Regional IP Anycast: Deployments, Performance, and Potentials

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Abstract

Recent studies show that an end system's traffic may reach a distant anycast site within a global IP anycast system, resulting in high latency. To address this issue, some private and public CDNs have implemented regional IP anycast, a technique that involves dividing content-hosting sites into geographic regions, announcing a unique IP anycast prefix for each region, and utilizing DNS and IP-geolocation to direct clients to CDN sites in their corresponding geographic regions. In this work, we aim to understand how a regional anycast CDN partitions its sites and maps its customers' clients to its sites, and how a regional anycast CDN performs compared to its global anycast counterpart. We study the deployment strategies and the performance of two CDNs (Edgio and Imperva) that currently deploy regional IP anycast. We find that both Edgio and Imperva partition their sites and clients following continent or country borders. Furthermore, we compare the client latency distribution in Imperva's regional anycast CDN with its similar-scale DNS global anycast network, while accounting for and mitigating the relevant deployment differences between the two networks. We find that regional anycast can effectively alleviate the pathology in global IP anycast where BGP routes clients' traffic to distant CDN sites. However, DNS mapping inefficiencies, where DNS returns a sub-optimal regional IP anycast address that does not cover a client's low-latency CDN sites, can harm regional anycast's performance. Finally, we show what performance benefits regional IP anycast can achieve with a latency-based region partition method using the Tangled testbed. When compared to global anycast, regional anycast significantly reduces the 90th percentile client latency by 58.7% to 78.6% for clients across different geographic areas.

CCS Concepts

• **Networks** → **Network measurement**; **Network performance analysis**; **Naming and addressing**; **Routing protocols**.

Keywords

Routing; IP Anycast; Regional Anycast

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1 Introduction

IP anycast [50] refers to the routing practice where a network announces the same IP prefix from multiple geographically-distributed locations. It is widely used by distributed systems such as root Domain Name Service (DNS) servers and Content Distribution Networks (CDNs) to reduce client latency and balance load. Unlike conventional DNS-based redirection services [13], IP anycast can direct client traffic to nearby CDN sites without a separate load-balancing system [11]. Partly due to its simplicity, several large CDNs, including Cloudflare [18], Google Cloud CDN [17], and Microsoft Azure [51], have all adopted IP anycast.

The simplicity of IP anycast comes with a downside: it gives a CDN operator little control over which sites its clients' traffic reaches. The Border Gateway Protocol (BGP) [56] routes a client's traffic to a CDN site based on its policies and network topology dynamics. Since BGP is a policy-routing protocol, its best-path selection algorithm does not incorporate performance metrics directly associated with end-to-end path latency. As a result, BGP often routes a client to an anycast site that is geographically distant from the nearest anycast site [7, 8, 19, 23, 40, 42, 43, 58], leading to high client latency. We refer to this pathology as catchment inefficiency. Interactive applications such as gaming and web browsing demand low latency [2, 52]. In a competitive market, providing low-latency access to clients worldwide is crucial for CDN providers to gain competitive advantages.

Recently, several private and public CDNs adopted regional IP anycast as a promising approach to address some of the limitations of IP anycast [12, 31, 47]. A CDN that employs regional IP anycast partitions its sites into various geographical regions, such as continents or large countries, and announces a distinct IP anycast prefix from the sites in each region. When a client makes a DNS query to one of the CDN's customers, the CDN's DNS returns a regional IP anycast address based on the client's location. For clarity, we hereafter refer to the anycast configuration where a network announces the same IP prefix from multiple sites without regional partitions as global IP anycast.

Regional IP anycast retains the simplicity of IP anycast while providing CDN operators with a degree of control over the sites that a client's traffic can reach. However, this approach has not been

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thoroughly studied. Questions such as *how a regional IP anycast CDN is deployed* and *whether regional IP anycast can effectively address the catchment inefficiency problem of global IP anycast* are unanswered. Understanding these questions can provide valuable insights into optimizing the deployment and performance of large-scale IP anycast systems.

This work aims to answer the above questions. We first conduct an in-depth study on the deployment strategies and the performance of two global-scale regional anycast CDNs: Edgio (formerly Edgecast and acquired by Limelight in 2022) and Imperva (formerly Incapsula and now part of Imperva). According to a prior study [31] and our recent survey (§ 4.1), these two CDNs are among the top-15 largest CDNs that currently deploy regional IP anycast. Furthermore, we discover that Imperva's own authoritative DNS server system uses global IP anycast and its sites and network configurations overlap significantly with its regional anycast CDN. Therefore, we choose Imperva's authoritative DNS server system as its global anycast counterpart and compare their performance differences. We use RIPE Atlas [66], a globally distributed set of probes, to send DNS queries to the domains hosted by Edgio and Imperva. We then send traceroute queries from RIPE Atlas probes to the IP addresses the probes receive and infer the geographic locations of the CDN sites the probes' traffic reaches, which we refer to as the catchment sites. From these steps, we are able to infer the regional site partition and the DNS mapping strategies of the two CDNs (§ 4.4), as well as the anycast sites of Imperva's DNS server system.

We find that Edgio and Imperva use different regional partition strategies (§ 4.3). Edgio divides its customers' clients into three or four regions, while Imperva divides its customers' clients into six regions. The region boundaries in both CDNs largely follow country or continent borders. Most clients receive IP prefixes originating from the CDN sites in the same geographical areas from DNS, but sometimes DNS returns a remote regional IP address to a client. We reached out to both Edgio and Imperva to discuss our findings and one responded and confirmed parts of our findings.*

The performance study of regional IP anycast reveals both the advantages and limitations of regional IP anycast (§ 5). We find that regional IP anycast can effectively limit the worst-case catchment inefficiencies experienced by global IP anycast by directing clients to regional IPs. For instance, regional anycast reduces the 90th percentile client latency for Imperva in North America from 110 ms to 38 ms. However, compared to global IP anycast, regional IP anycast suffers DNS mapping sub-optimality. DNS may map a client to a sub-optimal regional IP that does not include the client's low-latency CDN sites, offsetting regional IP anycast's advantages of reducing catchment inefficiencies. For instance, DNS mapping inefficiencies increase the 90th percentile client latency for Imperva in Latin America from 93 ms to 102 ms.

Finally, we examine the performance benefits of regional anycast without encountering sub-optimal DNS mapping. We conduct this study using the Tangled testbed, an open-access anycast testbed that allows researchers to run customized anycast experiments (§ 6). We use a latency-based scheme to partition the Tangled testbed into regions and assign each RIPE Atlas probe to the region that includes its lowest-latency site. We then deploy both global IP anycast and regional IP anycast on the Tangled testbed. In this case, regional IP anycast can achieve lower client latency than global anycast in all geographical regions. This result highlights the performance potentials of regional IP anycast.

An inherent limitation of this work is that we measure client latency using RIPE Atlas, like many previous studies [39, 42, 49]. Using a different set of clients, one may observe different latency values. Despite this limitation, we believe this work makes the following general contributions:

- We study in detail the deployments and performance of two regional IP anycast CDNs and compare one CDN's performance with a comparable global IP anycast system. To the best of our knowledge, this work is the first extensive study of regional IP anycast CDNs.
- We validate the performance advantages of regional anycast experimentally and discover its drawbacks in certain circumstances. We show that regional IP anycast can effectively mitigate the worst-case catchment inefficiency problem experienced by global IP anycast by directing clients to regional IP anycast addresses, but DNS mapping sub-optimality may offset some of this effect.
- We experiment with a latency-based region partition and client mapping scheme that addresses DNS mapping inefficiencies using the Tangled testbed. We find that this method reduces the latency for RIPE Atlas probes in all geographic areas compared to global anycast. This experiment shows the performance potentials of regional IP anycast.

Ethical Considerations Active measurements such as issuing pings and BGP announcements can cause extra load on the Internet infrastructure. We mitigate these concerns by conducting our measurements at reasonably low rates (*i.e.*, only one round of ping or traceroute for each anycast IP address) with publicly accessible infrastructure. Our BGP announcements use only prefixes that Tangled controls and Tangled's AS number. The prefixes we use do not serve any clients. We only measured the CDN providers with ping and traceroute, and we did not retrieve webpages which could incur extra costs for their customers. This work raises no other ethical issues.

2 Background and Motivation

In this section, we discuss the catchment inefficiency problem of IP anycast, the challenges in addressing it, and our motivation to study regional IP anycast.

2.1 The Catchment Inefficiency Problem

IP anycast is a popular technique used by CDNs to direct client traffic to their sites [31]. With this technique, a CDN operator relies on the inter-domain routing protocol BGP to select the site a client reaches. However, being a policy-routing protocol, BGP often fails to route a client to a low-latency site. Figure 1 shows an example we observe in our measurements. The CDN we study (Imperva) has two involved sites: one connected to Level 3 in Ashburn, Virginia, and the other connected to SingTel in Singapore. When both sites announce the same global IP anycast prefix, the probe located in Washington D.C. reaches the Singapore site, as SigTel is the

*Due to confidentiality agreement, we cannot disclose which provider responded to our inquiries or what parts of our findings were confirmed.

