IPv4 versus IPv6 - Who connects faster?

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***Abstract*—We compare IPv4 and IPv6 connectivity of dual-stacked hosts using a metric that measures Transmission Control Protocol (TCP) connection establishment time to 100 popular dual-stacked websites. We have deployed an implementation of this metric on 20 SamKnows probes connected to dual-stacked networks that are part of 18 different Autonomous Systems (AS). Using a year-long dataset gathered from these vantage points, we show how most of these websites centralise around Content Delivery Network (CDN) deployments and consequently show similar performance. We show that these CDN clusters are different for IPv4 and IPv6. Furthermore, some of these websites tend to be served by CDN caches deployed within service provider networks. We show how these CDN caches are largely absent over IPv6. The distributions of TCP connect times show how clusters serving popular websites over IPv6 have improved over time. We also illustrate cases where network policies inhibit hosts from connecting to websites over IPv6.**

I. INTRODUCTION

With the World IPv6 Launch day in 2012, several notable web service providers started providing content services over IPv4 and IPv6. In two years since then, a number of large IPv6 broadband roll-outs have happened[1]. For instance, Comcast, Deutsche Telekom AG and AT&T have demonstrated increased penetration of IPv6 in the fixed-line space, with Verizon Wireless and T-Mobile USA showing similar trends in the cellular space. In fact, Comcast recently[2] completed transition of their entire broadband network infrastructure to be 100% IPv6 ready. These efforts have eventually led to an increased global adoption of IPv6 to 5%, with Belgium (∼28.7%), Germany (∼11.9%) and USA (∼11.7%) leading the adoption rates as seen by Google's IPv6 adoption statistics[3] as of November 2014. These numbers demonstrate that IPv6 adoption is finally happening. Jakub Czyz *et al.* in [1] (2014) provide a high-level view of the current state of IPv6 adoption. They study the deployment from two lenses: a) prerequisite IP functions (addressing, naming, routing and end-to-end reachability), and b) operational characteristics (usage profile and performance). However, they measure IPv6 performance using an approximation of 10− and 20−hop round-trip time (RTT)s over a sample of dual-stacked nodes. In fact, they concede that a measure of actual client-to-service network performance would be a more ideal metric. In this study, we plug this gap by using a year-long dataset to measure IPv6 performance of operational dual-stacked websites from 20 dual-stacked vantage points.

A dual-stacked host with native IPv6 connectivity establishing a TCP connection to a dual-stacked website will prefer IPv6. Fig. 1 shows how the function, `getaddrinfo(...)` adheres to the default address selection policy [2] by resolving a service name to a list of endpoints in an order that prioritizes an IPv6-upgrade path. As a result, any application using `getaddrinfo(...)` to resolve service names will tend to prefer connections made over IPv6. We want to know whether customers with native IPv6 lines experience benefit (or an added penalty) when connecting to websites over IPv6.

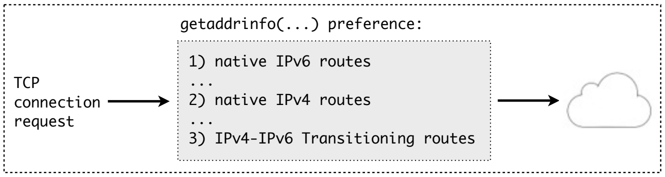

Fig. 1. *`getaddrinfo(...)` behavior as dictated by the default destination address selection algorithm [2]. The algorithm makes applications iterate over endpoints in an order that prefers an IPv6-upgrade path.*

In order to achieve this, we introduce a metric that measures TCP connection establishment times. We deploy an implementation of this metric on 20 SamKnows[4] probes connected behind dual-stacked networks. We ran measurements to a selectively chosen list of top 100 dual-stacked websites from these vantage points and collected measurement data for a year. We show insights uncovered by analyzing this year-long dataset. We explore raw TCP connection establishment times and uncover techniques to cluster websites around CDN deployments. We show how these clusters are different for the IPv4 and the IPv6 network infrastructure. These clusters also reveal which websites are currently being served by content caches deployed inside the service provider network. We show how these content caches are largely absent over IPv6. The gathered trends have allowed us to identify special cases where network policies have resulted in inhibiting IPv6 for certain websites for some hosts. We describe these special cases.

