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Quality of IPv6 Enablement of Universities: An International Study

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Abstract

This paper presents the findings of the first known large scale, quantitative study of the quality of IPv6 enablement of university websites. A mathematical algorithm that leverages multiple sources of data gathered from V6Sonar© "agents" distributed globally across multiple locations, was used to calculate the IPv6 effectiveness of 1000 university websites.

In this study, three web-based IPv6 accessibility tools were used to investigate the IPv6 accessibility (DNS records) of the websites of 1000 universities from 59 countries. Once accessibility was verified, a web-based user experience monitoring platform was used to collect extensive data measuring the IPv6 effectiveness of the IPv6 accessible web sites. The monitoring platform utilized agents deployed in various geographic locations in North America, Europe, and Asia to poll each university website.

The data collected in this study reveals the external facing Web service accessibility for each university and the IPv6 effectiveness of these services, if accessible. An analysis of the enablement and effectiveness of the university websites were made in respect to the website's assigned Regional Internet Registry (RIR) geographic region. The implications of the findings are that citizens worldwide, who use IPv6 to access the resources offered by universities, may experience performance degradation, variability in performance, and at times, no IPv6 connectivity at all. In addition, accessibility of a university website over IPv6 may be seen as a metric of the institution's overall technological readiness.

Introduction

The two challenges addressed by this study pertain to the fact that the level of IPv6 readiness of international universities is largely unknown. Secondly, the quality or "effectiveness" of universities that have IPv6 web services enabled is also unknown. This study addresses these two challenges by providing the first known published assessment of the IPv6 enablement of universities within a global scope.

Though the need to become ready for IPv6 implementation may not be on the forefront of a university's list of priorities, the effects of not becoming IPv6 ready can have negative implementations much sooner than administrators may anticipate. A university's adoption of IPv6 can affect the institution's teaching, research, innovation, and budget.[1] Partnering institutions and research facilities that are already IPv6 ready, especially those in countries that have already migrated to IPv6, will look to collaborate with other institutions of the same protocol readiness. Hence, being IPv6 ready will be a ruler of an institution's technological advancement. Further, agencies associated with grants are beginning to require IPv6, thus a lack of IPv6 could decrease the amount of monies for research and development.[2] For example, one of the review requirements for the National Science Foundation (NSF) Campus Cyberinfrastructure-Infrastructure, Innovation, and Engineering Program proposals are that the proposals address IPv6 deployment.[3] Therefore, IPv6 readiness can be vital to the growth of a university.

IPv4 exhaustion

The last remaining public IPv4 addresses were allocated by the Internet Assigned Numbers Authority (IANA) to the Regional Internet Registries (RIRs) on February 3rd, 2011. Four of the five RIRs have depleted their IPv4 address pools and are currently operating under final IPv4 address depletion policies. At the time of writing, only the African Network Information Center (AFRINIC) has IPv4 address space remaining for general allocation and assignment. IPv4 is now a legacy protocol and all future Internet growth will occur over IPv6.

If an organization, such as a university, desires to maintain competitiveness, interoperability, and growth, that institution must become proactive in adopting IPv6. However, anecdotal evidence and recent published studies[4,5,6,7] show that the rate of adoption remains low and suggest a low sense of urgency and lack of understanding among organizational decision makers regarding the potential consequences that IPv4 exhaustion will have on their organization's business model. A failure to proceed with IPv6 adoption can lead to a loss of customers, partners, students, and other opportunities. Furthermore, the risks and costs of maintaining an end-of-life protocol will increase over time in the absence of an IPv6 adoption plan.

Drivers of IPv6 adoption

In 2012, Forbes magazine explored six reasons for businesses to deploy IPv6 through their network.[8] Though the article is aimed at enterprises it is relevant to IPv6 adoption for institutions of higher education.

- Increased Costs: As IPv4 addresses become a scarce resource, the cost of operating and maintaining legacy networks will only increase over time.
- Website Accessibility: A university's website is an invaluable and always-available portal through which prospective students explore, apply, and gain a sense and connection to the institution. University websites may run the risk of failing to meet accessibility expectations, or not be accessible at all, if not enabled for IPv6.
- Growth of the "Global" University: The global IPv4 address pools are already exhausted, meaning that new users in many regions will increasingly have connectivity over IPv6. Universities do not exist in a vacuum, activities such as research and lecturing go beyond the traditional campus boundaries as universities collaborate and compete on a global level.
- User Experience: As IPv6 becomes more widely deployed, users may experience diminished quality when connecting to websites over IPv4. Additionally, universities failing to effectively deploy IPv6 may increasingly be viewed as technological laggards by prospective students.
- IPv6 is here: IPv6 is supported and enabled by default on all major operating systems. The multitude of student laptops, smartphones, and tablets that are running IPv6 by default will be generating traffic that may be invisible to security appliances in the campus network IT centers.
- Competiveness: IPv6 adoption can give universities a competitive advantage in obtaining research partnerships. As research institutions, universities are engaged in partnerships with other universities around the world, such as China, where IPv6 is already prevalent. To stay completive universities must continue modernizing, which means support for a

growing number of IPv6 services. [9, 10]