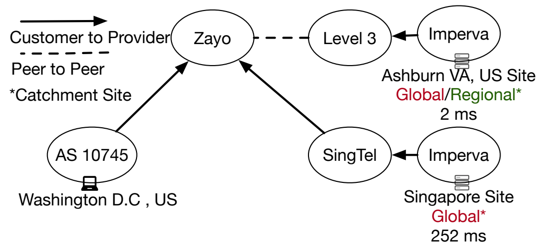


Figure 1: ***An example observed from Imperva's measurement results: with a global anycast configuration, the probe located in Washington D.C. reaches the CDN site in Singapore, while with regional anycast, the probe reaches the site in Ashburn, Virginia.***

customer of the probe's provider Zayo [28], while Level 3 is Zayo's peer. Under common BGP policies, ISPs prefer customer routes to peer routes. So the round trip time from this probe to the CDN is inflated by 250 ms. Furthermore, for routes with the same policy preference, BGP uses other metrics, such as AS path lengths, which are poorly correlated to performance, to select routes. Since a large AS may span multiple continents, routes with shorter (or the same) AS path lengths may have longer latencies than routes with longer (or the same) AS path lengths. A recent study [39] shows that for Microsoft CDN (a global IP anycast system), nearly 30% of users experience more than 30 ms latency inflation.

2.2 Challenges

There exist several proposals to improve client latency in a global anycast system. Ballani *et al.* [8] proposed to deploy anycast sites within a single provider. This proposal effectively limits BGP's policy routing, but it is sometimes necessary to connect an anycast system to many ISPs for scalability and robustness. Li *et al.* [42] proposed to introduce a new BGP attribute that encodes an anycast prefix's geographical origin. However, introducing changes to BGP is difficult in practice.

Alternatively, McQuistin *et al.* [49] proposed DailyCatch, a system that uses routine measurement to choose between a transit-provider-only and an all-peer configuration for an anycast system. This approach can effectively choose the better configuration between the two measured configurations, but can not optimize beyond that. Catchment inefficiencies can exist under either configuration. Zhang *et al.* [69] proposed AnyOpt, which uses pair-wise BGP experiments to choose an optimal site configuration for an anycast system among all possible site deployments, but pair-wise BGP experiments increase the operating overhead of CDN networks.

2.3 Regional IP Anycast

Regional IP anycast emerged as a promising approach to address the catchment inefficiency problem [12, 31, 47]. With regional IP anycast, a CDN divides its sites into multiple distinct geographic regions. It then assigns a distinct IP anycast prefix to each region. Sites in the same region will announce the same IP anycast prefix. We refer to such an IP prefix or address as a *regional IP prefix/address* or *regional IP* for short. The CDN then configures its DNS servers to assign a regional IP to a client based on the client's location. In the example shown in Figure 1, with the regional anycast configuration, the CDN announces different IP anycast prefixes in U.S. and Asia. The probe in the U.S. receives the U.S. IP prefix, and consequently, it reaches the Virginia site and enjoys a 2 ms RTT.

Unlike other proposals, regional IP anycast does not require changes to BGP, nor does it impose restrictions on how an anycast network connects to its providers. It eliminates the need for periodic BGP experiments and is complementary to DailyCatch, as it can mitigate catchment inefficiencies across various provider configurations.

2.4 Motivation

Despite its potential advantages, regional IP anycast is not well studied or widely deployed. In a blog article [47], LinkedIn described how they migrated their private CDN to a "prototype" regional anycast system and measured its client latency distribution. But their study is limited to LinkedIn's private CDN, which is primarily located in North and South America. Hao *et al.* [31] reported that two out of the top 20 CDNs (Edgio and Imperva) employ regional IP anycast without further performance analysis. Calder *et al.* [12] discussed the performance difference for Microsoft CDN when it employs a regional vs. a global anycast configuration.

This work aims to understand how regional anycast is deployed in practice and experimentally examine its performance benefits compared to global anycast. This study can provide new insights into how to design an anycast-based system that achieves low client latency worldwide. Additionally, if this study experimentally validates the performance benefits of regional anycast, it could motivate more CDNs to adopt regional anycast.

3 Measurement Infrastructure

We use two publicly available platforms: RIPE Atlas [66] and the Tangled testbed [9] to conduct our experiments. Our experiments were conducted in August 2022.

3.1 RIPE Atlas

RIPE Atlas is a measurement infrastructure that has more than 11,000 probes distributed around the world, each with the ability to execute pre-defined measurements periodically. Each probe's geographic location is publicly available. We leverage RIPE Atlas's user-defined measurement feature to send DNS queries, ping packets, and traceroute queries. We take the following steps to address the limitations of RIPE Atlas to suit our measurement purposes.

First, RIPE Atlas probes use user-reported geo-locations, which may contain errors, but we use the probes' built-in geocodes as ground truth to calculate the distance between a probe and its catchment site. To mitigate this issue and obtain stable measurement results, we discard the following probes: (1) probes with unreliable geocodes using the methods described in [29] and (2) probes that do not have a built-in stability tag (*e.g.*, "system-ipv4-stable-1d"). After this step, we retain 9,700+ out of 11,000+ RIPE Atlas probes.

Second, RIPE Atlas probes are unevenly distributed across different geographic areas and Autonomous Systems (ASes). An uneven distribution may lead to under- or over-estimation of performance in certain geographic areas or ASes. To address this limitation, we group the probes by <city, AS> pairs and present statistics based on probe groups as in [49]. We obtain the city code of a probe by mapping the probe to its closest airport within the same country and using the airport's International Air Transport Association (IATA) code [34] as the probe's city code. We use the probe's built-in AS number to identify its AS. Then, we use the median value measured from each <city, AS> probe group to represent the performance of a client residing in the same city and AS. Without specific mention, all CDFs, percentage, and percentile values we present here are computed based on probe groups, rather than individual probes. We obtain 6100+ unique probe groups.

Finally, RIPE Atlas has much more probes in Europe and North America than in other continents. Such bias may lead to results that either overestimate or underestimate the performance of regional IP anycast in different regions. To overcome this limitation, we present the performance results of the probes in different geographic areas separately. We categorize the probes into four geographic areas based on their density:

- **EMEA**: Europe, Middle East, and Africa. This area has 3,859 unique probe groups and 6,917 unique probes.
- **NA**: North America, excluding countries in Central America. This area has 1,154 unique probe groups and 1,716 unique probes.
- **LatAm**: South America and countries in Central America. This area has 141 unique probe groups and 177 unique probes.
- **APAC**: the rest of the globe. This area has 613 unique probe groups and 950 unique probes.

We note that this area definition is based on the location of a RIPE Atlas probe and is independent of the CDN region partition schemes we soon discuss.

3.2 The Tangled Testbed

Tangled is a worldwide open-access IP anycast testbed. It has 12 sites distributed around the world. We use Tangled to evaluate a latency-based regional anycast scheme and to compare global anycast with latency-based regional anycast (§ 6.2). We also considered the PEERING testbed [59], but opted for the Tangled testbed because the PEERING testbed has no site in Asia and the Pacific area. We list the distribution of Tangled sites by geographic area in Table 1.

4 Deployments

In this section, we dissect the deployments of two regional IP anycast CDNs: Edgio and Imperva. We describe how we conduct measurements to answer the following questions:

- How do these regional IP anycast CDNs assign their clients to regional IP addresses?
- How do these regional IP anycast CDNs partition their sites and announce regional IP prefixes?

4.1 Identifying Regional IP Anycast CDNs

First, we identify the set of public CDNs that deploy regional IP anycast. To do so, we acquire the top apex domain list from Tranco [41] in April 2022. An apex domain is a two-level domain [32], *e.g.*, `example.com`. We then use the CDNFinder's API [53] to identify the CDN providers of each domain. Specifically, we provide CDNFinder with the www-prefixed hostname (referred to as the website hereafter) of each apex domain, such as `www.example.com`. CDNFinder determines the CDN providers used by a website by analyzing the response header of each resource on its landing page. Since each resource identifier corresponds to a hostname, we can tally the number of hostnames served by a CDN provider. We choose the top-15 CDN providers ranked by the number of hostnames they serve. The top-15 CDN providers cover 65.7% of all Tranco's top-10k domains. By manually examining their official technical articles or configuration documents (see Appendix A), we identify that Edgio and Imperva are the only two CDNs that deploy regional anycast among the top-15 CDN providers, consistent with a prior study [31]. Therefore, we focus our study on these two CDNs.

4.2 Customers of Regional IP Anycast CDNs

Second, we select the representative customers of a regional IP anycast CDN. A CDN provider may negotiate different service packages with its customers and use different system configurations to implement different service packages. As this work does not aim to unveil various service packages of a CDN, we select and measure representative CDN customers to understand how the CDNs enable regional IP anycast for their customers in commercial platforms.

