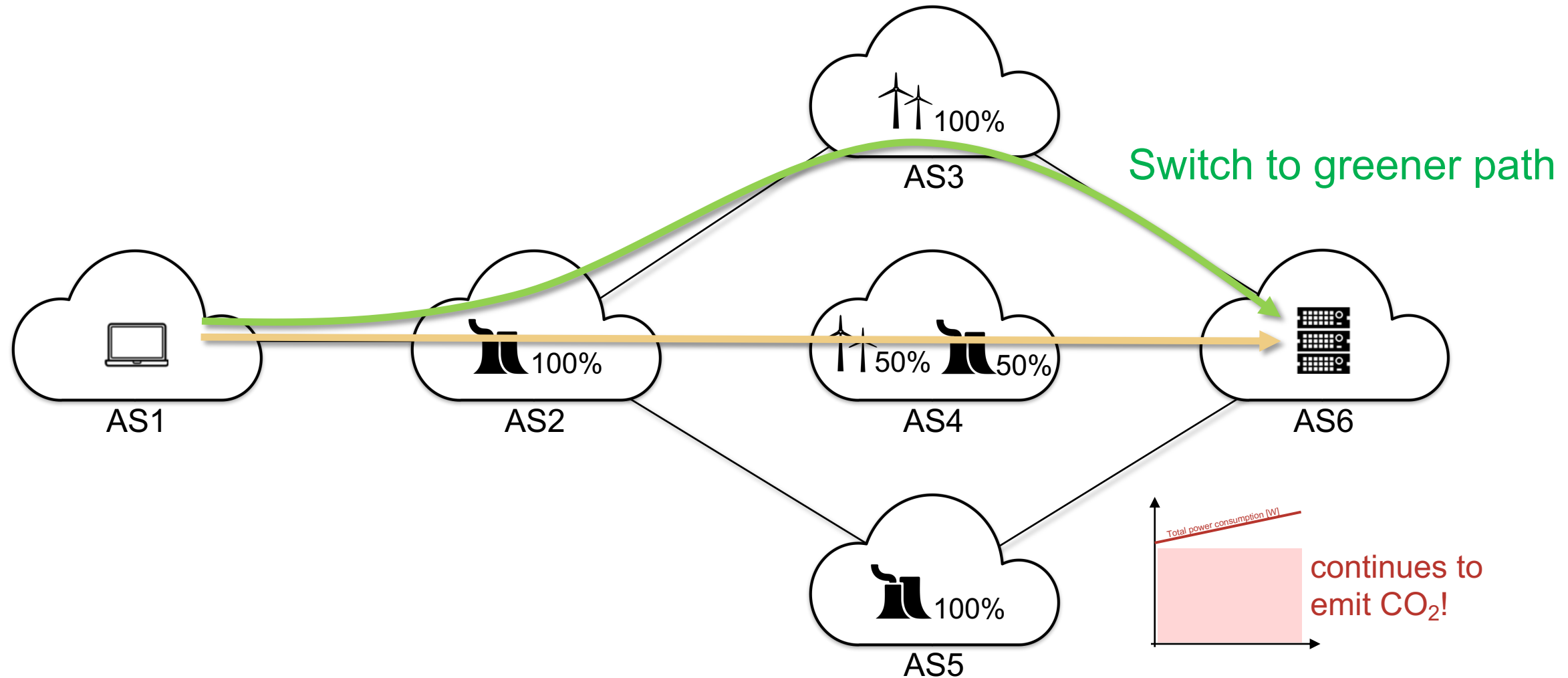
Carbon Footprint \neq Carbon Emission



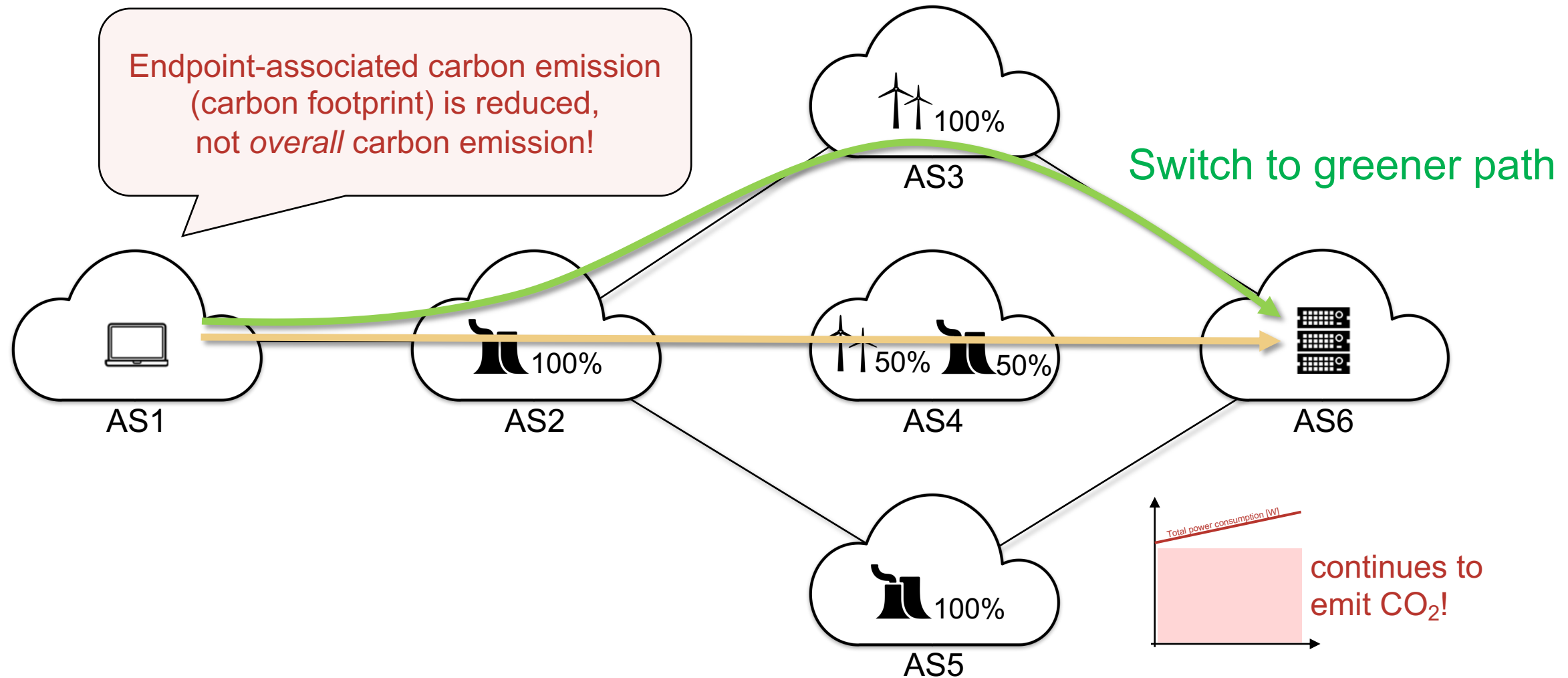
