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THE IPV6 INTERNET: AN ASSESSMENT OF ADOPTION AND QUALITY OF SERVICES

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ABSTRACT

The goal of this study is to deliver both an in-depth comprehensive analysis of the current state of IPv6 adoption and an assessment of the quality of services over the IPv6 Internet. Our assessment comprises an examination of eight data sets used to produce a comprehensive picture of IPv6 adoption across 12 metrics. We assessed the quality of services over the IPv6 Internet using eight globally distributed monitoring agents to compare the HTTP load times to targeted websites over IPv6 and IPv4. The results of our analysis confirm the findings of previous studies showing that IPv6 is in an accelerating adoption phase and that the IPv6 Internet is maturing in its ability to deliver quality of services on a par to IPv4. The long anticipated exhaustion of the Internet Assigned Numbers Authority (IANA) IPv4 global address pool occurred in February of 2011. Since that time, four of the five regional Internet registries (RIRs) have also exhausted their IPv4 address pools, leaving the African Network Information Centre as the only RIR with a pool of IPv4 addresses remaining for general allocation. As the availability of IPv4 addresses continues to diminish, the adoption and use of IPv6 is rapidly increasing. However, the quality of IPv6 deployments and implementations is not always equal, which can cause user experiences over the IPv6 Internet to suffer. For this reason, ongoing monitoring and measurement are essential to provide a comprehensive picture of IPv6 adoption and to evaluate the quality of services over IPv6.

KEYWORDS: IPv6, Internet, Technology Management, Technology Adoption, Diffusion

INTRODUCTION

The exhaustion of the IPv4 address space was a long anticipated event. Discussion threads concerning the shortage of IPv4 addresses were posted on the TCP/IP Mailing List as early as 1988 (Huston, 2008). In fact, Vint Cerf himself commented to a mailing list post on November 27, 1988, "We should be worried about this [IPv4 exhaustion] and should be thinking about how to expand the available space" (Cerf, 1988). The Internet Engineering Task Force (IETF) began working to find a successor to IPv4 in late 1990. In 1993 the IETF formed the IP Next Generation (IPng) Area to begin reviewing various proposed solutions for the next generation IP protocol. The new protocol was assigned protocol version number 6 to become IP version 6, or IPv6 (Bradner & Mankin, 1995).

To accommodate the continued growth of the Internet until IPv6 could be fully adopted, the Internet community implemented several short-term solutions to conserve and manage the remaining global IPv4 address pool. Some solutions, such as the establishment of Private IPv4 addresses and Network Address Translation (NAT), were designed specifically to slow down the rate of IPv4 address exhaustion until the permanent solution, IPv6 adoption, could be in place. Other solutions, such as Classless Inter-domain Routing (CIDR), Dynamic Host Configuration Protocol (DHCP), and the establishment of the Regional Internet Registries (RIRs) were designed to help conserve and economically manage the IPv4 address space (Hughes, 2010; White, Shah, & Cook, 2005).

Although IPv4 exhaustion was imminent and IPv6 offered significant technical advantages beyond a larger address space, adoption and usage of the new protocol remained marginal at best. Internet Service Providers (ISPs) and enterprise organizations were reluctant to commit the resources required to deploy IPv6. The time and cost required for infrastructure upgrades as well as a reliance on NAT were often cited as inhibitors to IPv6 adoption (Dell, 2012; Kaur, Singh, & Tan, 2013; White et al., 2005). However, after years of stagnation, empirical data suggest that IPv6 may now be in a phase of accelerating adoption (Czyz et al., 2015; Nikkhah & Gurin, 2016).

The migration from IPv4 to IPv6 is the most disruptive event the Internet community has faced to date and is dependent on the availability of both IPv6 applications and components in the Internet infrastructure, and also on the demand for those resources by Internet stakeholders (Nikkhah & Gurin, 2016). However, adoption alone is not enough. The transition to the IPv6 Internet cannot be fully realized until the quality of services provided over IPv6 is on a par with its predecessor, IPv4, so that users receive the same or better user experience (Nikkhah, Gurin, Lee, & Woundy, 2011). In the findings of our study we show that while IPv6 traffic volume on the Internet and the number of IPv6 reachable domains are still at a fraction of that of IPv4, other metrics indicate IPv6 is on a trajectory of increasing adoption and maturity.

This paper makes a significant contribution to the understanding of progress of Internet IPv6 adoption and provides empirical data concerning the performance and quality of the user experience on the IPv6 Internet. We extend our previous research presented at conference by analyzing an additional year of data from January 2016 through January 2017 to determine if the pace of IPv6 adoption is still on track (Pickard & Southworth, 2016). We also evaluate the five year IPv6 adoption projections made by Czyz et al. (2015) to assess if trends in IPv6 adoption have shifted significantly. Finally, we include results of measurements taken of the performance and quality of the user experience of the IPv6 Internet through the use of globally distributed network monitoring.

