Measuring and Comparing Internet Path Stability in IPv4 and IPv6

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***Abstract*—In just about 4 years, IPv6 will celebrate its 20th anniversary. While the protocol itself is already quite old, its deployment has only recently picked up speed. Not so many Internet service providers offer direct IPv6 connectivity to their customers, yet. Clearly, when IPv6 is available to customers, they expect that IPv6 offers at least the same – or even better – stability of connections in comparison to IPv4. The main goal of this paper is to investigate whether this is true today.**

In our paper, we present up-to-date measurement results on the stability of IPv4 and IPv6 paths in the real Internet, based on machines that are distributed over a large geographical area, as part of the NORNET CORE testbed infrastructure for multi-homed systems. The measurements not only cover high-speed research networks, but also consumer-grade ADSL connections – i.e. the ISP connection types of "normal" end-users – as well as a broad range of different ISPs. The measurements show that IPv6 paths are less stable than corresponding IPv4 paths. We also find that the use of load balancing is more prevalent in IPv6 than in IPv4.[1]

Keywords: NorNet Core, Internet, IPv4, IPv6, Path Stability, Resilience, Robustness

I. INTRODUCTION

Internet Protocol version 6 (IPv6) [1] is nearing its 20th anniversary, but replacing the incumbent IPv4 [2] has proven to be a cumbersome process. As of September 2014, only about 4% of the requests to Google servers come over IPv6 [3]. There are, however, clear signs that IPv6 deployment and usage is finally picking up speed, mostly driven by the depletion of the IPv4 address space [4], [5].

With IPv6 usage still in its infancy, we are only beginning to understand how IPv6 is deployed and used. There have been a number of measurement studies tracking IPv6 deployment, most of them focusing on control plane metrics such as the number of IPv6 addresses allocated, growth in the AS-level topology, traffic volume, BGP churn or traffic mix [4]–[10]. Some earlier work also includes performance-related metrics, such as differences in delay over IPv4 and IPv6 [4], [5]. One earlier study [11] (albeit old) includes router-level path length comparisons. Little is known, however, about the stability of IPv6 paths in comparison to IPv4 paths.

In this paper, we present the first measurement study of the routing stability of IPv6 paths, and compare it to the stability of corresponding IPv4 paths. The study is performed on the NORNET CORE infrastructure [12], which allows a direct comparison of multiple paths between the same set of end nodes. Our goal is to understand whether there are differences in the update dynamics of IPv6 vs. IPv4 paths in terms of the frequency or pattern of path changes. We approach this question through a controlled measurement study, where we monitor IPv4 and IPv6 paths between the same set of end nodes over a period of 3 months.

We find that IPv6 paths are more dynamic than corresponding IPv4 paths, and experience more path changes per day on average. While the measured IPv4 paths have 0.13 changes per day on average, IPv6 paths between the same source-destination (SD) pairs have 0.27 changes per day. We also observe more *load balancing* in IPv6 paths, i.e., intermediate routers that distribute traffic over more than one path. 26% of the measured IPv6 paths are load-balanced, while the corresponding number for IPv4 is 9%.

II. SYSTEM OVERVIEW AND EXPERIMENT SETUP

A. *The* NORNET CORE *Infrastructure*

Our path stability measurement system is part of the NORNET CORE[2] distributed testbed infrastructure [12]–[14]. The architecture of NORNET CORE is depicted in Figure 1: at each site, the research experiments are performed within virtual machines that run on one or more research systems. The *control box* is a machine that provides remote login for site maintenance purposes (e.g. repair or updates) via a separate gateway to the Internet, while the *tunnelbox* denotes the router that connects all systems to the different ISPs. Between the sites' tunnelboxes, static IP tunnels over all ISP combinations are established to route the NORNET CORE-internal traffic. That is, logically, the tunnels create a fully-meshed topology among the NORNET CORE sites. Inside the tunnels, private IPv4 addresses are used (due to lack of a large-enough public IPv4 address space). This allows for a connectivity that is free of network address translation among all NORNET CORE sites. The researcher has full control over the choice of tunnel for his traffic (by setting a packet's source address) and therefore

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[2] NORNET: https://www.nntb.no.