Our measurement study provides four main contributions:

- An active metric (and a corresponding implementation) to measure TCP connection establishment times alongwith a list of top 100 dual-stacked websites processed from Amazon 1M Alexa entries. We release these to the measurement community[5].
- Identification of CDN deployments and content-caches in service provider networks using Border Gateway Protocol (BGP)-based clusters processed from Internet

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[1] *http://www.worldipv6launch.org/measurements*

[2] *http://goo.gl/9IKXZ1*

[3] *https://www.google.com/intl/en/ipv6/statistics.html*

[4] *http://www.samknows.com*

[5] *happy.vaibhavbajpai.com*

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Protocol (IP) endpoints seen from globally distributed SamKnows vantage points. A quantification of disparity in IPv4 and IPv6 clusters is also made available.

- Distributions of TCP connection establishment times over an year-long dataset to compare IPv4 and IPv6 performance over each CDN cluster.
- A study of special cases such as `www.bing.com` globally stopping IPv6 services in 2013, and Google CDN blacklisting resolvers that inhibit some hosts from receiving their services over IPv6.

The paper is organized as follows. In Section II we survey studies measuring IPv6 performance. In Section III we introduce our measurement methodology, we describe our metric and related design choices, the measurement setup and current deployment. We capture our data analysis insights in Section V and conclude in Section V.

II. RELATED WORK

Jakub Czyz *et al.* in [1] (2014) provide a survey of studies measuring IPv6 adoption on the Internet. We therefore scope our survey to studies measuring IPv6 performance.

Kenjiro Cho *et al.* in [3] (2004) passively monitor Domain Name System (DNS) records for 3 months from within the WIDE research network to extract a destination list of ∼4K dual-stacked nodes. They study IPv6 performance by comparing RTT and AS-level forward paths using a day-long dataset of `ping` and `traceroute` measurements collected from 3 vantage points. They witnessed 16% unreachable destinations; while only a small proportion (among the rest) exhibited larger RTT over IPv6. Lorenzo Colitti *et al.* in [4] (2009) study IPv6 performance by measuring latency using HTTP requests to two experimental Google web service hostnames using a small fraction of Google users. They show how performance of native IPv6 (although small in 2009) is comparable to that of IPv4, but transitioning technologies add considerable latency. They also show how operating systems (and browsers) by default tend to favor connections over IPv6. These studies however are dated. We therefore defer our methodology comparison in favor of more recent studies discussed next.

Mehdi Nikkhah *et al.* in [5] (2011) study IPv6 performance by measuring average download speeds (95% confidence interval within 10% of mean) towards dual-stacked webpages within Alexa top 1M websites (also used by us) from 6 vantage points (as opposed to 20 vantage points used by us). They measure object size of the downloaded root page (without downloading embedded objects) and filter out websites where these sizes are not within 6% (over IPv4 and IPv6) of each other. They separate websites served by same (and different) origin AS over IPv4 and IPv6 and use AS paths (derived from BGP route tables) to further separate them over same (and different) paths. We currently do not capture AS paths, but we do extend this technique by using origin AS to cluster websites by CDN deployments and CDN caches in service provider networks. They [5] analyse performance by studying controlled averages. We instead show distributions of TCP connect times over an year-long dataset. Amogh Dhamdhere *et al.* in [6] (2012) study the deployment of IPv6 from three lenses: a) topology, b) routing dynamics and c) performance. The performance test extends on [5] in two ways: a) It downloads the smallest object (including embedded objects) that is atleast 10KB in size to overcome TCP slow start and b) It measures AS paths using TCP `traceroute` (instead of BGP routing tables). They [6] measure the time to fetch the page object towards a dual-stacked websites list generated from Alexa top 1M websites (also used by us). The performance measurements were conducted from 5 vantage points (as opposed to 20 vantage points used by us). Both studies [5], [6] show how IPv6 performance is comparable to IPv4 when forward AS-level paths are same, but much worse when they differ. They [6] reason how page fetch times (due to small size of typical pages) are more dominated by delay rather than available bandwidth. This is why we measure TCP connection establishment times since it allows us to capture this end-to-end delay at the transport layer. Hussein A. Alzoubi *et al.* in [7] (2013) study the performance implications of unilateral enabling of services over IPv6. They witnessed no performance penalty in disabling the opt-in service. Google used to impose such an opt-in policy to allow hosts to receive Google services over IPv6. However, we show how Google has recently changed the policy.

