Measuring the Deployment of IPv6: Topology, Routing and Performance

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ABSTRACT

We use historical BGP data and recent active measurements to analyze trends in the growth, structure, dynamics and performance of the evolving IPv6 Internet, and compare them to the evolution of IPv4. We find that the IPv6 network is maturing, albeit slowly. While most core Internet transit providers have deployed IPv6, edge networks are lagging. Early IPv6 network deployment was stronger in Europe and the Asia-Pacific region, than in North America. Current IPv6 network deployment still shows the same pattern. The IPv6 topology is characterized by a single dominant player – Hurricane Electric – which appears in a large fraction of IPv6 AS paths, and is more dominant in IPv6 than the most dominant player in IPv4. Routing dynamics in the IPv6 topology are largely similar to those in IPv4, and churn in both networks grows at the same rate as the underlying topologies. Our measurements suggest that performance over IPv6 paths is comparable to that over IPv4 paths if the AS-level paths are the same, but can be much worse than IPv4 if the AS-level paths differ.

Categories and Subject Descriptors

C.2.2 [**COMPUTER-COMMUNICATION NETWORKS**]: Network Protocols—*Routing Protocols*

Keywords

IPv6, BGP, Internet topology, routing, performance

General Terms

Experimentation, Measurement

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1. INTRODUCTION

The Internet operations, engineering and research communities are putting significant attention into a relatively new version (actually 15 years old) of the Internet Protocol – IP version 6 (IPv6) [1] – designed to solve several architectural limitations of the existing IPv4 protocol. The most essential characteristic of IPv6 is that it has provides orders of magnitude more address space than the world's foreseeable IP connectivity needs. IPv6 has become especially pertinent in the last two years because the global Internet address allocation architecture relies on the presence of a free pool of IP addresses to allocate to sites operating Internet infrastructure. The Internet Assigned Numbers Authority (IANA) exhausted its unallocated address pool in February 2011, and the Asia-Pacific region (represented by the APNIC RIR) followed suit in April 2011. The remaining RIRs too are expected to run out of unallocated addresses in the next few years [2]. This exogenous pressure from IPv4 address scarcity has driven widespread adoption of IPv6 into modern operating systems and network equipment. Major network operators and content providers are deploying IPv6 on both a trial and production basis [3], and some governments are mandating IPv6 support [4, 5]. But there is little hard data about how mature the IPv6 network is in terms of composition, topology, routing, and performance.

While IPv6 penetration remains small compared to IPv4, the IPv6 network topology has shown two distinct growth phases – for both ASes and AS links, an initial linear growth ($y{=}ax{+}b$) followed by exponential ($y{=}ae^{bx}$) gives the best fit with the data, with the change in trajectory occurring around 2008. The exponents for ASes and AS links are 0.13 and 0.16, respectively (Figure 1). It is interesting that the IPv4 network topology growth shifted from exponential to linear a decade ago [6]. While the current exponential growth of IPv6 hints that it may finally have shifted from an experimental or "toy" network to production, the nature of its growth is still largely undocumented. Which network types and geographic regions contribute the most? Does the growing IPv6 network appear to converge toward the existing IPv4 network? How do routing dynamics in IPv6 compare to IPv4? Does performance over IPv6 paths approach that over IPv4 paths?

In this study we use historical BGP archives and recent active measurements of the public IPv4 and IPv6 network infrastructures to analyze the state of maturity of IPv6 de-

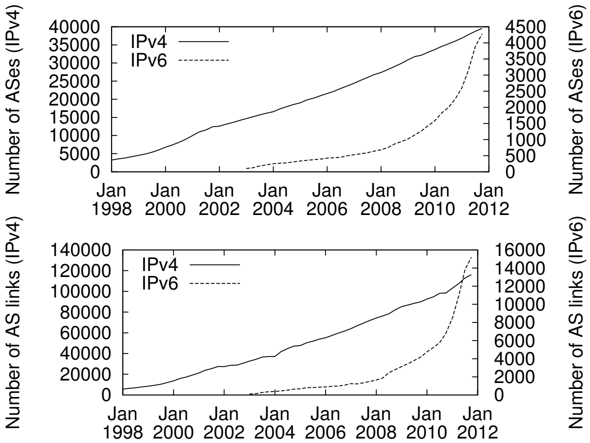


Figure 1: Both AS nodes and links grow linearly in IPv4 but exponentially (as of 2007) in IPv6.

ployment along three dimensions: topology, routing, and performance. Section 2 describes the data sources and supporting analysis techniques we use throughout the paper. We find that the IPv6 network is maturing, as indicated by its increasing similarity in size and composition (Section 3), AS path congruity (Section 4), topological structure (Section 5), and dynamics (Section 6), to the public IPv4 Internet. While core Internet transit providers have mostly deployed IPv6, edge networks are lagging behind. While all geographic regions show exponential growth in IPv6 adoption, early IPv6 deployment was stronger in Europe and the Asia-Pacific region than in North America. The IPv6 network is characterized by the presence of a single prominent player, Hurricane Electric (HE). Hurricane Electric currently appears in between 20% and 95% of IPv6 AS paths seen from different vantage points, and is more prominent in IPv6 than the most prominent player in IPv4. Further, when IPv4 and IPv6 AS paths differ, HE is the network most often added to the IPv6 path. Routing dynamics in the IPv6 topology are largely similar to those in IPv4. While routing churn grows linearly in IPv4 and super-linearly in IPv6, it is important to note that these trends match those of the underlying IPv4 and IPv6 AS topology growth. In terms of performance (Section 7), our measurements show that IPv6 data-plane performance closely matches IPv4 performance when the AS-level paths are the same, while it can be significantly worse when AS-level paths differ.

2. DATASETS AND METHODS

We use a variety of data sources and analysis methods, which we summarize here, providing more detail in sections that use specific data. Our analysis of the IPv6 Internet's size, routing behavior, and structure (Sections 3-5) relies on publicly available historical BGP tables. Section 6 uses BGP updates from the same public repositories to analyze routing dynamics of the IPv4 and IPv6 networks over time. We gather our own data using active measurements from five vantage points around the world, to compare and correlate IPv4 and IPv6 performance with other growth parameters. To compare the composition of the IPv4 and IPv6 graphs according to type of networks, we classify the business types of ASes using the algorithm presented in our previous work [6] and the business relationships of the links between them (*e.g.*, customer, provider, peer) using Gao's algorithm [7].

BGP topology data

We collected historical BGP data from the two major public repositories at RouteViews [8] and RIPE [9]. We rely only on these two data sources because no other source of topological/routing data (routing registries, traceroutes, looking glass servers, etc.) provides historical information. Routeviews and RIPE started collecting IPv4 BGP data as early as 1998; the first IPv6 collector, however, became active in 2003. Consequently, our IPv4 data spans 14 years from 1998 to 2011, while the IPv6 data is from 2003 to 2011. The use of Routeviews/RIPE repositories of BGP data has been shown to inadequately expose the *complete Internet topology* [10, 11, 12] – although this data captures most ASes, it misses a significant fraction of peering and backup links at the edges of the Internet [13, 12, 14]. However, we are mainly interested in customer-provider links used most of the time. AS links revealed by short term failures and transient routing events can "confuse" an evolutionary study, misinterpreting link disappearances and appearances due to transient failures as link deaths and births respectively. For example, the primary link l_p between ASes X and Y fails at time t_1, causing the activation of a backup link l_b between ASes X and Z. l_p is repaired at t_2 and the connectivity returns to its original state. Since we focus on primary links, our goal is to ignore the transient event during (t_1, t_2) and not detect l_b. On the other hand, a change of routing policy that makes l_b the primary link should be detected as the death of l_p and the birth of l_b. To remove backup and transient links, we apply the method of "majority filtering" described in our previous work [6] on the set of BGP AS paths obtained from BGP table dumps at Routeviews and RIPE collectors. We do not use BGP updates to construct our topology snapshots, as these reveal backup and transient links which we want to filter. The majority filtering method works as follows. For both IPv4 and IPv6, we construct a topology snapshot by collecting 5 sets of AS paths over a duration of 3 weeks, only using AS paths that were seen in a majority of those five samples. We collect such a topology snapshot every 3 months, resulting in 56 snapshots of the IPv4 topology and 36 snapshots of the IPv6 topology. We refer the reader to our previous work [6] for a detailed description of the data collection and pre-processing.