RELATED WORKS

There are many quantitative studies in the extant literature on the subject of IPv6 adoption and diffusion. Some studies adopted a narrow perspective assessing the status of IPv6 adoption, focusing on one specific adoption metric. For example, Nikkhah et al. (2011) used access to web content as the primary metric to measure and quantify IPv6 adoption. By comparing the web access performance over IPv4 and IPv6 to a list of websites based on Alexa's top 1 million websites, from various geographic vantage points, the authors found that IPv6 performance was similar to that of IPv4 when autonomous system paths were the same. Similar findings were made by Dhamdhere, Luckie, Huffaker, Elmokashfi, & Aben (2012), who analyzed the size, routing behavior, and structure of the IPv6 Internet using historical BGP tables. Their findings showed that the IPv6 Internet infrastructure is becoming increasingly similar to that of IPv4. In another study, Colitti, Gunderson, Kline, & Refice (2010) analyzed client behavior when connecting to IPv6-only and dual-stack hosts. Their data showed that IPv6 adoption, while varied across geographic regions, was increasing rapidly and that latency over native IPv6 was comparable to that of IPv4.

Other studies took a broader approach by using multiple metrics to assess IPv6 adoption. Domingues, Friaas, & Veiga (2007) used autonomous systems in BGP, RIR address allocations, Internet core peering, and IPv6-enabled top-level domains to assess IPv6 adoption. Latency experiments were conducted to measure IPv4 and IPv6 performance from a scientific network in Portugal to 28 globally distributed

target sites. Findings indicated that IPv6, at the time of the study, had not yet been broadly adopted. Nikkhah & Gurin (2016) assessed the evolution of IPv6 adoption by key Internet stakeholders, service providers, Internet technology developers, content providers, and users through three phases: stagnation, emergence, and acceleration. They developed a model that captures the interactions between IPv6 adoption factors and their impact on IPv6 migration status. Their model offered validation to the relationship between the decisions of stake-holders to adopt IPv6 and utility functions that depend on the adoption decisions of other stakeholders.
Our study is most similar to that of Czyz et al. (2015), who provided, a comprehensive picture of IPv6 adoption using a broad set of datasets and metrics. Their study assessed IPv6 adoption from the perspective of content providers, service providers, and content consumers using 10 years of data from 2004 to 2014. Findings showed IPv6 was used natively at a rapidly increasing rate across every measure of IPv6 adoption. The authors also developed models representing predictions of future IPv6 adoption for five years, from 2014 to 2019.

METHODOLOGY

We analyzed eight datasets to produce 12 metrics to yield a comprehensive assessment of IPv6 adoption and quality of services over IPv6 on the Internet, as summarized in Table 1. Where possible, we use the same datasets as Czyz et al. (2015) with the goal of extending their findings with an additional three years of data and to assess the predictions of their five-year IPv6 adoption forecast model against actual IPv6 adoption metrics. In the case of assessing IPv6 Internet traffic growth, we deviated from the previous study and used publicly available data from the Amsterdam Internet Exchange. We also used our own unique dataset for IPv6 performance obtained from globally distributed network monitoring agents.

	Dataset	**Metric**
1)	Prefix allocations from each RIR	IPv6 prefix allocations by the RIRs
		Ratio of IPv6 to IPv4 prefix allocations
2)	Route Views AS6447	IPv6 prefix announcements in BGP
		Ratio of IPv6 to IPv4 announce prefix
3)	Hurricane Electric root zone file	DNS authoritative nameservers
4)	Route Views AS6447	Unique IPv6 autonomous systems (ASes)
		Ratio of IPv4 to IPv6 unique ASes
		Unique IPv6 autonomous system paths

5)	Alexa top 10k	DNS resource records
6)	Google IPv6 statistics	Number of IPv6 users
7)	Amsterdam Internet Exchange	IPv6 traffic volume
8)	Network monitor data	Quality of services (HTTP load time performance)

Table 1. Datasets and associated IPv6 adoption metrics used in this study

PREFIX ALLOCATIONS

The first fundamental requirement of wide-scale IPv6 communication is the allocation of IPv6 address blocks from the RIRs to service providers and end-user organizations (Czyz et al., 2015). To measure IPv6 address availability, we used the allocation of IPv6 prefixes by the RIRs. It is expected that the number of prefix allocations made by the RIRs should increase as end-user adoption of IPv6 increases.

Each RIR makes its prefix allocation database available for public download. Using the IPv6 and IPv4 address block allocation datasets from each RIR from January 2014 through January 2017, we aggregated the prefixes into one single metric for each protocol. Figure 1 shows that between January 2014 and January 2017 the number of allocated IPv6 prefixes increased from 18,180 to 32,123, an increase of 76.7%. During the same period, IPv4 prefix allocations increased from 135,316 to 170,890, a gain of 26.2%. The solid line represents the ratio of total IPv6 to IPv4 prefix allocations, which was .13 in January 2014 and increased to .19 by January 2017.