Some driving factors are fairly unique to universities. For example, as government centers and institutions migrate to IPv6, researchers accessing resources using IPv4 may be increasingly hindered. Further, a delay in IPv6 transition can have detrimental effects on funding from government granting agencies. The National Science Foundation and the National Institute of Health (NIH) are already encouraging IPv6 adoption by building IPv6 requirements into their calls for proposals by using IPv6 capabilities as part of the award evaluation process.[11]

Collaborative research will become challenging as researchers from IPv6 enabled universities attempt to collaborate with colleagues at IPv4-only campuses. Furthermore, when faculty from IPv4-only campuses travel to regions where IPv4 address pools are exhausted they may not be able to connect back to the home campus to access intranet resources. Visiting faculty from campuses in regions where IPv4 addresses are exhausted, could be issued laptops with IPv4 support deactivated by group policy. Those faculty may experience connectivity problems when they arrive at an IPv4-only campus using an IPv6-only configured laptop.[11]

Global IPv6 adoption

Global IPv6 adoption is on the rise. Alain Fiocco, Senior Director and Head of the IPv6 High Impact Program at Cisco Systems, states that "Having clear metrics to measure on-going IPv6 adoption is the best way to foster deployment, monitor success and spot trouble areas, and in the end, make better business decisions."[12] Getting the clear metrics on each phase of IPv6 adoption is what Fiocco and his team at the IPv6 High Impact Program have accomplished with 6Lab, a website that contains daily consolidated and updated statistics on IPv6 adoption. Publicly available data and data compiled by special tools built by 6Lab are used to analyze data relating to IPv6 adoption. The 6Lab program segments world IPv6 adoption into four phases: planning, core network, content, and users. By all four phases, global IPv6 adoption is rapidly increasing.

Planning - Measured by looking at the number of IPv6 prefix allocations from the RIRs and how many of these allocated prefixes show up in Internet routing tables. By measuring the number of allocated IPv6 prefixes, it is possible to get an indicator of future IPv6 deployments. All three prefixes (Allocated IPv6 Prefixes – dashed line, Routable IPv6 Prefixes-dotted line, and Alive Allocated IPv6 Prefixes-solid line) exhibit an increasing trend (Figure 1).

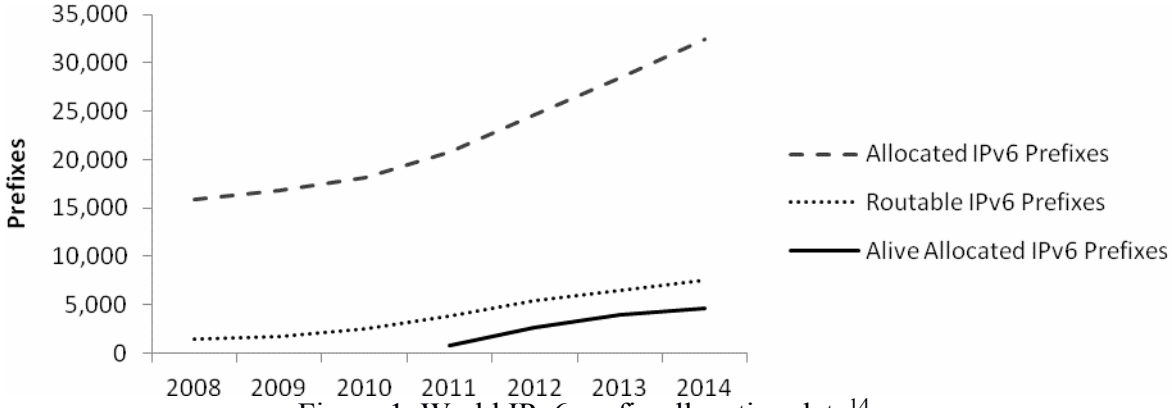

Figure 1. World IPv6 prefix allocation data[14].