BGP routing dynamics data

Our comparative analysis of routing dynamics of the IPv4 and IPv6 infrastructures is based on BGP updates collected by the Routeviews project. Routeviews collectors run BGP sessions with routers (or *monitors*) in many networks. Each monitor sends a BGP update to the collector every time there is a change in the preferred path from the monitor to a destination prefix. We use update traces from two Routeviews collectors: Routeviews6 for IPv6 data and Oregon-IX for IPv4 data. The IPv4 updates span the period from 1 Jan 2003 to 16 Feb 2012, while the IPv6 updates span 7 May 2003 through 16 Feb 2012. We use monitors from five networks that contributed both IPv4 and IPv6 routing data throughout the study period: AT&T, Hurricane Electric (HE), NTT-America, and Tinet, and IIJ. AT&T's IPv4 monitor was unavailable for three months in 2003, and its IPv6 monitor was unavailable between May 2005 and May

2007. Tinet's IPv6 monitor was unavailable between June 2008 and June 2010. If the multi-hop BGP session between a monitor and the collector is broken and re-established (session reset), the monitor re-announces all its known paths, producing large bursts of updates. This is a local artifact of the Routeviews measurement infrastructure, and does not represent genuine routing dynamics. We use the method developed by Zhang *et al.* [15] to identify and remove updates caused by session resets.

AS relationships
We use Gao's AS relationship classification algorithm [7] to infer the business relationship associated with each inter-AS link.[1] For each snapshot, we apply this algorithm to the set of IPv4 AS paths. Gao's algorithm classifies AS links into the following types: sibling, customer-provider, settlement-free peer, and unknown. Our focus is on customer-provider and settlement-free peering links, so we exclude the sibling and unknown classes, which account for fewer than 1% of the AS links in any snapshot.

AS classification
In our previous work [6], we developed a method to classify ASes according to their expected business type. The method relies on a machine learning decision tree classifier which uses as input two properties inferred for each AS – the average number of customers and average number of peers over the lifespan of that AS. By peers we mean settlement-free peers in a routing sense; we cannot know for sure if there is a settlement between them. In that study we used this method to classify each AS into four classes – Enterprise Customer (EC), Small Transit Provider (STP), Large Transit Provider (LTP), and Content/Access/Hosting Provider (CAHP) – with an accuracy of 85%. Note that the AS types we consider are quite distinct from each other in terms of their function and business goals. It is thus reasonable to expect that ASes do not change from one AS type to another during their lifetime. We validated this assumption in our previous work by running the classification algorithm using only a two-year dataset; we found that only 3% of AS classifications changed as compared to the entire dataset [6]. For this study we repeated the classification algorithm using the 14-year dataset described above to obtain a new classification. Of the ASes present in both datasets, only 2.4% had a different classification. We assume that an AS has the same business type in IPv6 as in IPv4. We further classify ASes according to their primary geographical region of operation, as reflected in the RIR database (WHOIS) where the AS is registered: ARIN (North America), RIPE (Europe, Middle East, and the former USSR), APNIC (Asia/Pacific), AfriNIC (Africa), and LACNIC (Latin America).

Performance data
Similar to the method employed by Nikkhah *et al.* [16], we measure the average time to fetch a page from webservers registered in the DNS with IPv4 and IPv6 addresses that have the same origin AS number in the longest matching BGP route. We use the Alexa list of the one-million most popular websites in the Internet, testing up to three webservers for each origin AS. We try to avoid a common problem with throughput measurements, namely never getting out of TCP's slow start phase, by seeking to download a page that is at least 10,000 bytes. If the web site's root page is smaller than that, we fetch the smallest object embedded in that page that is at least 10,000 bytes[2]. While a threshold of 10,000 bytes is not always sufficient to get out of slow start, it seeks to balance the tradeoff between finding a large number of web objects to download, and ensuring that those objects are sufficiently large. We fetch each page three times from each webserver, alternating IPv4 and IPv6 transport sequentially. Each measurement begins approximately five seconds after the previous one completes to avoid competing measurements but also to minimize the chance of network topology changes mid-measurement. We also measure the forward AS-level IPv4 and IPv6 paths using traceroute with TCP probes immediately after the sequence of performance measurements completes. We collected this data from five vantage points: a state network in New York; a research network in Japan; a commercial ISP in Japan; a commercial network in the Netherlands; and an enterprise customer in the Netherlands. We sanitized our measurements as in [16]: We excluded from performance evaluation those measurements where the standard error of the mean download time (for either IPv4 or IPv6) was greater than 10% (at the 95% significance level), or the object sizes in IPv4 and IPv6 were not within 1% of each other. This filtering left us with 544 dual-stack ASes represented in our dataset, consisting of 233 ECs, 106 STPs, 10 LTPs, and 195 CAHPs according to the previously described classification. We used scamper's tbit and traceroute implementations [17]; the former includes a test that fetches a page, negotiating TCP SACK and TCP timestamps, and records all packets sent and received during the test, which allows us to further examine the packet traces to infer why performance may differ.

3. GROWTH TRENDS BY BUSINESS TYPE AND GEOGRAPHIC REGION

While overall growth rates indicate that IPv6 deployment is accelerating, these growth rates differ by (business) type of network and geographic region. Since IPv6 provides essentially the same functionality as IPv4, we hypothesize that as IPv6 matures, the distribution of business types in IPv6 should resemble that in IPv4. Geographic coverage of IPv6 may not exhibit the same convergence with IPv4 given the pre-existing allocation of IPv4 address space around the world and various levels of pressure by different national governments to promote IPv6.

3.1 Growth trends by business type

Figure 2 shows the fraction of networks over time from each of the four business types mentioned in Section 2, for the IPv4 (top panel) and IPv6 (bottom panel) topologies. Above each panel, we show the total number of ASes in the IPv4 and IPv6 graphs over which the fractions are computed. At least since 1998 (when historical BGP data became available), the IPv4 topology has always consisted of a large fraction of EC networks; currently 90% of ASes are EC, while STPs and CAHPs comprise most of the remaining 10%. In 2003 only 35% of IPv6 networks were of type EC, but this fraction has increased steadily, currently at 60%. The relatively large fractions of STPs and CAHPs in the

[1]We are in the process of developing and validating a new AS relationship classification algorithm, but for this study we use Gao [7].

[2]Nikkhah *et al.* [16] fetched the root page regardless of size.

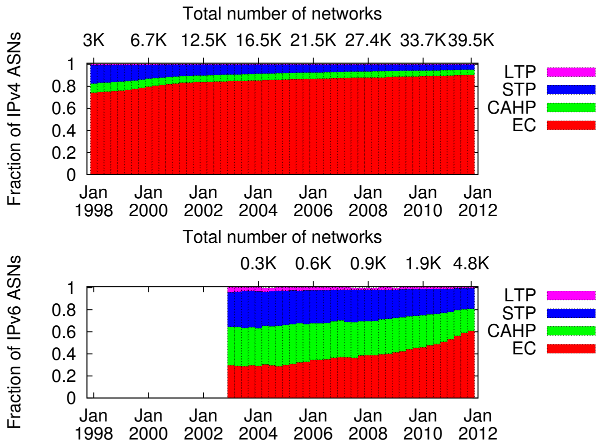


Figure 2: As IPv6 matures the fraction of EC ASes has grown from 35% to over 60% of the IPv6 graph, while IPv4 has seen little change, with ECs currently at 90%.

IPv6 topology suggests that IPv6 deployment has primarily occurred at the core of the network, driven by transit and content providers.

To further explore the evolution of business types in IPv6, we measure growth trends for each AS type in the IPv4 and IPv6 graphs. We find that ECs, STPs and CAHPs all grow linearly in IPv4 after 2001. The IPv6 graph has evolved differently. For ECs, STPs, and CAHPs, we find that an initial linear growth phase from 2003 (when data archiving began) until 2007-2008, followed by exponential growth until the present time gives the best fit with the data. The exponents for ECs, STPs, and CAHPs in the exponential growth phase are 0.16, 0.09, and 0.08, respectively.[3]

We also measure the growth rate (in ASes/month) of each business type in the IPv4 and IPv6 graphs (graph omitted due to space constraints). In both the IPv4 and IPv6 graphs, ECs show the highest growth rate, although the growth rate of ECs in the IPv4 graph (between 50 and 350 ASes/month over the last 14 years) has always been larger than in the IPv6 graph. Only since 2011 has the EC growth rate in IPv6 been comparable to that in the IPv4 graph. In fact, the growth rate of ECs in the IPv6 graph reached a peak of 182 ASes/month in mid-2011 and then declined, coincident with *World IPv6 Day* [18] in June 2011, and consistent with Aben's observation that the overall growth rate of IPv6 ASes peaked around the World IPv6 day [19]. The growth rate of STP and CAHP ASes in IPv4 has been almost constant over the last 14 years (between -2 and 20 ASes/month); interestingly, the growth rates for these types in the IPv6 graph are similar (between -2 and 40 ASes/month), and since 2010, the growth rates in IPv6 are larger than those in IPv4 (in fact, STPs and CAHPs show recent negative growth in the IPv4 graph). The recent spurt in the growth rate of IPv6 ECs to a level that is comparable with the growth rate of IPv4 ECs is encouraging: it implies that IPv6 deployment at the edges, which has historically lagged behind deployment at the core, is now catching up.