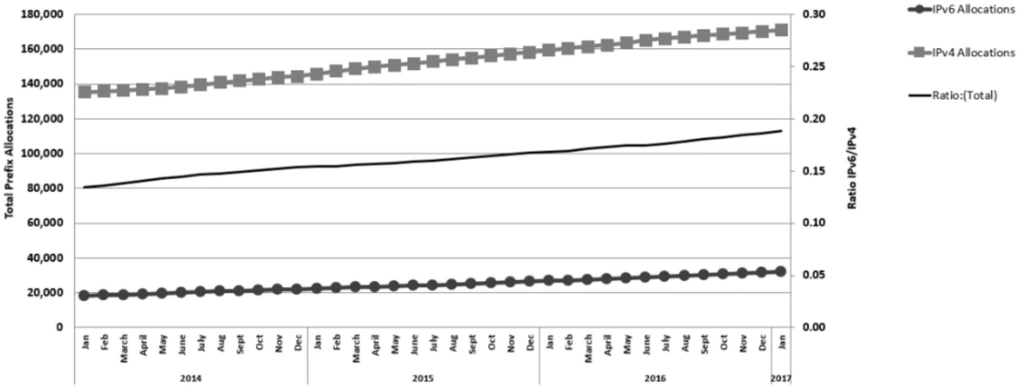

Figure 1. Cumulative prefix allocations aggregated from all RIRs.

We found that growth, in percentage terms, of IPv6 prefix allocations is outpacing that of IPv4 prefix allocations. This is expected behavior due to the fact that the IPv4 address space is exhausted and demand for substantial numbers of IP addresses can be met only through IPv6 allocations. We also found that while IPv6 allocation growth is outpacing that of IPv4 in percentage terms, the numeric increase in allocated IPv4 prefixes is greater than that of IPv6. This is also expected behavior since a typical /32 IPv6 allocation contains $7.9\text{x}10^{28}$ (79 billion-billion-billion) addresses while, IPv4 allocations, as per RIR exhaustion policies, are typically limited to a /22, which yields only 1,024 addresses. In other words, although the number of IPv6 prefix allocations is less than that of IPv4, the number of useable IP address contained in those allocations is exponentially larger than in the IPv4 allocations. For example, in 2015 the Asia-Pacific Network Information Centre (APNIC) made 3,980 IPv4 prefix allocations containing 4,304,012 addresses, a ratio of 1,081 addresses per allocation, and made 775 IPv6 prefix allocations of 35,383,205,120 addresses, a ratio of 45,655,748 addresses per allocation.

We also analyzed the aggregate monthly prefix allocations made by all RIRs from January 2014 to January 2017 as shown in Figure 2. Three distinct run-ups in the IPv4 allocations appear in Figure 2, the first in June-July 2014, then again in January-February 2015, and finally in May-June 2016. These run-ups coincide with allocations of IPv4 address prefixes returned by the IANA to each RIR. The RIRs allocated this returned address space in small /22 prefixes (APNIC "waiting list for unmet IPv4 requests," n.d.). Also shown in Figure 2 is the ratio of IPv6 versus IPv4 monthly allocations. A ratio of 1, as seen on March of 2013, indicates an equal number of allocations in a given month.

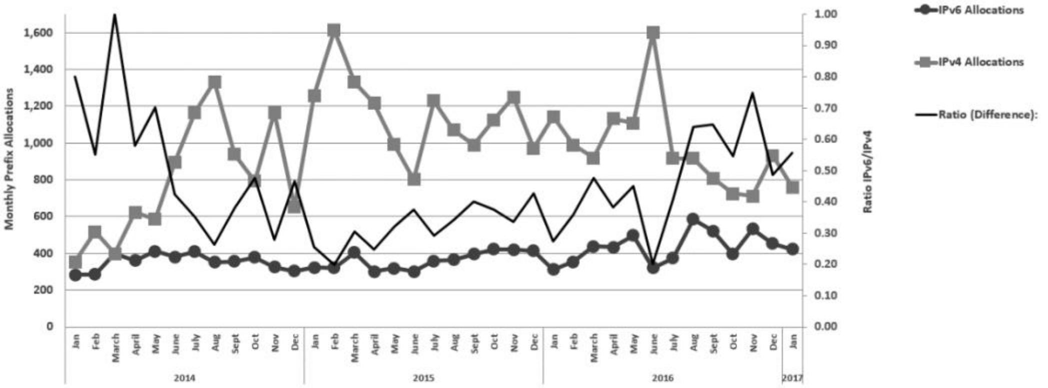

Figure 2. Number of prefix allocations by month aggregated from all RIRs.

