Investigating Location-aware Advertisements in Anycast IP Networks

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ABSTRACT

Anycast routing offers transparent service replication by distributing traffic across multiple Points of Presence (PoP). By advertising the same IP prefix from each PoP via BGP, traffic is routed to the nearest server, minimizing user latency. Despite its perceived benefits, prior research suggests IP anycast often falls short, with clients routed to distant replicas, increasing latency. Selective announcements made by anycast ASes contribute to this inefficiency, serving as a traffic engineering strategy to control incoming traffic flows.

In this work, we aim to shed light on the prevalence and rationale behind selective announcements in anycast networks. Through empirical evidence, we identify their significant adoption, primarily driven by the geolocation-agnostic BGP best path selection process. In particular, we observe that 84.06% of anycast ASes announce at least one of their anycast prefixes to a specific subset of their neighbors, whereas 80% of these selective announcers announce 100% of their prefixes selectively. This research represents an initial step towards comprehending the effects of selective and location-based routing policies in anycast IP networks.

CCS CONCEPTS

• **Networks** → **Network measurement**; **Public Internet**;

KEYWORDS

Internet Routing Policies; Anycast Routing

ANRW '24, July 23, 2024, Vancouver, AA, Canada

ACM ISBN 979-8-4007-0723-0/24/07.
https://doi.org/10.1145/3673422.3674885

ACM Reference Format:
Savvas Kastanakis, Vasileios Giotsas, Ioana Livadariu, and Neeraj Suri. 2024. Investigating Location-aware Advertisements in Anycast IP Networks. In *Applied Networking Research Workshop (ANRW '24), July 23, 2024, Vancouver, AA, Canada.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3673422.3674885

1 INTRODUCTION

IP anycast [34, 42, 49] is widely used to allows services to be transparently replicated across the Internet. By advertising, via BGP [50], the same IP prefix from each Point of Presence (PoP), traffic from any source on the Internet is routed to one of the PoPs according to properties of the path. Optimally users are associated with the nearest site (PoP), minimizing latency. Two of the most studied applications of IP anycast to date are root DNS servers [10, 12, 20, 21, 24, 36, 38, 43, 48, 51] and content delivery networks (CDNs) [7, 14, 15, 22, 23, 27]. This paper focuses explicitly on IP anycast for CDNs.

What makes IP anycast attractive is the mental model that it seems to permit. In particular, as one adds more anycast replicas in locations with many clients, it is generally believed [9, 15, 21] that: (1) overall client latency will decrease and (2) load from nearby clients will be more evenly distributed. Of course, inter-domain routing is not guaranteed to be optimal in terms of bandwidth, latency, or geographic proximity: at best, BGP can be relied upon for connectivity and policy-compliance.

Although user-to-site mapping generally follows geography [8, 33, 39], studies of routing have shown that actual network topology can vary [52], and recent observations have shown that the mapping depends heavily on the policies of many ASes, thus, can be unexpectedly chaotic [11, 32, 35, 39]. Lacking any useful information to distinguish between two or more anycast replicas, routers often select a distant, high-latency anycast site over the closer, low-latency one. Again, it is not surprising that inter-domain routing would not choose the best alternative, but it is surprising that the best alternative is often an unselected option [33, 37].

Additionally, an AS (anycast or unicast) may select to restrict the propagation of certain routes for traffic engineering purposes [16, 32, 53]. An anycast network might strategically employ selective announcements to fine-tune its routing dynamics for enhanced operational efficiency and user experience. By selectively announcing prefixes to specific neighboring networks, the anycast network can exert control over incoming traffic flows, directing them away from congested or underperforming nodes towards more optimal PoPs. This targeted approach allows the network to dynamically adapt to changing traffic patterns and network conditions, mitigating potential congestion issues and ensuring a smoother delivery of services to end-users.

In this study, our objective is to shed light on the prevalence of selectively announced prefixes within anycast networks and delve into the underlying reasons driving such practices. We present compelling evidence indicating that a significant portion of anycast ASes adopt selective prefix announcements as a traffic engineering strategy.

