Summary Review Documentation for


Authors: A. Dhamdhere, M. Luckie, B. Huffaker, k claffy, A. Elmukashfi, E. Aben

Reviewer #1

Summary: This is a very thorough longitudinal study of the evolution of the IPv6 internet topology, as compared to that of the IPv4 topology. The authors find some interesting results, including that the IPv6 topology is growing, and that routing dynamics and performance in the IPv6 & IPv4 topology are similar when AS paths have the same length, but worse otherwise. My score reflects the fact that there are a large number of studies of IPv6 deployment out there; however, this seems to be the most thorough study of IPv6 routing dynamics and topology, and, in contrast to other studies that seem to project gloom and doom for IPv6 (because they are performed from the perspective of the end users), this studies shows that v6 deployment is really happening in the core.

Strengths: See above.

Weaknesses: The paper is a bit tedious to read, due to the extremely large number of graphs and figures. Many of the measurement techniques are known and have been published already.

Comments to authors: The authors keep saying that IPv6 is growing exponentially is this a rigorous statement? What is the exponent?

I found the section on churn to be the weakest in the paper; why is your definition of churn the right one? Shouldn’t churn be measured on a per-prefix basis? Also, the newPR 18 has this large spike in 2006 that you explain away due to flapping of a single prefix; to my mind this suggests that your notion of churn is highly sensitive and thus perhaps the wrong definition. Also, why was 6.2 performed only on the IIJ monitors? Are your findings corroborated by the other vantage points?

Detailed comments:

Intro - 1st para: I though only IANA has run out of address space, and the RIRs still had space?

Sec 2, BGP topology data: Why are you only interested in primary links?

Sec 2, AS classification: it seems like using “avg lifespan of an AS” over 14 years is a bit of a strange classifier – couldn’t the type of an AS change over the course of 14 years?

Also, why is it valid to assume the business relationships are the same in v6 and v4? Do you have a way to support this assumption, for instance can you use published peering policies from peering DB to validate this?

One thing that was missing at the start of sec 3 and kept bothering me as I read through the paper, is that right away I would like to know the *absolute number* of ASes of each type in the v6 topology. The authors have expressed everything as fractions, which is fine, but this should be done only after the absolute number of ASes is given.

Who are these ASes that are unique to the IPv6 topology? This seems sort of interesting what countries are they in?

Reviewer #2

Summary: This paper examines numerous dimensions of past and current use of IPv6 in order to frame trends in its deployment. The data comes from both longitudinal passive BGP measurements, and more recent active probing measurements.

My rating reflects that the paper provides little in the way of productive insight. The many observations (more than 30 plots) often tell a mixed story that I didn’t see how to leverage beyond “yep, we’re in the middle of a transition”.

Strengths: The most interesting findings are (1) performance is comparable unless AS-level paths differ, (2) IPv6 topology appears to grow exponentially (but see below), (3) take caution in analyzing the IPv6 topology due to the dominance in it of one player.

Weaknesses: First, I think the paper would have been much more interesting if the authors had compared the state of IPv6 with what was the historical state of IPv4 when the IPv4 network was the same “size”. That would illuminate just what has fundamentally changed about the network, and might give us some sense of predicting just how the IPv6 trends might play out.

More generally, I would much rather have had a 6-page paper that concisely developed the most interesting results, rather than having them spread across a great amount of detailed text as is done in the current submission.

Comments to authors: I found the title to be a bit of a tease. It led me to expect some sort of projection regarding when we would consider the global network as having IPv6 deployed.

When arguing that something grows exponentially, please show it on a log-linear plot with a fitted line. I’m wary of doing this by eyeballing.

Regarding footnote 2, what motivated you to develop a new classification algorithm? Do you know of problems in [15]? If so, please tell us what they are.

When repeating the classification on the 14-year dataset (top left of page 3), how much changed from the original classification?
What does it mean for an average download time to be "within 10% of the mean with 95% confidence"? Is it simply either within 10% of the mean or not within 10%?

How many of the dual-stack ASes reflect web sites / content providers?

It seems obvious that IPv6 deployment would primarily occur first within the core rather than at the edge. The edge doesn’t get any utility from deployment until the core provides it.

What were the growth trends for LACNIC and AfriNIC?

Regarding the speculation at the end of 3.2 about use of PI address space, can’t you directly analyze for this?

*Why* does the most frequently removed AS turn out to be Telianet?

Why does it matter that the average IPv6 AS path length as seen by HE decreases, but not by others?

What reason besides HE’s open peering policy might account for AS’s directly connecting to it?