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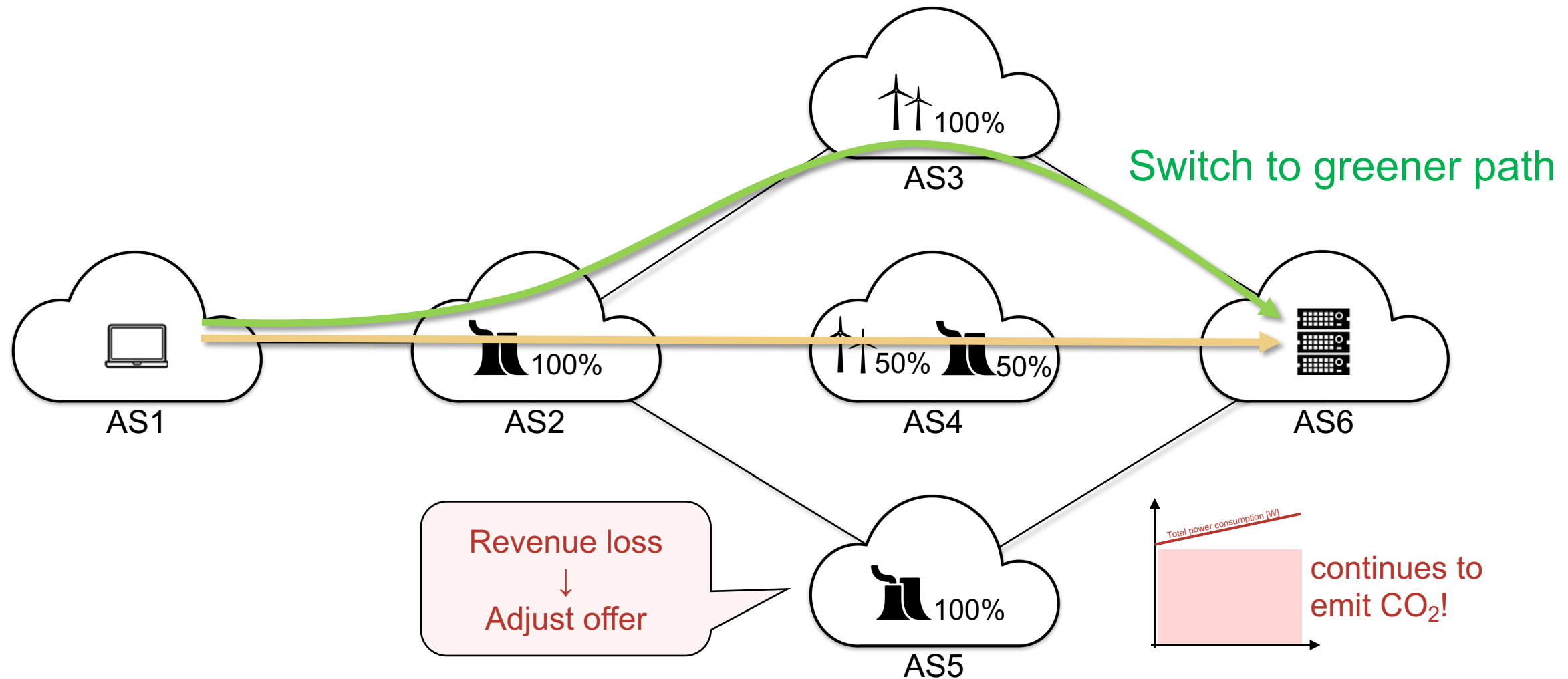
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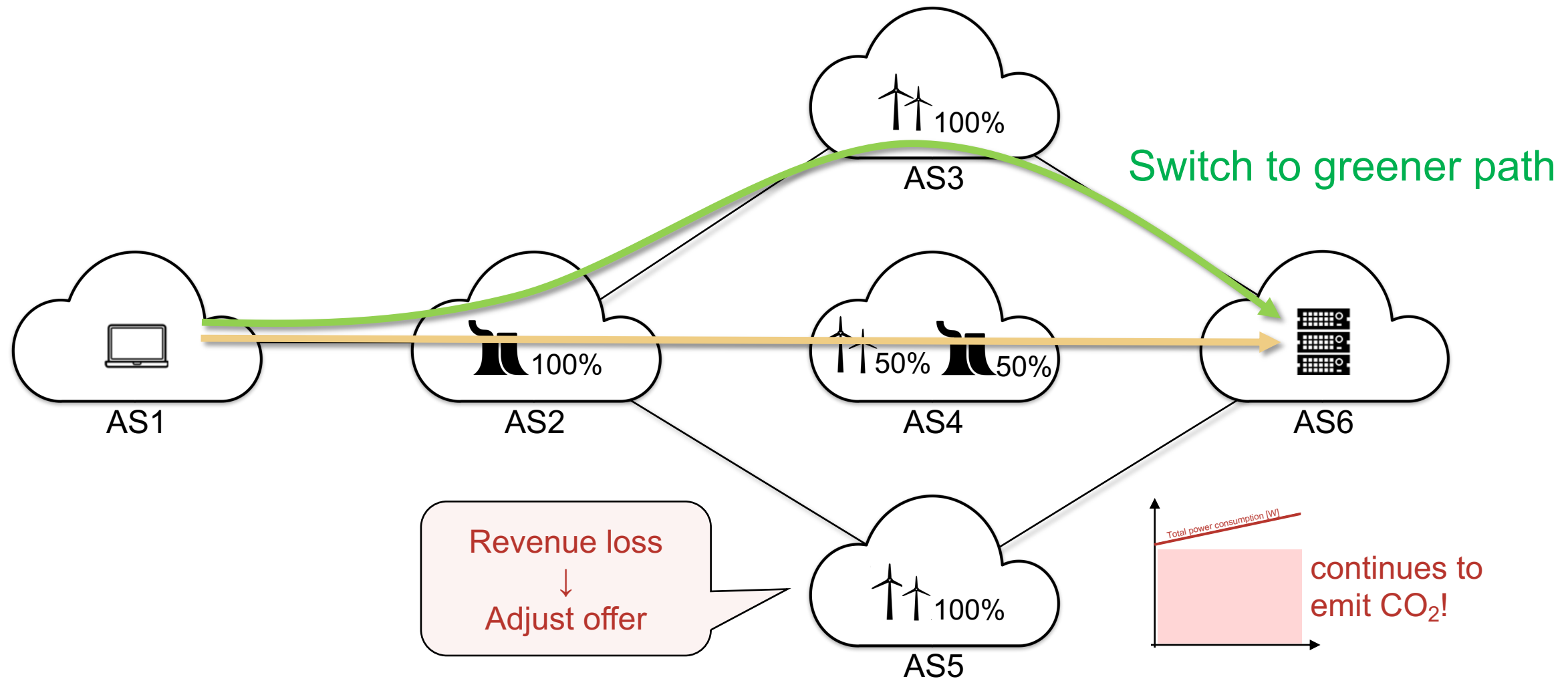