Core Network - Measured by looking at the percent of IPv6 transit Autonomous Systems (AS). This is accomplished by digging the BGP Routing Table and computing a weight and rank for each AS based on the number of times it show up in the AS path for all IPv4 and IPv6 prefixes.[13] Currently, all Tier1 providers have enabled IPv6 transit service.[12]

Content - Measured by looking at the number of websites reachable over IPv6. 6Lab looks into the DNS system to find how many domain names have a bounded AAAA record and checks that the site is actually reachable over IPv6 by opening an HTTP session to the home page over IPv6. According to the World Content Data presented on the 6lab website, there are at the time of writing about 5,700 websites reachable over IPv6, or about 12.4%, versus 45,780 which are not.[14]

Users - Both Google[15] and APNIC[2] measure and publish IPv6 end-user adoption on the web which are presented on the 6Lab site. Google's IPv6 statistics sight measures and displays in graphical form the availability of IPv6 connectivity among Google users. More specifically, it represents the percentage of users that access Google over IPv6. Native IPv6 traffic is represented by the dashed line, tunneled IPv6 traffic is represented by the solid line, and total IPv6 traffic is represented by the dotted line (Figure 2).

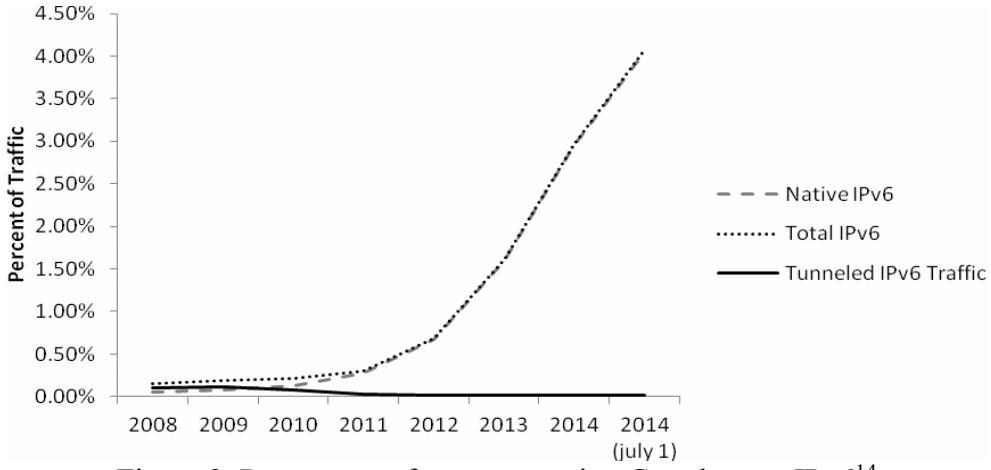

Figure 2. Percentage of users accessing Google over IPv6[14]

IPv6 deployment statistics are also maintained by the National Institute of Standards and Technology (NIST). NIST monitors the Domain Name System (DNS), Mail, and Web external core network services of private industry enterprises, federal government agencies, and universities in the United States for IPv6 deployment progress.[16]

Methodology

The sample population of university websites investigated in this study were taken from the Center for the World University Ranking (CWUR) top 1000 universities of the world. The CWUR publishes the only global university ranking based on the quality of student education and training and the quality of research. Eight objective indicators are used by the CWUR to compile the top 1000 list: quality of education, alumni employment, quality of faculty,

publications, influence, citations, broad impact, and patents.[17]

The information from the CWUR website was entered into a datasheet (Figure 3). The datasheet listed the name of the university, the country of origin, and the URL linked to the university and its rank in the CWUR's top 1000 universities. The validity of each URL was tested by inputting the university's URL into a search engine's address bar to verify that the URL did connect to the corresponding university. Once this step was completed, the URLs were input into three different web-based tools to determine if the URL had an associated DNS AAAA record (AAAA records are a domain name to IPv6 address mapping): (1) The Website IPv6 accessibility validator on the IPv6 test website[18], (2) the Hurricane Electric© BGP Toolkit, [19] and (3) the DNS Lookup tool available as part of V6Sonar©, a proprietary user experience monitoring platform developed by Nephos6©.[20] The following returned information was recorded in the datasheet for each university URL.

- Canonical Name (CNAME) (if present)
- A record
- AAAA record

In cases where universities were using a CNAME record, these records were traced back to the actual web server containing the A and/or AAAA record. If multiple A and/or AAAA records were available, all records were listed in the datasheet. Figure 3 is a screenshot of the created datasheet

