The State of IPv6: Measuring Global Adoption

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On September 24th, 2015 the American Registry for Internet Numbers (ARIN) became the fourth Regional Internet Registry (RIR) to run out of IPv4 addresses. With four of the five RIRs no longer making general IPv4 address allocations, adoption and use of IPv6 is taking place at an accelerated pace.

The research presented in this paper is an extension of the previous work published by Czyz, Lekel-Johnson, Allman, Osterweil, Zhang in 2014. The goal of this study is to empirically understand the adoption of IPv6 as the Internet transitions to the next generation IP protocol. We measure IPv6 adoption through eight adoption metrics gleaned from eleven datasets. Data collection covers a two year period from January 2014 through December 2015.

In addition, we address the implications of the sudden uptick in IPv6 adoption, as it continues on a path of accelerated expansion. The long awaited transition from IPv4 to IPv6 has implications for all organizations who will soon be making the change; many of which may not be prepared for how to systematically approach such an undertaking. Factors such as project planning, IPv6 saturation, infrastructure assessment, policy redesign, and network continuity are discussed as key areas that will need to be addressed as organizations begin to adopt IPv6.

Key words: IPv6 adoption, Internet, IPv4 Exhaustion

Introduction

Another milestone in the exhaustion of IPv4 addresses was reached on September 24, 2015, when ARIN issued the final IPv4 addresses remaining in its free pool. Now, only AFRINIC, the RIR for Africa, has IPv4 resources remaining for allocation to Local Internet Registries (LIRs) and end users under the normal status-quo policy. These resource will, however, also soon be exhausted. Current projections are that AFRINIC's free pool will be depleted sometime in 2018. With the last remnants of the global IPv4 address pools rapidly drying up, the future growth of the Internet will take place over the next generation of IP, IPv6. Only IPv6 provides the scalability to provide Internet addresses for the billions of people and tens of billions of smart devices yet to be connected to the Internet.

IPv4 address exhaustion was not a surprise to anyone in the Internet community. The limitations of the IPv4 address space were identified as early as 1988 in discussion threads on the TCP/IP Mailing List[1] . In response to a post on November 27, 1988, Vint Cerf commented, "We should be worried about this [IPv4 exhaustion] and should be thinking about how to expand the available space"[2]. To forestall IPv4 exhaustion until a permanent solution could be adopted, several interim solutions were implemented by the Internet community. Some of these solutions, such as the establishment of Private IP addresses and deployment of network address translation (NAT), were specifically designed to slow down the rate of IPv4 address exhaustion, while others, such as Classless Inter-Domain Routing (CIDR) and the establishment of the RIRs, were designed to conserve and economically manage the remaining IPv4 address space. These stopgap measures were so successful over the past two decades that IPv6 adoption has been anemic at best. Evidence show that this is changing and that IPv6 adoption is now taking place at an accelerated pace.

In this paper we extend the research of Czyz et al. 2014[3] to provide an up-to-date assessment of the current state of IPv6 adoption. Our goal is to further contribute to the Internet community's understanding of the progress of the Internet's largest transition. To achieve this goal we measure eight metrics from eleven datasets collected from January 2014 through December of 2015 and present our findings.

Related works

The transition of the Internet to IPv6 is a topic of extensive study. There are many works found in the extant literature that provide valuable empirical and analytical data on the process of IPv6 transition. Some studies focus on the technology adoption factors that influence or distract from IPv6 adoption. Some apply Rogers' Diffusion of Innovation theories to IPv6 adoption[4,5], while others draw on technology adoption and assimilation theories[6]. One paper modeled IPv6 adoption to game-theoretical tools[7]. A few previous works examined the readiness of organizations to adopt IPv6[8,9]. While many others explore the adoption of IPv6 from the perspective of the Internet, focusing on quantitative analysis of metrics measuring levels of deployment, traffic, and performance[3,10-13].

Our study extends that of Czyz et al. who employed a broad approach to measuring IPv6 deployment, assembling a breadth of observations and comparing datasets against each other. Their findings provided a better understanding of the systemic state of IPv6 deployment through the use of multiple measured metrics and datasets, each focused on one or more aspects of IPv6 adoption[3].

Methodology

Since our goal was to extend the research of Czyz et al. we focus on using the same or similar metrics and methods as closely as possible. Specific details on each metric is discussed in the sections that follow for each metric. Table 1 summarizes the datasets that we analyzed and the associated metrics each measured.