PREFIX ANNOUNCEMENTS

The prefix allocation data shown in Figure 1 and Figure 2 clearly show that the number of IPv6 prefix allocations is steadily increasing. However, prefixes must be announced in the global BGP routing table before they can be used. We used BGP data from the University of Oregon Route Views Project to measure prefix advertisement growth in BGP. The Route Views routers use AS6447 for multi-hop BGP sessions to peer with backbones and other autonomous systems (ASes) at various Internet locations ("University of Oregon route views project," 2005). A possible bias in this metric noted by Czyz et al. (2015) is that Route Views gives the perspective of the Internet as seen through a single AS which does not give the complete Internet topology. However, for the purpose of showing trend, it is assumed that the increase in IPv6 prefix announcements as seen by AS6447 is representative of the Internet topology as a whole.

Figure 3 shows the number of IPv6 prefix announcements increasing 126.5% from 16,537 in January 2014 to 37,460 in January 2017. Over the same period, the number of IPv4 prefixes increased 38% from 491,660 to 678,400. The solid line shows that the ratio of IPv6 to IPv4 prefixes increased from .03 in January 2014 to .06 in January 2017, indicating that the increase in the number of announced IPv6 prefixes is outpacing that of IPv4 in the global BGP table. This is not a surprising trend due to the exhaustion of the global IPv4 address pool.

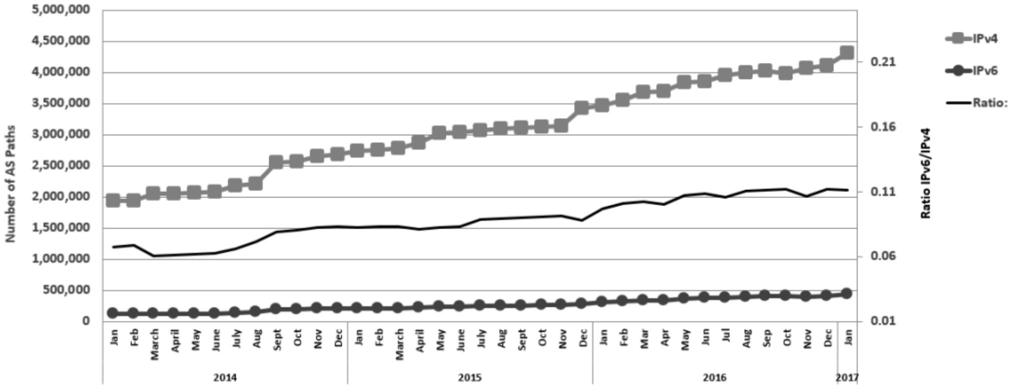

Figure 3. Prefixes as seen in the Global BGP table of AS6447.

AUTHORITATIVE NAMESERVERS

Support for IPv6 in the global Domain Name System (DNS) is another important indicator of IPv6 adoption. We measured the level of support for IPv6 in the DNS as the number of Top Level Domain (TLD) servers that are reachable over IPv6. Reachability of nameservers over IPv6 is considered evidence of IPv6 adoption, especially among Internet Content Providers (ICPs) who make their content accessible across public websites (Czyz et al., 2015; Nikkhah & Gurin, 2016). At the highest level of the DNS hierarchy are the authoritative nameservers that serve the DNS root zone, commonly known as the root servers. The DNS root zone has been IPv6 enabled since 2008. All of the 13 root authoritative nameservers are reachable over IPv6 ("Root servers," n.d.).

The Root Zone Database contains all of the TLDs, which includes domain suffixes such as .com, .net, .org, .us, .fr, etc. We assessed the number of TDL nameservers that are IPv6-enabled and reachable using data made publicly available by Hurricane Electric (HE). HE downloads the root zone file daily, queries for AAAA records, and checks for glue records in the root zone for each TLD nameserver ("Global IPv6 deployment progress report," n.d.). In January 2014, HE reported approximately 381 TLDs, of which 91% had native IPv6 connectivity. In January of 2017 there were 1,530 TLDs, of which 98.1% had IPv6-enabled nameservers. These data indicate that the root zone and TLDs of the Internet naming system are IPv6-ready (Czyz et al., 2015).

UNIQUE AUTONOMOUS SYSTEMS

To measure the overall penetration and density of IPv6 on the Internet, we used the number of unique ASes and unique AS paths as seen in BGP. An increasing number of unique ASes is indicative of increasing IPv6 adoption among ISPs (Czyz et al., 2015; Dhamdhere et al., 2012; Grégr, Podermanski, & Švéda, 2014). An increase in the number of unique AS paths indicates a maturing of connectivity or increased connectivity quality between autonomous systems over IPv6 (Czyz et al., 2014; Dhamdhere et al., 2012; Nikkhah & Gurin, 2016).