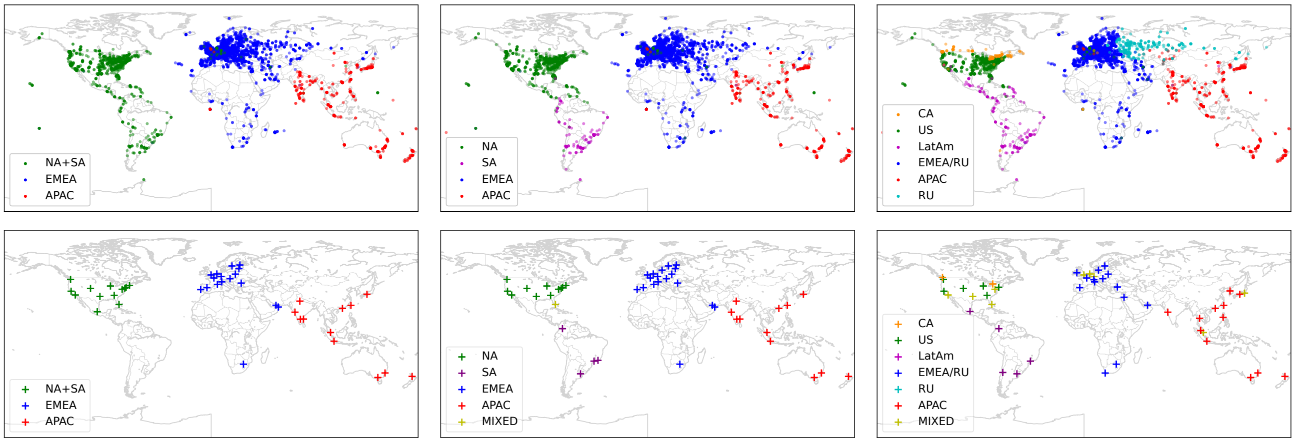
For this step, we first resolve all hostnames uncovered by CDNFinder to use Edgio or Imperva as their CDN providers to IP addresses. The results from CDNFinder in the previous step show that 2.98% of the top-10K websites are using Edgio or Imperva, in which Edgio serves 209 websites and Imperva serves 89 websites. We further extract 187 (96 and 91, respectively) distinct hostnames that point to Edgio or Imperva from these websites. To emulate a worldwide clientele, we compile a list of /24 client IP prefixes that cover the IP address span of the entire RIPE Atlas. We then use Google DNS [6] with the EDNS Client Subnet Extension (ECS) [20] to resolve all hostnames, an approach used in [10, 38].

We discover the number of unique IP prefixes each hostname resolves to and filter those hostnames that are not served by Edgio or Imperva's regional IP anycast networks. We record the IP address(es) (the `A` record) in each DNS response we receive. Out of Edgio's hostnames, 52.1% (50 out of 96) resolve to three distinct IP addresses each when accessed by the emulated worldwide clientele. We refer to this set of hostnames as *Edgio-3*. And 35.4% (34 out of 96) Edgio's hostnames resolve to four distinct IP addresses. We refer to this set of hostnames as *Edgio-4*. In contrast, the majority of Imperva's hostnames resolve to the same number of IP addresses. Specifically, 85.7% (78 out of 91) Imperva's hostnames resolve to six distinct IP addresses each. We refer to this set of hostnames as *Imperva-6*.

For the remaining hostnames that CDNFinder identifies as using Edgio or Imperva, they either resolve to a single IP address or multiple IP addresses matching the number of Edgio's or Imperva's published CDN sites, or IP addresses associated with other CDNs. We conclude that these hostnames are not (solely) served by Edgio's or Imperva's regional IP anycast CDN and exclude them from this study.

4.3 Client Partitions

To characterize which IP address(es) a client in a geographic region receives, we use RIPE Atlas probes to resolve a hostname that belongs to a customer of Edgio's or Imperva's regional IP anycast CDN. We then cluster RIPE Atlas probes based on the IP addresses they receive. For each hostname, we group the probes that receive the same IP address together. We run the experiments for all hostnames in the three sets: Edgio-3, Edgio-4, and Imperva-6. We find



(a) *Edgio-3 (www.straitstimes.com)* **(b)** *Edgio-4 (www.asus.com)* **(c)** *Imperva-6 (www.stamps.com)*

Figure 2: ***The first row shows the regional IP a RIPE Atlas probe receives in different regional anycast CDNs; the second row shows the CDN sites that announce a regional IP anycast prefix. Probes and CDN sites are color-coded by regional IPs. A site that announces more than one regional IP is shown in yellow with the legend "MIXED". Figures a & b show that Edgio divides its sites into four regions, but only returns three regional IPs to the clients of its Edgio-3 customers. Figure c shows Imperva divides its clients into six regions, but it has no sites in one of the regions (Russia).***

that the clustering results for each hostname in the same set remain the same.

To visualize client partitions, we pick one representative hostname from each hostname set that illustrates stable and consistent deployments while remaining top-ranked in Tranco's list. These hostnames are `www.straitstimes.com`, `www.asus.com`, and `www.stamps.com`*, which belong to the Edgio-3, Edgio-4, and Imperva-6 sets, respectively. The first row in Figure 2 shows how the probes that receive the same regional IP addresses for the three hostnames are distributed globally. We depict the probes that receive the same regional IP with the same color.

For both Edgio hostnames and Imperva hostnames, the client partition appears to happen at the continent or large-country level. For example, for Edgio-3 hostnames, the probes in North America and South America receive the same regional IP, and the probes in Europe, Africa, and Middle East receive the same regional IP. For Imperva hostnames, the probes in Russia receive different regional IPs from those in Europe; and the probes in the U.S. and Canada are also separated from each other, each receiving a distinct IP.

We use the country code of each RIPE Atlas probe to evaluate whether the probes in the same country always receive the same regional IPs for the same hostname and find that the majority of countries receive only one regional IP. For the probes from all 172 countries, 81.7%, 84.7% and 79.3% of the countries only receive one regional IP for the representative Edgio-3, Edgio-4, and Imperva-6 hostnames, respectively. For countries that receive two or more regional IPs, we find two cases. In the first case, the IP addresses of the probes are geolocated to different countries. For instance, the probes whose IPs belong to international transit providers are often geolocated to their home countries, not the countries they reside in. Second, the countries are either at the border of two regions or across two different continents. For instance, 10 out of 547 probes in Russia receive the EMEA regional IPs in Imperva-6.

*At the time when the measurement was carried out, `www.stamps.com` was still being hosted by Imperva.

Takeaways: Both Edgio and Imperva employ regional anycast CDNs that predominantly map clients to regional IPs based on geographic locations, such as continents or countries where the clients are located.

4.4 CDN Site Partitions

Next, we aim to understand how Edgio and Imperva partition their hosting sites into different regional IP anycast networks. To do so, we need to locate the CDN sites that announce a regional IP anycast prefix. We describe the site-mapping process as follows.

First, we obtain the locations of Edgio and Imperva's CDN sites. Both Edgio and Imperva publish their Points of Presence (PoPs) on their websites [24, 36]. We aggregate those locations at the city level and combine multiple PoPs in the same city as one site. We use these published site locations at the city level as the ground-truth locations of their sites.

Secondly, in order to determine the location of the CDN site announcing a regional IP, we perform traceroutes from each RIPE Atlas probe to the regional IP received by the probe from DNS. We then geolocate the IP address of the penultimate hop (referred to as p-hop hereafter) using the traceroute output. We use the ground-truth CDN site location to map each p-hop to its closest CDN site, as in [49]. This step also reveals the location of the catchment site of a probe, which we use to compute the distance between a probe and its catchment site in § 5.

IP geolocation is a task performed by many previous studies [5, 29, 42, 44, 45, 49, 64, 65]. This step involves substantial work, but it is not our main contribution. We summarize the work here and leave the detailed description in Appendix B. We first use the geo-hints in the reverse DNS (rDNS) name of a p-hop's IP to infer its location [44, 45]. If the geo-hints are unavailable, we use the location of a RIPE Atlas probe whose RTT is within 1.5 ms to the p-hop [29] to infer its location. The threshold is chosen according

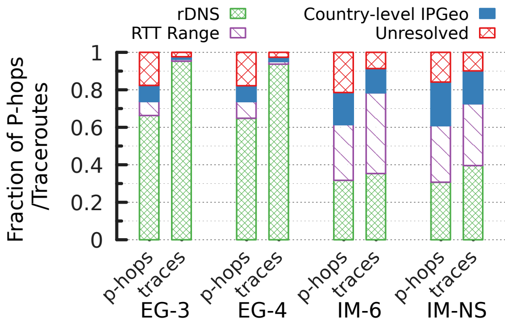


Figure 3: ***The p-hops bars illustrate the proportion of p-hops successfully IP-geolocated by a technique, as well as the fraction of unresolved p-hops for each network. The traces bars indicate the fraction of traceroutes with successfully IP-geolocated p-hops by a technique, as well as the fraction of traceroutes with unresolved p-hops. Abbreviations used: EG for Edgio, IM for Imperva, and IM-NS for Imperva's DNS server network.***

	EG-3	EG-4	EG-Pub	IM-6	IM-NS	IM-Pub	Tangled
APAC	14	15	19	16	17	17	2
EMEA	15	16	26	15	15	15	5
NA	13	12	24	12	12	12	3
LatAm	1	4	10	5	5	6	2
Total	43	47	79	48	49	50	12

Table 1: The number of sites in each geographic area of different networks *(EG/IM-Pub: Edgio and Imperva's Published sites)*.

to the typical size of a metropolitan area, as the speed-of-light latency in fiber is roughly 100 km per 1 ms RTT. We refer to this technique as RTT Range. Third, if we cannot resolve a p-hop's geolocation after the previous two steps, we use the country information from three IP-geolocation databases (MaxMind [48], ipinfo [37], and EdgeScape [67]) to infer the location of the p-hop. If all IP-geolocation databases return the same country location for the p-hop, and the CDN provider only lists one site in the country, we use the listed site location as the p-hop's location. We refer to this technique as country-level IPGeo.