Table 1. Summary of datasets related metrics and time period of measurement.

Dataset	**Metrics**	**Time Period**
RIR Prefix Allocations	A1 - Address Allocation	Jan 2014 – Dec 2015
Route Views AS6447	A2 - Network Advertisements	Jan 2014 – Dec 2015
Hurricane Electric	N1 – Authoritative Nameservers	Dec 2015 Snapshot
Route Views AS6447	T1 - Topology	Jan 2014 – Dec 2015
Alexa Top Hosts	R1 – Server Side Readiness	Dec 2015 Snapshot
Goggle IPv6 Stats	R2 – Client Side Readiness	Jan 2014 – Dec 2015
Amsterdam Internet Exchange (AMS-IX)	U1 – Traffic Volume	Jan 2015 – Dec 2015
Alexa Top 500 Hosts	P1 – Performance	Dec 2015

Address allocations (A1)

As IPv6 demand increases, the RIRs will need to allocate more prefixes to meet that demand. For these prefixes to actually be used they must also be advertised in the global Boarder Gateway Protocol (BGP) tables.

The first metric measured (A1) is the number of IPv6 prefixes allocated by the RIRs to national, local, registries and Internet Service Providers (ISPs). Each of the RIRs publishes this information in a daily list of the address block allocations it has made. These lists are publicly available for download from each registry.

We downloaded the address block allocation datasets from each RIR and analyzed the data from January 2014 through December of 2015, aggregating the prefixes from each RIR into one single metric. In Figure 1 we see that in January 2014 there were 18,181 IPv6 prefix allocations and that by December 2015 there are 26,481, an increase of 8,300 (46%). During the same two year period the number of IPv4 prefix allocations grew by 22,961 (17%) from 135,316 to 158,277. The solid line represents the ratio of total IPv6 to IPv4 prefix allocations which grew from .13 in January 2014 to .16 in December 2015. Figure 2 shows in percentage terms the growth of prefix allocations.

While the numeric increase in allocated IPv4 prefixes was 2.75 times that of IPv6 prefixes, it is cautioned to note that a typical IPv6 prefix allocation at 2^{96} is much larger than a typical IPv4 allocation at 2^{10}. A typical IPv6 allocation from a RIR to an ISP might be a /32 which would contain 7.9×10^{28} or (79 billion-billion-billion) addresses while a typical IPv4 allocation of a /22, which is now the largest allocation per many RIR IPv4 exhaustion policies, yields only 1024 addresses.