What caused the abrupt decrease in average path length (figure 9a) in early 2008?

Why is it significant that about 50% of STPs/CAHPs are also present in IPv6?

In what dimension do ECs “dominate” the combined AS topology?

Ideally the lines in figure 12 would instead be drawn as points, since (particularly for K=10) the linear interpolation between points is not well-grounded.

Why does the AT&T monitor see only half as many updates per AS?

Regarding v4/v6 BGP dynamics being "qualitatively similar", where do we see that?

What’s the significance associated with a $\tau$ value of 0.4. Does this really equate to "little correlation"? What’s the significance of correlation decreasing (why should we care)?

“We can imagine two possible causes” - to what degree can you concretely investigate these?

Why is it worth even discussing the increase in 2006 given it was caused by a single prefix flapping, and same for the peak in 2010?

Is it clear that the difference in volume of updates is indeed simply a function of different growth rates? Might it instead reflect something else?

It’s not quite clear that your data shows that web page download is dominated by RTT. It could be the main issue is packet loss, and its presence happens to correlate with larger RTT.

**Reviewer #3**

**Summary:** The paper looks at different properties of the IPv6 deployment and how it evolves over time. It compares it with the evolution of the early IPv4 network and looks at differences between IPv6 and IPv4 paths today.

**Strengths:** The results of the study are interesting and help understand the maturing of IPv6.

**Weaknesses:** It is not clear that the results in the paper provide much insight in when IPv6 might really take off.

Insights provided by the paper are quite limited compared with the number of graphs.

It might have been interesting to look in a bit more depth at the unique role of HE and the impact it has on IPv6’s evolution.

**Comments to authors:** The paper presents an interesting analysis. Some minor presentation issues are listed below.

One result of the paper is the observation on the growing role of Hurricane Electric. Is there a way of speculating the impact of one big player like this, e.g. based on IPv4 history.

The title suggests that the paper will provide insights in when IPv6 may be taking over (although maybe it is just meant to be tongue in cheek). The paper does not really do that, and the conclusion in fact points at the exhaustion of the IPv4 pool as a likely cause for IPv6 growth. It would be good to have the title, abstract and tone of the paper be consistent.

The paper has a very large number of graphs. The most interesting results relate to some of the trends early in the paper and to convergence of the performance of IPv4 and IPv6. It is not clear that the results in the middle (Sections 4 and 5) focus on finer details. It is not clear what their significance is to the evolution of IPv6 and so these sections add relatively little value.

**Reviewer #4**

**Summary:** This paper presents a comprehensive look at the state of IPv6 deployment at present, including BGP dynamics, as well as performance implications of the current situation.

**Strengths:** This paper does a fairly thorough job of probing the current deployment of IPv6 from an interdomain routing perspective. It analyzes the data in a way that yields a fair number of insights regarding regional differences and ISP differences w.r.t. deploying v6. It also presents interesting data on the performance of paths over v6 vs v4, and some related reasons from a BGP routing perspective.

**Weaknesses:** The paper is mainly focused on interesting questions, but on occasion descends into presenting data with no clear purpose or conclusion. However this happens in only a few places. As usual, questions about missing information in BGP data is an issue, although minor here IMO.

**Comments to authors:** This paper does a nice job of focusing attention on questions that are interesting and yield insight. The relative deployment levels in different types of ASes, as well as across different regions, are examples of this. Another is the analysis that relates relative performance to the v4 / v6 paths. Further, the paper mostly presents statistics in a clear and comprehensible way, without excessive complication. Overall I learned quite a bit from reading this paper and found it a good read.

Some minor nits: the issue of peering links in the AS graph is somewhat swept under the rug. I don’t think missing out on peering links is fatal to your analysis, but it should be discussed more directly. The second paragraph of Section 2 sidesteps the issue of peering links, and the link-based analysis (eg Fig 13) doesn’t point
out how the results may be affected by invisible peering links. It would help to be more up front here.

There are points where some more thoughtful discussion could be in order. For example, one of your main conclusions is that v6 deployment is lagging at the edge. I think this confirms common beliefs, but it would be helpful to think about "why" this is the case. What is it that makes an edge AS slow to deploy v6? And given that edge ASes are likely to suffer first from address space exhaustion, what can you say about the experiences of edge ASes in regions like APNIC where they have apparently responded to address space exhaustion first? Likewise, in discussing churn as a function of network size, what should we intuitively expect?

There are some sections where the analysis doesn’t seem to lead anywhere, for example the questions of churn seen from different vantage points, or the fraction of top-K ASes in both graphs.