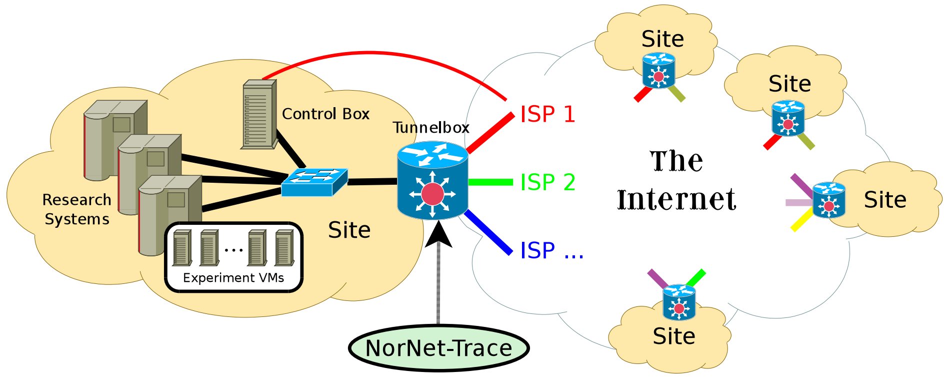

Figure 1. The NorNet Core Architecture

No.	Site Name	Location	First ISP	Second ISP	Third ISP
1	Simula Research Laboratory	Fornebu, Akershus/NO	UNINETT[F]	Kvantel[F]	Telenor[1,A]
2	Universitetet i Oslo	Oslo, Oslo/NO	UNINETT[F]	PowerTech[A]	Broadnet[1,A]
3	Høgskolen i Gjøvik	Gjøvik, Oppland/NO	UNINETT[F]	PowerTech[A]	–
4	Universitetet i Tromsø	Tromsø, Troms/NO	UNINETT[2,F]	PowerTech[A]	Telenor[1,A]
5	Universitetet i Stavanger	Stavanger, Rogaland/NO	UNINETT[2,F]	PowerTech[A]	–
6	Universitetet i Bergen	Bergen, Hordaland/NO	UNINETT[F]	BKK[F]	–
7	Universitetet i Agder	Kristiansand, Vest-Agder/NO	UNINETT[F]	PowerTech[A]	–
8	Universitetet på Svalbard	Longyearbyen, Svalbard/NO	UNINETT[2,F]	–[?]	–
9	NTNU Trondheim	Trondheim, Sør-Trøndelag/NO	UNINETT[F]	PowerTech[A]	–
10	Høgskolen i Narvik	Narvik, Nordland/NO	UNINETT[F]	PowerTech[A]	Broadnet[1,A]
11	Høgskolen i Oslo og Akershus	Oslo, Oslo/NO	UNINETT[F]	–[?]	–
12	Universität Duisburg-Essen	Essen, NRW/DE	DFN[F]	Versatel[1,A]	–
13	Karlstads Universitet	Karlstad, Värmland/SE	SUNET[2,F]	–	–
14	Hainan University	Haikou, Hainan/CN	CERNET[2,F]	China Unicom[2,F]	–

[1] Only IPv4; IPv6 is not available from ISP.
[2] Only IPv4; IPv6 available from ISP but not deployed in site's network.
[F] High-speed fibre connection.
[A] Consumer-grade ADSL connection.
[?] Negotiations with ISPs are still in progress.

Table I
THE NORNET CORE SITES IN JULY 2014

over the outgoing ISP choice at the local site as well as the incoming ISP choice at the remote site.

The NORNET CORE sites and their ISP connections are listed in Table I [14]: currently, NORNET CORE consists of 11 sites in Norway as well as 3 sites at universities abroad (Germany, Sweden, China). All of the sites use the local research network ISP (i.e. UNINETT[3] in Norway, DFN[4] in Germany, SUNET[5] in Sweden and CERNET[6] in China) for their primary connection, by high-speed fibre access (at least 100 Mbit/s, some sites with 1 Gibt/s). From the research network ISP, IPv6 is always available, but some sites have not yet deployed it in their site-local network. Various types of additional ISP connections are installed at the sites. Particularly, these connections are more diverse and in many cases consumer-grade ADSL lines. The experience here was that, although IPv6 is nearly two decades old, it is still a challenge for mostly the larger ISPs to provide native IPv6 connectivity. So, it was e.g. impossible to obtain it from Telenor[7], Broadnet[8] or Versatel[9]. The only exceptions are smaller ISPs like PowerTech[10] or BKK[11], which directly offer IPv6 to their customers.