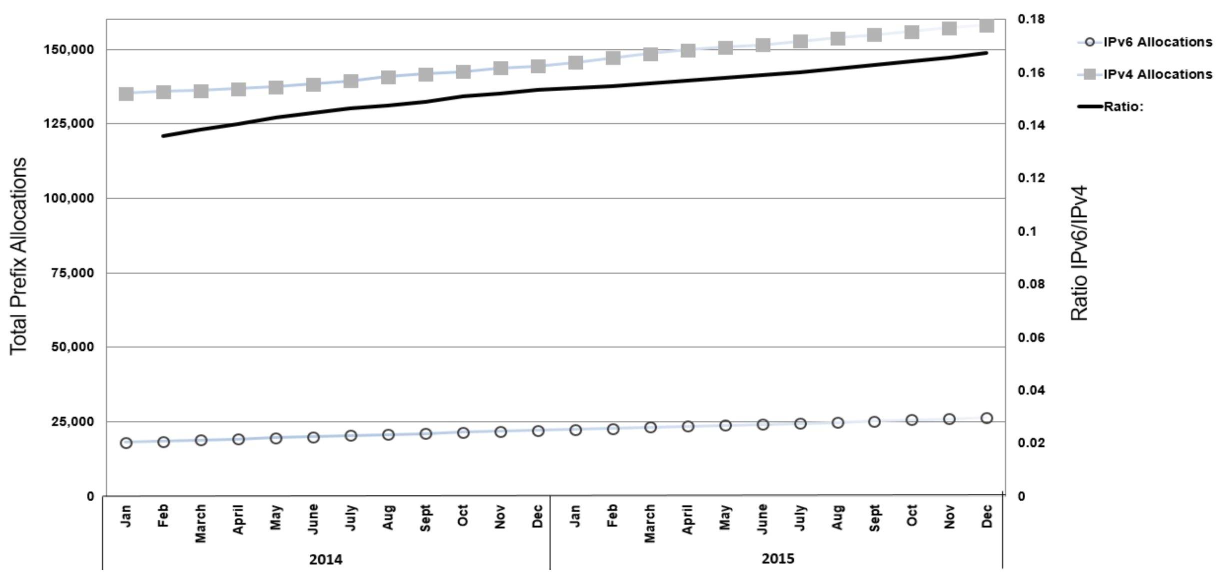

Figure 1. Total prefix allocations aggregated from all RIRs from January 2014 to December 2015. Also the ratio of IPv6 to IPv4 prefixes is shown. Although both are increasing, the ratio of IPv6 to IPv4 prefixes grew from .13 to .16.

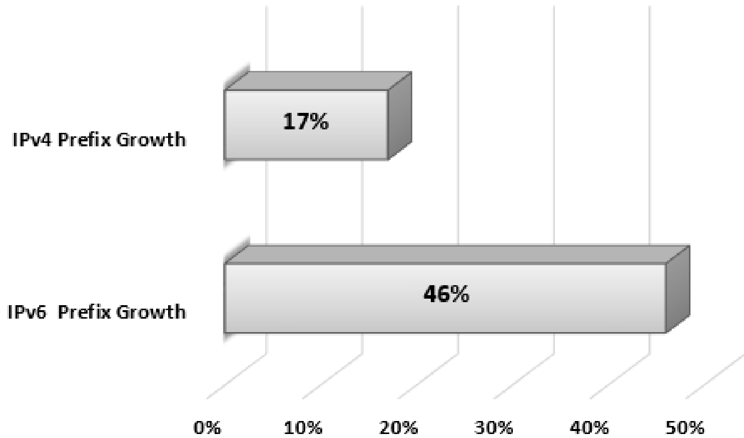

Figure 2. Percent increase of prefix allocations from January 2014 to December 2015.

Next we analyzed the aggregate number of prefixes allocated each month across all RIRs from January 2014 to December 2015. IPv6 allocations over the two year period varied from approximately 300 to 400 per month. Monthly IPv4 allocation fluctuated more but trended higher, starting at around 350 in January 2014 and climbing to around 1000 by December 2015 as shown in Figure 3. There are three distinct run-ups in the IPv4 allocations, May-July 2014, January-March 2015, and September-November 2015. Each of these spikes coincides with allocations of returned IPv4 addresses by the Internet Addressing and Numbers Authority (IANA) to each or the RIRs. Also shown is the ratio of monthly IPv6 versus IPv4 allocations. A ratio of 1 would indicate an equal number of allocations. In January 2014 the monthly IPv6/IPv4 allocation ratio came in at .80 coinciding with a dip in IPv4 allocations and then leveled out and ending December 2015 at approximately .42.

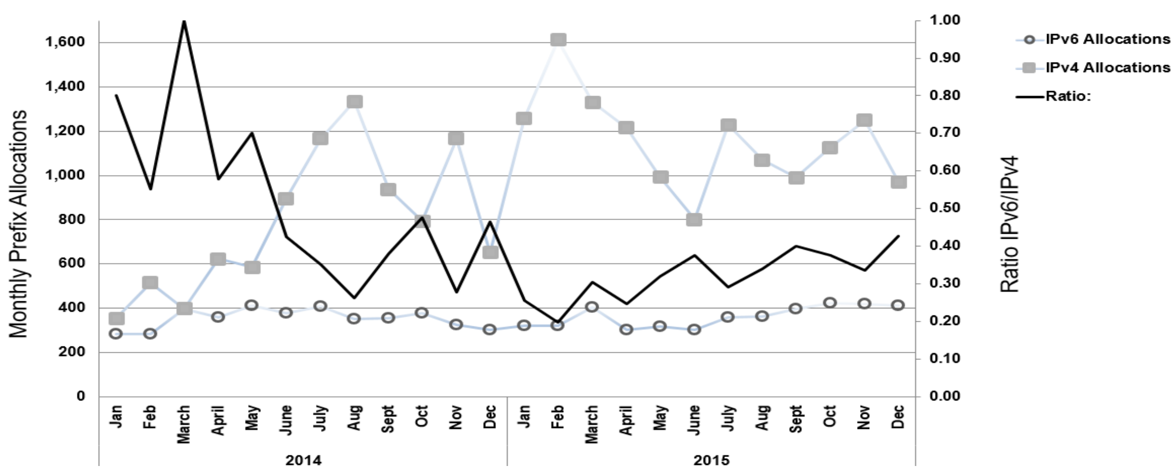

Figure 3. Number of prefix allocations by month aggregated from all RIRs. The spikes in IPv4 allocations coincide with dates at which reclaimed IPv4 address blocks were returned to the RIRs by IANA.