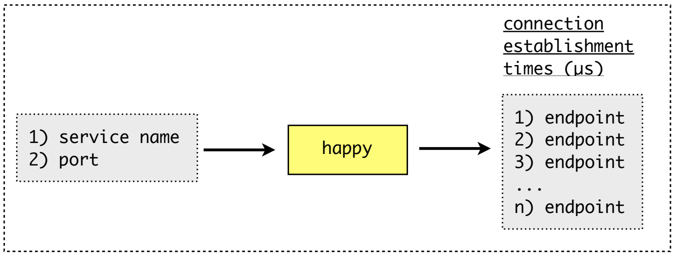

Fig. 2. *`happy`: A tool to measure TCP connection establishment times. The input parameter is a tuple (service name, port number) and the output is the connection establishment time for each endpoint (measured in microseconds). The tool has been open-sourced and is available at: happy.vaibhavbajpai.com*

III. METHODOLOGY

In this section, we describe our methodology. We introduce our metric and a corresponding implementation. We describe our rationale in selecting a list of dual-stacked websites and illustrate the overall measurement setup that utilizes SamKnows probes. We show the scope and lifetime of our measurement trial by presenting the global vantage point distribution.

A. Metric, Implementation and Features

We have defined a metric that measures the time taken to establish a TCP connection to a given endpoint. The input parameter of the metric is a tuple (service name, port number) and the output is the TCP connection establishment time for all endpoints the service name resolves to, typically measured in microseconds, as shown in Fig. 2.

The `happy` tool, is an implementation of our metric. The tool can read one or more service names at once and apply `getaddrinfo(...)` to resolve their DNS entries to `A` and `AAAA` resource records. The list of service names can either be supplied as command-line arguments or as a separate file. It then uses non-blocking TCP `connect(...)` calls to concurrently establish connections to all endpoints seen in the

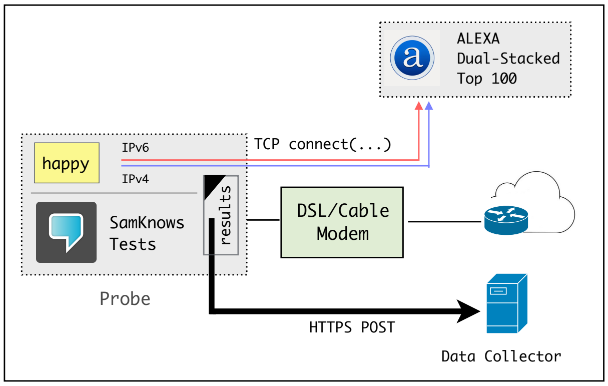

Fig. 3. *A measurement setup on top of the SamKnows platform. A dual-stacked probe in addition to the standard SamKnows tests, executes a happy test. The happy test runs every hour and measures TCP connect times to 100 dual-stacked websites both over IPv4 and IPv6. The locally collected measurement results are pushed every hour to a data collector using HTTP.*

resource records of each service name. It calculates the time it takes for the TCP `connect(...)` call to complete as a measure of the elapsed time. In order to allow delineating connection timeouts it also keeps a flag as an indication on whether the connection got established. This indication is made once a socket in a `select(...)` call becomes writeable with no pending socket errors. We do not account the DNS resolution time in the measured connection establishment time. This is done to avoid slow resolvers from biasing our connection establishment time results. The tool enforces a small delay (25ms by default) between concurrent TCP `connect(...)` calls to avoid generating bursty TCP `SYN` traffic. This delay, however, does not come in the way of pending TCP `connect(...)` calls. As such the measured times are not skewed by this feature. We also added the capability to lock the output stream to allow multiple processes to coordinate writes to the same output stream. This is useful when multiple `happy` instances try to append results to a single regular file from a resource-constrained device.

B. Selection of Websites

We wanted to measure a representative list of popular dual-stacked websites. A large list will allow us to capture the perspective of dual-stacked hosts that frequently visit popular regional websites. The top websites within that list when combined with a widely distributed vantage point will additionally allow us to also capture the perspective of dual-stack hosts from a global standpoint.