With the current site setup, we get in total: 750 IPv4 relations and 292 IPv6 relations. That is, 458 IPv4 relations have no corresponding native IPv6 connectivity, yet. Except for the DFN connection of the Universität Duisburg-Essen site,

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[3] UNINETT: https://www.uninett.no/.
[4] Deutsches Forschungsnetz (DFN): https://www.dfn.de/.
[5] Swedish University Computer Network (SUNET): http://www.sunet.se/.
[6] China Education and Research Net. (CERNET): http://www.cernet.edu.cn/.
[7] Telenor: https://www.telenor.no/.
[8] Broadnet: http://www.broadnet.no/.
[9] Versatel: http://www.versatel.de/.
[10] PowerTech: http://www.powertech.no/.
[11] Bergenshalvøens Kommunale Kraftselskap (BKK): https://www.bkk.no/.

all IPv6 connectivity is currently limited to the mainland of Norway. However, the geographical distances of the locations are already up to[12] about 2,000 km (1,250 mi). The yet IPv4-only connection to two different ISPs in Haikou adds inter-continental, long-distance connectivity to the setup. With 11 different ISPs and different types of connections, we believe that we can already cover an interesting subset of the Internet that is representative for today's users.

B. *Measurement Setup*

We have designed and developed the `NorNet-Trace` measurement service that runs on all tunnelboxes. This tool is designed to give NorNet Core users more detailed knowledge about the tunnels that connect the various sites. It performs regular `traceroute`-like measurements [15], [16] via all local ISPs to all remote sites' ISP connections, via IPv4 as well as IPv6 (if both sides support IPv6, of course). That is, with increasing hop count, ICMP Echo Request messages are sent to the destination. Once the hop count of a packet has reached 0, a router on the way replies with an ICMP Time Exceeded message. The destination, however, replies with an ICMP Echo Reply. The hop count setting necessary to reach the destination gives the path length between source and destination. Such a measurement is performed about every 10 min; all results are imported into the NorNet Core topology database. The results for each measurement contain:

- Measurement time stamp,
- Source and destination sites and ISPs,
- Path length,
- Round-Trip-Time (RTT) and IP address for each hop.

For each hop count setting, 3 probes are made. The recorded RTT is the average of all received responses. If there is no response, the RTT and hop IP address are recorded as undefined ("*" value). A lack of response may be caused by a router's bandwidth limitation for ICMP messages (a security mechanism [15, Subsection 2.4]) or – of course – by a problem on the path. Probes where the only change is an undefined value are removed from our dataset. Based on the remaining records, we calculate a sequence of path changes for each relation.

III. RESULTS

Based on the experiment described above, we present results for the *path length distribution*, the *use of load balancing* and the *path stability* of IPv4 and IPv6 paths. We also analyse the pattern of routing changes in the monitored paths, to understand whether path changes typically arrive in bursts or happen independently at random times.

As noted above, NorNet Core does not have IPv6 connectivity at all sites/providers. In our analysis, we distinguish between IPv4 source-destination (SD) pairs where we also have corresponding IPv6 connections, and those where IPv6 is not available at one or both end points. We denote the two sets of SD pairs as IPv4$_6$ and IPv4$_X$ respectively. As will be clear in the sequel, the IPv4$_6$ and IPv4$_X$ paths in our dataset have quite different characteristics. While our main focus in this paper is on comparing IPv6 and IPv4$_6$ paths, we also include IPv4$_X$ data in the analysis.

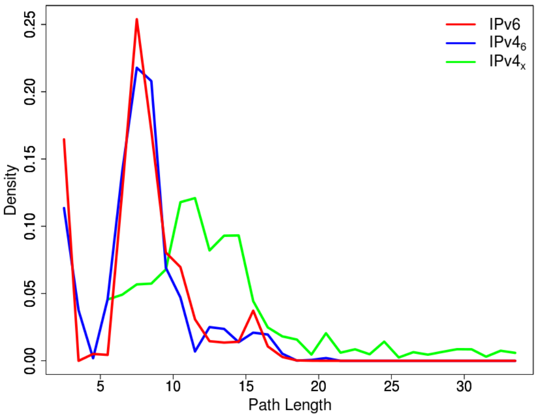

Figure 2. Path Length Distributions

A. *Path Length Distribution*

Figure 2 shows the distribution of path lengths for IPv6, IPv4$_6$ and IPv4$_X$ measured between NorNet Core sites. In the figure, a path between a given SD pair is counted once every time the measurement is run. In other words, each path is weighted according to how often it is seen in our measurements.