The site-mapping process described above requires sending traceroutes from RIPE Atlas probes and manual labor to examine uncommon geo-hints. Due to time and measurement traffic limitations, we are unable to map the CDN sites of all hostnames served by Edgio and Imperva. Instead, we mapped the CDN site partitions for four hostnames from each of the Edgio-3, Edgio-4, and Imperva-6 hostname sets, respectively. For each set, we include three randomly chosen hostnames and the representative hostnames used in § 4.3 and found that the site partitions for those hostnames are identical. In addition, we measure the client latency distribution for twelve additional Edgio-3, Edgio-4 and Imperva-6 hostnames, respectively, and show in Appendix C that the performance benefits of regional anycast to these additional Edgio and Imperva hostnames are similar. Therefore, we assume that the two CDNs we study either do not vary the site partition strategies among the hostnames in each hostname set we identify, or if they vary the site partition strategies for different hostnames, the variation does not significantly degrade the performance benefits of their regional anycast CDNs. Therefore, for an in-depth study, without specific mention, we present results for the representative hostnames only.

Figure 3 summarizes the fraction of p-hops we successfully geolocate for the representative Edgio-3, Edgio-4, and Imperva-6 hostnames by each technique. We also show the fraction of traceroutes whose p-hops are successfully IP-geolocated by each technique. As we can see, we are able to resolve the majority of the p-hops observed in the traceroute output.

Table 1 shows the CDN sites we uncover after mapping p-hops to their CDN sites. We uncover 48 out of 50 Imperva's published sites, and all 48 sites overlap with Imperva's DNS authoritative server sites. Edgio publishes 79 sites, while we only uncover 43 sites for the Edgio-3 hostname and 47 sites for the Edgio-4 hostname. Furthermore, we find that Edgio-3's CDN sites only overlap with 33 of its authoritative DNS server sites, while Edgio-4's CDN sites overlap with 37 of its DNS server sites. This result suggests that Edgio uses separate networks for its regional anycast CDN sites and DNS sites. Additionally, it employs distinct network configurations for other network services (§ 4.2) beyond the regional anycast CDN services we are studying. We spoke with one of the CDN providers and validated parts of our CDN and DNS site inferences.

CDN Site Partitions After the site-enumeration step, we are able to depict the location of a CDN site that announces a regional IP prefix. Figure 2 shows the result. We represent a CDN site with a colored cross symbol. The color corresponds to the regional IP it announces. We use the same color-coding scheme as in client partitions. If a site announces more than one regional IPs, we color the site yellow.

We make the following observations. First, in both Edgio and Imperva, client and site partitions are mostly consistent. Edgio partitions its sites into four regions, while Imperva into six regions. Clients in the same geographical regions receive the regional IPs originating from the CDN sites in the same regions except in two cases. For the Edgio-3 hostname, the probes in South America receive North America's regional IP. This finding shows that different customers receive different types of services from a CDN. Some customers' content may not be hosted by Edgio's South America sites. So clients will not be directed to those sites. For Imperva, although most probes in Russia receive distinct regional IPs as shown in Figure 2, these IPs are announced by three sites in Europe (Amsterdam, Frankfurt, and London), which also announce the EMEA regional IPs. We do not observe any Imperva sites in Russia.

Second, most sites only announce one regional IP prefix, but there exist sites that announce multiple regional IP addresses. We refer to this behavior as cross-region announcement. A closer examination of Figure 2b and Figure 2c show that the sites which announce multiple regional IPs usually locate near the border of two different regions. Cross-region announcements can help shorten client latency without adding additional sites. For instance, Edgio-4's "mixed" site in Florida, U.S. can serve both clients in North America and in South America. However, we later discover that cross-region announcements can lead to inefficient catchments, increasing the RTTs of some probes (§ 5.2).

Do CDN sites change the regional IP prefixes they announce over time? We enumerated the CDN sites that announce the regional IP

Condition	CDN	Local DNS				Authoritative DNS			
		APAC	EMEA	NA	LatAm	APAC	EMEA	NA	LatAm
$\Delta RTT < 5ms$	Edgio-3	94.2%	96.7%	98.6%	99.1%	94.2%	98.7%	98.8%	99.1%
	Edgio-4	91.0%	97.3%	97.4%	92.9%	94.8%	98.8%	98.2%	94.7%
	Imperva-6	86.3%	78.3%	88.0%	85.6%	87.1%	78.0%	89.3%	86.5%
✓Region, $\Delta RTT \geq 5ms$	Edgio-3	3.5%	1.3%	0.2%	0.0%	4.0%	0.8%	0.1%	0.0%
	Edgio-4	3.6%	0.7%	0.7%	3.5%	3.4%	0.7%	0.6%	3.5%
	Imperva-6	10.5%	19.4%	8.2%	11.7%	10.8%	21.0%	9.0%	12.6%
×Region, $\Delta RTT \geq 5ms$	Edgio-3	2.4%	2.0%	1.2%	0.9%	1.8%	0.5%	1.1%	0.9%
	Edgio-4	5.4%	2.0%	2.0%	3.5%	1.8%	0.4%	1.2%	1.8%
	Imperva-6	3.2%	2.3%	3.8%	2.7%	2.1%	1.0%	1.7%	0.9%

Table 2: We tabulate three types of DNS mapping results by percentages of probes: ✓/×Region indicates whether a probe receives a regional IP intended for its geographic location or vice versa; ΔRTT is the difference between a probe's RTT to the regional IP returned by DNS and the lowest one among its RTTs to all regional IPs. When ΔRTT exceeds 5 ms, we consider DNS mapping inefficient.

prefixes for three hostnames in Edgio-3, three hostnames in Edgio-4, and three hostnames in Imperva-6 weekly for two months. We find that for the same hostname, the sites that announce their regional IP prefixes in this two-month period remain the same.

Takeaways: Edgio and Imperva's site and client regional partitions are largely consistent, but there exist regions in which clients are assigned to regional IPs originating from CDN sites in different geographic regions.

4.5 Reachability of Regional IP addresses

Are regional IP prefixes globally reachable? We are interested in understanding whether a CDN restricts the BGP announcements of a regional IP anycast prefix to a geographic area. If it does, a client outside a geographic area cannot reach the regional IP prefix announced from that area. To do so, we send ping packets from RIPE Atlas probes to the regional IP addresses they do not receive from DNS. We run this experiment for each representative Edgio-3, Edgio-4, and Imperva-6 hostname. The results show that all probes can reach the regional IP addresses DNS returns to the probes in other regions. Global reachability provides robustness to regional anycast: even if DNS returns a regional IP unintended for a client's geographic area, the client can still reach the CDN site announcing the unintended regional IP.

5 Performance

In this section, we study the performance of Edgio's and Imperva's regional IP anycast CDNs. We aim to answer the following questions:

- How effectively does DNS map a client to the lowest-latency or a close-to-lowest-latency regional IP?
- What are the performance benefits of regional IP anycast compared to global IP anycast?

We use two metrics for this study: network latency and geographic distance.

Network latency or latency We measure a probe's round trip time (RTT) to its catchment site to quantify the client latency distribution achieved by an anycast system. The lower the latency, the better the performance.

Geographic distance We also measure the geographic distance between a probe and a CDN site as in previous work [22, 39, 42]. Since we have inferred the location of a probe's catchment site in § 4.4, we can compute the geographic distance between a probe and its catchment CDN site.

5.1 DNS Mapping Efficiency

To study DNS mapping efficiency, we measure how often DNS returns the lowest- or a close-to-lowest-latency regional IP to a client. We consider any regional IP with less than 5 ms RTT difference to a probe's lowest-latency regional IP as close-to-lowest regional IP. We instruct RIPE Atlas probes to send DNS queries to the representative hostnames served by Edgio and Imperva and record the returned IP addresses. Then we instruct each probe to ping all regional IPs associated with a hostname. Because DNS mapping results depend on whether a local resolver implements EDNS Client Subnet Extension [20], we run these experiments with two different DNS configurations:

Local DNS (LDNS) we configure each RIPE Atlas probe to use its local DNS resolver to send DNS queries when resolving a hostname.

Authoritative DNS (ADNS) For comparison, we configure each RIPE Atlas probe to send DNS queries directly to the authoritative name servers of a CDN, which are responsible for resolving customer domains to CDN's IPs. By doing this, the authoritative name servers of the CDN can determine the IP addresses they return based on the IP addresses of the querying clients.

We divide the experimental results into three groups and tabulate the results in Table 2. In the first group, DNS effectively returns a regional IP with less than 5 ms RTT difference to a client's lowest-latency regional IP ($\Delta RTT < 5\ ms$). We consider 5 ms a reasonable threshold to differentiate the performance of two CDN sites. We consider DNS mapping efficient in this case. In the second and third groups, DNS returns a regional IP whose RTT exceeds a client's minimum RTT among all regional IPs by 5+ ms.

We sub-divide the cases where a client receives a regional IP with an RTT more than 5 ms longer than the lowest-latency regional IP based on the causes of DNS mapping inefficiencies. According to the study in § 4.3, regional anycast CDNs map a client to a regional IP based on its geographic location; clients residing in the same geographic regions often receive the same regional IPs. If DNS maps a client to a regional IP outside its geographic area, we refer to this case as incorrect region mapping (×Region), which is likely due to IP geolocation errors. If DNS maps a client to a regional IP intended for clients in its geographic area (✓Region), but the RTT to this regional IP exceeds a client's RTT to the lowest-latency regional

IP by more than 5 ms, we consider this case as sub-optimal region mapping.