	A	B	C	F	G
1	University	Country	URL	IPv4	IPv6
35	University of Vienna	Austria	www.univie.ac.at	131.130.70.8	2001:62a:4:1:0:0:80:108
36	Medical University of Vienna	Austria	www.meduniwien.ac.at	149.148.224.122	N
37	University of Innsbruck	Austria	www.uibk.ac.at	138.232.1.217	N
38	Vienna University of Technology	Austria	www.tuwien.ac.at	128.130.35.76	N
39	Innsbruck Medical University	Austria	www.i-med.ac.at	193.171.76.177	N
40	University of Graz	Austria	www.uni-graz.at	143.50.174.42	N
41	Medical University of Graz	Austria	www.meduni-graz.at	193.170.105.154	N
42	Johannes Kepler University of Linz	Austria	www.jku.at	140.78.3.160	N
43	University of Natural Resources and Life Sciences, Vienna	Austria	www.boku.ac.at	141.144.187.10	N
44	Graz University of Technology	Austria	www.tugraz.at	129.27.80.155	N
45	Hasselt University	Belgium	www.uhasselt.be	193.190.2.76	2001:6a8:2100:500:0:0:0:21
46	University of Liege	Belgium	www.ulg.ac.be	139.165.51.73	2001:6a8:2d80:100:0:0:0:11
47	Katholieke Universiteit leuven	Belgium	www.kuleuven.be	134.58.64.12	2a02:2c40:0:80:0:0:80:12
48	Ghent University	Belgium	www.ugent.be	157.193.43.50	N
49	Universite libre de Bruxelles	Belgium	www.ulb.ac.be	164.15.59.215	N
50	Universite catholique de Louvain	Belgium	www.uclouvain.be	130.104.5.100	N
51	Vrije Universiteit Brussel	Belgium	www.vub.ac.be	134.184.129.2	N
52	University of Antwerp	Belgium	www.uantwerpen.be	143.169.244.150	N
53	Universite de Namur	Belgium	www.unamur.be	138.48.4.201	N
54	University of Mons	Belgium	www.umons.ac.be	193.190.208.124	N
55	Federal University of Sao Carlos	Brazil	www.ufscar.br	200.9.84.70	2001:12f0:503:300:0:0:0:70
56	Federal Univesity of Rio Grande do Sul	Brazil	www.ufrgs.br	143.54.2.20	2801:80:40:1:0:0:0:20
57	Federal Univesity of Parana	Brazil	www.ufpr.br	200.17.203.23	2801:82:8020:0:8377:0:101:12

Figure 3. Selection of datasheet

Once all university websites were queried, each URL that returned AAAA records was then evaluated for IPv6 effectiveness using V6Sonar©. V6Sonar© assesses IPv6 effectiveness in terms of user experience accessing a website over IPv6 as compared to that of IPv4. To measure IPv6 effectiveness, seven V6Sonar© agents, located in various geographic locations (Figure 4), polled each URL for a period of 4 days at 30 minute intervals. The locations of the agents were:

Atlanta, Seattle, New York, Hong Kong, Netherlands, Singapore, and Slovenia.

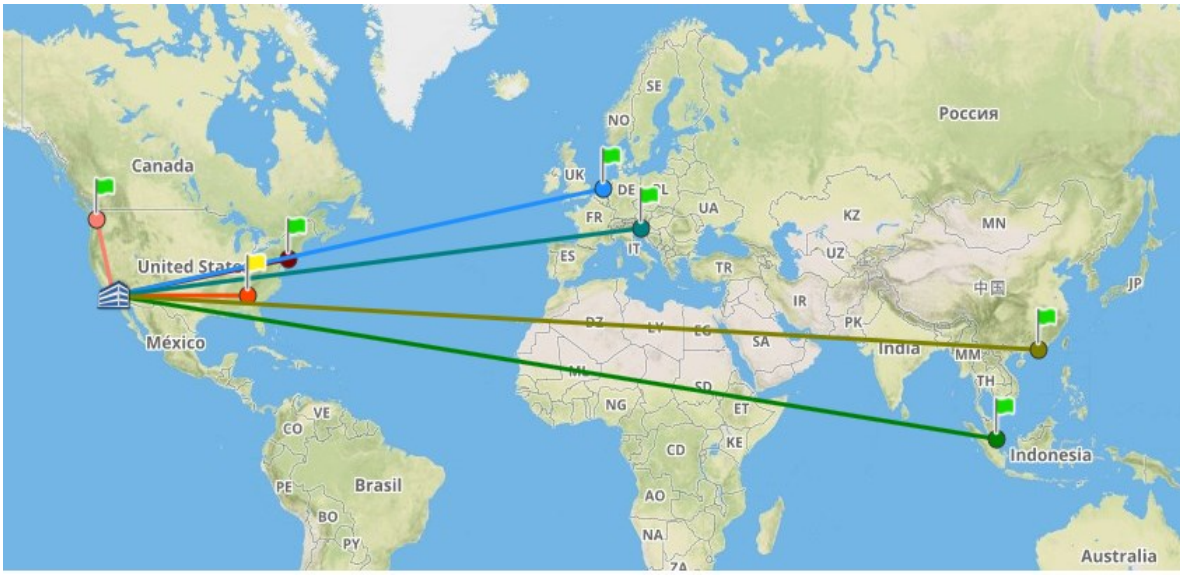

Figure 4. Visualization of the location of the six global V6Sonar© agents.