We first observe that there are no clear differences between IPv4$_6$ paths and IPv6 paths. For both of these groups, about 65% of paths are between 7 and 12 hops long, and almost no paths are longer than 18 hops. We observe some outlier paths of only 2 or 3 hops. On closer inspection, we see that these paths are all internal to one of the ISPs (PowerTech). It is likely that this provider uses some kind of tunnelling (e.g. based on MPLS) inside their network.

Next, we observe that IPv4$_X$ paths are substantially longer than IPv4$_6$ and IPv6 paths. As discussed above, the IPv4$_X$ paths included in this study are qualitatively different from the IPv4$_6$ paths, both in terms of geographic distribution and technology.

B. *Load Balancing*

Load balancing is sometimes used in IP networks for redundancy and traffic engineering purposes. This is typically implemented by using Equal Cost Multipath (ECMP) [17], which distributes flows equally over a number of equal-cost paths based on a hashed value of the packet header 5-tuple (i.e. source and destination IP address, transport protocol number and source and destination ports). Our goal in this work is to measure path stability, and it is therefore important to know whether there is a router that performs load balancing on the path between a source and a destination. Therefore, we use

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[12] Essen/DE ↔ Narvik/NO.

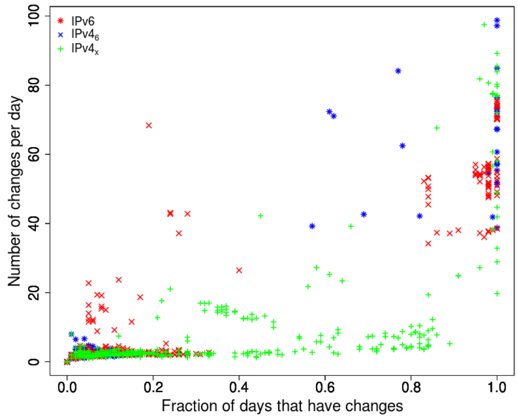

Figure 3. Path Changes per Day vs. Days with Path Changes

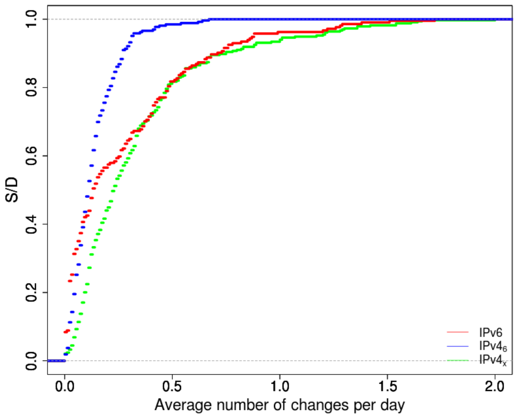

Figure 4. Number of Path Changes per Day for Non-Load-Balanced Pairs

ICMP messages to monitor paths, and a load balancer will distribute our probes equally over available paths. This can result in the inference of several paths between a source and a destination, some of which might not be real [18].

Luckily, it is not difficult to identify load-balanced paths from our dataset, as can be seen from Figure 3. This scatterplot shows, for each monitored SD pair, the fraction of days with path changes, and the average number of path changes *on days with at least one change*. Looking first at the IPv6 and IPv4$_6$ SD pairs, we see a very clear dichtonomy in the data, where most SD pairs are either in the bottom left corner, or in the top right corner. In other words, most SD pairs fall into one of two categories: they either see a limited number of path changes in a small subset of the measured days, or they see tens of changes per day quite frequently. The latter behaviour is exactly the kind that we would expect from a load-balanced path. For IPv4$_X$ paths, this dichtonomy is less clear, as we have a number of SD paths with a significant number of path changes in a high fraction of days, and no path changes in others.

In order to continue our analysis of path stability, we must distinguish load-balanced paths from non-load-balanced paths. Looking at IPv6 and IPv4$_6$ SD pairs, we note that 214 out of 292 IPv6 paths and 266 out of 292 IPv4$_6$ paths have fewer than 2 path changes per day on average, while the remaining 78 IPv6 and 26 IPv4$_6$ SD pairs have more than 10 path changes per day. From this, we conclude that 27% of the IPv6 SD pairs and 9% of IPv4$_6$ SD pairs are load balanced. For IPv4$_X$ SD pairs, it is more difficult to distinguish between load-balanced and non-load-balanced paths, since some SD pairs experience a high number of changes that do not resemble load balancing. Using a very conservative threshold of 2 path changes per day, we find that 27% of IPv4$_X$ SD pairs experience load balancing. A more realistic threshold of 10 changes per day puts this number at 9%, similar to IPv4$_6$.