Network advertisements (A2)

For prefixes to be used on the Internet they must be advertised in the global routing table. Our next metric (A2) therefore is the number of IPv6 prefixes found in the global BGP routing table. For this metric we used data from the University of Oregon Route Views Project as reported on Geoff Huston's CIDR Reports web site[14,15]. The Route Views Routers use AS 6447 for multi-hop BGP sessions to peer with backbones and other autonomous systems (ASes) at various Internet locations. We looked at the active BGP entries for each month starting with January 2014 through December 2015. Figure 4 shows the number of announced IPv6 prefixes was 16,537 in January 2014 and by December 2015 the number of IPv6 prefixes had increased to 27,236, an increase of 10,699 (65%). Over the same two year period the number of IPv4 prefixes rose from 491,660 to 580,660, an 18% increase. The solid line in the figure is the ratio of IPv6 to IPv4 advertised prefixes which increase from .033 in January 2014 to .046 in January 2015.

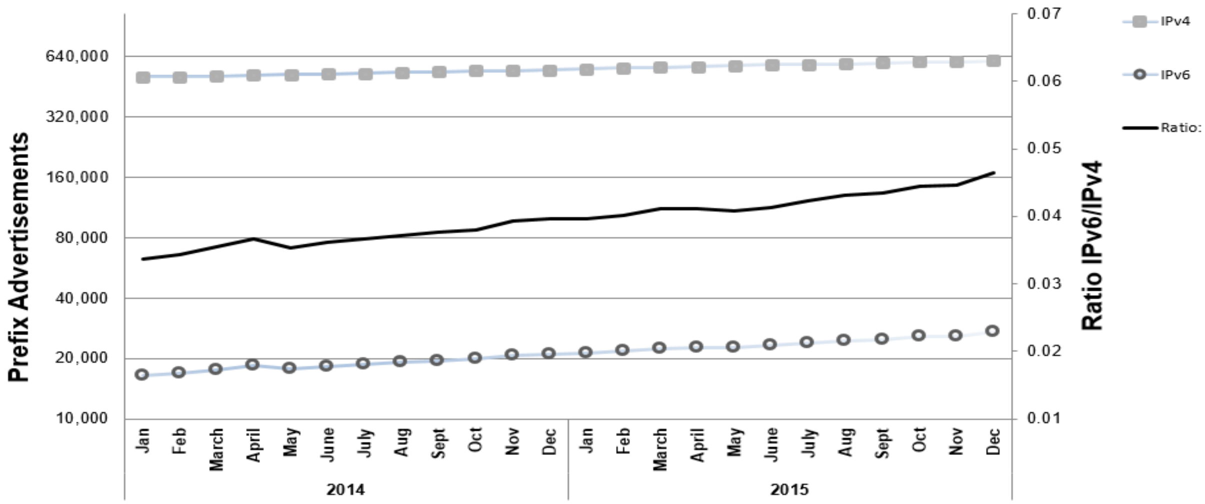

Figure 4. Prefixes seen in the Global BGP table of Route Views AS 6447. The ratio line indicates that the number of IPv6 prefixes being advertised on the Internet is growing faster than IPv4 prefixes.

DNS authoritative nameservers (N1)

The next metric measured (N1) is support of IPv6 in the Domain Name System (DNS). Support is defined as the number of Top Level Domain (TLD) servers that are configured with IPv6 addresses and are reachable over IPv6. This is considered evidence of IPv6 adoptions, especially by content providers[3].