From Table 2, we can see that for Edgio's two representative hostnames, DNS maps more than 90% of the probes in all regions to regional IPs within 5 ms difference to their lowest-RTT regional IPs. Both incorrect region mapping and sub-optimal region mapping contribute to DNS inefficiencies. DNS mapping inefficiencies are more dominant in APAC and LatAm regions.

Imperva-6's DNS mapping is less efficient than Edgio's. The majority of the DNS inefficiencies are caused by inefficient regional mappings as shown in the (✓Region, $\Delta RTT \geq 5ms$) row in Table 2, due to Imperva-6's six-region partition scheme. Imperva-6 partitions the probes and sites in NA into two regions: Canada and the U.S. Around 10% probes in Canada and the U.S. are located near the Canada and U.S. border. Some of these probes have shorter RTTs to regional IPs in the other country. As a result, DNS maps only 88.0% of probes in NA to their low-latency regional IPs.

Similarly, Imperva-6 partitions Russia into a separate region. Probes in Russia receive distinct regional IPs which originate from three sites in Europe (Amsterdam, Frankfurt, and London). In this case, some probes in Russia have shorter RTT to EMEA (excluding Russia) regional IPs than to its own regional IPs and vice versa. For example, a probe in Russia reaches the site in Amsterdam, but its lowest-latency regional IP originates from a site in Copenhagen, Denmark. Its latency to the EMEA regional IP is 30 ms less than the latency to the Russian regional IP. As a result, for the EMEA region, only 78.3% of the probes receive regional IPs within 5 ms to their lowest-latency regional IPs in the Imperva-6 CDN.

Takeaways: This study reveals that regional anycast experiences DNS mapping inefficiencies, which causes 0%-21% of the probes in different regions to experience 5+ ms increased latency. Both incorrect regional mapping and DNS mapping based on a rigid regional partition can lead to sub-optimal performance.

5.2 Client Latency

In this section, we measure the performance of Edgio's and Imperva's regional anycast CDNs using the metrics we describe above: network latency and geographic distance. To measure client latency, we instruct a RIPE Atlas probe to ping the regional IP address it receives from DNS and record the RTT for each of the representative hostname of Edgio-3, Edgio-4, and Imperva-6 customers. In the meantime, we also plot the distance between a probe and the regional anycast site it reaches, as the speed-of-light latency lower-bounds the network latency. Figure 4 (a) and (b) show the cumulative distributions of the RTTs and the distance values of RIPE Atlas probes to Edgio-3, Edgio-4, and Imperva-6 regional anycast CDNs. We combine the measurement results for Edgio-3 and Edgio-4 for comparison.

We highlight two observations. First, the latency and distance values for probes in LatAm improve significantly in Edgio-4 compared to Edgio-3. The 80th percentile client latency decreases from 132 ms to 76 ms. Recall that Edgio maps the probes in South America to sites in North America in the Edgio-3 configuration. This result shows that mapping clients to the regional IPs of nearby CDN sites improves client latencies.

Percentile	Imperva-6 (Imperva-NS)			
	APAC	EMEA	NA	LatAm
80-th	38 (38)	31 (31)	25 (35)	68 (57)
90-th	63 (59)	45 (53)	38 (110)	102 (93)
95-th	98 (87)	67 (165)	54 (221)	120 (101)

Table 3: The tail latency comparison between Imperva-6 and its DNS global anycast network (Imperva-NS). RTTs are in the unit of millisecond. Green indicates a 5+ ms latency reduction in Imperva-6 and red indicates a 5+ ms increase.

Second, for both Edgio and Imperva, the 98th-percentile client latency in the NA and EMEA regions is less than 100 ms, the human interaction application threshold [52]. In the APAC region, however, more than 6.7% of Edgio-4 probe groups and 7.8% of Imperva-6 probe groups experience RTTs exceeding 100 ms. Similarly, in the LatAm region, more than 15.9% probe groups of Edgio-4 and 10.2% probe groups of Imperva-6 experience 100+ ms RTTs.

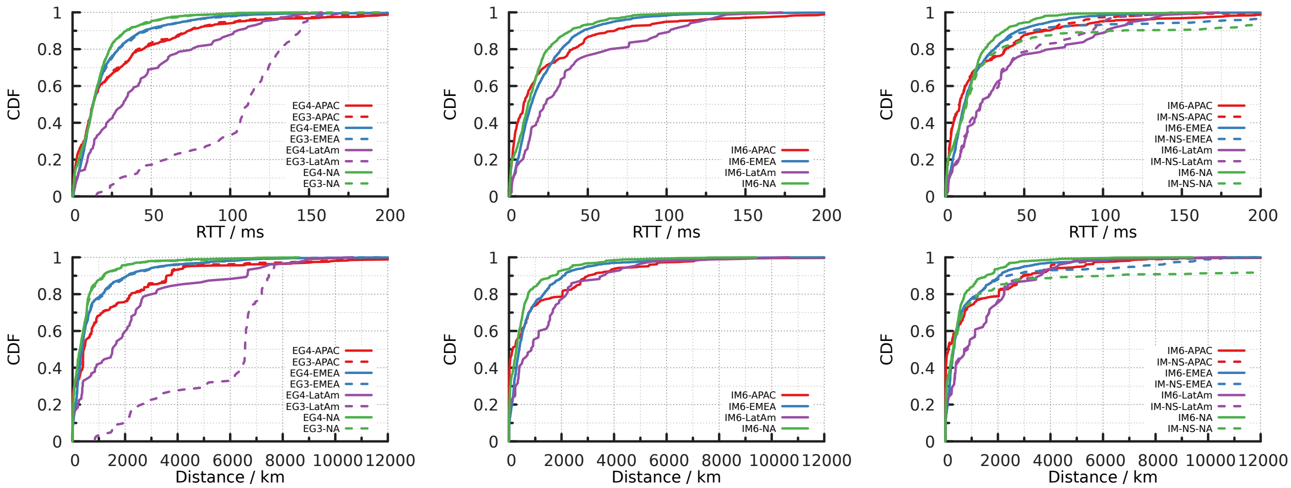
We investigate the reasons behind the occurrence of 100+ ms RTTs in regional anycast, using Imperva-6 as the specific case study. We find that a total of 148 probe groups of Imperva-6 experience 100+ ms RTTs. We categorize them into two sets: the first set comprises probe groups that have less than 100 ms RTTs to other alternative regional IPs. The second set consists of probe groups whose RTTs to all regional IPs exceed 100 ms. Among the probe groups in the first set, 48.0% of them receive the correct regional IPs from DNS, which are intended for their respective regions; the alternative regional IPs with less than 100 ms latencies lie outside their geographic regions. This result indicates that DNS's limitation to map a client to a regional IP based on the client's geographic location causes the 100+ ms latencies for those probe groups. For the remaining 52.0% of the probe groups in the first set, DNS returns regional IPs that do not correspond to their intended geographic areas, suggesting that IP geo-location errors are the underlying cause of the 100+ ms latencies. For probe groups in the second set, we have identified two factors that contribute to the 100+ ms latencies: cross-region announcements and poor intra-region connectivity. For example, Imperva has a site in California, US that announces its regional IPs for the APAC region. One probe group in China reaches this site and experiences 100+ ms latencies. In another example, a group of probes in Argentina reach their catchment site in Brazil via Italy, as there is no available network path between the probe group and the catchment site within the LatAm region.

5.3 Regional vs. Global Anycast

Next, we aim to study the performance impact of regional anycast when compared to global anycast.

A Comparable Global Anycast Counterpart Ideally, we aim to analyze the performance of a regional anycast CDN in comparison to the performance of the same CDN when configured to employ global anycast. This means announcing a global IP anycast prefix from all CDN sites, maintaining the same set of peers and policy configurations used for regional anycast. Such a study can unambiguously reveal the benefits or drawbacks of regional IP anycast.

Lacking access to a real-world CDN, we cannot conduct such a study. Instead, we use the DNS global anycast network of a regional anycast CDN to emulate its comparable global anycast counterpart. A common practice among CDN providers is to deploy their



(a) *Edgio-3 vs. Edgio-4* (b) *Imperva-6* (c) *Imperva-6 vs. Imperva-NS with same config*

Figure 4: ***The CDFs of client latency (first row) and the geographical distance to a client's catchment site (second row) of: (a) Edgio-3 (EG-3) and Edgio-4 (EG-4), (b) Imperva-6 (IM-6), (c) Imperva-6 and its DNS global anycast network (IM-NS) after excluding non-overlapping sites and peering ASes.***

authoritative name servers using global anycast at the same sites where they deploy hosting servers [13, 26, 62]. Using the anycast site enumeration method we describe in § 4.4, we find that all 48 sites we uncover for Imperva-6 overlap with the sites of its DNS global anycast network. We refer to Imperva's DNS global anycast network as Imperva-NS. Edgio's CDN sites do not overlap significantly with its authoritative name server network so we exclude Edgio from this study.