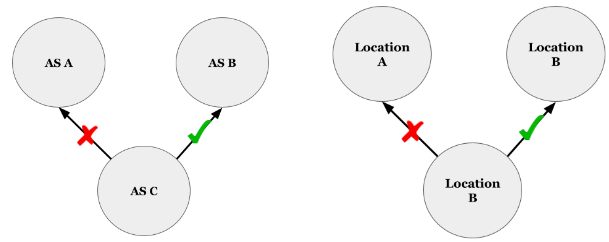
Specifically, our contributions are as follows:

- We measure the adoption of *selective announcements* across all anycast ASes.
- We derive a methodology to capture the *AS-level catchment* of anycast ASes, i.e., the direct neighbors that receive announcements for an anycast prefix.
- We measure the *regionality* of anycast ASes, i.e., the degree at which an AS decides to propagate their announcements across regional and global neighbors.
- We publish the artifacts (source code and data) of our study to facilitate future research on location-aware BGP path selection and anycast catchment prediction [31].

Our investigation indicates that the primary motivation behind this approach stems from a deficiency in backbone infrastructure for coordinating and managing routing announcements across PoPs. Consequently, anycast networks often resort to leveraging regional providers to establish connections between their PoPs. To the best of our knowledge, this is the first study of the interplay between selective announcements and IP anycasting on CDN operations.

2 SELECTIVE ANNOUNCEMENTS IN ANYCAST IP NETWORKS

Inter-domain routing does not follow the shortest path principle, but its based on the economic, performance or security needs of the organization. ASes independently define their routing policies [25, 29] in order to select routes to a certain destination when multiple routes are available, and to decide to which neighbors to propagate the routes they know.



(a) Selective announcement per AS. **(b) Selective announcement per location.**

Figure 1: Selective Announcement Types.

2.1 BGP Routing Policies

The Gao-Rexford Model In the BGP selection process [19, 30], a router evaluates multiple routes for the same destination IP prefix from different AS neighbors, choosing the most preferable route. *Locpref*, the highest-priority metric, determines route selection, typically with customer routes assigned the highest *locpref* values due to revenue generation and provider routes the lowest due to cost. Gao and Rexford [25] demonstrated that this *locpref* ordering is crucial for global routing system convergence, termed the Gao-Rexford model.

The Valley-free Rule After selecting the best route, a router may propagate it to neighboring ASes following the *valley-free rule*. This rule dictates that a customer route can be shared with any neighbor AS, while routes from peers or providers can only be shared with customers. This policy prevents an AS from providing free transit to peers or providers, conserving resources and avoiding unnecessary traffic costs.

2.2 Selective Announcements per AS

In theory, routing policies need to follow the Gao-Rexford model and the valley-free rule in order to be *safe* to converge to a stable state under any link or node failure.

Nonetheless, network operators can arbitrarily configure their policies, without any coordination with their neighbors, therefore, a number of ASes might not follow the Gao-Rexford rules and that routing policies are more complex than what the state-of-the-art [25] can model [8, 26, 28, 32, 41, 53]. Moreover, an AS may select to further restrict the propagation of certain routes to specific neighbors for traffic engineering purposes. By selectively advertising routes to different neighbors an AS may be able to control the links which will carry traffic for a specific route. For example, in Fig. 1a, *AS C* announces their prefixes to its neighbor *AS B* but not to *AS A*.

The deviations from the Gao-Rexford model can be likely explained by the evolving economic incentives in a changing

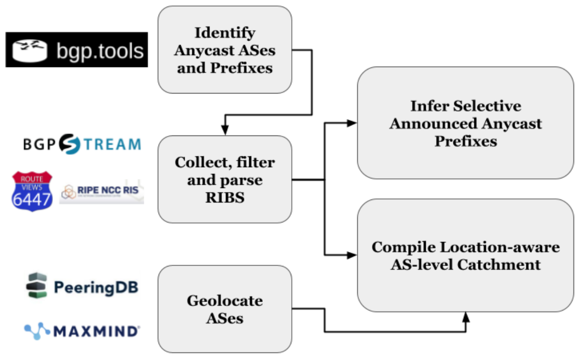


Figure 2: Tools used and overview of the methodology.