[3] We omit the graph due to space constraints

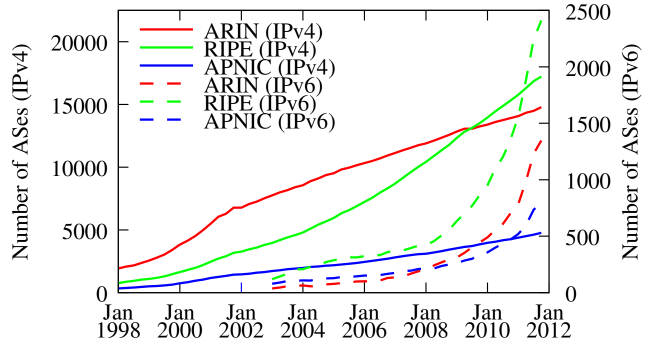


Figure 3: Regional growth in IPv4 and IPv6 ASes. RIPE overtook ARIN in the IPv4 graph in 2009; RIPE has always been ahead in IPv6.

3.2 Growth trends by geographical region

Figure 3 shows the number of ASes in different geographical regions over time, according to the RIR WHOIS mappings described in Section 2. We omit the two smallest registries (LACNIC and AfriNIC), which have so few ASes compared to the three large registries (ARIN, RIPE and APNIC) that they are barely visible in the graph. The graph shows that for IPv4, the growth rate of RIPE-registered ASes has exceeded that of ARIN-registered ASes for the last decade (though both ARIN and RIPE showed linear growth in this period), and as of 2009 the RIPE region has more ASes than the ARIN region, a big difference from the early days of IPv4. For the IPv6 graph, on the other hand, the growth trend for each of the ARIN, RIPE and APNIC registries shows two distinct periods since 2003 – an initial linear phase followed by an exponential phase (with exponents 0.13, 0.13 and 0.11, respectively) until the present time. For ARIN and RIPE, the change from linear to exponential happened around 2007-2008, while for APNIC it was at the start of 2009. Unlike IPv4, however, the RIPE region has always had more ASes in IPv6 than ARIN. APNIC had more ASes than ARIN until 2008, when the IPv6 AS growth rate in the ARIN region changed to exponential. *While the RIPE and APNIC regions led early adoption of IPv6, adoption in the ARIN region is accelerating, and the number of ARIN-registered and RIPE-registered ASes in IPv6 currently grow at the same rates.*

The business type classification of the previous section reveals more insight into growth across different geographic regions. Although growth in ECs in different regions mostly follows the same trends as for all ASes (shown in Figure 3), STPs and CAHPs behave differently. In the IPv4 graph, the growth rate of ARIN-registered STPs was almost identical to that of RIPE-registered STPs (around 5 ASes/month) until 2002. Since 2002, however, the growth rate of ARIN-registered STPs has slowed to 1.5 ASes/month, while that of RIPE-registered STPs is around 3 ASes/month. Consequently, the number of RIPE-registered STPs soon surpassed ARIN-registered STPs. This difference may derive from contrasting regulatory environments which led to more competition in the transit market in Europe than in North America. Another possible explanation is the tendency of small Eastern European networks to use Provider-Independent (PI) address space [20] which is typically advertised in BGP with its own ASN, rather than Provider-Aggregatable

Peer	ASN	Name	Type	BGP source	When
ACOnet	1853	Austrian Academic Computer Network	CAHP	RIS RRC 05	Oct 2003
IIJ	2497	Internet Initiative Japan	STP	Routeviews 2/6	Jul 2003
NTT	2914	NTT Global IP Network	LTP	Routeviews 2/6	Jul 2003
Tinet	3257	Tiscali International Network	LTP	Routeviews 2/6	Oct 2003
HE	6939	Hurricane Electric	LTP	Routeviews 2/6	Jul 2003
AT&T	7018	AT&T Services	LTP	Routeviews 2/6	Apr 2004
BIT	12859	BIT BV	STP	RIS RRC 03	Jan 2003

Table 1: BGP vantage points (VPs) providing both IPv4 and IPv6 routing data since 2003. Six of the seven networks are transit providers, which may bias our view of the topology because we miss peering links below.

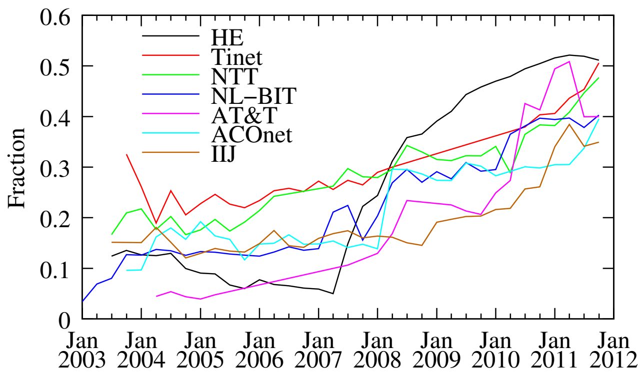


Figure 4: Fraction of dual-stacked origin ASes reachable over an identical AS-level path in both IPv4 and IPv6. Currently, more than 40% of the AS-level paths used to reach an origin are the same in both protocols.

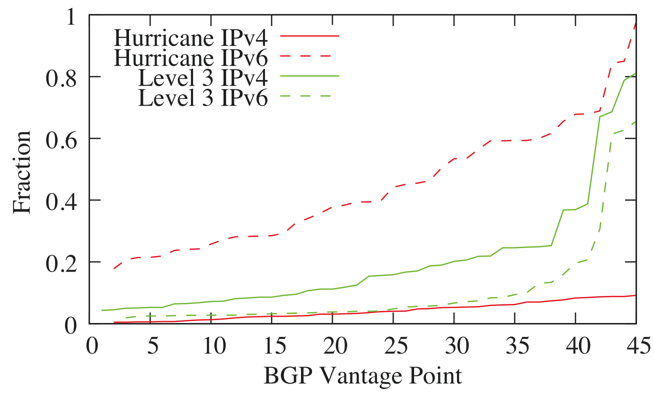


Figure 5: Fraction of origin ASes reached via an AS for each BGP vantage point in October 2011. Hurricane is relatively more prominent in the IPv6 topology than Level3 is in the IPv4 topology.

(PA) address space which is typically advertised in BGP by a provider network. In the IPv6 graph the number of STPs and CAHPs in the RIPE region has exceeded that of the ARIN region since 2003 (the start of IPv6 data collection), consistent with the stronger community pressure in Europe for operators to support IPv6, including European Commission funding for IPv6 deployment from its early stages.

4. EVOLVING STRUCTURE OF IPV4 AND IPV6 TOPOLOGIES: AS PATHS

Similar to our belief that the composition of a maturing IPv6 topology should look more like the IPv4 topology, we also expect a convergence to occur between the best AS path between a given pair of ASes in IPv4 and IPv6. Another reason to compare IPv4 and IPv6 AS path congruity is its correlation with performance. In Section 7 we show that *IPv6 data plane performance is worse than IPv4 when the AS paths differ, but when the AS paths are the same, IPv6 performance is comparable to that of IPv4.* Improved congruity between IPv4 and IPv6 paths seem to improve IPv6 performance, which is likely to further promote IPv6 deployment. To explore trends in congruity between IPv4 and IPv6 paths, we first calculate the fraction of AS paths from a given vantage point (VP) toward dual-stacked origin ASes (*i.e.*, ASes that advertise both IPv4 and IPv6 prefixes) that are identical in IPv4 and IPv6. If there are multiple IPv4 or IPv6 AS paths available between a given VP and an origin AS, we report it having an identical AS path if any of the paths are the same. If they differ, we dissect the differences, in terms of which ASes are added and removed from those paths. This analysis also reveals the presence of dominant players in the IPv6 topology.