We investigated sources that can reveal this information. For instance, Alexa ranks and maintains listings of the most popular websites on the Internet. The public REST API, however, provides the capability to retrieve only the top 100 website names. This is not enough, since only a fraction of these top 100 website names are dual-stacked today. Hurricane Electric (HE), a major IPv6 tunnel-broker based in the US, maintains a list of top 100 dual-stacked website names[6]. The backend uses the top 1M website names list made available by Amazon. However, we noticed that some of the popular websites (e.g. Wikipedia) are missing from this list even though they are dual-stacked. It appears some websites provide `AAAA` records only for domain names starting with `www`. For example, `www.bing.com` does have a `AAAA` record while `bing.com` does not (In this particular case, a request to fetch the latter leads to a redirect to the former). Since, HE does not follow `CNAME`s, they miss some dual-stacked websites in their top dual-stacked website list calculation.

We decided to use Amazon's top 1M website names list[7] used by HE as input to prepare a top 100 dual-stacked website names list using our own custom script. Our script prepends each website name with the label `www` to make an additional DNS request and it also explicitly follows `CNAME`s. This way, we do not miss any of the popular dual-stacked websites like `wikipedia.org`. It is also important to note that we only measure websites in this work. As such the connection establishment times and their comparison over IPv4 and IPv6 reflect the performance as seen over TCP port 80.

C. Measurement Setup

We cross-compiled `happy` for the OpenWrt platform and deployed it on SamKnows probes. These probes, in addition to the happy test, also perform standard SamKnows IPv4 measurements. The test is executed on the top 100 dual-stacked websites list and the measurement runs every hour. Due to the inherent storage limitation of the probes, the locally collected measurement results are pushed every hour to our data collector using a REST based architectural style on top of HTTP as shown in Fig. 3.

TYPE	IPv4 AS	IPv6 AS	LOCATION	PROVIDER	PROBE ID
RESIDENTIAL	AS31334	AS31334	BREMEN	KABELDEUTSCHLAND	#02
RESIDENTIAL	AS3320	AS3320	BREMEN	DEUTSCHE TELEKOM	#04
RESIDENTIAL	AS50989	AS1257	STOCKHOLM	SITAB	#11
RESIDENTIAL	AS4685	AS4718	FUKUOKA	ASAHI NET	#12
RESIDENTIAL	AS12715	AS12715	MADRID	JAZZ TELECOM	#13
RESIDENTIAL	AS9031	AS9031	ALLEUR	EDPNET	#17
RESIDENTIAL	AS3320	AS3320	BREMEN	DEUTSCHE TELEKOM	#19
RESIDENTIAL	AS2518	AS2516	SHIZUOKA	BIGLOBE NEC	#20
RESEARCH	AS513	AS513	CERN	CERN	#16
NREN	AS680	AS680	BREMEN	DFN	#01
NREN	AS2614	AS2614	TIMISOARA	ROEDUNET	#08
NREN	AS2611	AS2611	LOUVAIN	BELNET	#15
NREN	AS680	AS680	BREMEN	DFN	#18
LAB	AS5607	AS5607	LONDON	BSKYB-BROADBAND	#05
LAB	AS3269	AS3269	TORINO	TELECOM ITALIA	#06
LAB	AS8903	AS8903	MADRID	BT ESPANA	#07
LAB	AS2856	AS5400	IPSWICH	BT UK	#10
IXP	AS18070	AS18070	NIIGATA	NDAC	#14
BUSINESS	AS24956	AS24956	BRAUNSCHWEIG	GAERTNER DATENSYSTEME	#03
BUSINESS	AS13030	AS13030	OLTEN	INIT SEVEN	#09

Fig. 4. *Deployment status of our measurement trial as of July 2014. Each vantage point is a SamKnows probe which is part of a larger SamKnows measurement platform. Most of these probes are deployed behind residential networks and receive native IPv6 connectivity from their service provider. A part of these probes are also connected within NREN.*

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[6] *http://bgp.he.net/ipv6-progress-report.cgi*