IP transit and peering market. During the past two decades, the Internet peering strategies have evolved to become more open, diverse and denser [40]. As a result, ASes may prefer peer over customer routes for performance reasons, since for more than 90% peering paths outperform customer paths [6].

2.3 Selective Announcements per Location

Anycast ASes offer enhanced reliability and performance by directing users to the nearest PoP, reducing latency and improving overall user experience. However, a notable characteristic of some anycast ASes is the absence of a centralized backbone infrastructure to interconnect these dispersed PoPs [53]. For example, in Fig. 1b, the origin AS has a PoP in *Location B* and decides to announce prefixes from this PoP only to ASes that operate in *Location B* and not to distant ASes (e.g., ASes that operate in *Location A*), for latency optimization reasons.

This decentralized architecture can lead to the occurrence of selective announced prefixes [32, 53]. In the case of anycast ASes, this selective advertising can arise from the fact that each PoP connects separately to regional upstream providers, often resulting in varying routing policies and capabilities across different PoPs. Since there is no centralized backbone to manage and coordinate routing announcements, each PoP may independently determine which routes to advertise based on factors such as network capacity, peering agreements, and traffic optimization strategies.

In this work, we focus on the scenario of location dependent selective announcements. To the best of our knowledge, this is the first effort to study the phenomenon of selective announced anycast prefixes due to geolocation factors.

3 DATA SOURCES AND METHODOLOGY

The goal of this paper is to study the selective routing policies of all anycast ASes in the interdomain routing system per geographical region. An overview of our methodology can be found in Fig. 2 and consists of the following steps:

ASN	AS Name	RUM Uptime	# of PoPs
13335	Cloudflare	99.43	197
16509	Amazon	99.37	166
15133	BytePlus	99.30	59
54113	Fastly	99.20	102
20940	Akamai	99.19	183
60068	CDN77	98.65	63
16276	OVH	99.20	43
21859	Zenlayer	99.20	78
199524	G-Core	99.14	91
15169	Google	98.96	135
30081	Cachefly	98.62	66
22822	Edgio	97.75	72

Table 1: Top Anycast Networks based on RUM Uptime.

Identify Anycast ASes and Prefixes To initiate our study, we compile a map of anycast ASes and their associated anycast prefixes. To that end, we leverage the bgp.tools anycast prefixes and ASes dataset [18] (the methodology to detect such prefixes is described in [17]). This is an important step, in which we narrow down our analysis only to anycast IP prefixes announced by anycast ASes.

Due to space constraints, we provide only the characteristics of the top anycast ASes based on their RUM uptime [1] in Table 1, but the methodology applies to every anycast AS. RUM (Real User Monitoring) uptime measures service availability and performance based on actual user experiences, providing a realistic assessment of network reliability. This makes it suitable for ranking anycast ASes, as it reflects user-centric metrics across diverse geographical locations. Note, however, that we investigate all anycast ASes on the Internet and publish the results in our online repository [31].

Collect, Filter and Parse RIBS In this step, we collect the BGP routing tables of all (691) anycast ASes (identified in the previous step) on the 1st of November, 2023, through the BGPStream API [47] which includes the route collectors of RIPE RIS [44] and RouteViews [45]. To gain the best view in terms of geographical distribution and coverage, in this project we make use of all available public route collectors up to this date (63). Note, that some of the BGP collector peers may contribute only partial routing tables (for example they may send only prefixes received by their customers to the BGP collector) [46]. For those ASes, we may overestimate the number of selectively advertised anycast prefixes. Therefore, our results should be considered as an upper bound of selective advertisements of anycast prefixes.