The fact that load balancing is more widespread in IPv6 than in corresponding IPv4 paths is surprising. One possible explanation could be that the IPv6 topology is simpler or more sparse than the IPv4 topology, giving more equal-cost paths for ECMP load balancing.

C. Path Stability

Next, we look at the path stability for each SD pair, excluding SD pairs with load balancing. We report on the average number of path changes per day. We also go into the temporal distribution of these changes, to understand whether path changes tend to arrive in bursts or spread over time.

Figure 4 shows the CDF of the average number of path changes per day for non-load-balanced SD pairs. We observe a clear difference between IPv6 and IPv4$_6$ paths: IPv6 paths are less stable, i.e. they experience more path changes. 18% of IPv6 SD pairs experience more than 0.5 path changes per day, while this is true for only 1.5% of IPv4$_6$ SD pairs. No IPv4$_6$ pairs see more than 0.7 changes per day. 3.7% of IPv6 pairs experience more than 1 path change per day on average.

The IPv4$_X$ paths in our dataset are less stable than for IPv6 and IPv4$_6$. As discussed above, these paths are often longer (e.g. the inter-continental connection to China), which may explain the added instability.

Seeing the differences between IPv6 and IPv4$_6$ SD pairs, we next seek to understand more about how path changes are distributed in time. We sometimes observe that a path is unstable for a period of a few hours or sometimes a day, before it returns to its normal stable behaviour. To investigate this in more detail, we group path changes from a single SD pair that appear close in time into *events*. The idea behind this is that path changes that appear close in time can often be caused by the same underlying event. Examples of such events can be a configuration change, the addition or removal of a link or a router, or faults of various kinds that lead to rerouting plus restoration. We use a threshold of 1 hour to group path changes into events. We believe this threshold is a reasonable trade-off between capturing related changes and avoiding to

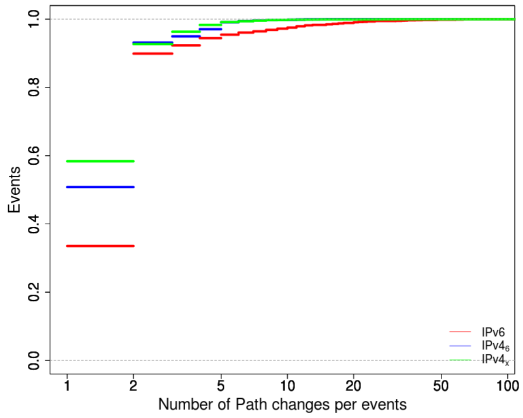

Figure 5. Number of Path Changes per Event

group unrelated changes. We have repeated this grouping with a threshold of 2 hours, with very similar results.

Figure 5 shows the CDF of the number of changes per event for the different groups of connections. Again, we observe clear differences between IPv6 and IPv4$_6$ paths, with larger events (more changes per event) for IPv6. In IPv4$_6$, 52% of all events consist of just a single path change, while the corresponding number for IPv6 is just 34%. 54% of the events for IPv6 consist of two path changes. Looking at events of size 2, we find that these are very often rerouting plus restoration events, where packet flows return to their original path after a short transient period. The lower number of these events explains much of the difference in stability between IPv6 and IPv4$_6$.

IPv4$_X$ SD pairs follow largely the same pattern as IPv4$_6$, with a somewhat higher fraction (59%) of events with a single path change.

IV. CONCLUSIONS AND FUTURE WORK

While IPv6 can quite soon celebrate its 20th anniversary, its deployment by ISPs is still a novelty. Nowadays, only some ISPs already offer IPv6 to their customers. So, it is time to look at the performance of IPv6, particularly at the stability of paths. In this paper, we have presented the results of such measurements in a realistic Internet setup, based on the NORNET CORE testbed infrastructure for multi-homed systems. Based on a setup with a variety of ISPs and different connection types over a large geographical area, we have observed the following:

- The path lengths do not significantly differ between IPv4 and IPv6.
- However, IPv6 paths change more frequently than IPv4 paths.
- Load balancing is more common for IPv6 than for IPv4, most likely due to a simpler or more sparse topology that gives more equal-cost paths for ECMP load balancing.

As part of our ongoing and future work, we are continuing to run our measurements, so that we will be able to track the changes in the future. We also plan to look closer at path similarities and temporal correlations in updates for IPv4 and IPv6 paths, in order to better understand whether the two paths go over the same infrastructure.

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