[7] *http://s3.amazonaws.com/alexa-static/top-1m.csv.zip*

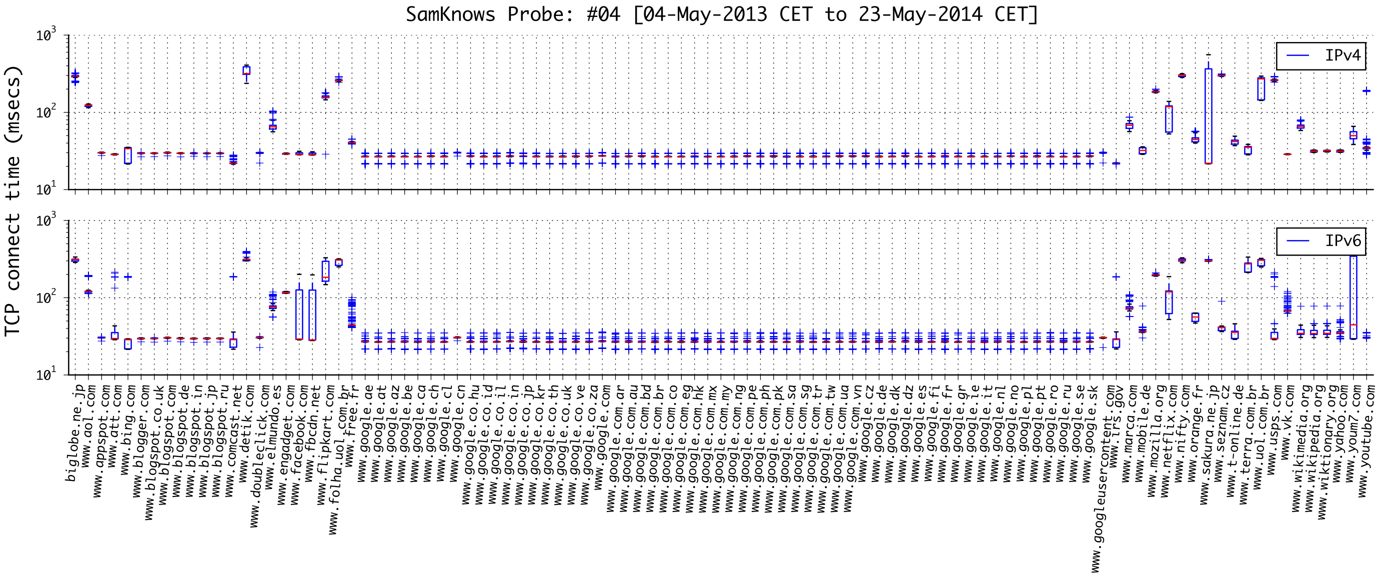


Fig. 5. *Box plots showing distributions (in log-scale) of TCP connection establishment times to 100 dual-stacked websites. The SamKnows probe is connected at a premium Deutsche Telekom customer. It has native IPv4 and IPv6 connectivity via DTAG - Deutsche Telekom AG [AS3320].*