Infer Selective Announced Prefixes Anycast ASes often employ selective announcement strategies, where they announce subsets of their anycast prefixes to specific neighboring ASes.

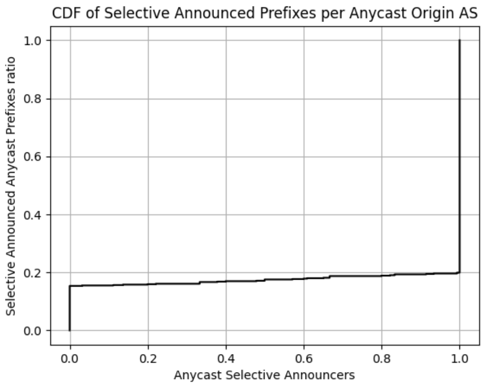


Figure 3: Selective announced prefixes per anycast AS.

In this step, we follow the approach of [53] to infer the selective announced prefixes in the interdomain routing system. The methodology of inferring selective announcements (also described in 2.2) relies on the assumption that if a prefix is received through a more expensive route than what is expected, either the origin AS or an intermediate AS in the AS-path applied selective export routing policies.

To label a selective announced prefix, we use the state-of-the-art AS-relationships [13] as well as the routing tables for all anycast ASes collected in the previous step. We follow the logic and conventions of [53]: *if a customer prefix is received through a peer/provider route, then this is a selective announced prefix*. Similarly, *a peer prefix is selectively announced if it is received through a provider route*.

From a total of 691 anycast ASes, we found that 581 ASes (84.06%) announce at least one anycast prefix to only a subset of their neighbors. In Fig. 3, we plot the CDF of selective announced prefixes per anycast origin AS. We find that 80% of the selective anycast ASes announce *all* of their prefixes selectively. Specifically, all the top anycast ASes mentioned in Table 1, announce 100% of their anycast prefixes selectively, while, the average selective announced prefix ratio across all anycast ASes is 82.5%[1].

Augment ASes with location specific characteristics To contextualize our findings within a geographical framework, we geolocate *all* ASes, up to this date, into their respective countries and regions. By incorporating geolocation data, we aim to uncover regional trends and disparities in anycast deployment and routing behavior.

When geolocating an AS, we consider: a) *the prefixes that an AS announces* as well as b) its *public peering locations*. Towards that goal, we extract country-level information for all prefixes announced by an AS from MaxMind [2] through the RIPEstat API [4] as well as the countries of the public peering locations from PeeringDB API [3]. We further use the United Nations dataset [5] to map countries to their respective regions. We leverage these data in the following step of our methodology as well as in our analysis in Section 4, where we classify the neighbors of an anycast AS into *regionals* or *globals* based on their geographic footprint.

Compile the Location-aware AS-level Catchment A catchment refers to the geographic region served by a specific PoP and represents the set of prefixes that are routed to that particular anycast site. When a user sends a request to an anycast IP address, the routing infrastructure directs that request to the PoP that is topologically closest to the user in terms of network hops.

In this work, instead of mapping IP prefixes to PoPs we map IP prefixes to ASes, which are the direct neighbors responsible for routing traffic to and from the anycast site at an AS-level granularity, namely, the *AS-level catchment*. Moreover, we rely on the intuition that when anycast routing is deployed, the nearest PoP site to the end-user is going to attract the traffic. Therefore, when the vantage point AS (VP) routes to an anycast prefix, usually this route is going to be approximate to the origin AS in terms of geographic distance (e.g., in the same geographic region). To achieve this:

- We geolocate all vantage point ASes (VPs) using MaxMind, based on the IP addresses of the routers providing the Routing Information Base (RIB) entries.
- We map the country of each VP to its respective region through the UN dataset [5].
- We group all the direct neighboring ASes responsible for carrying traffic for a specific prefix according to the regions of the VPs.

We delve into the intricacies of the geolocation specific routing policies of anycast ASes in Section 4.