Furthermore, we uncover the set of peering ASes to which a CDN announces both its regional IP anycast prefixes and its DNS global IP anycast prefixes. Even if a CDN deploys its hosting servers and its authoritative domain name servers at the same site, it may announce its regional CDN IP anycast prefixes and its global DNS IP anycast prefixes to different peers with different policy configurations. Uncovering the common set of peering ASes enables us to emulate a global anycast network that shares the same sites and peers with a regional anycast CDN. We map the valid penultimate hop (p-hop) in each RIPE Atlas probe's traceroute to a regional anycast IP (or the global DNS anycast IP) to the AS or the Internet Exchange Point (IXP) that owns the p-hop's IP address. We use RouteViews' BGP archive [57] of the same day when we collect the probes' traceroutes and the published IP prefixes from PeeringDB [27] to construct the IP-to-AS or IP-to-IXP mapping. In 49.0% of the traceroutes, the p-hops' IPs belong to IXPs and are not visible in BGP. After this step, for each overlapping site between Imperva-6 and Imperva-NS, we construct the set of common peers (ASes or IXPs) at that site.

Moreover, we assume that Imperva does not apply different latency-impacting policies when it announces a regional anycast IP prefix or a DNS global anycast IP prefix to the same peer at the same site. We validate this assumption by comparing the RTTs from the same probe reaching the same site via a regional IP or via a DNS global anycast IP. We find that the RTT differences are negligible (as shown in Figure 8 in Appendix D).

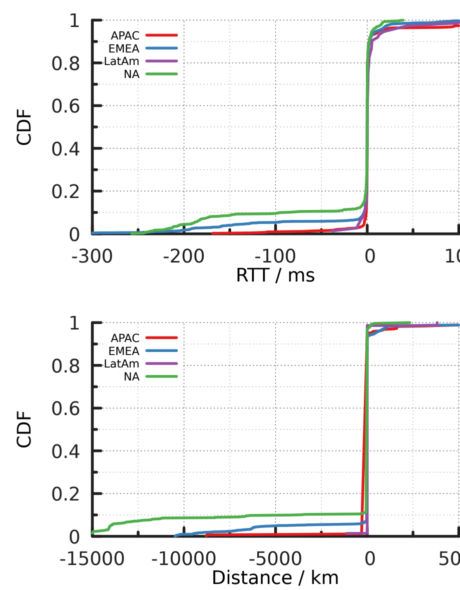


Figure 5: ***CDFs of RTT and distance differences between regional and global anycast.***

After completing these steps, we consider that the portion of Imperva-NS that includes the 48 overlapping sites with Imperva-6 and the overlapping set of peers with Imperva-6 at each site emulates the comparable global anycast counterpart of Imperva-6. This is because any site a probe reaches in the emulated global anycast network also announces a regional IP prefix to the same set of peers, and the RTT differences between reaching the site via a global anycast IP or a regional anycast IP are negligible.

Finally, to perform the comparison between regional anycast and global anycast, we instruct each RIPE Atlas probe to traceroute to its regional IP received via DNS when querying the representative hostname served by Imperva-6 and a global anycast IP of

Region (# probe groups)	$\Delta RTT < -5ms$ $\lvert\Delta RTT\rvert \leq 5ms$ $\Delta RTT > 5ms$	Closer Site	Same Site	Further Site
APAC (440)	15	26.7%	60.0%	13.3%
	395	0.0%	99.7%	0.3 %
	30	3.3%	33.3%	63.3 %
EMEA (2529)	219	69.9%	26.0%	4.1 %
	2130	1.0%	98.1%	0.8 %
	180	1.7%	22.8%	75.6%
LatAm (74)	5	0.0%	100.0%	0.0%
	60	0.0%	100.0%	0.0%
	9	11.1%	77.8%	11.1%
NA (584)	79	79.7%	19.0%	1.3%
	473	0.6%	97.9%	1.5%
	32	0.0%	68.8%	31.3%

Table 4: We examine the number of probe groups that have better/similar/worse RTTs (5 ms chosen as the threshold) in regional anycast than in global anycast. In each performance group, we examine the percentage of probe groups that reach closer, same, or further sites.

Imperva-NS, respectively. We filter the probes in the following cases: 1) probes that do not have a valid p-hop in their traceroute outputs; 2) probes that reach a non-overlapping site in Imperva-6 and Imperva-NS; and 3) probes that reach their catchment sites via a non-overlapping peer AS in Imperva-6 and Imperva-NS. In total, there are 4,417 probe groups with successfully resolved p-hops and we retain 82.1% (3,627 out of 4,417) of them after this filtering step.

Comparison of Imperva-6 and Imperva-NS Figure 4c plots the CDFs of the probe groups' RTTs to regional IPs in Imperva-6 and to global anycast IPs in Imperva-NS after excluding two networks' non-overlapping peers and sites, respectively. For probes in EMEA and NA, we see improved tail latency for regional anycast. For example, the 90th percentile RTT of probes in NA decreases from 110 ms to 38 ms. For probes in APAC and LatAm, regional anycast performs slightly worse than global anycast. Figure 5 plots the RTT difference and the distance difference between a probe's catchment site in Imperva-6 and in Imperva-NS. We observe that the percentage of probes with a distance reduction in regional anycast correlates well with the percentage of probes with latency reduction.

Further, we examine in detail the probes whose RTTs differ by 5 ms in Imperva-6 and Imperva-NS and how the RTT differences correlate with a probe's distance difference between its global anycast catchment site and its regional anycast catchment site. Table 4 summarizes the results. For the EMEA and NA regions, we find that when the probes achieve better performance in regional anycast, the majority of them reach closer sites in regional anycast than in global anycast. In the EMEA region, 69.9% (out of 219) probe groups that achieve more than 5 ms latency reduction reach closer sites in regional anycast. In the NA region, 79.7% (out of 79) probe groups that achieve more than 5ms latency reduction reach closer sites.

For the EMEA region, 7.1% probe groups (180 out of 2529) experience more than 5 ms longer latency in regional anycast than in global anycast; the majority (75.6%) of them reach further away sites. This result is consistent with our observation in § 5.1 that DNS mappings in the EMEA region are inefficient. Overall, there are more probe groups in EMEA that improve their performance in regional anycast. So we observe that the client latency distribution has improved in regional anycast. The probe groups with significant latency differences in other cases are few and we do not observe a consistent pattern.

For probe groups in each region that have similar performance in regional anycast and global anycast, between 97.9% to 100% of them reach the same sites. For probe groups in each region that have better or worse performance, some of them also reach the same sites. We examine the traceroute outputs of those probes and find that some of them reach the same sites via different AS paths and others have the same AS paths but different RTTs. BGP's route-selection uncertainty [4] and route instability (*e.g.*, temporary congestion) could potentially explain the RTT differences in these cases.

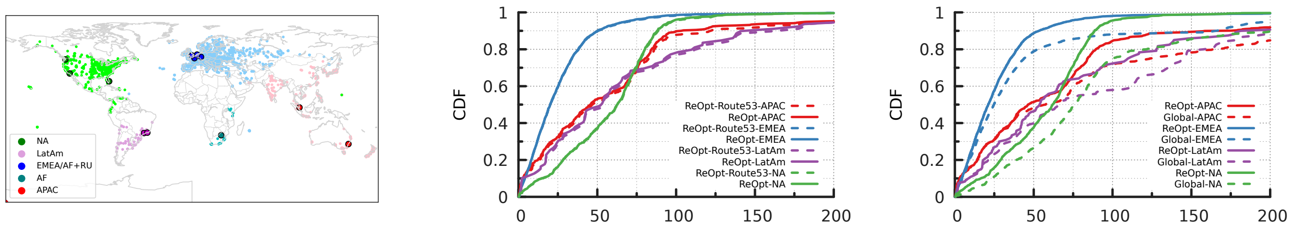
Takeaways: In the EMEA and NA regions, Imperva's regional anycast CDN effectively directs clients to nearby CDN sites and reduces client tail latency compared to global anycast. For example, the 90th percentile client latency is reduced by 72 ms for probe groups in NA, and the 95th percentile client latency is reduced by 98 ms and 165 ms for probes in EMEA and NA, respectively.

5.4 Case Studies: Causes of Latency Reduction

We have shown that regional anycast can reduce client latencies by restricting the CDN sites a client reaches to a specific geographic area. This result begets the question: why does the client not reach the same site in global anycast? To understand the reasons, we compare the traceroutes from probes to their catchment sites in regional anycast (Imperva-6) with those in global anycast (Imperva-NS). For probe groups with more than 5 ms latency reduction in regional anycast, we map each valid IP address in a traceroute output to the corresponding AS number with pyASN [30] and RouteViews BGP table dumps [57] archived on the same day we ran the traceroutes. We use the same method described in § 5.3 to identify IP addresses of IXPs. We also obtain AS relationships from CAIDA's AS relationship database [28]. We find two distinct cases where regional anycast can "override" common BGP policies to prevent clients from reaching distant CDN sites.

Overriding AS Relationship Preferences A common BGP policy is to prefer customer routes to peer routes and prefer peer routes to provider routes. As we show in Figure 1, this routing policy can cause probes to reach remote CDN sites within a large provider's customer cones instead of nearby CDN sites connected to the large provider's peers. Such situations frequently occur when a global IP anycast prefix from a CDN is announced to a non-tier-1 provider and subsequently announced to a tier-1 provider. Similar scenarios also happen when a client network peers with a large ISP that receives a global IP anycast prefix from a remote CDN site, but the client network also has a transit service provider that connects to a nearby regional anycast site. With regional anycast, clients will not receive the regional IPs advertised by those sites preferred more by BGP from DNS, thereby reaching closer sites and achieving lower latencies. In total, we observe that overriding this BGP policy accounts for 44.1% of the cases where regional anycast reduces client latencies in Imperva-6.