Each agent polling task involved the following process conducted over both IPv4 and IPv6:

- DNS query and answer
- IP TCP connection to web server established
- HTTP download times for all resources on the website

The results were then recorded and calculated for IPv6 effectiveness by the V6Sonar© tool. The IPv6 effectiveness score for a website is calculated by multiplying the probabilities of two conditional probabilities and is expressed by the formula:

$$\text{Effectiveness} = P1 * P2$$

With P1 = Probability that a user who has IPv6 access will connect over IPv6 according to Happy Eyeballs[21] and P2 = Probability that once connected over IPv6 the user will be as happy with the web download as with IPv4. Each probability is calculated using several data sets related to response times, Happy Eyeballs operation, browser types and IPv6 adoption.

Happy Eyeballs (RFC 6555) specifies that operating systems and browsers should attempt TCP connections over IPv6 and IPv4 simultaneously, and choose the protocol that returns the first successful connection. Prior to Happy Eyeballs, clients used a mechanism defined by RFC 3484 which attempted to help drive IPv6 adoption by preferring and connecting over IPv6 if both protocols were available.

Figure 5 shows example output from the V6Sonar© tool. The percentages and times represent real-time data provided by the tool for a website under test at each polling time interval. For each score and protocol performance, a green arrow indicates the current measurements were better than those taken at the previous time interval; a red arrow indicates the current measurements

were worse. The score shown at the top is the total global IPv6 effectiveness score averaged from all six agents, and in this example is 95%. The IPv6 effectiveness scores from agents is also shown by region (North America, Europe, and Asia), as well as the IPv4 performance time in milliseconds (ms), and the IPv6 performance time in milliseconds (ms). These scores are refreshed and displayed at the polling time interval specified.

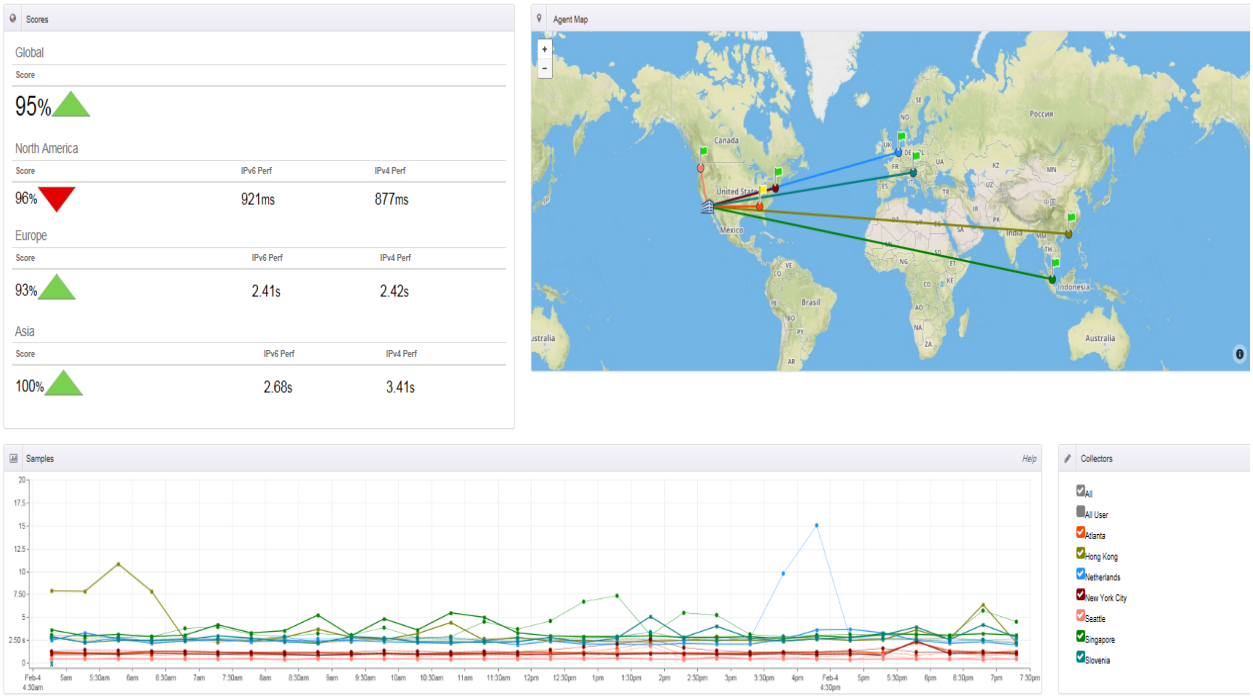

Figure 5. Example of IPv6 effectiveness output from V6Sonar©

Findings and results

Of the 1000 university Web sites queried only 126 (12.5%) returned AAAA records. Of the top 25 ranked universities, only seven returned AAAA records as shown in Table 1.