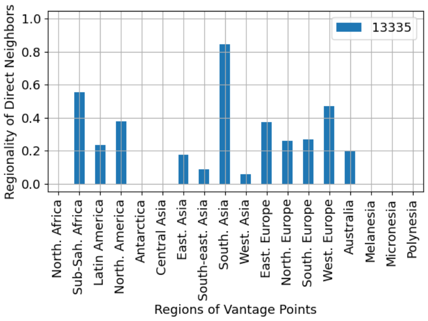
4 REGIONALITY OF DIRECT NEIGHBORS OF ANYCAST ASES

In this section, we aim to answer whether anycast ASes deploy selective announcements based on the geographic scope of their direct neighbors. To do so, we quantify the *regionality* levels of the direct neighbors of all anycast ASes per the regions of the vantage points.

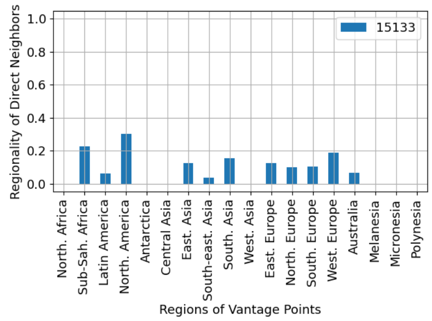
4.1 Definition of Regionality

We label an AS as *regional* if: a) more than 90% of its prefixes are announced in a single region (for details on regions see [5]), and/or b) more than 90% of its peering links exist in the same region. For instance, *ASa* announces half of its prefixes in Italy and the other half in Spain. Both countries are in the Southern Europe region. Furthermore, *ASa* peers with

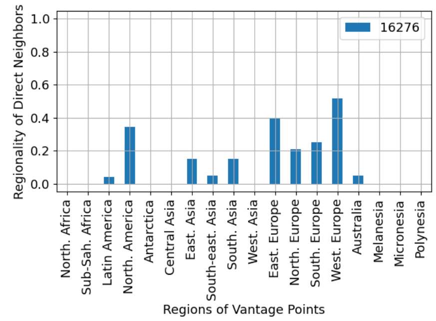
[1] Due to space constraints we refer the reader to [32, 53] for the validity of the selective announcements inference algorithm.



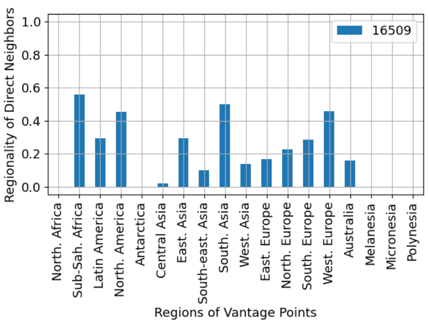
(a) Cloudflare.



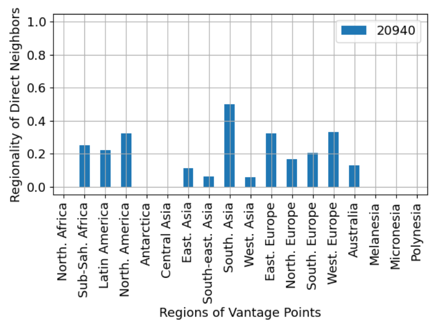
(b) BytePlus.



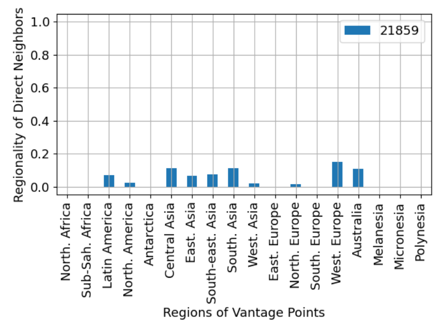
(c) OVH.