The authoritative name servers that serve the DNS root zone, commonly known as the "root servers", have been IPv6 enabled since 2008. Of the 13 name root servers, all but two, e.root-servers.net and g.root-servers.net, are reachable over IPv6. The Root Zone Database contains all of the Top Level Domains (TLDs) which includes domain suffixes such as .com .net .org .us .fr etc. We measure here the number of TDL nameservers that are IPv6-enabled and reachable over IPv6. This information is made publicly available by Hurricane Electric (HE)[16]. HE downloads the root zone file daily to get a list of all TLDs and their associated nameservers. A query is then made for AAAA records for the names of those nameservers. Finally a check is made for AAAA records (glue records) in the root zone for those nameservers. In January 2014 there were approximately 381TLDs, 91% of which had native IPv6 connectivity. At the end of December, 2015 there were 1199 TLD nameservers of which 97.6% had native IPv6 connectivity and could be reached over IPv6.

Topology (T1)

Routing on the Internet consists of two components: address prefixes and autonomous system numbers (ASNs). In metric A2, network advertisements, we measured the number of IPv6 prefixes in the global BGP tables as seen by AS6447. Now in metric T1, we look at the maturity of IPv6 adoption on the Internet in terms of AS connectivity and AS paths. To understand better the Internet IPv6 topology we examine the number of autonomous systems globally that support IPv6 and the number of unique AS-paths. As noted by [3] autonomous system adoption is indicative of support for IPv6, while the number of autonomous system paths is an indicator of maturing connectivity between autonomous systems.

To capture this metric we again use data obtained from AS6447[15]. Figure 5 shows 7,905 unique ASes seen in January of 2014 compared to 10,862 seen at the end of December 2015, an increase of 37.4%. Although not included in the figure, the numbers for IPv4 over the same period were 46,164 in January 2014 to 53,000 in December 2015, an increase of 14.8%.

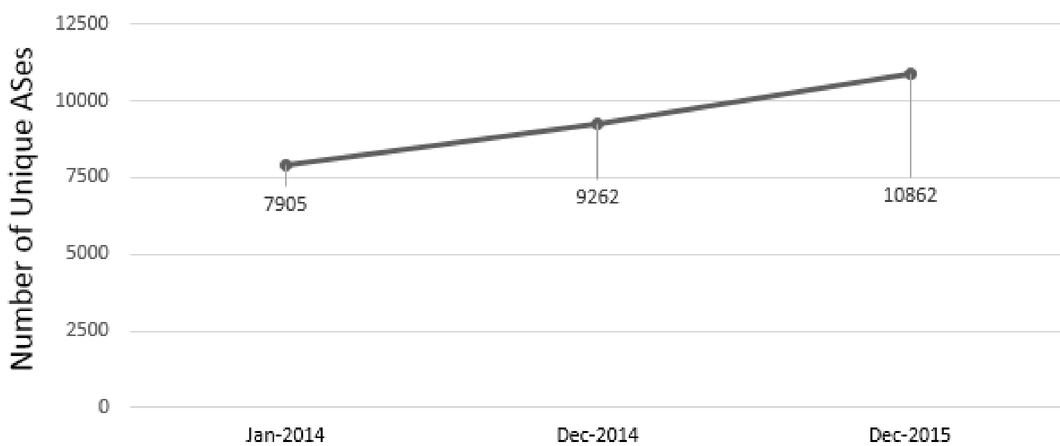

Figure 5. Number of unique IPv6 ASes seen in the global BGP table from December 2013 to December 2015.

Figure 6 shows that the number of unique IPv6 AS paths advertised within the BGP table in January 2014 was 122,160 compare to 305,100 at the end of December 2015, an increase of 150%. The number of unique IPv4 AS paths advertised within the BGP table in January 2014 was 1,814,200 compare to 3,149,400 at the end of December 2015, an increase of 73.5%. The ratio line shows that the number of unique IPv6 AS paths is increasing compared to IPv4.