CWUR Ranking	University	Country	AAAA Record Returned
1	Harvard University	USA	N
2	Stanford University	USA	Y
3	Massachusetts Institute of Technology	USA	N
4	University of Cambridge	UK	N
5	University of Oxford	UK	N
6	Columbia University	USA	N
7	University of California, Berkeley	USA	Y
8	University of Chicago	USA	N
9	Princeton University	USA	N
10	Yale University	USA	Y

11	Cornell University	USA	N
12	California Institute of Technology	USA	N
13	University of Tokyo	Japan	N
14	University of Pennsylvania	USA	Y
15	University of California, Los Angeles	USA	Y
16	Kyoto University	Japan	N
17	New York University	USA	Y
18	Swiss Federal Institute of Technology in Zurich	Switzerland	Y
19	Johns Hopkins University	USA	N
20	University of California, San Diego	USA	N
21	University of Michigan, Ann Arbor	USA	N
22	Hebrew University of Jerusalem	Israel	N
23	Northwestern University	USA	N
24	Seoul National University	South Korea	N
25	University of Wisconsin-Madison	USA	N

Table 1. AAAA query results from Top 25 rated CWUR universities

A visual representation of the 126 universities that returned an AAAA record was created by using the mapping service of Batchgeo.com. Batchgeo is a service that creates Google Maps from inputted data such as address, cities, states, postal codes, or IP addresses. For all universities that returned an AAAA record, the corresponding IPv6 address was copied into the Batchgeo window and a global map was created pinpointing the locations as presented in Figure 6.

Figure 6: Map showing geographic location of universities returning AAAA records (Courtesy

Batchgeo).

The number of university websites returning AAAA records was also cross-referenced to the Regional Internet Registry under which they operate and this information is presented in Table 2.

RIR	University URLs Tested	Number Reporting AAAA Records
AFRINIC	10	0
APNIC	279	30
ARIN	262	31
LACNIC	32	9
RIPE NCC	417	56
Total	**1000**	**126**

Table 2. The number of university web sites reporting AAAA records per RIR regions.

Next, all 126 university web-site URLs that returned AAAA records were entered into V6Sonar © and assessed for IPv6 effectiveness. Table 3 shows the 25 university websites which returned the highest IPv6 effectiveness as measured and recorded by the average score from all six globally deployed V6Sonar© agents. Higher percentages equal a higher level of IPv6 effectiveness, which means a higher return on the investment an organization has made enabling IPv6 on their external Web services.

University	Domain	IPv6 Effectiveness Measure			
		N. Am	Europe	Asia	Global
University of Victoria	www.uvic.ca	100.00%	99.59%	95.24%	99.27%
Karlsruhe Institute of Technology	www.kit.edu	95.99%	98.54%	95.27%	96.78%
University of Albany, SUNY	www.albany.edu	96.57%	98.34%	88.23%	96.15%
Federal University of Rio Grande do Sul	www.ufrgs.br	98.07%	93.73%	93.55%	96.02%
Texas A&M University	www.tamu.edu	91.62%	97.41%	98.06%	94.41%
University of Maribor	www.um.si	98.70%	97.50%	56.80%	93.14%
Pennsylvania State University	www.psu.edu	96.59%	97.95%	55.99%	92.07%
Federal University of Santa Caterina	www.ufsc.br	99.40%	80.08%	86.11%	91.09%
0Chinese University of Hong Kong	www.cuhk.edu.hk	87.86%	93.35%	96.66%	90.84%
University of British Columbia	www.ubc.ca	91.76%	90.97%	82.76%	90.38%
University of Saskatchewan	www.usask.ca	86.70%	91.47%	93.85%	89.23%
Tulane University	tulane.edu	90.51%	96.15%	58.80%	88.56%
University of Iceland	www.hi.is	97.89%	79.37%	72.02%	88.31%
Nara Institute of Science and Technology	www.naist.jp	99.01%	95.35%	13.02%	87.18%
University of Iowa	www.uiowa.edu	95.26%	81.40%	66.47%	86.93%
Stony Brook University	www.stonybrook.edu	86.07%	86.93%	88.48%	86.66%
Simon Fraser University	www.sfu.ca	85.01%	89.82%	82.95%	86.42%
University of Pennsylvania	www.upenn.edu	82.21%	93.45%	84.12%	86.33%

Swiss Federal Institute of Technology in Lausanne	www.epfl.ch	74.50%	99.45%	98.03%	86.01%
University of Vermont	www.uvm.edu	84.76%	92.88%	62.40%	84.82%
University of Osnabruck	www.uni-osnabrueck.de	72.48%	98.70%	94.53%	84.25%
Sofia University	www.uni-sofia.bg	73.27%	97.67%	91.55%	83.95%
University of California, Berkeley	www.berkeley.edu	80.01%	86.17%	94.14%	83.87%
University of Oulu	www.oulu.fi	74.03%	98.36%	83.40%	83.58%
University of Twente	www.utwente.nl	74.79%	92.72%	87.14%	82.50%

Table 3. Twenty-five sites with the highest IPv6 effectiveness as measured and recorded by all global v6Sonar © agents.