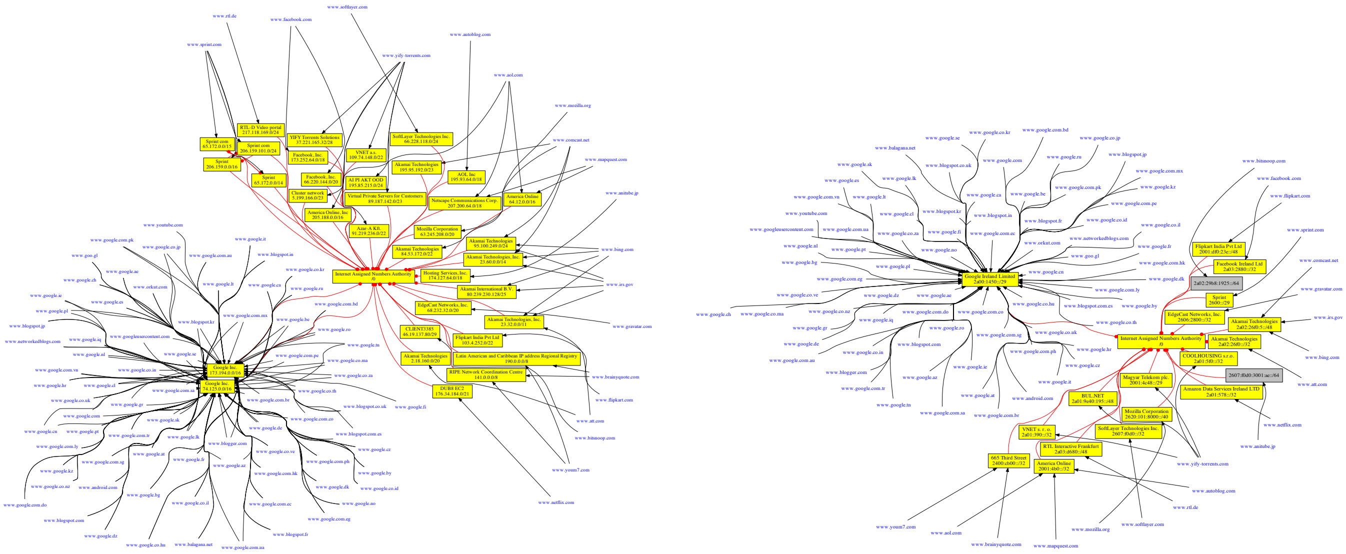


Fig. 6. *An IPv4 (left) and IPv6 (right) WHOIS-based aggregation of websites as seen by this (above) probe depicts how most of the websites centralize on core CDNs and major cloud platforms. (The plots are vector graphics and hence zoomable.)*

D. Measurement Trials

We wanted to measure from different locations of the Internet and wanted to ensure that access to certain websites is not blocked administratively. As such, we strategically deployed SamKnows probes to cover a diverse range of origin-ASes. Fig. 4 shows the current deployment status of the SamKnows probes that are part of our measurement trial. An associated table shows the origin AS (both over IPv4 and IPv6) of each vantage point along with its geographic location. Most of these probes are deployed behind residential networks and receive native IPv6 connectivity. Some probes are also deployed in National Research and Education Network (NREN). We have been collecting this data since March 10, 2013. This has allowed us to collect time series of TCP connect times that may be representative enough to provide us with insights on how IPv6 connectivity to websites compares to IPv4 connectivity.

IV. DATA ANALYSIS INSIGHTS

We performed a pre-processing run on the dataset to reduce the volume of raw measurements. In this work, we do not look at TCP connection failure rates. As such we pruned out entries where the test reported a TCP connection timeout event. We also removed entries where the test failed in situations where it ran out of socket descriptors (a rare but plausible