Again, data from the University of Oregon Route Views Project AS6447 are used for this metric. As shown in Figure 4, the number of unique IPv6 ASes increased 62.4% from 7,905 in January of 2014 to 12,838 in January of 2017. Over the same period, unique IPv4 ASes increased 22.3% from 46,164 to 56,458. The ratio of IPv6 to IPv4 ASes increased from approximately 0.18 in January of 2014 to approximately 0.23 in January 2017.

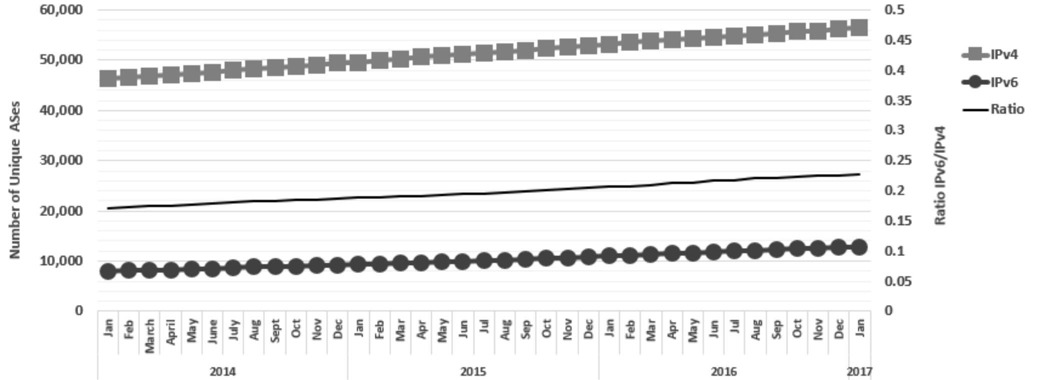

Figure 4. Number of unique ASes as seen from AS6447.

UNIQUE AUTONOMOUS SYSTEM PATHS

Figure 5 shows that the number of unique IPv6 AS paths in January 2014 was 122,160 compared to 430,900 in January 2017 an increase of 252.7%. This is an indication that the IPv6 topology of the Internet is maturing (Czyz et al., 2016; Dhamdhere et al., 2012). The number of unique IPv4 AS paths advertised within the BGP table in January 2014 was 1,814,200 compared to 3,873,500 in January 2017, an increase of 113.5%. The ratio line shows that the number of unique IPv6 AS paths as compared to IPv4 AS paths is steadily increasing from .07 to 0.11.

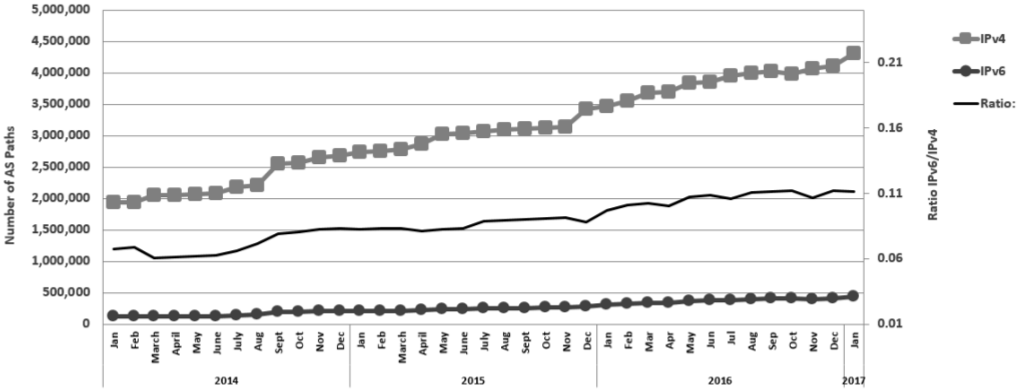

Figure 5. Number of unique AS paths as seen from AS6447.

DNS RESOURCE RECORDS

Estimating the deployment of IPv6 among content providers can be done by the number of websites accessible over IPv6 (Czyz et al., 2015; Nikkhah & Gurin, 2016). This is an important metric for services providers as it is an indication of the IPv6 traffic they can expect over IPv6.

The dataset used for this metric is the Alexa top 1 million most popular websites. Alexa is a popular source of the top domains on the Internet ("Alexa top sites," n.d.). We filtered off the top 10,000 sites from the Alexa top 1 million list and used the DNS DataView tool to check for the presence of an AAAA record in the DNS for each site URL. Of the top 10,000 websites, we found that 1306 or 13% returned AAAA records in January 2017, representing a 308% increase over the results reported in January 2014 in which 3.2% returned AAAA records.

A possible bias with using the Alexa top 1 million websites is noted by Grégr et al. (2014). The Alexa top 1 million websites database aggregates subdomains into the associated TLD, and therefore subdomains are not included in the analysis of AAAA records. However, the Alexa database is the most comprehensive publicly available list of popular global websites and has a basis in the extant literature as a valid method of assessing IPv6 service penetration (Czyz et al., 2015; Nikkhah et al., 2011).