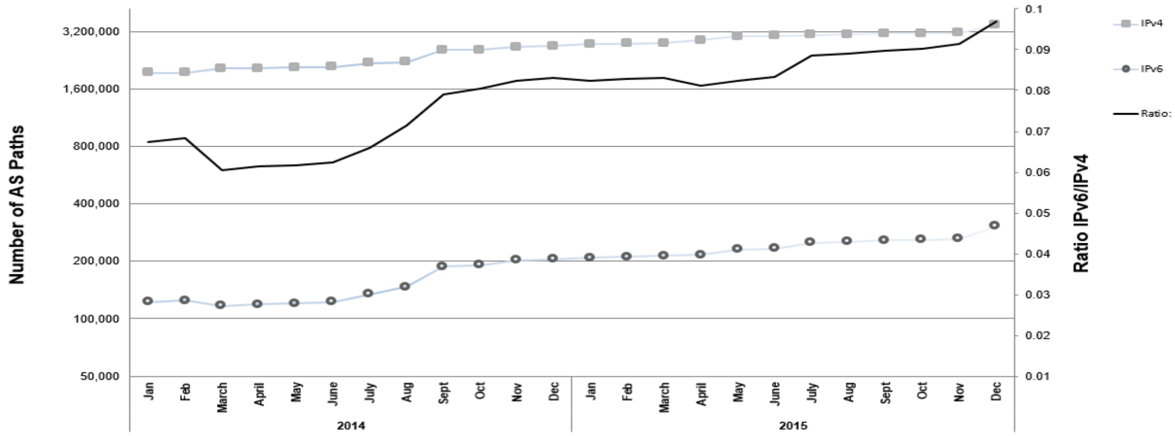

Figure 6. Number of unique AS paths. The number of IPv6 unique AS paths is increasing at a faster pace than IPv4 as shown by the solid ratio line. IPv6 unique AS paths has grown by 150%.

Server-side readiness (R1)

End-to-end reachability will be evaluated with two metrics, the readiness of service-level devices (R1) and the readiness of client-level devices (R2).

One way to assess the prevalence of IPv6-enabled services is to measure the number of the most popular web sites that are reachable over IPv6. For this metric we pulled the 10,000 most popular web sites from Alexa's top web sites listing[17]. Next, we use the free DNS DataView[18] tool to check each web site for the presence of an AAAA record in DNS. Of the top 10,000 web sites we found 830 (8.3%) of URLs came back with AAAA records. An 88% increase over the results recorded in December of 2013 by Czyz et al. as shown in Figure 7.

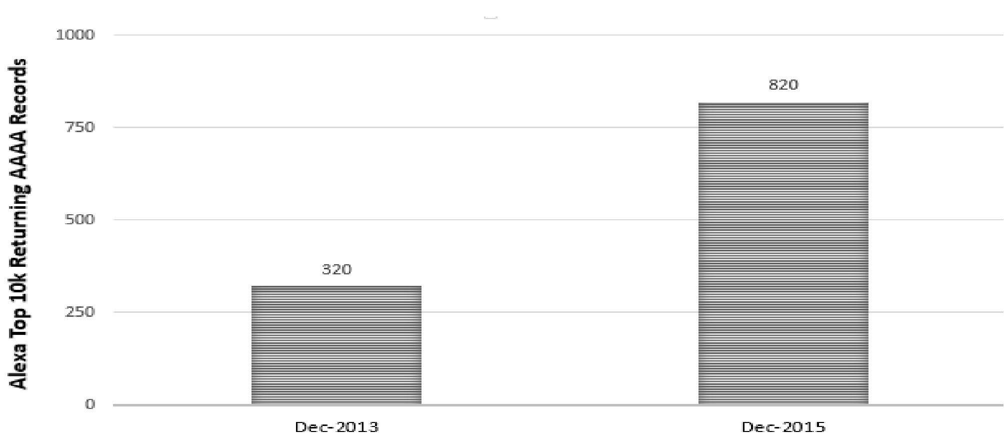

Figure 7. Number of Alexa top 10,000 Web Sites returning AAAA records shows an 88% increase from December 2013.

Client-side readiness (R2)

Of course to reach IPv6 enabled Web sites clients must need to be IPv6-enabled as well. Today all major operating systems support IPv6, but how many clients are actually using IPv6? For this metric (R2) we turn to Google's IPv6 statistics page[19]. Google measures client IPv6 use 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 8 shows that over the two year period from January 2014 to December 2015 the number of users accessing Google.com over IPv6 increased from around 2.5% to just over 9%.