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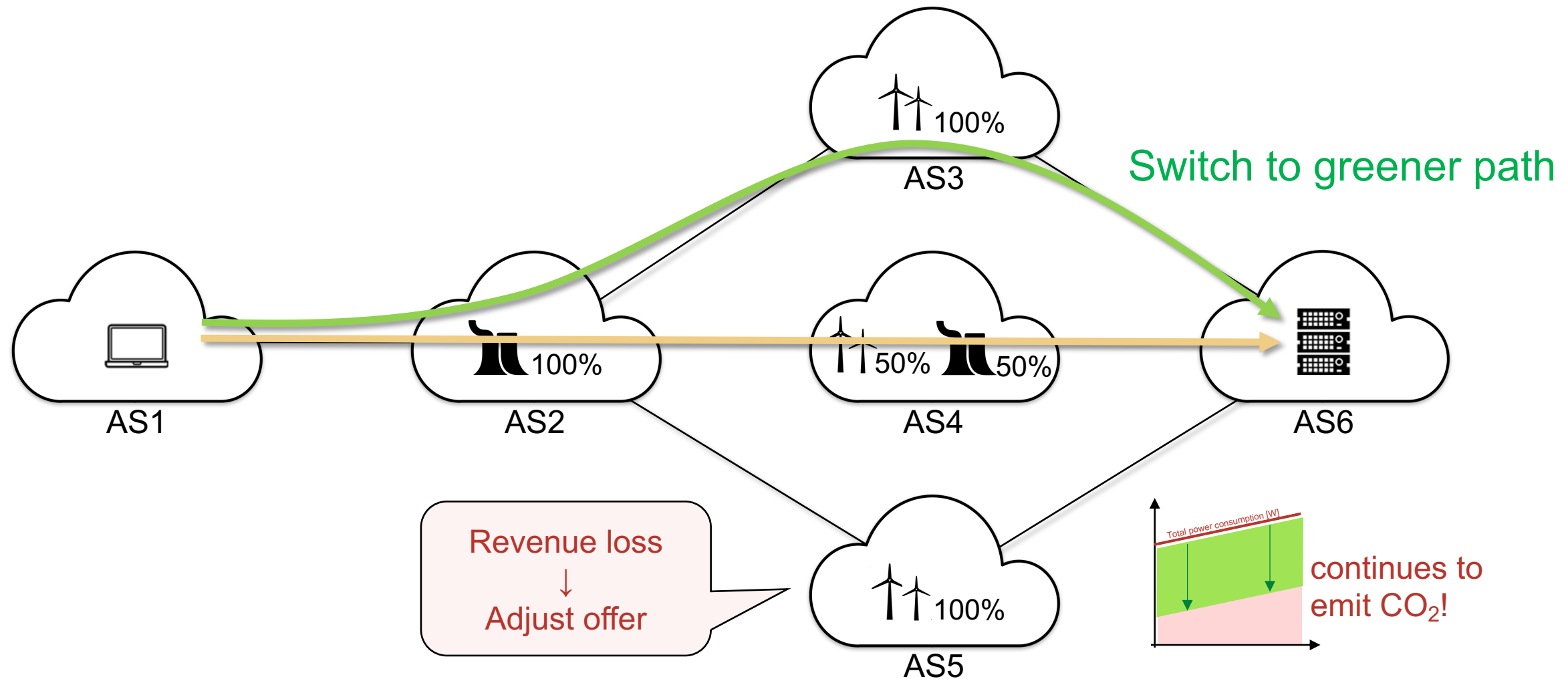
How to Actually Reduce Emission?