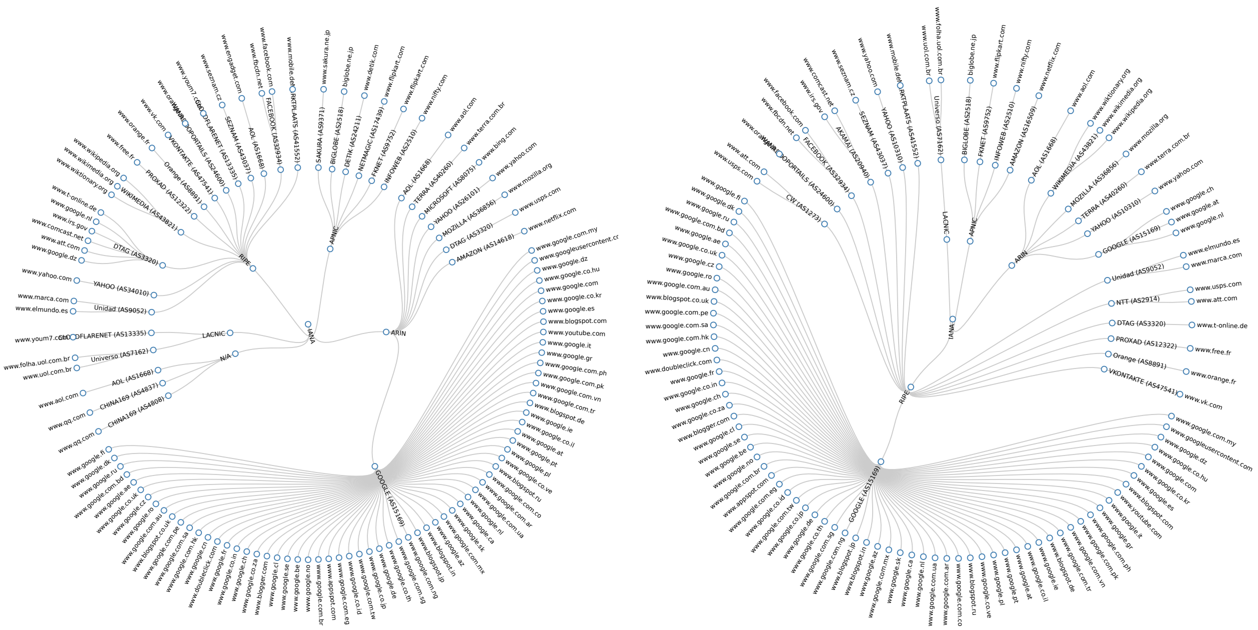


Fig. 7. *An IPv4 (left) and IPv6 (right) BGP-based aggregation of websites as seen by one vantage point. The endpoints are aggregated to the announced BGP prefixes as seen by RIPE RIS route collectors. The leaves represent individual websites. The level-2 nodes represent the AS announcing the BGP prefix and its holder name. Finally, the level-1 nodes represent the RIR that allocated the address block to the AS. The SamKnows probe is connected at a premium Deutsche Telekom customer. It has native IPv4 and IPv6 connectivity via DTAG [AS3320].*

occurance). We investigated time scales where the variation in TCP connection establishment times is small enough to allow statistically meaningful aggregation. Since applications usually honor the order of endpoints returned by `getaddrinfo(...)` when establishing a TCP connection, we decided to pick the first endpoints returned in each measurement over a day for both address families, and aggregated their TCP connect times centered around the median. The calculated Interquartile Range (IQR) ranges around the median are low. As such, each data point in subsequent analysis refers to the median of TCP connection establishment times seen by IPv4 and IPv6 endpoints over a day.

A. *Measuring Raw TCP Connect Times*

Fig. 5 shows box plots of raw TCP connection establishment times to 100 dual-stacked websites from one of the SamKnows probes over the entire year-long duration. This probe is connected behind a residential network in Bremen. The host is subscribed to a premium triple-play service from Deutsche Telekom and as a result receives native IPv4 and IPv6 connectivity at home. It can be seen how several websites appear to show similar performance over IPv4 and IPv6. However, there are also websites such as `www.facebook.com`, `www.fbcdn.net` (served by Facebook CDN) and `www.youm7.com` (served by Cloudflare CDN) where the the probe reports substantially higher variance over IPv6. In fact observing the time-series of TCP connection establishment times for `www.facebook.com` for this probe show how TCP connection establishment times have tangibly improved over time as shown in Fig. 8. Additionally websites like `www.att.com`, `comcast.net` and `www.irs.gov` appear significantly faster over IPv4 than IPv6. This is discussed in the following sections.

B. *Website Clusters*

1) WHOIS-based: It can be seen from Fig. 5 that several related websites, such as `www.google.*` within each address family show very similar behavior. In fact, the median TCP connection establishment times and the IQR values of many disparate websites within the same address family are also comparable. For instance, `www.att.com` (a DSL network provider), `www.comcast.com` (a cable network provider), and `www.irs.gov` (the US tax collection agency) show very similar performance. One possible explanation is that these websites are provided via common CDNs. Looking at the collected IP endpoints, we found that these websites either resolve to the same endpoint or a set of endpoints that belong to the same allocated address block. Digging through the `WHOIS` information for each of the endpoints (obtained via programmatic APIs from the RIRs) seems to indicate that

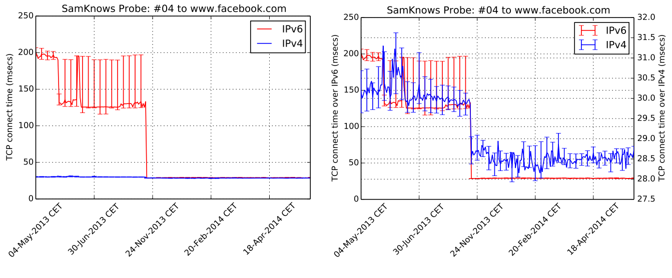
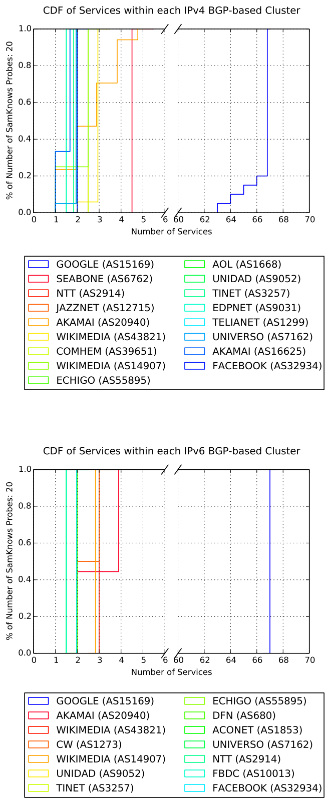