Overriding Peering Type Preferences Another common BGP policy is to prefer public peers to route server peers at an Internet Exchange Point (IXP) [60]. Public peers are ASes that directly exchange route advertisements and traffic over the fabric of an



(a) *ReOpt's site and client partitions*

(b) *Regional w/ and w/o DNS configuration*

(c) *Regional w/ ReOpt partitions vs. Global*

Figure 6: ***(a) Large colored dots show where Tangled sites are located. Small dots show where the probes are. Probes are assigned regional IPs announced by the same-color sites. (b) CDFs of probe RTTs between Route 53 DNS mapping and direct probe-to-regional-IP assignment. (c) Regional vs. global performance comparison using the Tangled testbed and the ReOpt client and region partition scheme.***

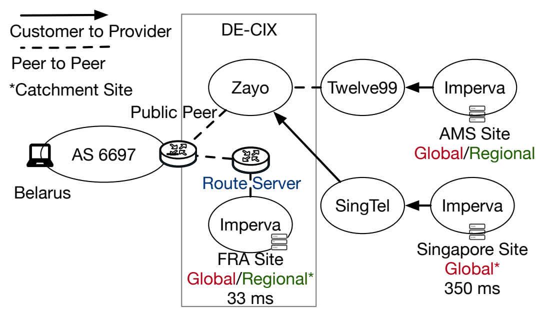


Figure 7: ***With a global anycast configuration, the Belarusian probe in AS 6697 reaches the CDN site in Singapore because public peering is more preferred to route server peering; with regional anycast, the probe reaches the site in Germany.***

IXP. In contrast, route server peers are ASes that exchange route advertisements via an intermediary route server [1]. Routers generally prefer public peers over route server peers, as public peering typically offers better performance than route server peering [60].

This BGP policy can also cause probes to reach remote CDN sites connected to public peers instead of nearby CDN sites connected to route server peers. We show an example in Figure 7. AS 6697 has a public peering with Zayo and a router server peering with Imperva at DE-CIX [21]. With global anycast, AS 6697 prefers the route to the global IP anycast prefix advertised by Zayo to the route advertised by Imperva at the FRA site because Zayo is a public peer and Imperva is a route server peer. However, Zayo prefers the route advertised by SingTel, as it is a customer route. Consequently, the probe located in Belarus in AS 6697 reaches the Singapore site in the global anycast. In contrast, in regional anycast, the probe does not receive the regional IPs of the Singapore site and hence reaches the closer FRA site.

Using IXPs' published route server feeds and CAIDA's AS relationship database [28], we identify that 1.6% of the cases where regional anycast reduces client latencies fall into this category. This number is small because many IXPs do not publish route server feeds so we cannot infer two ASes' peering type. For the rest of the cases where regional anycast improves performance, we are not able to clearly identify the reasons. This result could be due to missing IP hops in traceroutes, imperfect AS or AS relationship inferences, or unknown BGP policies.

6 Potentials

The measurement study in previous sections reveals the impact of DNS mapping inefficiencies on regional anycast's performance. This naturally leads us to question how much performance improvement regional anycast can achieve over global anycast if we improve its DNS mapping strategies. In this section, we explore this question using the Tangled testbed.

6.1 Latency-based Regional Partition

We develop a region partition and client mapping strategy, referred to as ReOpt, to address DNS mapping inefficiencies. First, we partition the Tangled testbed into geographic regions using the K-Means algorithm [46]. This step partitions geographically-close sites into regions. Second, we measure the unicast latency from each probe to each Tangled site and assign the probe to the region where its lowest unicast latency site is. Finally, we generate the country-level client-to-region mapping. For each country, we map all probes in the same country to the region where the majority of the country's probes are assigned to. This final step enables a network operator to use country-level IP geolocation to map a client to a regional IP.

To obtain the optimal number of regions, we vary the number of regions from three to six and calculate the average client latency under each regional partition. We find that a 5-region partition has the lowest average client latency on the Tangled testbed. Figure 6a shows the site partition and the client mapping of ReOpt's regional anycast configuration.

We observe two main differences between ReOpt's regional partitions and the regional partitions used by Edgio and Imperva. First, there is a separate region in Africa in ReOpt, while that region is part of the EMEA region in both Edgio and Imperva's regional partitions. Second, some probes in Central America are separated from probes in South America and are mapped to the North America region, but they are grouped together with the probes in South America in Edgio-4 and Imperva-6.

6.2 Global vs. Regional on Tangled

Next, we configure the Tangled testbed to deploy both global IP anycast and regional IP anycast and study their performance differences. When deploying global IP anycast, we configure all 12 sites in the Tangled testbed to announce one IP prefix to all their peering ASes and measure the RTTs from RIPE Atlas. When deploying regional anycast, we configure the sites in each of the five regions, as determined by the ReOpt algorithm, to announce a distinct regional IP prefix to all their peering ASes.

We then conduct two regional anycast experiments. In the first experiment, we directly assign each probe a regional IP that contains its lowest-unicast-latency site and measure the RTT to each probe's assigned regional IP. We use this step to study the optimal regional anycast performance without IP geo-location errors and without aggregating probes by country.

In the second experiment, we use a commercial DNS provider, Amazon Route 53 [3], to configure a country-level client-to-regional-IP mapping. Route 53 supports both country-level and continent-level DNS mappings. We create a test domain name and delegate it to Route 53 and use Route 53's country-level mapping configuration tool to map clients from a country to a regional IP based on the mapping generated by the ReOpt algorithm. We then instruct the RIPE Atlas probes to ping the test domain name and measure their RTTs.

Figure 6b shows the CDFs of the probes' RTTs when we directly assign a probe to a regional IP and the probes' RTTs when we use Route 53. We can see that the performance of regional anycast is similar under these two configurations, while Route 53 mapping causes a slight performance degradation in the APAC and SA regions. This result suggests that IP geolocation errors in the country-level DNS mapping service provided by commercial DNS providers like Route 53 have a negligible adverse impact on implementing regional anycast.

Then we compare the performance of regional anycast with that of global anycast on the Tangled testbed. Figure 6c compares the CDF of the probes' RTTs under ReOpt's regional anycast configuration with Route 53 with that under the global anycast configuration. We observe that in the regional IP anycast configuration, the client latency in all regions has improved compared to the global anycast. For instance, ReOpt's five-region configuration shortens the 90th percentile latency for the probe groups in NA from 232.6 ms to 88.6 ms. This result shows that with latency-based region partition and client mapping, regional anycast can outperform global anycast, even in the presence of DNS mapping inefficiencies.

We note that latency-based regional partition and client mapping requires that a CDN operator measures the client latency distribution to its regional IPs. This requirement increases the design complexity of regional anycast. However, managing client-to-regional-IP mapping is still simpler than managing client-to-site mapping, as done in DNS-based CDNs, because a regional IP covers multiple sites and an operator need not manage load-balancing and fault tolerance among those sites.

7 Related Work

There exists a large body of work measuring the IP-layer anycast adoption in the Internet [14] or characterizing the performance of global IP anycast systems, including root DNS servers [7, 8, 16, 19, 25, 39, 40, 42, 43, 58, 68] and global anycast CDNs [11, 16, 39].

The blog article [47] discusses why LinkedIn adopted regional anycast for its private CDN and it reports that the client latency improved after the CDN switched from global anycast to regional anycast.

Differently, this work characterizes the deployments and studies in-depth the performance of two global-scale public regional anycast CDNs. We experimentally validate regional anycast's performance advantages and uncover its drawbacks. In addition, we use the Tangled testbed to explore how to improve the performance of regional anycast.

The performance challenges of global anycast systems motivated a few proposals to improve its performance [8, 22, 26, 42, 49, 61, 69]. Among the existing proposals, we consider regional anycast as the most promising approach as we discuss in § 2. Therefore, we aim to understand the deployments and performance of two real-world regional IP anycast CDNs in this work. We leave a comparison between regional anycast and other proposals as future work.

This work builds on McQuistin *et al.*'s work [49] of using the penultimate hops in traceroute outputs to infer the number of AS-level connections an anycast network has. Differently, in this work, we combine multiple sources, including rDNS, penultimate hops, IP-geolocation databases, RTT ranges, and RIPE Atlas probe locations to enumerate the CDN sites that announce an anycast IP prefix. iGreedy [15] identifies an IP anycast prefix and geolocates the anycast instances using iterative latency measurements from known vantage points. We experimented with iGreedy for anycast site enumeration and found that it mapped fewer published CDN sites than the method we used in this work.

8 Conclusion

Regional anycast, combining IP anycast and DNS redirection, has been deployed in practice. Yet how well it performs and how a CDN deploys it remain unknown. In this paper, we perform a comprehensive study to characterize the deployments and performance of two real-world regional IP anycast CDNs. In particular, we explore the region division strategies of the CDNs and how they map clients to regions. We find that the CDNs divide their networks into regions by continents or large countries and similarly, the CDNs assign clients to regional IPs by the continents or the countries they reside in. Our measurements show that regional IP anycast in general can mitigate the catchment inefficiency problem experienced by global IP anycast, but poor DNS mapping, where DNS returns regional IPs originating from sub-optimal CDN sites to clients, could worsen client latencies. Using the Tangled testbed, we show that with a latency-based region partition method, regional anycast can reduce client tail latencies in various geographical areas, overcoming DNS mapping inefficiencies. Based on these results, we conclude that deploying regional anycast is worthwhile, as it can effectively override BGP's sub-optimal route selections by upper-bounding the distance between clients and their CDN catchment sites.