How to Actually Reduce Emission?



How to Actually Reduce Emission?



Carbon-Aware Global Routing in Path-Aware Networks

Seyedali Tabaeiaghdaei
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Jonghoon Kwon
ETH Zürich

Simon Scherrer
ETH Zürich

Adrian Perrig
ETH Zürich

ABSTRACT

The growing energy consumption of Information and Communication Technology (ICT) has raised concerns about its environmental impact. However, the carbon footprint of data transmission over the Internet has so far received relatively modest attention. This carbon footprint can be reduced by sending traffic over carbon-efficient inter-domain paths. However, challenges in estimating and disseminating carbon intensity of inter-domain paths have prevented carbon-aware path selection from becoming a reality.

In this paper, we take advantage of path-aware network architectures to overcome these challenges. In particular, we design CIRo, a system for forecasting the carbon intensity of inter-domain paths and disseminating them across the Internet. We implement a proof of concept for CIRo on the codebase of the SCION path-aware Internet architecture and test it on the SCIONLab global research testbed. Further, through large-scale simulations, we demonstrate the potential of CIRo for reducing the carbon footprint of endpoints and end domains: With CIRo, half of domain pairs can reduce the carbon intensity of their inter-domain traffic by at least 47%, and 87% of end domains can reduce their carbon footprint of Internet use by at least 50%.

CCS CONCEPTS

• **Applied computing** → **Forecasting**; **Multi-criterion optimization and decision-making**; • **Networks** → **Network measurement**; **Network simulations**; **Network performance modeling**; **Data path algorithms**; **Control path algorithms**; Topology analysis and generation; • **Hardware** → **Renewable energy**.

KEYWORDS

Green Networking, Internet Carbon-Emission Modeling and Measurement, Inter-Domain Routing, Carbon-Aware Routing, SCION

ACM Reference Format:

Seyedali Tabaeiaghdaei, Simon Scherrer, Jonghoon Kwon, and Adrian Perrig. 2023. Carbon-Aware Global Routing in Path-Aware Networks. In *The 14th ACM International Conference on Future Energy Systems (e-Energy '23)*, June 20–23, 2023, Orlando, FL, USA. ACM, New York, NY, USA, 15 pages. <https://doi.org/10.1145/3575813.3595192>

1 INTRODUCTION

Growing concerns regarding climate change encourage companies to measure and reduce their carbon footprint, i.e., the amount of carbon emission that can be attributed to them. This also applies to their use of Information and Communication Technology (ICT), as ICT has a notable contribution of 2.7% to global CO₂ emissions [39], which is expected to grow significantly – approximately four times – until 2030 [3]. Hence, reducing the carbon footprint of ICT use is becoming increasingly relevant for enterprises, manifesting in carbon-neutrality statements of major technology corporations.

While these efforts are laudable and impactful, promising opportunities for further carbon-footprint reduction exist. Indeed, previous research has identified a range of such opportunities. However, most of these proposals apply to local aspects: intra-domain networking (i.e., within a single domain), data-center optimizations, or neighbor-domain cooperation (cf. §8). In contrast, inter-domain networking (i.e., among multiple domains), which accounts for around 13% of total ICT energy consumption, has so far received less attention. An exception is the work by Zilberman et al. [70] who identify carbon-aware networking as a high-potential research area and sketch the concept of carbon-intelligent routing, i.e., leverage differences in network paths' carbon intensity (i.e., carbon emission per unit of data transmitted) to reduce the carbon footprint of communications.