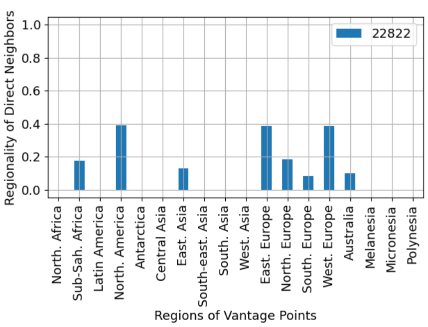
(d) Amazon.



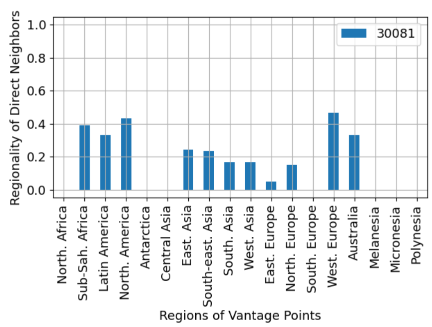
(e) Akamai.



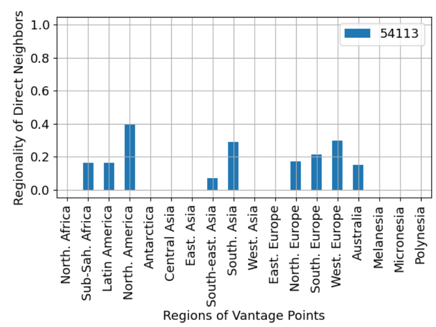
(f) Zenlayer.



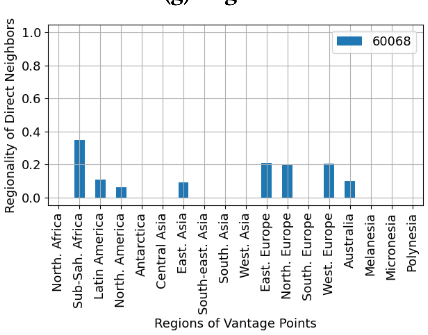
(g) Edgio.



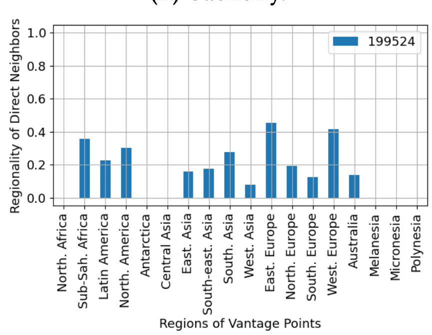
(h) Cachefly.



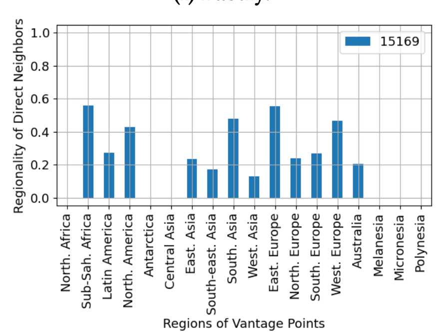
(i) Fastly.



(j) CDN77.



(k) G-Core.



(l) Google.

Figure 4: Regionality levels of the direct neighbors of the top Anycast ASes. In specific regions, big CDNs (e.g., Google, Cloudflare, G-Core, Amazon) rely on regional neighbors to carry their traffic to/from the rest of the Internet. This could be due to regulatory considerations, missing backbone or strategic business interests.

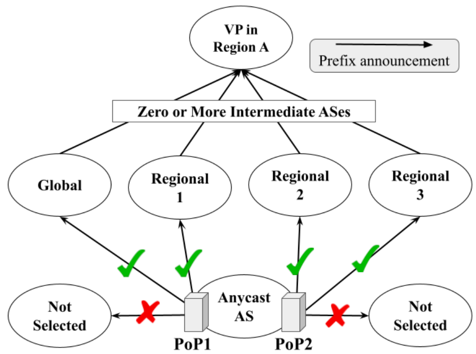


Figure 5: The Anycast AS connects to different ASes in different PoPs. Large PoPs (e.g., PoP1) tend to be connected to both regional and global ASes, while regional PoPs (e.g., PoP2) are typically connected only to regional ASes.

three neighbors in: Portugal, Malta, and Greece, all located in Southern Europe. Thus, *ASa* qualifies as a regional AS.