Reviewer #5

Summary: This paper presents a systematic study that measures the IPv6’s deployment status in the BGP routing system. The authors obtained BGP update data from BGP monitors, and extract much useful information about IPv6’s deployment, including the growth rate of ASes that announce IPv6 prefixes, how the IPv6 topology evolves over time, and how the routing dynamics of IPv6 evolves. They also measured the performance differences between IPv4 and IPv6 networks. They made several notable findings, including IPv6’s deployment at edge networks increased in the past two years and routing dynamics of IPv6 networks are similar to those of IPv4 networks.

Strengths: The work is timely and thorough, examining IPv6’s deployment from many angles. The paper is well-written.

Weaknesses: The work is limited in scope. It only shows IPv6’s deployment in the network, while the more interesting questions are the fraction of end systems that deploy IPv6 and the fraction of IPv6 traffic on the Internet.

Comments to authors: I think your work is thorough, measuring many aspects of IPv6 deployment that I myself have not thought of. The paper is also well written. I enjoyed reading this paper.

Section 4: It’d be useful to shed some light on why AS paths in IPv4 and IPv6 differ, why HE in IPv4 was not as important as in IPv6. It seems that once two ISPs peer with each other, they would be able to exchange both IPv4 and IPv6 routing updates.

Figure 10: I am surprised to see that the average IPv6 path is shorter than that of IPv4. The IPv4 topology is supposed to be denser than IPv6 and hence has a shorter average path length. It’d be useful to explain more about this not-so-intuitive result.

Section 6: Why is churn a linear function of the topology size? Previous work shows that BGP path exploration could be exponential. Second, why both IPv6 and IPv4 stabilized after a certain year (2004/2006 respectively)? A deeper explanation will be helpful.

Convergence times: it’s amazing to see route flappings caused by misconfigurations could sustain for an entire year! You may use the analysis tools you developed for this work as a routing health monitor, raising alarms when such sustained flappings were detected.

Section 7: Again, I am surprised to see a significant fraction of IPv6 paths are better. It’d be helpful to use traceroute to dig deeper into the causes, as they are not obvious. ASes that deploy IPv6 should have also deployed IPv4. The IPv6 topology is then a subgraph of the IPv4 topology, and its path latency should be no better than that of IPv4.

Also, why not use ping to directly measure path RTTs, and large file downloads to measure the available path bandwidth? The download times of small files are determined by several factors together, although they are dominated by RTTs. The results may not be generalized into conclusions such as IPv4 and IPv6 have similar performance if they share the same AS paths.

Response from the Authors

We have revised the paper significantly in light of the reviewer comments. The major changes are as follows:

- The reviewers felt that the title was misleading, hinting at a definite answer on when IPv6 would be deployed. While our results show that IPv6 deployment is indeed maturing, making predictions about the extent of IPv6 deployment is beyond the scope of this paper. We have changed the title.

- The reviewers felt that there were too many figures. We have removed 6 figures from the submitted version, summarizing the main insights from those figures in the text.

- We have included results for curve-fitting experiments showing that the IPv6 topology (ASes and AS links) has been growing exponentially exponential since 2008.

- The reviewers wanted more insight into some of our observations, e.g., "why is Hurricane Electric so prominent in the IPv6 topology", "why does TeliaNet get removed from many paths", and "why is IPv6 deployment lagging at the edges". Unfortunately, the data available to us does not allow us to answer such questions with certainty. We conjecture that the dominant position of HE in the IPv6 topology is due to its aggressive peering policy. We conjecture that IPv6 deployment lags at the edges due to a lack of incentive for edge networks to deploy IPv6.

- The reviewers felt that the section on comparing IPv4 and IPv6 routing dynamics was disconnected from the rest of the paper. We have tried to motivate this section better. In particular, we have emphasized why BGP dynamics measured from different vantage points can be a useful measure of the maturity of the underlying topology and enforcement of business relationships. Comparing convergence times and path exploration in IPv4 and IPv6 has performance implications.

- The reviewers wanted to see a comparison of the state of IPv6 with historical state of IPv4 when the IPv4 network was the same "size". While this would indeed be interesting to do, we unfortunately do not have the data to enable such a study. Our earliest snapshots of the IPv4 topology are from 1998, when the IPv4 topology was already larger than the IPv6 topology today.

- We have added some additional analysis on ASes that are unique to the IPv6 topology, differences in our classification using the 14-year dataset and the previous (12-year) dataset, and the fraction of dual-stack paths that perform better in IPv6.