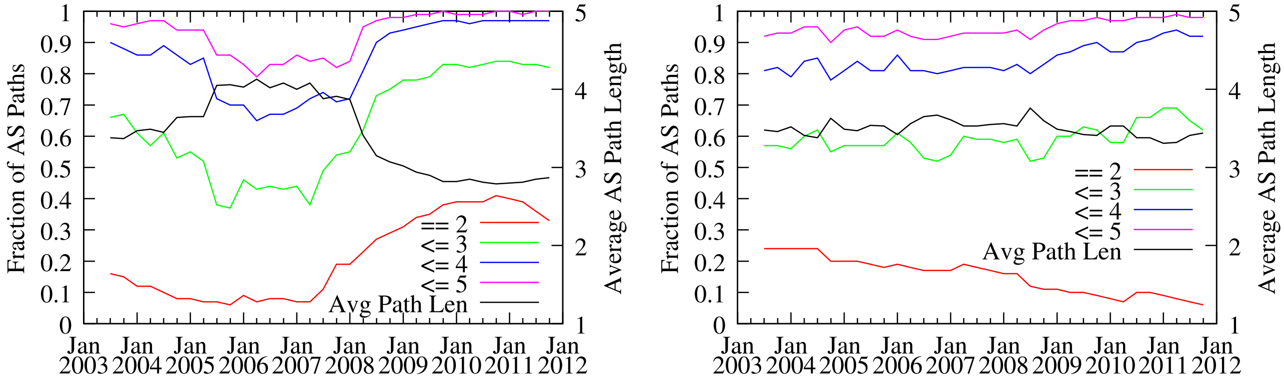
We first measure the evolution of IPv6 from seven vantage points listed in Table 1 (four LTPs, two STPs, and one CAHP) which have provided BGP data to Routeviews and RIS since 2003. For each topology snapshot, we use the set of majority-filtered (as described in Section 2) AS paths exported by these six monitors. We remove all prepending from AS paths, and discard paths with AS sets or loops. This filtering process rejects 0.1% of AS paths due to AS sets or loops.

Identical AS paths in IPv4 and IPv6

Figure 4 plots the fraction of dual-stack paths that are identical in IPv4 and IPv6 from each vantage point over time. According to this metric, IPv6 paths are maturing slowly. In January 2004, 10-20% of paths were the same for IPv4 and IPv6; eight years later, 40-50% of paths are the same for six of the seven vantage points. The most significant trend in this data is the rise in prominence of Hurricane Electric. In April 2007 only 5% of its dual-stacked paths were identical, but in 2012 just over 50% of dual-stacked paths are the same from Hurricane's perspective.

Different ASes in IPv4 and IPv6 AS paths

Since only between 40% and 50% of the AS paths from different vantage points to dual-stacked origin ASes are the same, the next question is: how do the paths differ? We compute the AS edits required to make the IPv4 paths identical to the



(a) Hurricane Electric, IPv6.

(b) Combined Tinet, NTT, IIJ IPv6.

Figure 6: Average AS path lengths to dual-stacked origin networks over time from different vantage points, and the fraction of paths of length 2 (directly connected), length ≤ 3, and so on. In January 2011, HE was directly connected to 40% of dual-stacked origin ASes in IPv6. Since 2003, other transit providers have observed the fraction of directly connected dual-stack ASes decrease.

IPv6 paths – specifically, which ASes are most often added and removed from AS paths that differ. Between 2011 and 2012 Hurricane Electric was added to between 20% and 50% of IPv6 paths that were different to a corresponding IPv4 path, depending on the vantage point. There were no other ASes added to IPv6 paths as frequently and consistently across vantage points as Hurricane. No AS is consistently missing from IPv4 paths.

ASes most frequently seen in AS paths

Next, we examine the AS paths from all BGP vantage points (VPs) that provide a full table[4] to Routeviews and RIPE collectors in October 2011 to determine the relative *prominence* of ASes in the IPv4 and IPv6 topologies. We define the *prominence* of an AS X to a VP as the fraction of origin ASes that are reached through it.[5] While the AS that appears most often depends on the VP in question, we find that for all IPv6 VPs, Hurricane Electric appears in the largest fraction of AS paths (between 20% and 95%, see Figure 5). Contrast this with the importance of Hurricane Electric in the IPv4 topology, where it appears in fewer than 10% of AS paths from any given vantage point. Level3 (AS3356), the largest player in the IPv4 space in terms of this metric, appears in between 5% and 80% of IPv4 AS paths, depending on the vantage point. This data suggests that *Hurricane Electric is more prominent in the IPv6 graph than the most prominent player in the IPv4 graph.*

AS path lengths in IPv4 and IPv6

Even though the IPv4 AS graph continues to grow in the number of ASes (linearly, after initial exponential growth until 2002), the average AS path length as measured from Routeviews/RIPE vantage points is *almost constant around 4 AS hops* since January 1998 [6]. We emphasize that this result is based on ASes that provide data to Routeviews and RIPE collectors, and does not necessarily reflect the average AS path length that an arbitrary AS sees. Figure 7 shows the average path length (in AS hops after removing AS prepending) in the IPv4 and IPv6 topologies over time, as measured from all Routeviews and RIPE vantage points. The average AS path length for IPv6 shows a *decreasing trend*, and showed a sharp decrease since 2008. This result is counter-intuitive, given the relative sparseness of the IPv6 topology as compared to the IPv4 topology. We dig deeper into the possible reasons for the decreasing IPv6 AS path length, by measuring the average AS path length from different IPv6 capable monitors over time.

Figure 6 shows the average AS path length seen from the perspective of Hurricane Electric (6(a)), and from the other vantage points (6(b)). The average path lengths from vantage points other than HE are similar, hence we group them together. The plot also shows the number of AS paths of length 2 (origin AS is directly connected to the VP), of length ≤ 3, and so on. Our main observation is that the average IPv6 AS path length seen by Hurricane Electric decreases, while for other transit providers it is almost constant. The fraction of ASes directly connected to Hurricane in IPv6 increased from 10% in Jan 2007 to 40% in Jan 2010, perhaps as a result of Hurricane's open peering policy in IPv6 [21]. Other transit providers saw the fraction of dual-stacked networks that are directly connected decline (indicated by the curve labeled "==2" in Figure 6(b)), further confirming the rising dominance of HE in the IPv6 topology. We conclude that the overall decreasing trend seen in the average IPv6 AS path length is due to this increasing dominance of HE in the IPv6 topology. We recommend caution in analyzing graph properties of the IPv6 AS topology; due to its relatively small size, the presence of even a few important ASes such as Hurricane Electric can significantly affect overall graph properties.

5. EVOLVING STRUCTURE OF IPV4 AND IPV6 TOPOLOGIES: AS GRAPHS

We next directly compare the IPv4 and IPv6 topologies over time. Again we hypothesize that as the IPv6 network matures, its topological structure should grow more congruent with IPv4's structure, *i.e.*, an increasing fraction of ASes and AS links will be common to both topologies, the most

[4]We define a VP as having a full table if it has BGP paths to at least 35,000 IPv4 ASes and 3,900 IPv6 ASes.

[5]This metric is related to *betweenness centrality*, but only uses paths observed from a single VP.

highly connected ASes should grow to be more similar in both topologies, and upstream IPv4 and IPv6 providers for the same edge AS should eventually converge.

5.1 Common ASes and AS links in the IPv4 and IPv6 graphs

For each topology snapshot, we find the set of ASes that are present in either the IPv4 or the IPv6 AS topology, which we call the combined topology. In each snapshot, more than 99% of ASes and more than 96% of AS links in the combined topology were present in the IPv4 topology, *i.e.*, *the number of ASes that are unique to the IPv6 topology is negligibly small*. Consequently, we focus most of our analysis on the set of ASes from the combined topology that were present in the IPv6 topology.

Common ASes present in IPv6 topology

Figure 8 shows the fraction of ASes from the combined topology that are present in the IPv6 topology. We measure these fractions for all ASes, and further classify ASes according to business type. We find that the fraction of ASes from the combined topology that are seen in the IPv6 topology varies widely depending on business type. Almost all LTPs are now seen in the IPv6 topology; The 3 exceptions are AS1 (owned by Level 3 Communications, but no longer the primary ASN), AS7132 (owned by AT&T. AS7018, also owned by AT&T is in the IPv6 topology), and AS3786 (owned by LG DACOM. AS9316 owned by the same organization is in the IPv6 topology). Significantly, *around 50% of STPs and CAHPs from the combined topology are also present in IPv6, while fewer than 10% of ECs are seen in the IPv6 topology.* Since the combined AS topology is dominated by ECs, the overall fraction of ASes seen in IPv6 is similarly low, which further confirms our earlier observation that IPv6 adoption is faster in the core of the network while the edge (ECs) has been slow to deploy IPv6.