NUMBER OF IPV6 USERS

All major client operating systems and browsers today support IPv6, and most prefer IPv6 over IPv4 when both protocols are available. This metric measures how many clients are actually using IPv6 to access web resources. To report the number of IPv6 users, we used Google's IPv6 statistics page ("IPv6 Adoption Statistics," n.d.). Google measures IPv6 availability by adding a measurement JavaScript to a random sample of visits to various Google properties. The measurement JavaScript uses HTTP to fetch a URL from an IPv4-only hostname and a URL from a dual-stack hostname, in random order. Figure 6 shows that over the period from January 2014 to January 2017 the number of clients accessing Google.com over IPv6 increased from around 2.5% to 15.5%. More clients using IPv6 should motivate more Internet content providers to enable IPv6.

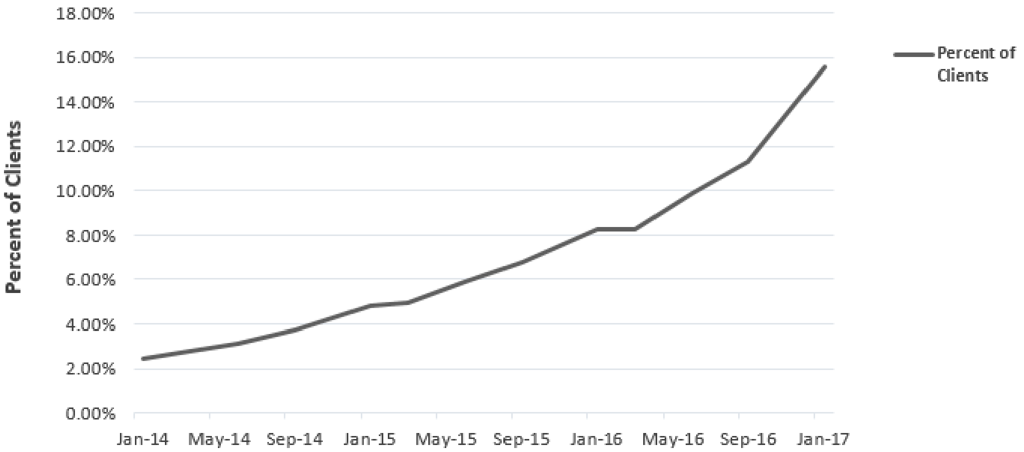

Figure 6. Percent of users accessing Google over IPv6.

IPV6 TRAFFIC VOLUME

To get a snapshot of Internet IPv6 traffic volume, we used publicly available statistics from the Amsterdam Internet Exchange (AMS-IX). AMS-IX is the largest Internet Exchange Point (IXP) in the world in terms of average throughput with a capacity of 23Tb/s and connects 804 autonomous systems globally. The average aggregated Internet traffic on all AMX-IX connected network ports in January of 2017 was 3.5Tb/s, or 3,500Gb/s. The average monthly total IPv6 traffic in January 2017 was 51.3Gb/s, or about 1.5% of the total Internet traffic seen on AMX-IX networks ("Statistics," n.d.). While 1.5% of traffic may seem insignificant, it is a 150% increase over the 0.6% recorded in December 2013 by (Czyz et al., 2015). A possible bias in this measure is that AMX-IX is only one Internet exchange point and carries a fraction of the total Internet volume. However, because we were interested in the trend and not raw volume numbers, we made the assumption that the percent of IPv6 volume increase seen by AMX-IX is likely representative of Internet traffic as a whole.

QUALITY OF SERVICES (PERFORMANCE)

To measure IPv6 quality of services on the Internet, we calculated average HTTP load times of target websites over IPv6 and compared the results to the load times over IPv4. The use of HTTP load time provides an operational metric that takes into account DNS response time, TCP connect time, full webpage load time, and application load time, which closely reflects user experience with services delivered over IPv6 (Popoviciu, 2016).

By filtering the Alexa top 100 for sites that were reachable over IPv6, we identified 32 websites to use as the target sites for our monitoring. We used eight globally distributed network monitoring agents located in Dallas, Paris, Sydney, Tokyo, San Francisco, Slovenia, New York, and Singapore to download the web content of each of the 32 target sites every hour for 30 days. After the 30-day data collection ended, the raw data from each agent was compiled for a total of 256 data points (32 target websites multiplied by eight agents) for IPv6 and for IPv4.