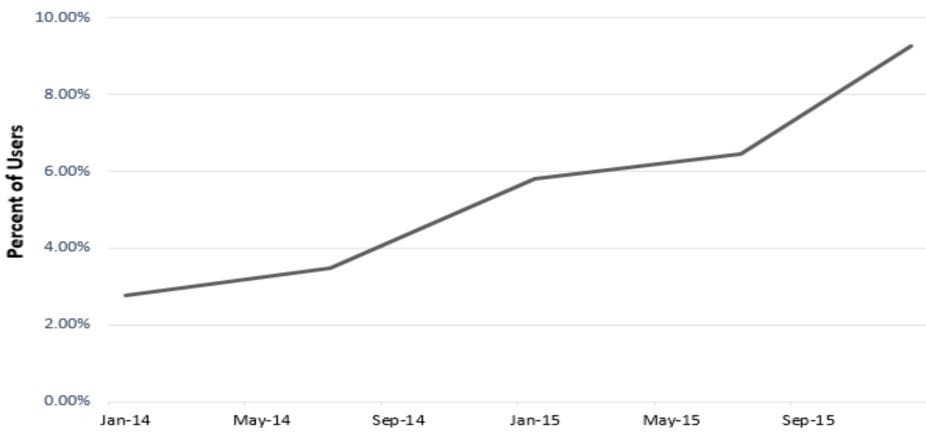

Figure 8. Percent of users accessing Google.com over IPv6

IPv6 traffic volume (U1)

The traffic volume metric (U1) is a measure of how much Internet traffic is over IPv6. To get a snapshot of Internet IPv6 traffic volume we used publicly available statistics from the Amsterdam Internet Exchange (AMS-IX) [20]. The AMS-IX is one of the largest Internet exchange points (IXP) in the world and connects more than 776 autonomous systems worldwide. AMS-IX tracks the percentage of native IPv6 traffic using s-flow statistics.

The average aggregated Internet traffic on all AMX-IX connected network ports from January 2015 to December 2015 was 2.250Tb/s. The average IPv6 traffic was 30Gb/s, or about 1.3% of the total Internet traffic seen on AMX-IX networks. While 1.3% of traffic may not seem like much, it is a large increase over the 0.6% as seen by Czyz et al in December 2013[3]. In addition, the trend of increasing IPv6 traffic is strong, from an average of approximately 15Gb/s in January of 2015 to an average of approximately 35Gb/s by the end of December 2015, a 133% increase.

Performance (P1)

To measure network performance we used globally distributed network monitors to capture the http load times of Web sites over IPv6 and IPv4. Five v6Sonar monitors provided by Nephos6, Inc.[21] were used to pull HTTP content from the Alexa top 500 Web sites that were IPv6 enabled, which was eighty eight sites. The v6Sonar monitors used were located in Tokyo, Sydney, Paris, Dallas, and on the PC at the author's home residence. Each agent pulls the Web content from each URL giving the IPv4 load time and the IPv6 load time in milliseconds. Load time is the cumulative time for the agents, to perform a TCP 3-way handshake, DNS lookup, and download http content from the target Web server. The load times for IPv4 and IPv6 can then be compared. An example of the output from a test is shown in Figure 9. We found that IPv4 http load time averages were faster in 70% of our readings. More data will need to be collected to validate this findings. It should be noted that this is test is not a reflection of the protocols themselves but rather a byproduct of implementations and possibly routing policies along the packet paths.

HTTP Result

Agent Name	Real Load (IPv4)	Real Load (IPv6)
N6System Tokyo	252 ms	392 ms
N6System Sydney	563 ms	555 ms
N6System Paris	267 ms	518 ms
N6System Dallas	827 ms	808 ms
agent 34627a6270697338BE59E1F8CEF53C3A	890 ms	966 ms

Figure 9. Example output from v6Sonar showing the results of a performance test to www.google.com from six globally distributed monitoring agents. The test performed was HTTP Get of Web content.

Discussion of findings

Czyz et al's 2014 study provided a model for assessing IPv6 adoption through the first at large empirical study of the state of IPv6 adoption by analyzing ten different datasets and producing results on twelve adoption metrics. Their study provided qualitative and quantitative evidence that IPv6 "is being used natively for production and at a rapidly-increasing rate" [3]. In this study we extended the work of Czyz et al. using the same or similar datasets to re-evaluate each adoption metric two years after their original work. Our data from eleven datasets shows a continuation of the trend observed by Czyz et al., that IPv6 adoption is continuing to increase at a rapid rate across all metrics. Table 1 shows the status each metric at the beginning of our study in January of 2014 and at the end in December of 2015.

Table 2. Measure of operational characteristics of each metric beginning January 2014 and ending December 2015. Each metric showing an increase it its measure of IPv6 adoption.