Previous research on green inter-domain networking leveraged carbon efficiency to the optimization metric of the Border Gateway Protocol (BGP) [42]. Unfortunately, this direction faces several challenges. **Inefficient Green Route:** A strict carbon-aware routing can result in a highly inefficient end-to-end path, incurring a high primary cost, latency, bandwidth, loss, or jitter (cf. §8.1). To meet the application requirements, an optimization of the routing constraints needs to be made, requiring a more fine-grained metric space. **Ossification:** Carbon-aware routing can thus only be offered as additional optimization options, rather than the conventional BGP route. When carbon-aware routing offers efficient alternative paths, routing tables, routing policies, forwarding tables, and packets need to be updated to reflect the optimization criteria. Updating these components presents a challenge – as

More in the Paper

Carbon Intensity Modeling

Inter-Domain CIDD
Per-Hop CIDD
Single Path CIDD

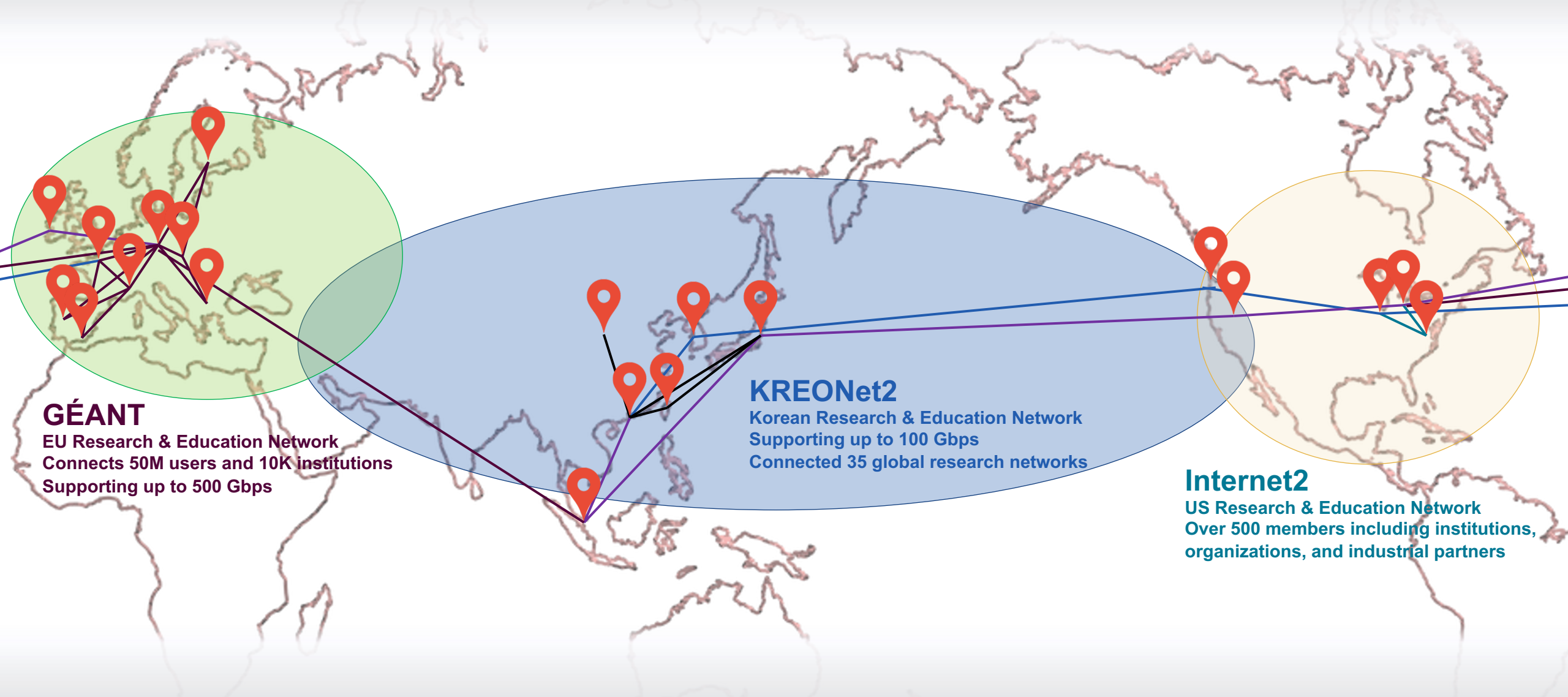
Detailed System Design

Forecasting Module
Dissemination Module
Header Design

Evaluation

SCION vs. BGP
Carbon intensity vs. Latency

Global Research and Education Network



GÉANT
 EU Research & Education Network
 Connects 50M users and 10K institutions
 Supporting up to 500 Gbps

KREONet2
 Korean Research & Education Network
 Supporting up to 100 Gbps
 Connected 35 global research networks

Internet2
 US Research & Education Network
 Over 500 members including institutions,
 organizations, and industrial partners