We also measured the fraction of ASes from the combined topology that are present in IPv6, separately for each geographic region (figure omitted due to space constraints). *We find that this fraction is less than 20% for each geographic region.* As of late 2011, the APNIC region (for which 16% of ASes from the combined topology are present in IPv6) is slightly ahead of RIPE (14%), which is well ahead of ARIN (9%). Interestingly, this ordering is the same order in which the registries either ran out (APNIC in April 2011 [2]) or are projected to run out of IPv4 addresses (RIPE in August 2012, and ARIN in June 2013). As early as 2003, news reports claimed APNIC to run out of allocatable IPv4 addresses first, with RIPE and ARIN soon to follow [22].

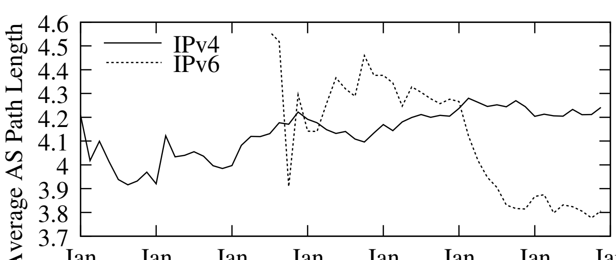


Figure 7: Average IPv4 AS path length is almost constant, while in IPv6 it decreases.

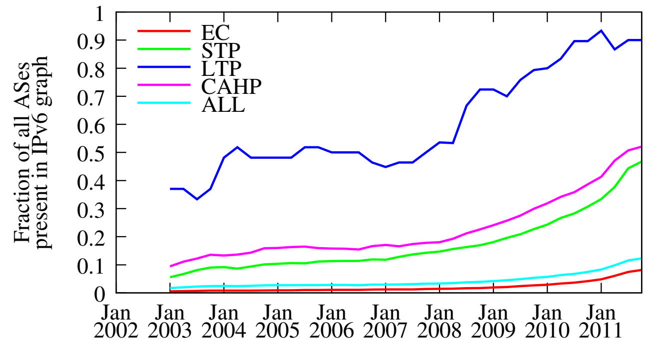


Figure 8: Fraction of ASes from the combined (IPv4+IPv6) graph that are present in the IPv6 graph, classified according to business type and geographical region. Less than 10% of ECs, while 90% of LTPs are present in the IPv6 graph.

ASes unique to the IPv6 topology

We briefly comment on the small set of ASes that were present only in the IPv6 topology. In our latest topology snapshot from October 2011, 109 ASes were only in the IPv6 topology. Of these, 42 ASes (34 ECs, 5 STP, and 3 CAHPs) were in the IPv4 topology in some previous snapshot (and hence we were able to assign business types to these ASes). Inspection of the as-names and descriptions of the other 67 ASes (as they appear in the RIR whois databases) reveals that 27 can be trivially matched with ASes in the IPv4 topology that have similar names and descriptions. This overlap hints at organizations using separate ASes to provide IPv4 and IPv6 connectivity. Furthermore, we found that 2 ASes unique to the IPv6 topology were administered by universities that used IPv4 address space announced from the respective national research and education networks ASes. This shows that organizational boundaries of the entities that manage ASes in the IPv4 and IPv6 topology do not always align.

Common top ASes

We measure the fraction of the top-K ASes (in terms of AS degree) from the IPv4 topology that are also top among the top-K ASes in the IPv6 topology. As the IPv6 network matures, we expect that the top ASes from the IPv4 topology will also appear as the top ASes in the IPv6 topology. Figure 9 shows the fraction of the top-K ASes from the IPv4 topology that are also among the top-K ASes in the IPv6 topology, for K=10, 50 and 100. This fraction has increased from around 20% in 2003 to more than 60% currently. Until 2008, however, the top-K fraction for K=10 was significantly smaller than that for K=50 and K=100, indicating that the largest ASes in the IPv4 topology were either not present in IPv6, or were not among the largest ASes in the IPv6 topology. This difference has decreased sharply in the last 3-4 years – currently 60% of the top-10 ASes from IPv4 are also in the top-10 for the IPv6 topology.

Common AS links

Finally, we are interested in the common set of AS links between the IPv4 and IPv6 topologies. As mentioned in

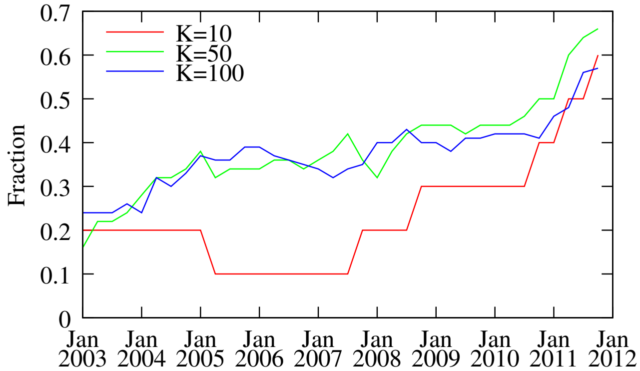


Figure 9: Fraction of ASes from the top-K ASes in the IPv4 graph that are also in the top-K ASes in the IPv6 graph. The fractions increase for different K values.

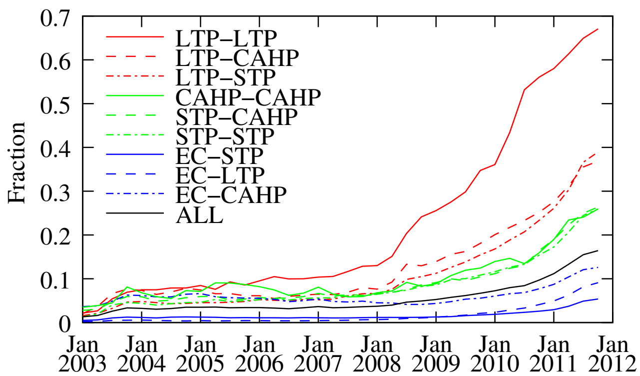


Figure 10: Fraction of AS links from combined (IPv4+IPv6) graph that are present in the IPv6 graph, classified according to business type of link endpoints.

Section 2, our BGP vantage points are likely to miss some AS links, particularly peering links lower in the hierarchy than the Routeviews/RIPE BGP monitors. We are, however, interested in the fraction of links from the IPv4 topology which were also seen in the IPv6 topology. The aforementioned visibility issues should affect both the IPv4 and IPv6 graphs similarly, and hence our analysis should not be impacted by missing peering links in the measured IPv4 and IPv6 topologies. Figure 10 shows the fraction of AS links from the combined topology that also appear in the IPv6 topology over time. We compute this fraction for all AS links and also classify them based on the business types of the endpoints. As with ASes, the fraction of AS links seen in the IPv6 topology is less than 20% for the overall graph. This fraction varies widely, however with the business type of the AS on each end of the link. Links involving ECs are the least represented in the IPv6 graph, while larger fractions of links involving STPs, LTPs, and CAHPs are seen in the IPv6 graph. This is again consistent with our previous finding that the pace of IPv6 adoption is higher in the core of the network but lags at the edge (represented by ECs).

6. EVOLVING DYNAMICS OF IPV4 AND IPV6 INFRASTRUCTURE

Continuing to explore our hypothesis that a maturing IPv6 network should look more like the IPv4 network, we compare the evolution of routing dynamics in IPv4 and IPv6. In particular, we focus on the evolution of update churn, correlation between the update churn seen from different vantage points, path exploration, and convergence times in IPv4 and IPv6. We focus on these metrics for the following reasons. First, we hypothesize that both IPv4 and IPv6 should show a similar relation between update churn and the size of the underlying topology. Second, due to business relationships and dense interconnection among ASes, churn becomes localized, and each vantage point does not see the same set of routing events. Consequently, correlation between update churn seen at different vantage points can serve as a measure of the maturity of the underlying network and business relationships. Finally, previous work has shown that end-to-end delays and loss rates are significantly higher during routing events [23]. It is thus useful to compare the extent of path exploration and routing convergence times during routing events. If these metrics are significantly worse in IPv6 as compared to IPv4, then it could deter the adoption of IPv6.