Table 4 shows the 25 university sites which returned the lowest IPv6 effectiveness as measured and recorded by the average score from all six globally deployed V6Sonar© agents. Low effectiveness can be attributed to many factors; varying IP connectivity through the global infrastructure between IPv6 and IPv4, peering issues between the website host and the provider, ineffective IPv6 management by the provider, or possible issues with the IPv6 service itself on the server. Regardless of the root cause of the low effectiveness scores, universities with low IPv6 effectiveness are not realizing full return on their investment to enable IPv6 on their external Web services. As seen in the table, some sites had an IPv6 effectiveness of 0%. These scores could be due to an anomaly during the testing process. Verifying these results through a second and longer duration effectiveness test is part of the future works of this study.

University	Domain	IPv6 Effectiveness Measure			
		N. Am	Europe	Asia	Global
Stanford University	www.stanford.edu	51.47%	50.28%	40.97%	49.77%
University of Cologne	www.uni-koeln.de	46.82%	42.57%	63.92%	47.45%
National Chiao Tung University	www.nctu.edu.tw	59.42%	20.06%	55.54%	45.35%
University of Veterinary Medicine Vienna	www.vetmeduni.ac.at	28.25%	65.45%	19.52%	40.03%
Hunan University	www.hnu.edu.cn	47.22%	23.78%	27.69%	36.72%
University of Lisbon	www.ulisboa.pt	9.08%	70.39%	0.00%	29.15%
UNESP, Sao Paulo State University	www.unesp.br	13.49%	22.12%	91.31%	26.03%
Ludwig Maximilian University of Munich	www.uni-muenchen.de	20.17%	36.83%	20.17%	25.92%
Mississippi State University	www.msstate.edu	6.74%	28.81%	75.75%	22.85%
Chiang Mai University	www.cmu.ac.th	5.66%	19.26%	76.98%	19.12%
Katholieke Universiteit Leuven	www.kuleuven.be	16.61%	14.61%	4.01%	14.37%
University of Nantes	www.univ-nantes.fr	2.84%	31.22%	1.99%	12.54%
New York University	www.nyu.edu	5.00%	19.65%	14.15%	11.18%
Monash University	www.monash.edu.au	2.62%	1.13%	3.36%	2.20%
University of Oregon	uoregon.edu	0.00%	0.00%	0.00%	0.00%
Case Western Reserve University	www.case.edu	0.00%	0.00%	0.00%	0.00%

North Carolina State University	www.ncsu.edu	0.00%	0.00%	0.00%	0.00%
National Sun Yat-sen University	www.nsysu.edu.tw	0.00%	0.00%	0.00%	0.00%
Ruhr University of Bochum	www.ruhr-uni-bochum.de	0.00%	0.00%	0.00%	0.00%
Tehran University of Medical Sciences	www.tums.ac.ir	0.00%	0.00%	0.00%	0.00%
Federal University of Bahia	www.ufba.br	0.00%	0.00%	0.00%	0.00%
Federal University of Parana	www.ufpr.br	0.00%	0.00%	0.00%	0.00%
Federal University of Sao Carlos	www.ufscar.br	0.00%	0.00%	0.00%	0.00%
National University of La Plata	www.unlp.edu.ar	0.00%	0.00%	0.00%	0.00%
University of Porto	www.up.pt	0.00%	0.00%	0.00%	0.00%

Table 4. Twenty-five sites with the lowest IPv6 effectiveness as measured and recorded by all global v6Sonar © agents.

Table 5 shows the university sites which returned an IPv6 effectives of greater than 80% as measured by V6Sonar© agents located globally.