- KREONet2
- GÉANT
- Internet2
- Amazon



Summary

The first Internet-wide carbon footprint monitoring system

Enabling endpoints to select the greenest paths

Introduces green competition between ISPs

Expected savings: 20% CO₂ reduction for global ISPs

Q&A

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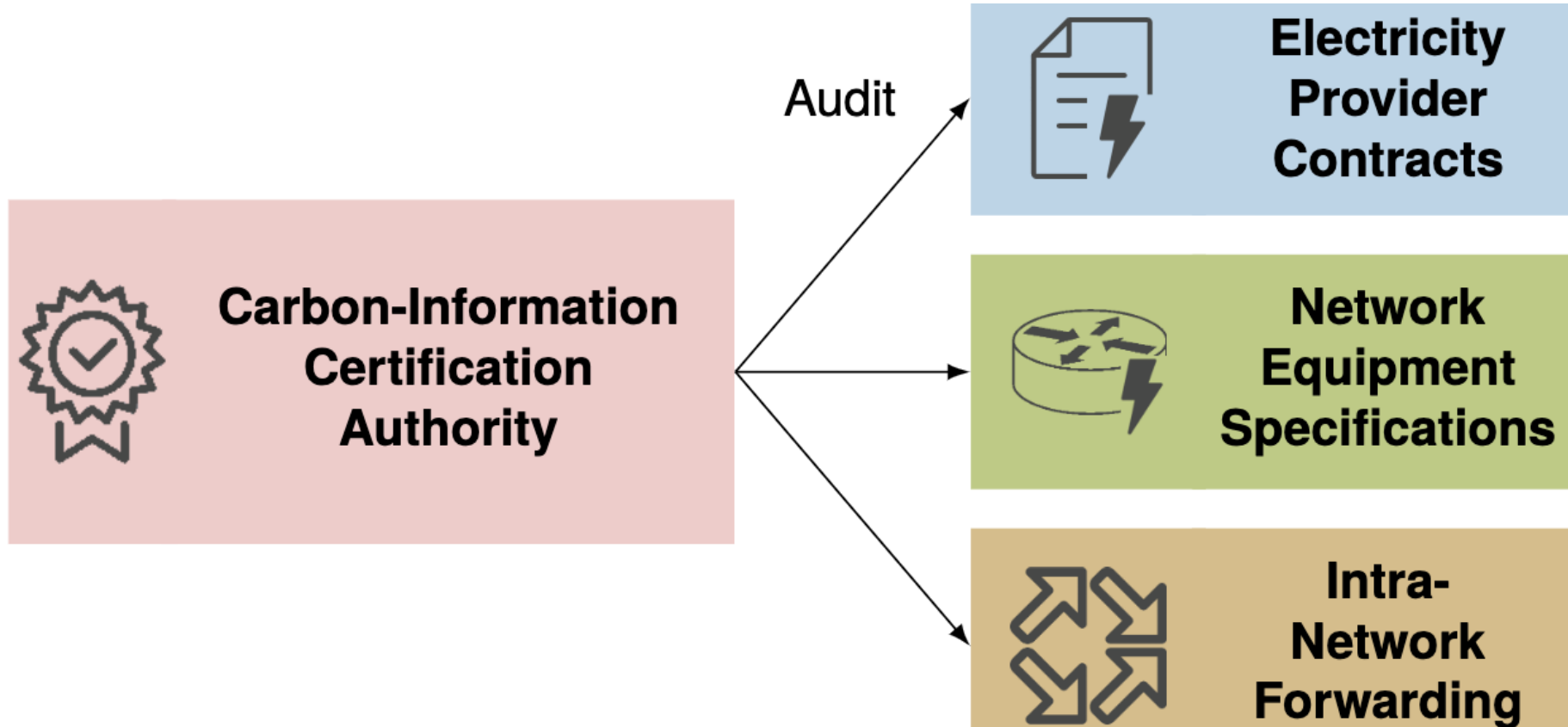
8092 Zürich, Switzerland