6.1 Churn as a function of topology size and vantage point

Interdomain routing scalability has been a topic of major concern in recent times [24, 25] for two reasons – increasing routing table size, and increasing rate of BGP updates (churn). The latter can be a more serious concern, because failing to process updates in a timely manner can trigger a wide-scale instability and result in traffic blackholing. Some of these concerns were put to rest by observations that churn in the IPv4 topology grows slowly [26, 27], and at the same rate as the underlying topology. More recently, however, Huston [28] compared IPv4 and IPv6 BGP update time series and concluded that while IPv4 churn has grown slowly (linear), IPv6 churn has been increasing exponentially. This qualitative difference between the evolution of update churn in IPv4 and IPv6 raised speculation on whether routing dynamics in IPv6 are fundamentally different from those in IPv4. In order to investigate these differences, we next compare the evolution of BGP churn in IPv4 and IPv6. We define churn as the rate of BGP updates received from a vantage point (*e.g.*, updates per day). This definition of churn is consistent with previous related work in the area.

Churn as a function of topology size

To understand how churn has evolved with respect to network size, we track the growth in the number of updates, normalized by the size of the underlying AS topology. To calculate this metric, we bin the total number of updates per day into three-month windows, find the median daily churn (using the average daily churn gives similar results) for each window, and divide it by the average number of ASes in the topology during that time window. Figure 11 plots this metric for IPv4 (top) and IPv6 (bottom).

In IPv6 this number has remained mostly stable since Jan 2004 at $\approx$ 3 updates per origin AS, except at the AT&T monitor which sees half that many. In IPv4, except for the AT&T and NTT monitors, this metric stabilized in 2006 at $\approx$ 5 updates per origin AS. Other monitors that peer

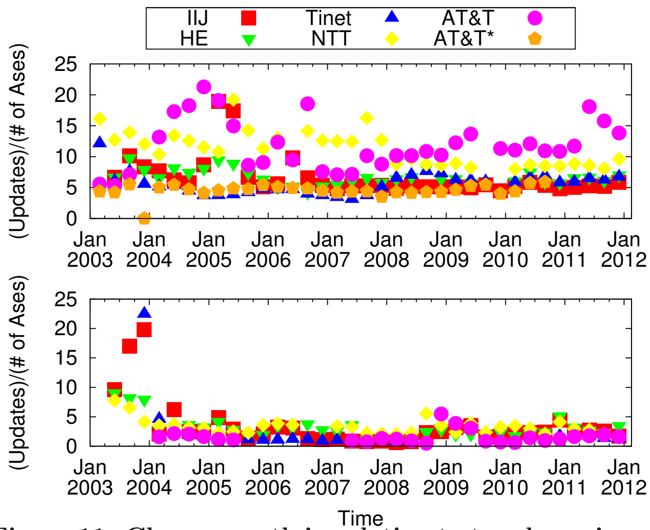


Figure 11: Churn growth in relation to topology size in IPv4 (top) and IPv6 (bottom). BGP churn, in both IPv4 and IPv6, grows linearly with the number of ASes.

with the Oregon-IX collector show similar behavior. We hypothesize that the anomalies exhibited by the AT&T and NTT monitors are caused by non-stationary periods, which we confirm by filtering out noise from the AT&T time series as described in [26] and plotted in Figure 11 (top panel) as AT&T*. Similar to the other monitors, this filtered AT&T* time series exhibits a stable ratio of 5 updates per origin AS.

To summarize, while previous work has pointed to the qualitatively different growth trajectories of IPv4 and Ipv6 churn, we showed that churn in both protocols grows at the same rate as the underlying topology. We emphasize that understanding the evolution of update dynamics requires examining more than temporal evolution; we must also consider the evolution of the underlying topology. Measuring churn normalized by the size of the underlying topologies reveals a richer picture, namely that *BGP update dynamics in IPv4 and IPv6 are qualitatively similar and their growth is a function of the growth in the number of ASes.* Explaining why the average number of updates per AS is 5 in IPv4 and 3 in IPv6 is an interesting open question. We believe that this has to do with the nature of the underlying topologies and prevalent operational practices such as business relationships and traffic engineering.

Churn seen from different vantage points

The churn seen from different vantage points can shed some light on the maturity of the underlying topology, because as ASes establish denser interconnections and enforce business relationships, *churn becomes more localized*, i.e., some routing events only affect a limited part of the Internet.

We calculate the cross-correlation between all pairs of daily churn time series in IPv6 and IPv4 respectively, for the monitors in Figure 11. We use the non-parametric Kendall's τ rank correlation coefficient [29], a measure of association between random variables based on the ranking of their sample data. Kendall's τ takes value in the range [-1,1]; a value of 1 denotes a perfect correlation and a value of -1 denotes anti-correlation. Figure 12 shows the calculated correlation

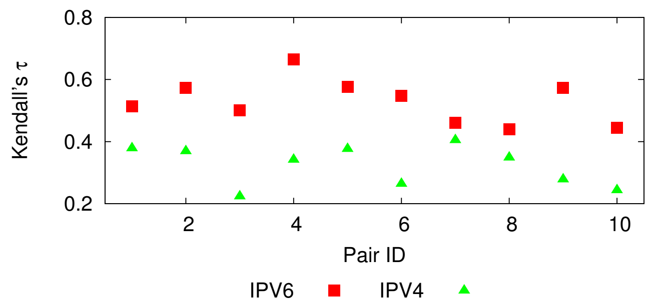


Figure 12: Correlation of the BGP churn time series across monitors. IPv6 monitors exhibit stronger correlation than IPv4 monitors.

coefficients between all pairs of IPv6 time series, as well as between all IPv4 pairs. IPv4 pairs show little correlation, with τ values mostly below 0.4, but IPv6 pairs show strong positive correlation, with τ values mostly above 0.5. The lack of correlation between IPv4 monitors indicates that churn is highly dependent on the location and configuration of the corresponding router. As stated earlier, this is likely due to denser interconnection and enforcement of business relationships in the IPv4 topology. We have studied this effect in our previous work, where we showed that correlation between IPv4 churn time series doubles after filtering out updates triggered by routing events that affect only a limited part of the Internet [26].

To summarize, we find that the churn seen by different BGP vantage points shows stronger correlation in IPv6 as compared to that in IPv4. Two factors might contribute to the stronger correlation between IPv6 time series than in IPv4. *First, the IPv6 AS graph is much smaller and thus provides less isolation (i.e., routing changes will have a larger scope of impact). A second possibility is that since IPv6 deployment is still at an early stage, business policies may be less enforced and monitored, which would also result in less isolation of BGP messages.* As IPv6 deployment proceeds, we expect both of these factors to change; the IPv6 topology is growing exponentially, interconnection is becoming denser, and business relationships in IPv6 will start to be enforced. Thus, we expect the correlation of IPv6 churn seen from different BGP monitors to decrease over time and become similar to that in IPv4.

6.2 Path exploration and convergence times

Routing changes have different outcomes. Some changes result in the withdrawal (addition) of a prefix from (to) the routing table. Other changes alter the reachability information to a prefix (e.g. rerouting). In addition, routing changes can be transient or long-lasting. The effects of routing instability on data plane characteristics such as loss rate have been well studied [23]. It is thus important to compare routing changes in IPv6 and IPv4. But, first we must identify and group prefix updates that constitute a routing change. When an underlying incident triggers a routing change, it often results in several updates for each affected prefix (i.e., convergence sequence). The duration of this convergence sequence is referred to as *convergence time*. A *prefix event* is a sequence of updates for a given prefix that are likely triggered by the same underlying cause. We use the definition

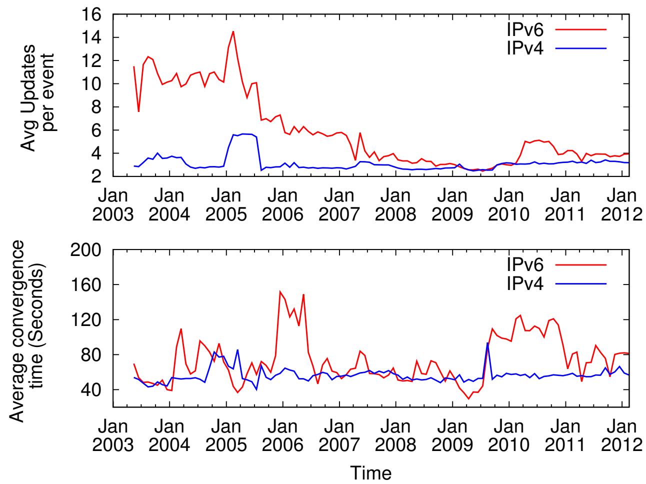


Figure 13: Comparing path exploration and convergence times (IIJ). The average number of updates per routing change event gradually converges between IPv4 and IPv6. The average convergence time in IPv6 is burstier, with a lower bound at a similar level as in IPv4.

by Wu *et al.* [30] to identify prefix events: *Two consecutive updates for the same prefix belong to the same prefix event if they are no more than 70 seconds apart. The maximum duration for a prefix event is set to 10 minutes. Events with duration longer than 10 minutes are considered to be flapping.* These prefix events can be classified based on the best known path to the affected prefix before and after the event [31, 32]. After identifying all prefix events in our time series, we compute two metrics reflecting their impact: path exploration (average number of updates observed per event) and convergence time. When a route to a prefix fails, BGP may explore several routes before converging to a new route or withdrawing the prefix altogether. A longer path exploration extends BGP convergence time which will likely impede data plane performance.