From the agent data collected, 74% of the measures had average IPv6 HTTP load times within 10% of IPv4 or faster, which is considered similar performance levels (Dhamdhere et al., 2012; Nikkhah et al., 2011). Figure 7 shows a comparison of IPv6 vs. IPv4 load times in terms of milliseconds. Figure 8 shows a comparison of IPv6 to IPv4 load times in +/- percent. A positive number indicates shorter load times over IPv6. A negative number indicates a shorter load time over IPv4. In both charts the outliers to the negative were to a single website in Russia seen from the vantage points of agents in the United States (U.S.) and Europe. Further investigation showed that this was likely caused by the target website configuration because one website element was taking twice the amount of time to load over IPv6. We also found that 30 of the 32 websites targeted by our Paris agent all reported slower IPv6 load times. Again, no common cause could be found in the data to explain why the Paris agent had such a high ratio of slow IPv6 to IPv4 load times; however, we were able to narrow the cause down to TCP wait times and DNS request times.

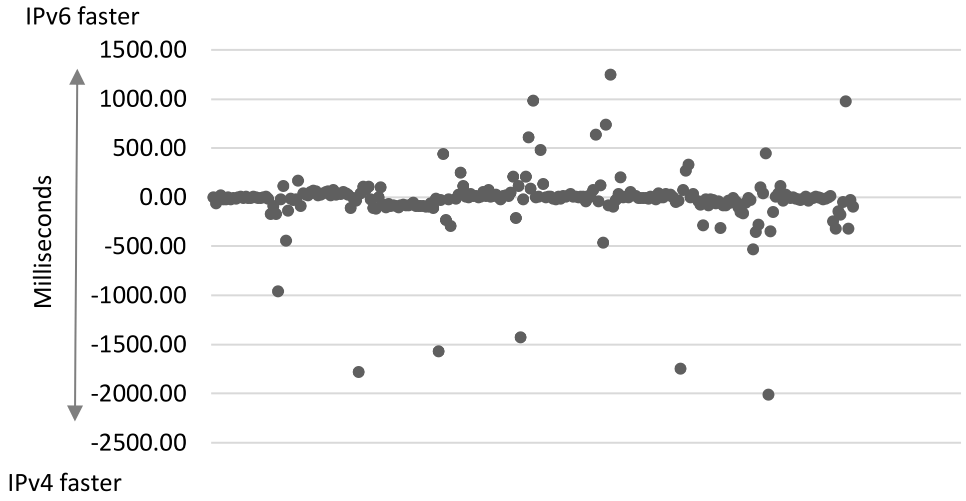

Figure 7. The millisecond difference between IPv4 and IPv6 HTTP load times for all measures.

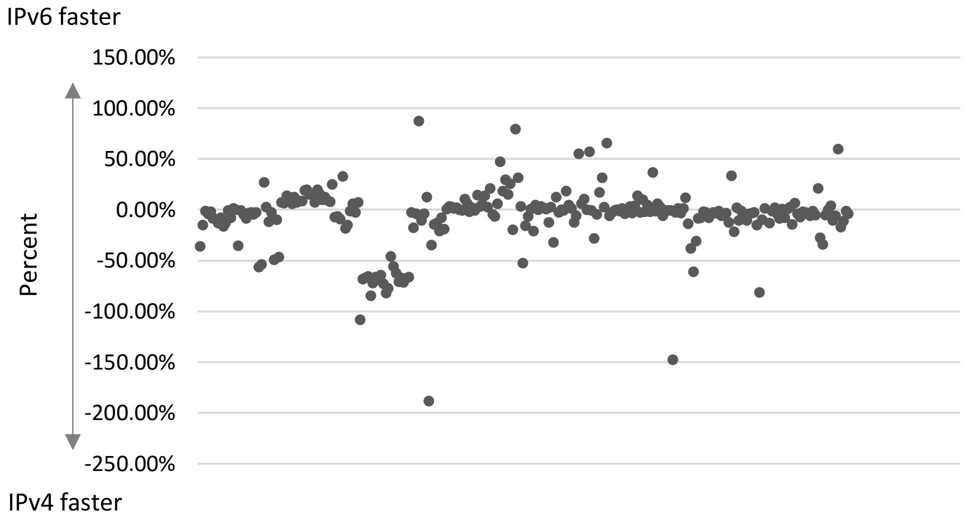

Figure 8. The percentage between IPv4 and IPv6 load times of all measures; 0% indicates load time were the same on both protocols.

DISCUSSION OF FINDINGS

In this study we evaluated the level of adoption and quality of services of IPv6 on the Internet through 12 metrics from data spanning a three-year period. We found empirical evidence showing that the trend of accelerating IPv6 adoption is continuing across all 12 metrics. We also found in our investigation that IPv4 prefix allocations have become smaller than historically now that the RIRs are operating under final IPv4 policies. Table 2 shows each adoption metric at the beginning of our study in January of 2014 and at the end of the study in January 2017 along with the percent increase for each metric over the three-year period of the study.