<https://netsec.ethz.ch>

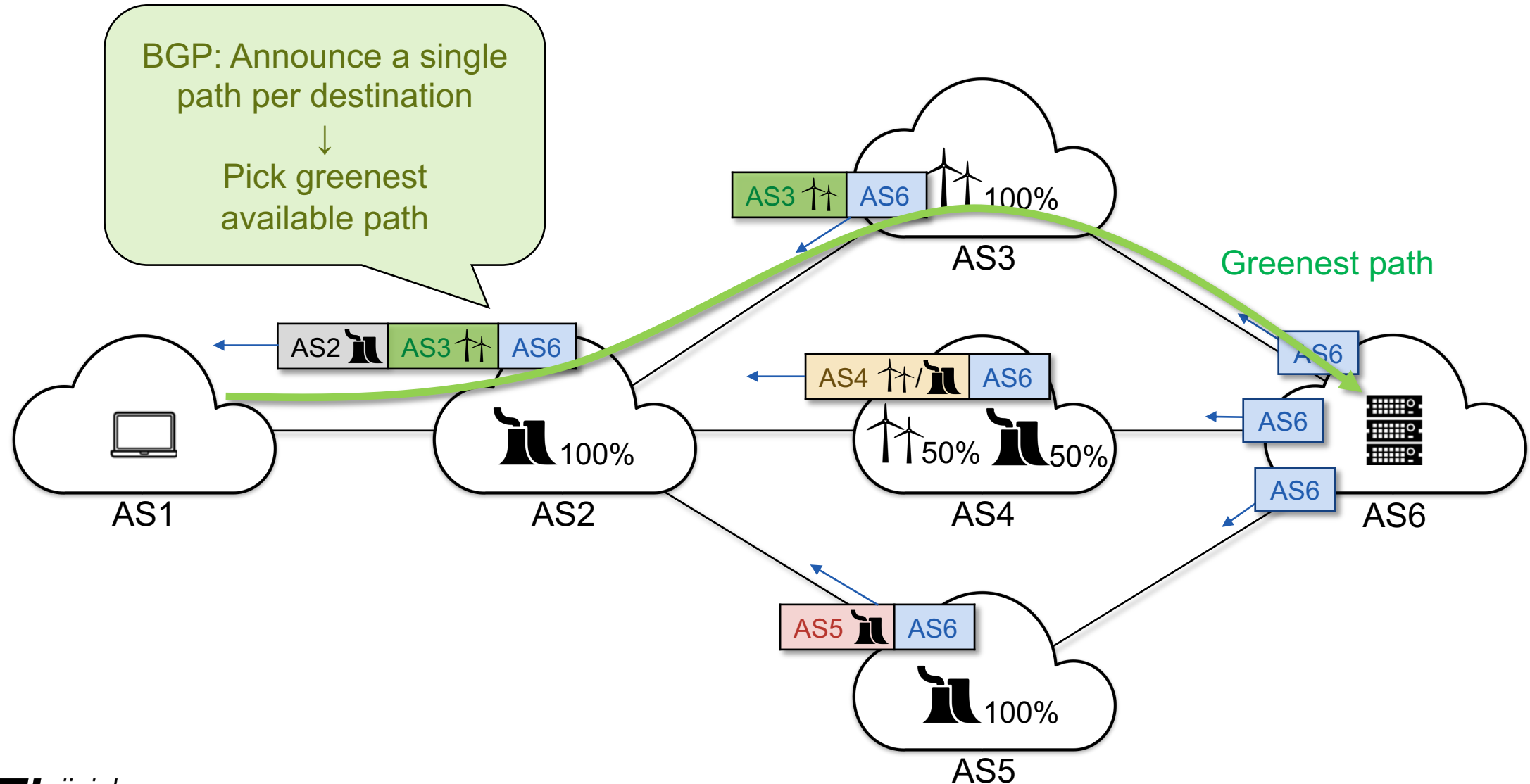


Backup Slides

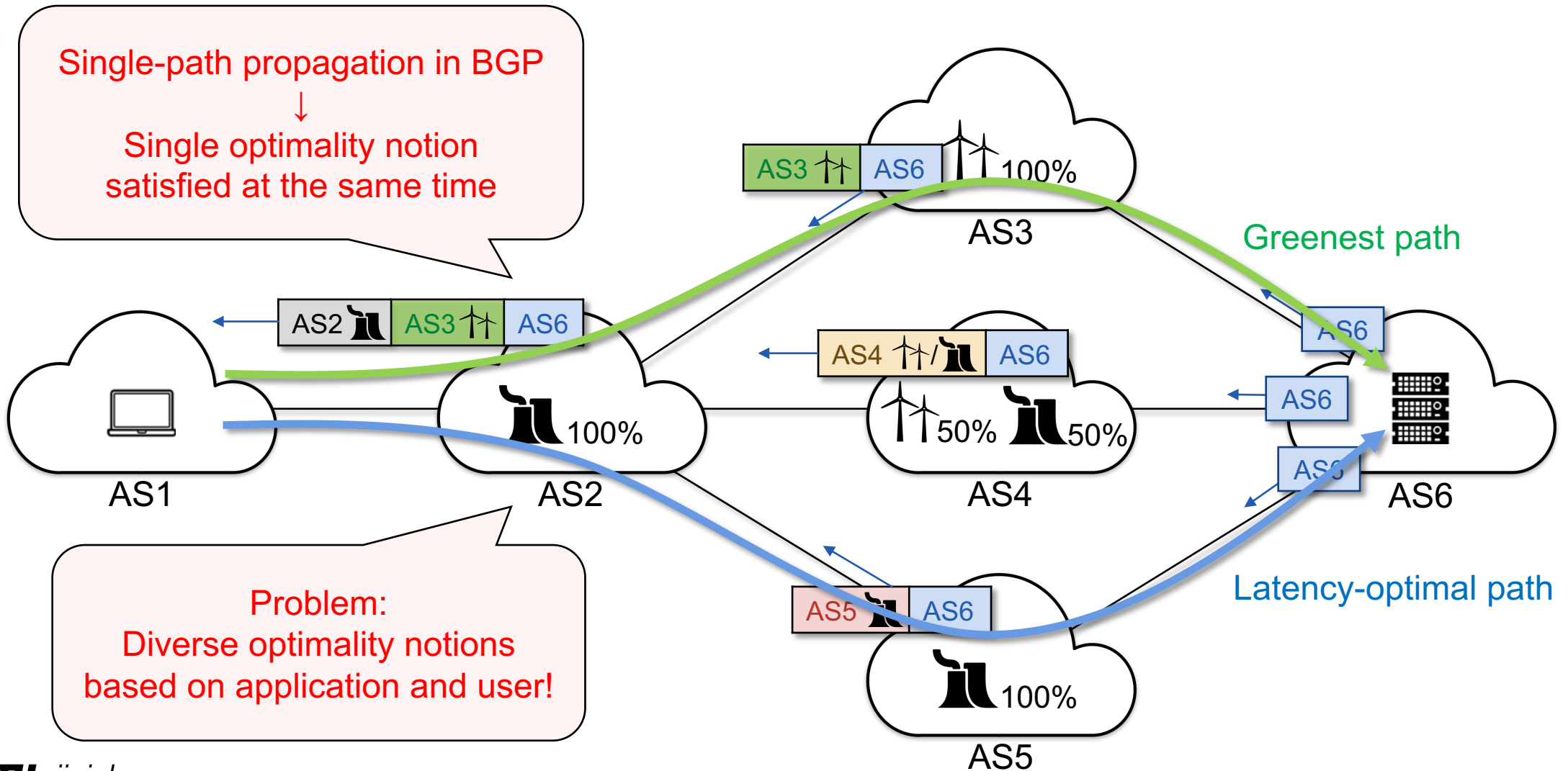
Trustworthy Carbon Information