Path exploration

Path exploration is often more pronounced in events that lead to a complete withdrawal of a prefix (AW events) [32]. The top panel in Figure 13 compares the average number of updates per an AW event in IPv6 and IPv4 as seen from the perspective of IIJ[6]. In IPv4, this number has mostly remained stable below 4. We also observe a slight increase in post-withdrawal path exploration after 2009. In IPv6, on the other hand, this number was around 10 updates until early 2005, it then decreased gradually and stabilized around 4. When investigating AW events that took place in the first two years of the study period, we find that our monitors explored monotonically longer paths before sending the final withdrawal. In IIJ for example, the median length of the longest explored path was 18 hops in January 2004 and gradually dropped to stabilize around 7 hops in 2008. We can imagine two possible causes for this gradual reduction in path exploration. First, ten years ago only a few hundred ASes had deployed IPv6, and routing policies may have been less enforced, allowing exploration of many more alternative paths. Second, the early IPv6 graph was sparser, so paths were naturally longer (see Figure 7), leading to proportionally longer convergence times (i.e., more path exploration) [33]. The trends identified above are consistent across monitors.

[6]Due to space limitations, we only present results for the IIJ monitor. Other monitors show qualitatively similar results.

Convergence times

The bottom panel in Figure 13 shows the evolution of BGP convergence time from the perspective of IIJ, measured as the monthly average of all prefix event durations (i.e., the time difference between the first update and the last update in an event). The average convergence time in IPv4 is stable around 50 seconds, but is higher and less stable in IPv6. During 2004, IPv6 convergence time was slightly higher, similar to the path exploration metric. We also recorded two periods with sustained higher convergence times, in 2006 and 2010. A closer look at the data showed that the increase in 2006 was caused by one prefix that flapped between two paths that only differed in the ATOMIC_AGGREGATE attribute (i.e., one path is announced as aggregated while the other as not). The fact that a single prefix has a large impact on the measured convergence time is surprising. However, our data shows that the small size of the IPv6 routing system makes it vulnerable to such effects. The number of prefix events per day rose sharply from ≈ 200 before this instability to ≈ 350 due to the unstable prefix; this single flapping prefix experienced 150 instabilities per day. On the other hand, the number of prefix events per day is two orders of magnitude larger in IPv4 than in IPv6. When we exclude events related to this prefix, the convergence time drops to the same level as prior to the instability. A similar flapping that involved five prefixes caused the peak in 2010. We believe that this activity was triggered by an IGP misconfiguration in the origin AS. These peaks were evident in all monitors, consistent with the earlier observed strong correlation between IPv6 monitors. Apart from these anomalous periods, IPv6 generally matched IPv4 in terms of convergence time.

To summarize, *the evolution of path exploration and convergence time shows that the characteristics of routing changes in IPv6 are gradually becoming similar to those in in IPv4. This is an encouraging trend, as it suggests an increasing maturity in IPv6 deployment. Furthermore, any performance degradations resulting from routing changes in IPv6 should be no worse than we see in IPv4.*

7. IPV4 VS. IPV6 PERFORMANCE

Figure 14 plots the the relative performance as measured by relative download times for all five vantage points we use (method described at the end of Section 2). Confirming the results of Nikkhah *et al.* [16], 79% of paths we observed had IPv6 performance within 10% of IPv4 (or IPv6 had better performance) if the forward AS-level path was the same in both protocols, while only 63% of paths had similar performance if the forward AS-level path was different. However, our measurements (and theirs) are dominated by the path RTT because the transfers are typically small (although we only analyze measurements of transfers over 10K bytes). The dashed lines in Figure 14 plot the relative

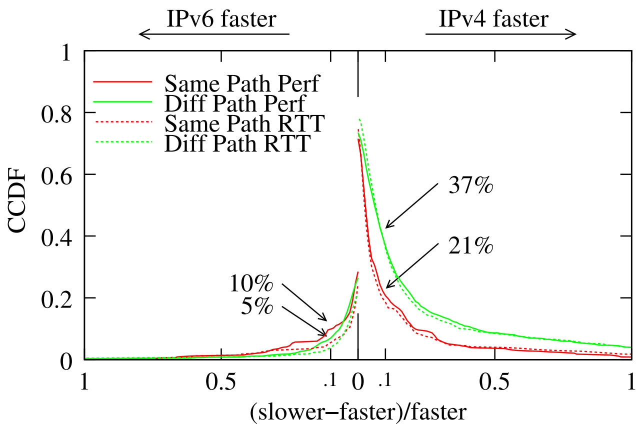


Figure 14: Relative performance between IPv4 and IPv6 measured by the relative mean fetch times (solid lines) and minimum SYN/ACK RTT (dashed lines). Because small pages (although over 10K bytes) are fetched, performance is dominated by relative RTT. The annotations at x=0.1 represent the points where performance is at least 10% worse in IPv4 or IPv6. IPv4 and IPv6 performance is more likely to be similar if the same AS-level paths are used for both IP protocols.

RTTs measured to the same (IPv4 and IPv6) webservers; the solid lines (relative fetch time) and the dashed lines (relative RTTs) are barely distinguishable. When IPv6 performance is better, it is more likely correlated with a different forward AS-level path. However, the correlation between RTT and fetch time is weaker when IPv6 performance is better, for reasons we do not yet understand.

Implications of correlation between performance and topological congruence
The significant correlation between data plane performance between two endpoints and the congruity of the AS path between them inspires us to ask: how far are we from topological parity between IPv4 and IPv6?

Recall from Section 4 that only 40-50% of AS paths are actually identical. There are several reasons why the AS paths in IPv4 and IPv6 could be different – the ASes or AS links seen on the IPv4 path may not be present in the IPv6 topology, or networks may simply choose different routes for IPv4 and IPv6. With the data available to us, we cannot confirm why the AS paths differ; we can, however, measure how much congruence between IPv4 and IPv6 AS paths is possible today. For each link in an IPv4 AS path toward a dual-stacked origin AS, we examine whether that link is present in the IPv6 topology, regardless of the AS path on which it appears. Figure 15 shows that currently, 60-70% of AS paths *could* be identical in IPv4 and IPv6 without configuring a new BGP peering session, because for these paths each IPv4 link is already present in the IPv6 topology, just not yet part of an observable BGP-policy-compliant path between the edges. We take a step further and examine what would happen if each IPv6-capable AS were to establish equivalent peerings in IPv6 and IPv4. Figure 16 shows the fraction of IPv4 AS paths where each AS on the path appears in the IPv6 topology. If current IPv6-capable ASes

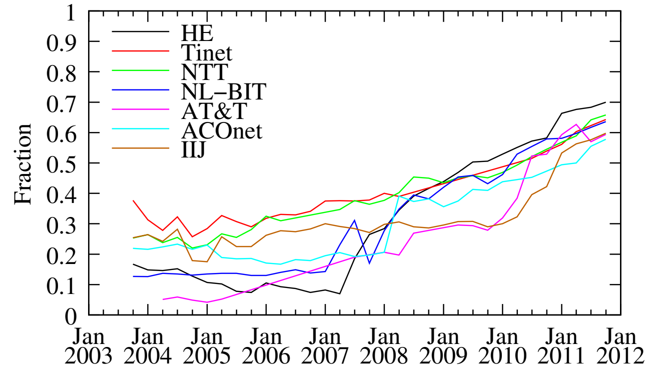


Figure 15: Fraction of dual-stack ASes reachable using an IPv4 AS path where all AS links in that path are in the IPv6 AS-level graph. If IPv6 BGP paths chosen were consistent with IPv4 paths, then 60% to 70% of ASes could be reached over a path congruent in IPv4 and IPv6.