Metric			
	January 14	**January 17**	**Change**
IPv6 prefix allocations by the RIRs	18,180	32,123	+ 76.7%
Ratio of IPv6 to IPv4 prefix allocations	.13	.19	+46.1%
IPv6 prefix announcements in BGP	16,537	37,460	+126.5%
Ratio of IPv6 to IPv4 announce prefix	.03	.05	+66.6%
DNS authoritative nameservers	91%	98.1%	+7.8%
Unique IPv6 autonomous systems	7,905	12,838	+62.4%
Ratio of IPv4 to IPv6 unique ASes	.18	.22	+22.2%
Unique IPv6 AS paths	122,160	430,900	+252.7%
Ratio of IPv4 to IPv6 unique AS paths	.07	.11	+57.1%
DNS resource records	320	1306	+308.1%
Number of IPv6 users	2.5%	15.5%	+520%
IPv6 traffic volume	.6%	1.5%	+150%

Table 2. Measure of change for each metric

IPv6 adoption is happening at an increasing rate, as seen in the increases in prefix allocations, prefix announcements, unique ASes, and unique AS paths. These metrics indicate that organizations are obtaining IPv6 prefixes and announcing them in BGP. Web content is also increasingly available over IPv6 as seen by the 306% increase in DNS resource records, making 13% of Alexa's top 10,000 websites reachable over IPv6. The volume Internet traffic over IPv6 is still quite low compared to IPv4; however, it has seen an increase of 150% over the three-year period.

Analyzing the quality of services to the top Alexa websites that are reachable over IPv6, we found the performance of HTTP load times to these sites over IPv6 was similar to that of IPv4 in 74% of our measurements. Previous research by Czyz et al. (2015) and Dhamdhere et al. (2012) found that IPv4 and IPv6 roundtrip time and web download times were similar when both IPv4 and IPv6 had the same AS path. In our analysis we found that the physical path of the packets, as seen by traceroutes, had more to do with differences in HTTP load times than AS paths. Even within the same AS, we noted that a different path through the AS was significantly faster even over the same protocol.

One of the stated goals of this paper was to see if the projected five year forecast of IPv6 adoption made by Czyz et .al (2015) is on course. We conclude that the IPv6 adoption trend is following the lower end of the threshold made by their prediction model. Their model predicted the ratio of allocated IPv6 to IPv4 prefixes would be between .25-.50 by 2019. Our findings show the ratio is 0.19 as of January 2017. Their model predicted the ratio of IPv6 traffic on the Internet would be between .03 and 5.0 by 2019. Our findings show the ratio is 0.015 as of January 2017.

The bulk of the published literature on IPv6 adoption is devoted to measuring current levels of IPv6 adoption as compared to either IPv4 or to previous levels of IPv6 adoption over time. The trend in the findings of previous studies shows that while IPv6 adoption is increasing, the rate of increase has, until recently, called into question wither IPv6 would ever be fully adopted to replace IPv4. The significant acceleration in IPv6 adoption across multiple metrics found in this study suggest that the findings of previous studies questioning the future of IPv6 as a successor to IPv4 are less likely to hold true. However, a notable gap still exists in the IPv6 adoption literature. There is a need for quantitative analysis to provide clear insight as to when overall IPv6 adoption will likely reach a level of critical mass which will trigger a rapid acceleration toward full adoption. Such predictive data would be useful for organizations to make the business case for IPv6 adoption.

CONCLUSIONS AND FUTURE WORK

In this study our goal was to assess the current level of IPv6 adoption on the Internet and to measure the quality of services over the IPv6 Internet as compared to IPv4. We conclude from our analysis of the data that IPv6 adoption is increasing at an accelerated pace and that the Internet is finally migrating towards IPv6, confirming the findings of previous studies. Based on the results of our analysis we further conclude that the critical adoption measure for acceleration of IPv6 adoption is the number of domains advertising AAAA records and reachable over IPv6. This measure represents content providers making their content available over IPv6. As the number of users connecting over IPv6 increases, more content providers should enable their content over IPv6. As more content is available over IPv6, the infrastructure of the IPv6 Internet itself will grow and mature. As the IPv6 Internet grows and matures, more users will be able to connect over IPv6. These positive dependencies, according to Nikkhah and Guerin (2016), can create a self-sustaining spiral of IPv6 adoption.

If the number of IPv6 domains reachable over IPv6 continues to grow at its current pace, 25% of Internet domains will be reachable over IPv6 by December 2018. However, based on the rapid growth of clients using IPv6, that milestone could be reached considerably sooner.

Adoption alone, however, is not enough. Nothing is gained by widespread IPv6 adoption if the quality of services, and thus the user experience over IPv6, is not on a par with that of IPv4. To that end, there is a need for continued monitoring of the quality of services over the IPv6 Internet. Future work is needed to find correlations to performance differences in the HTTP download times of IPv4 and IPv6. Increased understanding of the factors influencing IPv6 adoption is also needed and should include investigations into the incentives and impediments within and between global regions. We call on the community to continue to extend our analysis into both the quantity and the quality of IPv6 deployment on the Internet.

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