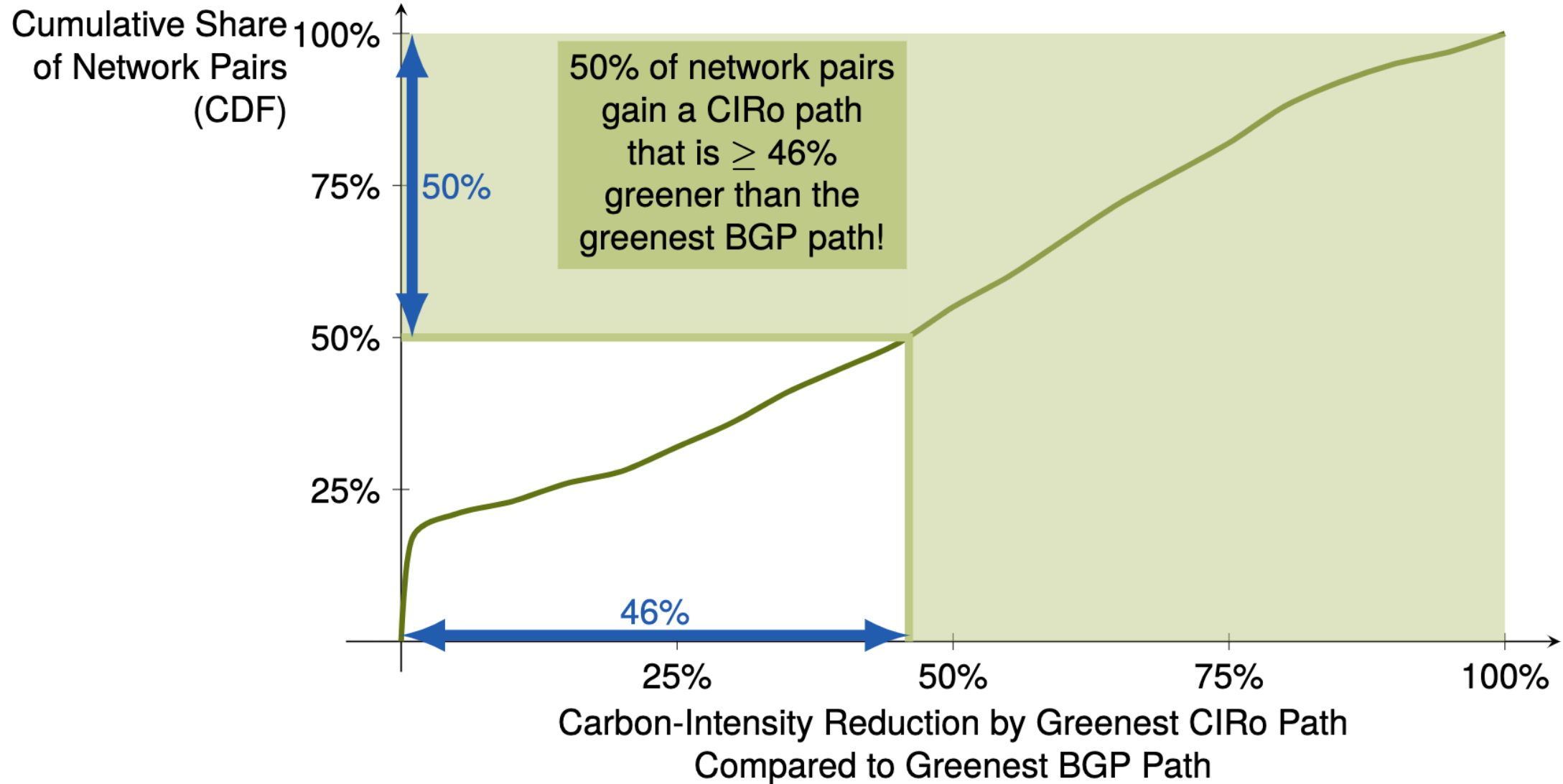
Carbon-Aware Global Routing with BGP?



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Difference in Greenest Path



Carbon Intensity vs. Latency