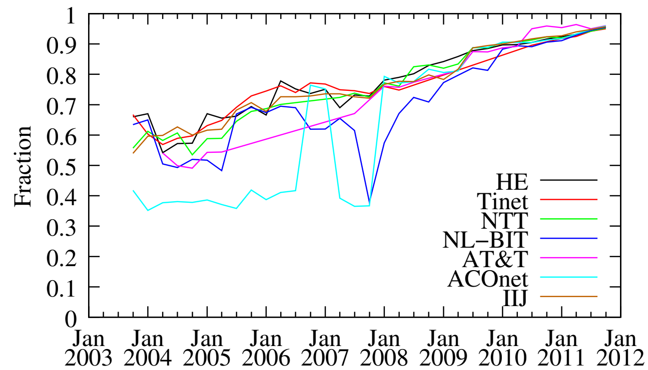


Figure 16: Fraction of dual-stack ASes reachable using an IPv4 AS path where all ASes in that path are in the IPv6 AS graph. If current IPv6 capable ASes established peerings equivalent in IPv4 and IPv6, then 95% of paths would be identical.

established equivalent peerings in IPv4 and IPv6, 95% of AS paths could be identical in IPv4 and IPv6, *i.e.*, for an AS link on such a path, both ASes are present in the IPv6 topology, and both ASes already peer in IPv4. If these ASes also started IPv6 peering, we could see the AS paths converge. These results are encouraging, but they are even more motivating when juxtaposed with performance measurements which show IPv4 and IPv6 data plane performance is comparable when the AS paths are the same. Together, these results demonstrate the undeniable benefit of BGP peering parity between IPv4 and IPv6 AS-level topologies.

8. RELATED WORK

Many attempts have been made to evaluate the status of IPv6 adoption and penetration [34, 35, 36, 37, 38, 39, 40, 41, 42, 43]. None have found significant activity, even though IPv6 has been implemented on all major network and host operating systems. Current levels of observable IPv6 activity fall well below 1% [40, 42, 43]. Google plots a time-series of the percentage of Google users that would access www.google.com over IPv6 if it had an IPv6 address, which moved from 0.1% in September 2008 to 0.6% in May 2012 [3]. By some accounts, IPv6 development is progressing faster in Asian countries, *e.g.*, China [44]. Notably, the 2008 Summer Olympics in Beijing was the first major world event with a presence on the IPv6 Internet [45]. These measurement studies were either focused on IPv6 *capability*, *i.e.*, how many websites and clients were IPv6 capable, or on the actual levels of IPv6 traffic on the network. In our work, we have focused on IPv6 deployment at the level of organizations, represented in BGP as Autonomous Systems. Huston and Michaelson [46] of APNIC examined a range of types of data collected over four years (January 2004 to April 2008) in search of IPv6 deployment activity. They analyzed interdomain routing announcements, APNIC's web access logs, and queries of reverse DNS zones that map IPv4 and IPv6 addresses back to domain names. All of their metrics showed some increase in IPv6 deployment activity starting in the second half of 2006, but they emphasized the data's limitations, since it mostly reflected some interest in IPv6 rather than usable IPv6 support. More recently, Michaelson [47] measured the disparity between IPv6 capability at the network level, and IPv6 capability of end-users. Karpilovski *et al.* [48] measured IPv6 deployment using data on address allocation, BGP routing, and traffic. They concluded that even though IPv6 address allocations were increasing, actual traffic levels remained negligible. Huston [49] continuously tracks the evolution of the IPv6 topology and routing, with some high-level comparisons with the current state of IPv4. Aben [50] provides an interactive look into the deployment of IPv6 at the AS-level, further divided by country. To the best of our knowledge, ours is the first work to compare and contrast IPv6 evolution with that of the IPv4 ecosystem.

BGP update dynamics and scalability have been active topics of research during the last decade or so, mostly for the IPv4 topology, *e.g.* [33, 32]. Lately, however, there has been some concern about the *scalability of BGP interdomain routing* [25]. Huston [28] compared update churn in IPv4 and IPv6, and found that while churn in IPv4 does indeed appear "flat", that in IPv6 increases exponentially. In this paper, we compared IPv4 and IPv6 update dynamics, and showed that they are qualitatively similar. The apparent difference between the absolute volume of IPv4 and IPv6 updates over time is simply a function of the different growth rates of the underlying topologies – the IPv4 topology grows linearly, while the IPv6 topology grows exponentially.

A recent measurement study by Nikkah *et al.* [16] compared performance (measured in terms of web page download times) over IPv4 and IPv6, with the goal of determining whether the control plane or the data plane was responsible for worse performance over IPv6. They found that while the data plane performs comparably in IPv4 and IPv6, differences in the control plane (routing) are responsible for performance differences seen between IPv4 and IPv6. We show web page download time is dominated by RTT because the pages fetched are typically small, so these performance measurements are dominated by delay rather than available bandwidth. We also demonstrate there is significantly more gain that could be made with the existing ASes that have deployed IPv6; if equivalent links are established in IPv6 as in IPv4 then 95% of existing paths could be identical.

9. CONCLUSIONS AND FUTURE WORK

With the Internet Assigned Numbers Authority (IANA) now having exhausted its pool of available IPv4 addresses, and the Regional Internet Registries (RIRs) scheduled to run out in the near future, there has been growing interest in how IPv6 is being deployed and used. In this paper, we undertook the first study of the evolution of IPv6 deployment, comparing and contrasting it with how IPv4 has evolved over the last decade and a half. Our findings hint that the IPv6 network is indeed maturing, and while the increasing pace of IPv6 uptake over the last two years is an encouraging sign, IPv6 adoption is distinctly non-uniform, both topologically and geographically. From the topological perspective, IPv6 deployment is ahead in the core of the network, driven by transit and content providers, while it lags at the edges, which mostly consist of enterprise customers. While the data at our disposal does not allow us to study *why* deployment is lagging at the edge, we conjecture that this is due to a lack of incentives for edge networks to deploy IPv6, given available alternative strategies, e.g., NAT. For many edge networks, deploying IPv6 represents a cost (transitioning infrastructure, training staff, increased management/troubleshooting overhead) without a tangible benefit. A single player, Hurricane Electric, predominates the IPv6 topology significantly more than the most predominant AS in the IPv4 topology. This suggests that several graph-theoretic metrics (e.g., average AS-path length) could be significantly skewed by the single large player in IPv6. In terms of geographical trends, IPv6 adoption is higher in Europe and the Asia Pacific region. We conjecture that adoption in the Asia-Pacific region was spurred by IPv4 address exhaustion, which happened first in that region. A big push toward IPv6 by network operators in the RIPE region could explain why Europe is ahead of North America. From the point of view of routing dynamics, we find that IPv6 behaves mostly like IPv4. The differences in the growth of the absolute volume of updates in IPv4 and IPv6 stem from the different growth rates of the two topologies – IPv4 now grows linearly in terms of ASes and prefixes, while IPv6 grows exponentially. Finally, we find that performance over IPv6 paths is comparable to that over IPv4 if the AS-level paths are the same, while it can be significantly worse when AS-level paths are different. Interestingly, we found that while only 40-50% of AS paths are currently identical in IPv4 and IPv6, up to 95% of AS paths could be identical, if current IPv6-capable ASes established equivalent peerings in IPv4 and IPv6.

There are several avenues for future work. First, we plan to keep collecting and processing topology and routing data for both IPv4 and IPv6. We plan to release to the research and operational communities periodic data tracking the evolution of IPv6 topology and routing, to enable comparison with IPv4 evolution over the last 15 years. We expect that such monitoring will become more useful as networks move toward deploying IPv6 in production. In particular, it will be interesting to measure if IPv6 deployment accelerated following the World IPv6 Launch [51] event, scheduled for June 6, 2012. Complementary to our efforts in measuring IPv6 deployment, we are developing a quantitative model of IPv6 adoption at the organization level, which we will parameterize and validate using our our ongoing measurements. A crucial factor in determining whether IPv6 is widely adopted is the end-to-end performance achievable over IPv6, and whether that performance is comparable to that achievable over IPv4. We plan to continue and extend our current IPv6 performance measurements to identify or rule out other causes of performance disparity beyond RTT, such as loss, fragmentation, segmentation, and packet reordering, and make results available to the community.

10. ACKNOWLEDGEMENTS

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