Metric/Measured Aspect	**IPv6 Status**		
	Jan 14	**Dec 15**	**Change**
A1: IPv6 Prefix Allocation	18,180	26,481	+ 46%
A1: IPv6 to IPv4 Prefix Allocation Ratio	.13	.17	+31%
A2: Announced IPv6 Prefixes	16,537	27,236	+65%
A2: IPv6 to IPv4 Announce Prefix Ratio	.033	.046	+39%
N1: Authoritative Nameservers	91%	97.6%	+7%
T1: Topology	7,905	10,862	+37.4%
T1: Unique IPv6 AS Paths	122,160	305,100	+150%
R1: Server Side Readiness	320	830	+88%

R2: Client Side Readiness	2.5%	9%	+260%
U1: IPv6 Traffic Volume	15Gb/s	35Gb/s	+133%

Our findings are consistent with, although on the low side, the projected polynomial trends calculated by Czyz eta al[3]. for metrics A1, prefix allocation and U1, IPv6 traffic volume. Per their calculations, at the end of 2015. Because IPv6 prefix allocations are so large, the rate of increase in the number of allocations may hold steady, however, we would expect the IPv6 traffic volume to increase at a more rapid rate as more enterprises adopt IPv6 and more mobile users are put on IPv6 networks.

Table 3. Comparison of current findings for metrics A1 and U1 as compared to the projection of Czyz et al[3].

Metric	**Jan 2013**	**Jan 2016 Projection by Czyz et al.[3]**	**Our finding Dec 2015**
A1: IPv6 Prefix Allocation	.10	.2 - .4	.17
U1: IPv6 Traffic Volume	.005	.01 - . 03	.013

Recommendations and conclusions

Despite standardization twenty years ago in 1995, the adoption of IPv6 has progressed slowly. Our findings of increased IPv6 adoption however, shows a significant jump in IPv6 usage, particularly in the last few years since the IANA's exhaustion of IPv4 address space. The data shows that the Internet is not only ready for IPv6, but is now seeing significant traffic over that protocol. For enterprise organizations still waiting to adoption IPv6, a tipping point will soon be reached where the costs of extending IPv4, will far outweigh the costs of IPv6 adoption. Once that threshold is reached, the question will not be whether organizations will lose by delaying IPv6 adoption; it will be how much will be lost. These losses may not be direct losses; they may occur as lost opportunities or the inability to connect with emerging markets. Whether direct or opportunity costs, they still have the same effect on an organizational bottom line. It is not too late to stay on top of the global transition to IPv6. However, the longer organizations delay the adoption of IPv6, the greater the chances for implementation errors. However, following the principals outlined here, IPv6 can be gradually deployed into the production environment, by adequately prepared staff, with minimal impact of the overall IT budget.

We offer here some recommendations to organizations to organization decision makers planning for IPv6 adoption.

- Planning for IPv6 should commence as soon as possible. This is a systematic process that can take anywhere from three to five years, or even longer and will involve more than your typical hardware and software upgrades. It will required extensive auditing, testing, and the reconfiguration of every device and application on the network; some of which may not have been touched in numerous years.

- You must ensure the availability of IPv6 skills of every IT employee within the organization. Focus areas should include IPv6 equipment, IPv6 security, IPv6 deployment, vendor-specific configuration, IPv6-based software development, and user training. A properly trained IT staff is a prerequisite to the other critical aspects of adoption.

- An assessment of the existing environment for IPv6 readiness must be made to determine the organization's readiness to deploy IPv6. Everything on the network; not just PCs and servers, must assessed. All existing equipment, hardware, and software must also be audited. Additionally, any non IPv6-compliant hardware or must be upgraded, which may require additional licensing fees, for IPv6 support or replaced. IPv6 support on the Network Management Systems (NMS) and the organization’s application portfolio must also be part of the assessment as well as applications that use hard-coded IPv4 addresses or IP address stored in 32-bit numeric fields, these will need to be re-coded or replaced.

- Policy frameworks will require updating to accommodate IPv6. Purchasing, development, and security policies will need to be updated to include the changes that occur with IPv6 adoption. Purchasing policies should require that IPv6 compatible products be updated through a regular refresh cycle. Policies can also be used to encourage migration to IPv6 by mandating the use of IPv6 enabled, or at least dual-stack applications. Security policies should specifically address IPv6 attributes to prevent the formation of dynamic tunnels and other security vulnerabilities.

- Finally, disruption of the existing communications should not be disrupted because of IPv6 adoption. Because the network must continue to provide constant availability, all deployment tasks must be accomplished in a way that does not impact the quality, performance or security of the existing network.

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