University	Domain	IPv6 Effectiveness Measure			
		N. Am	Europe	Asia	Global
University of Victoria	www.uvic.ca	100.00%	99.59%	95.24%	99.27%
Karlsruhe Institute of Technology	www.kit.edu	95.99%	98.54%	95.27%	96.78%
University of Albany, SUNY	www.albany.edu	96.57%	98.34%	88.23%	96.15%
Federal University of Rio Grande do Sul	www.ufrgs.br	98.07%	93.73%	93.55%	96.02%
Texas A&M University	www.tamu.edu	91.62%	97.41%	98.06%	94.41%
University of Maribor	www.um.si	98.70%	97.50%	56.80%	93.14%
Pennsylvania State University	www.psu.edu	96.59%	97.95%	55.99%	92.07%
Federal University of Santa Caterina	www.ufsc.br	99.40%	80.08%	86.11%	91.09%
Chinese University of Hong Kong	www.cuhk.edu.hk	87.86%	93.35%	96.66%	90.84%
University of British Columbia	www.ubc.ca	91.76%	90.97%	82.76%	90.38%
University of Saskatchewan	www.usask.ca	86.70%	91.47%	93.85%	89.23%
Tulane University	tulane.edu	90.51%	96.15%	58.80%	88.56%
University of Iceland	www.hi.is	97.89%	79.37%	72.02%	88.31%
Nara Institute of Science and Technology	www.naist.jp	99.01%	95.35%	13.02%	87.18%
University of Iowa	www.uiowa.edu	95.26%	81.40%	66.47%	86.93%
Stony Brook University	www.stonybrook.edu	86.07%	86.93%	88.48%	86.66%
Simon Fraser University	www.sfu.ca	85.01%	89.82%	82.95%	86.42%
University of Pennsylvania	www.upenn.edu	82.21%	93.45%	84.12%	86.33%
Swiss Federal Institute of Technology in Lausanne	www.epfl.ch	74.50%	99.45%	98.03%	86.01%
University of Vermont	www.uvm.edu	84.76%	92.88%	62.40%	84.82%

University of Osnabruck	www.uni-osnabrueck.de	72.48%	98.70%	94.53%	84.25%
Sofia University	www.uni-sofia.bg	73.27%	97.67%	91.55%	83.95%
University of California, Berkeley	www.berkeley.edu	80.01%	86.17%	94.14%	83.87%
University of Oulu	www.oulu.fi	74.03%	98.36%	83.40%	83.58%
University of Twente	www.utwente.nl	74.79%	92.72%	87.14%	82.50%
University of Missouri-Kansas City	www.umkc.edu	74.19%	99.02%	70.81%	82.35%
Kaiserslautern University of Technology	www.uni-kl.de	70.88%	94.86%	92.24%	81.79%
Tsinghua University	www.tsinghua.edu.cn	94.22%	89.43%	2.48%	81.29%
Yokohama National University	www.ynu.ac.jp	72.84%	93.75%	82.72%	81.28%
National Technical University of Athens	www.ntua.gr	70.08%	96.44%	86.94%	81.26%
University of Sao Paulo	www5.usp.br	70.77%	94.24%	88.72%	81.08%
American University of Beirut	www.aub.edu.lb	81.81%	80.95%	76.16%	80.82%
Darmstadt University of Technology	www.tu-darmstadt.de	73.03%	96.37%	68.10%	80.49%
Delft University of Technology	www.tudelft.nl	73.91%	84.56%	94.07%	80.07%

Table 5. Sites with effectiveness >80% as measured by global agents

Conclusions and future work

The data from IPv6 adoption statistics sites such as 6Lab, NIST, and Google IPv6 Statistics all show that global IPv6 adoption is happening at an accelerating pace. As users increasingly connect to the Internet over IPv6, it is critical that universities not only make their Web content accessible to those users, but that they ensure the quality of the user experience connecting to that content over IPv6.

This study makes two primary conclusions: (1) The majority of university websites globally are not reachable to users over IPv6 and (2) the user experience over IPv6 to the few university websites that are reachable over IPv6 is lower than that over IPv4. Of the 1000 university website URLs queried, 874 (87.5%) did not return AAAA records, meaning these sites are likely not accessible to users connecting over IPv6. Of the 126 websites tested for IPv6 effectiveness, only 10 returned what the researchers considered a high IPv6 effectiveness (>90%) meaning that the user experience connecting to those sites was comparable or better than that over IPv4. Universities with low IPv6 effectiveness are not realizing their full return on investment. For example, a university which has $100k invested in IPv6 enablement at the Internet edge and an IPv6 effectiveness of 60%, has wasted $40k.

Any organization, including universities, failing to make their Web content available over IPv6 is potentially compromising business agility, interoperability, growth, and ultimately competiveness. However, simply enabling IPv6 is not enough. Organizations must test and evaluate the quality of access to their Web content over IPv6 as measured by user experience. Vendor implementation of Happy Eyeballs varies, and some client operating systems and browsers may attempt to connect over IPv6 if both IPv4 and IPv6 are available. Users on such

platforms that encounter a negative user experience, such as long wait periods or timeouts, when connecting to an organization's website are likely to blame the website, and not IPv6 connectivity. This type of negative experience can drive users to competitor's sites and damage an organization's brand.

The IPv6 effectiveness testing performed in the study was conducted in a relatively short time window of four days with agents polling the website Web servers every 30 minutes. A second and more exhaustive round of testing should be conducted to validate the results in this study and to see if the IPv6 effectiveness measurement averages, when collected over a longer term, are similar or different. Additionally, future work is needed to determine what factors, if any, exist which may be correlated with low or high IPv6 effectiveness scores. An understanding of any such factors may enable organizations to take measures to optimize the user experience in accessing their external Web content over IPv6.

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