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Appendix

Appendices are supporting material that has not been peer-reviewed.

A Collection of CDN's Technical documents

Existing work [31, 54] has revealed that Edgio and Imperva are the two CDNs deploying regional anycast. To validate this observation and obtain a more recent view, we manually collect and examine the official technical documents to identify the studied CDNs' redirection mechanisms. As illustrated in Section 4.1, we obtain a list of the top 15 CDN providers by retrieving CDNFinder's API [53]. We note that we here focus on the CDN platform of each provider while global anycast could be available with other components to support specific services, *e.g.*, DNS or Cloud hosting. We also eliminate two other CDNs from our top list: (1) Facebook CDN, because it is deployed as a private CDN that supports Meta/Facebook's services; (2) Automatic CDN, which works as a plugin to accelerate the static assets of sites that are tied to Wordpress.com.

B IP Geolocating p-hops

We determine the catchment site of a RIPE Atlas probe by IP-geolocate the penultimate hop (p-hop) from its traceroute output to an IP anycast address. We then use the p-hop's geo-location to locate a CDN site. If the CDN site has an on-site router, the p-hop is often the site router so that we can observe a co-located CDN site and infer that the CDN site announces the regional IP address we traceroute to. If a CDN site does not have a site router and connects to a remote IXP via a link-layer connection [1], we will not observe a CDN site co-located with a p-hop. In this case, we assume that the CDN site closest to the p-hop announces the regional IP we traceroute to.

Because IP-geolocation at the city-level is not reliable [33, 55, 63], we combine a number of sources, including IP-geolocation databases, reserve DNS (rDNS) records, and RTT ranges to infer a p-hop's location. We use three IP-geolocation databases: MaxMind [48], ipinfo [37], and EdgeScape [67] to provide the possible locations of the p-hop. And we describe this process as follows.

Reverse DNS (rDNS): We first infer the location of a p-hop from its rDNS name [44, 45]. If a p-hop has an rDNS name and the name contains a geo-hint at the city level (*e.g.*, operator-defined codes, IATA/ICAO codes [34], or CLLI code [35]), we use the geo-hint to map the p-hop to a PoP location published by Edgio or Imperva. For instance, an rDNS name `ae-65.core1.amb.edgecastcdn.net.` indicates a p-hop is located in Amsterdam, Netherlands.

If the rDNS name does not contain any valid geo-hints at the city level, we will check the domain name's country code Top-Level Domain (ccTLD). If the CDN provider (Edgio or Imperva) has only one anycast site deployed in the ccTLD's country, we will map the p-hop to that site's city-level location.

RTT range: If a p-hop does not have an rDNS name or we could not infer its location from the rDNS name, we then attempt to use the location of the RIPE Atlas probe that went through the p-hop [29] and has less than 1.5 ms RTT to the p-hop to infer its location. The threshold is chosen according to the typical size of a metropolitan area, as the speed-of-light latency in fiber is roughly 100 km per 1 ms RTT. First, we query three IP-geo databases to estimate the p-hop's location, which may return different results. Then, we filter the invalid results based on the speed-of-light distance between the p-hop and the RIPE Atlas probe, and use the valid location closest to the RIPE Atlas probe as the p-hop's location. By this method, the location of the p-hop can be resolved when both the position of the probe and the IP-geo databases are correct at the same time.

Country-level IPGeo: The two steps above could resolve the majority of Imperva and Edgio's p-hops' locations. If after the above two steps, the location of the p-hop is still unresolved, we will use the country information from the IP-geolocation databases to infer the location of the p-hop. If all IP-geolocation databases return the same country location for the p-hop, and the CDN provider only lists one site in the country, we will use that listed site location as

Table 5: Top CDNs and their documents to demonstrate the types of redirection.

CDNs	Redirection Method	Documents
Google Cloud CDN	Global Anycast	`https://cloud.google.com/cdn`
Cloudflare	Global Anycast	`https://www.cloudflare.com/network/`
Amazon Cloudfront	DNS	`https://docs.aws.amazon.com/AmazonCloudFront/latest/DeveloperGuide/HowCloudFrontWorks.html`
Akamai	DNS	`https://www.akamai.com/our-thinking/cdn/what-is-a-cdn`
Fastly	DNS & Global Anycast	`https://docs.fastly.com/en/guides/using-fastly-with-apex-domains`
Stackpath	Global Anycast	`https://www.stackpath.com/edge-academy/what-is-anycast`
Edgio (EdgeCast)	**Regional Anycast**	`https://docs.edgecast.com/cdn/Content/HTTP_and_HTTPS_Data_Delivery/How_Do_Our_HTTP-Based_Platforms_Work.htm`
bunny.net	DNS	`https://bunny.net/network/smartedge`
Alibaba Cloud	DNS	`https://www.alibabacloud.com/help/en/alibaba-cloud-cdn`
Imperva (Incapsula)	**Regional Anycast**	`https://www.imperva.com/learn/performance/route-optimization-anycast/`
Microsoft Azure*	Global Anycast	`https://docs.microsoft.com/en-us/azure/cdn/cdn-overview`
ChinanetCenter/Wangsu	DNS	`https://en.wangsu.com/product/9`
CDN77	DNS	`https://www.cdn77.com/network`
Tencent Cloud	DNS	`https://intl.cloud.tencent.com/products/cdn`
Vercel	DNS	`https://vercel.com/docs/concepts/edge-network/regions`

* Azure provides an Azure Route Server that can support multi-region anycast deployment similar to regional anycast, but it essentially works by leveraging the front load balancer and only uses for private networks over cloud infrastructure (`https://docs.microsoft.com/en-us/azure/route-server/anycast`).

Percentile	Imperva-6				Edgio-3				Edgio-4			
	APAC	EMEA	NA	LatAm	APAC	EMEA	NA	LatAm	APAC	EMEA	NA	LatAm
50-th	10 (10)	14 (12)	11 (14)	23 (22)	13 (12)	12 (12)	12 (12)	110 (110)	12 (12)	12 (11)	12 (12)	33 (25)
90-th	66 (90)	48 (43)	33 (35)	109 (109)	76 (61)	40 (41)	31 (33)	145 (144)	75 (62)	39 (41)	31 (32)	112 (110)
95-th	103 (124)	65 (62)	50 (49)	153 (162)	121 (121)	63 (73)	45 (45)	154 (148)	115 (121)	62 (71)	47 (44)	135 (126)

Table 6: Latency comparison between selected hostnames and other hostnames. RTTs are in the unit of milliseconds. Numbers in parentheses are RTTs of the aggregated results of the other hostnames. Tail latencies of Imperva-6 in EMEA and NA are similar.

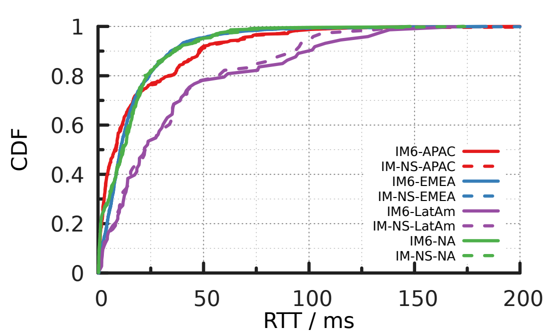

Figure 8: ***CDFs of the RTTs of the probes that reach the same CDN site via a regional IP anycast address and a global IP anycast address in Imperva-6 and Imperva-NS, after excluding the non-overlapping sites and peering ASes of the two networks.***

the p-hop's location, this is an effective way to discover the single site in one country.

Unresolved: We find that for the three sets of hostnames (Edgio-3, Edgio-4, and Imperva-6), we cannot resolve the locations of the p-hops of 2.3% to 9.9% valid traces. Increasing the RTT threshold will lead to an inaccurate inference. For those unresolved p-hops, even if we use IP geo-location databases to approximate their locations, we do not find more CDN sites. Therefore, we leave those p-hops unmapped.

C General performance

To ensure that the performance of the selected hostnames is representative, we conduct 12 additional measurements to random hostnames for each regional configuration and aggregate the results in Table 6. As a comparison, the performance of the representative hostnames is similar to that of the other hostnames, suggesting that the performance results of regional anycast are generalizable to other Edgio and Imperva hostnames.

D Same-Site Latency Comparison

When we study the performance of Imperva-6, we compare it with Imperva's DNS global anycast network (Imperva-NS) after excluding the non-overlapping sites and peers of the two networks. We assume that when Imperva announces a regional IP anycast prefix and a DNS global IP anycast prefix at the same site to the same set of peers, it does not apply different latency-impact policies to these prefixes. To validate this assumption, we compare the RTT of a RIPE Atlas probe that reaches the same site via a regional IP anycast address with the RTT of the probe that reaches the site via a global IP anycast address. We include only the results from the probes that reach the CDN sites via the common set of peering ASes observed in Imperva-6 and Imperva-NS.

Figure 8 shows the result. The differences in the RTT distributions are negligible, which indirectly validate that Imperva does not apply different latency-impacting policies to its regional IP anycast prefixes and its DNS global IP anycast prefixes. Because if it does, we should observe significantly different RTT distributions.