By leveraging the *AS-level catchment* dataset (mentioned in Section 3) and the methodology of classifying ASes based on their geographic scope, we quantify how many direct neighbors of anycast ASes (i.e., ASes which receive announcements for anycast prefixes of the anycast AS) are *regional* ASes and how many are *global* ASes. We define as *regionality R* the portion of regional neighbors that prefer and use an anycast announcement against the total number of neighbors that prefer and use the announcement.

As demonstrated in Fig. 5, the Anycast AS connects to different sets of ASes in different PoPs and selectively announces its prefixes only to 4 out of its 6 direct neighbors, when the source AS locates in *Region A*. Additionally, large PoPs (e.g., PoP1) tend to be connected to both regional and global ASes, while regional PoPs (e.g., PoP2) are typically connected only to regional ASes. As a result, a VP in the region of a PoP with solely regional transit providers (i.e., PoP2) is more inclined to reach the anycast AS through regional ASes. This allows us to infer more accurately the providers that would transit the traffic from a VP in Region A to the PoP of the anycast AS in that region.

In the following step, we measure the extent at which anycast ASes rely on regional ASes to carry their traffic to/from the rest of the Internet.

4.2 Regionality Analysis

In Fig. 4, we observe that selecting a regional upstream provider or peer to carry the traffic to and from an anycast prefix is a common practice among anycast ASes. Cloudflare prefers regional ASes when the source locates at the Subsaharan Africa, the Southern Asia and the Western Europe in more than 45% of the times. Amazon, Google and Cachefly exhibit more than 40% of regionality levels when the source AS locates in the aforementioned regions.

In regions like Sub-Saharan Africa, Western Europe, South Asia and Northern America, we observe high levels of regionality by large CDN players like Google, Amazon, Akamai and Cloudflare. Factors such as: a) specific infrastructure footprint, b) lower transit fees and c) strict regulatory conditions, drive the need for efficient traffic routing to ensure optimal user experience. Companies invest in local infrastructure and peering agreements to gain market penetration, comply with regulations, and enhance network resilience. By optimizing performance and ensuring redundancy, they can deliver faster content delivery and mitigate the impact of network disruptions, ultimately improving the quality of service for users in these regions.

On the other hand, ASes like CDN77, Edgecast and Zenlayer rely mainly on global ASes to carry their traffic to and from the rest of the Internet. A possible reasoning of this behavior is that these ASes prioritize global scalability and reach over regional optimization, especially if their services cater to a broad and geographically diverse user base.

As shown above, a part of the studied anycast ASes have high *regionality* levels while others prefer global providers. This highlights the need to further investigate the correlation between selective announcements and location-based routing policies. Our results can lay the grounds for understanding the confounding factors of: a) the anycast inefficiencies and b) the location-agnostic BGP best-path selection process.

5 CONCLUSION

The opacity surrounding anycast operations has profound implications in our ability to predict, understand, and debug such networks effectively. Through the analysis of BGP data, we identify and characterize selective and region-specific announcements, introducing a novel metric, "*regionality*", to delineate varying anycast strategies. Our findings indicate a substantial proportion of anycast ASes employing selective announcements in a *per location* basis, with the majority announcing all their prefixes selectively.

Looking ahead, we aim to quantify the extent at which geography influences BGP routing policies in anycast ASes. By enhancing our predictive capabilities with location-specific information, we aspire to contribute towards a deeper understanding and improved management of anycast networks.

ACKNOWLEDGMENTS

This research was supported, in part, by the UKRI Trustworthy Autonomous Systems Node in Security [EPSRC grant EP/V026763/1] and Ioana Livadariu was internally funded by SimulaMet.

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