Fig. 8. *Time-series to www.facebook.com from SamKnows Probe #04 from May 2013 to April 2014. It can be seen how this probe witnessed significantly improved TCP connect times over IPv6 since November 2013. The right plot (in two separate scales) shows how TCP connect times over IPv4 also improved at the same tme, but on a much smaller scale.*



`IPv4 Cluster`	`#(↓)`
`GOOGLE (AS15169)`	67
`SEABONE (AS6762)`	05
`NTT (AS2914)`	03
`JAZZNET (AS12715)`	03
`AKAMAI (AS20940)`	03
`WIKIMEDIA (AS43821)`	03
`COMHEM (AS39651)`	03
`WIKIMEDIA (AS14907)`	03
`ECHIGO (AS55895)`	02
`AOL (AS1668)`	02
`UNIDAD (AS9052)`	02
`TINET (AS3257)`	02
`EDPNET (AS9031)`	02
`TELIANET (AS1299)`	02
`UNIVERSO (AS7162)`	02
`AKAMAI (AS16625)`	02
`FACEBOOK (AS32934)`	02

`IPv6 Cluster`	`#(↓)`
`GOOGLE (AS15169)`	67
`AKAMAI (AS20940)`	04
`WIKIMEDIA (AS43821)`	03
`CW (AS1273)`	03
`WIKIMEDIA (AS14907)`	03
`UNIDAD (AS9052)`	02
`TINET (AS3257)`	02
`ECHIGO (AS55895)`	02
`DFN (AS680)`	02
`ACONET (AS1853)`	02
`UNIVERSO (AS7162)`	02
`NTT (AS2914)`	02
`FBDC (AS10013)`	02
`FACEBOOK (AS32934)`	02

Fig. 9. *CDF showing the distribution of number of services within each cluster as seen by all probes. A complementary table shows the number of services within each cluster (across all probes) centered around the median.*

major portions of the websites map to address blocks owned by organizations such as Google and Akamai as shown in Fig. 6.

2) BGP-based: The `WHOIS`-based aggregated clusters are coarse-grained. This is due to the fact that a Local Internet Registry (LIR) can decide to split an allocated address block into multiple smaller chunks. The LIR can then decide to announce these smaller chunks from different ASes. Therefore, we decided to map the collected IP endpoints to announced BGP prefixes as seen by RIPE RIS[8] route collectors. We capture the AS, its holder name, and the RIR that allocated the address block for each announced BGP prefix as an additional metadata in our dataset. Fig. 7 for instance, shows an equivalent BGP-based cluster of websites as seen from the vantage point of this SamKnows probe. It can be seen how aforementioned websites like `www.att.com`, `www.comcast.net` and `www.irs.gov` get clustered behind Deutsche Telekom AG (DTAG) for IPv4, but are dissassociated behind separate clusters for IPv6. These websites are being served over IPv4 by Akamai content caches deployed directly within the DTAG service provider network. However, these caches appear to be missing over IPv6. This correlates with the relative difference between TCP connection establishment times seen over IPv4 and IPv6 for these websites. The BGP-based clusters shown in Fig. 7 are specific to this vantage point. Fig. 9 shows the distribution of number of websites as seen across all probes, both over IPv4 and IPv6. The variation most likely is due to some of the websites getting pushed into service provider networks as content caches. An associated table lists all the clusters in descending order of aggregated number of websites centered around the median. Going forward we use these clusters to perform the rest of the analysis.

C. Distribution of TCP Connect Times

In our pursuit to cover all vantage points, we narrowed down the list to clusters that were seen in *both* address families and by *all* probes. The resultant clusters: Google, Akamai, Facebook and Wikimedia are used in the analysis going forward. Fig. 10 and Fig. 11 show the distribution of TCP connection establishment times as seen by each probe. Fig. 12 on the other hand shows box plots of observed TCP connection establishment times for each probe and a CDF as seen by all probes combined. It can be seen how probes deployed in Japan (#12, #14, and #20) do not appear in Wikipedia-EU CDN measurements, but in fact measure against Wikipedia CDN (not shown). It can also be seen how probes connected behind

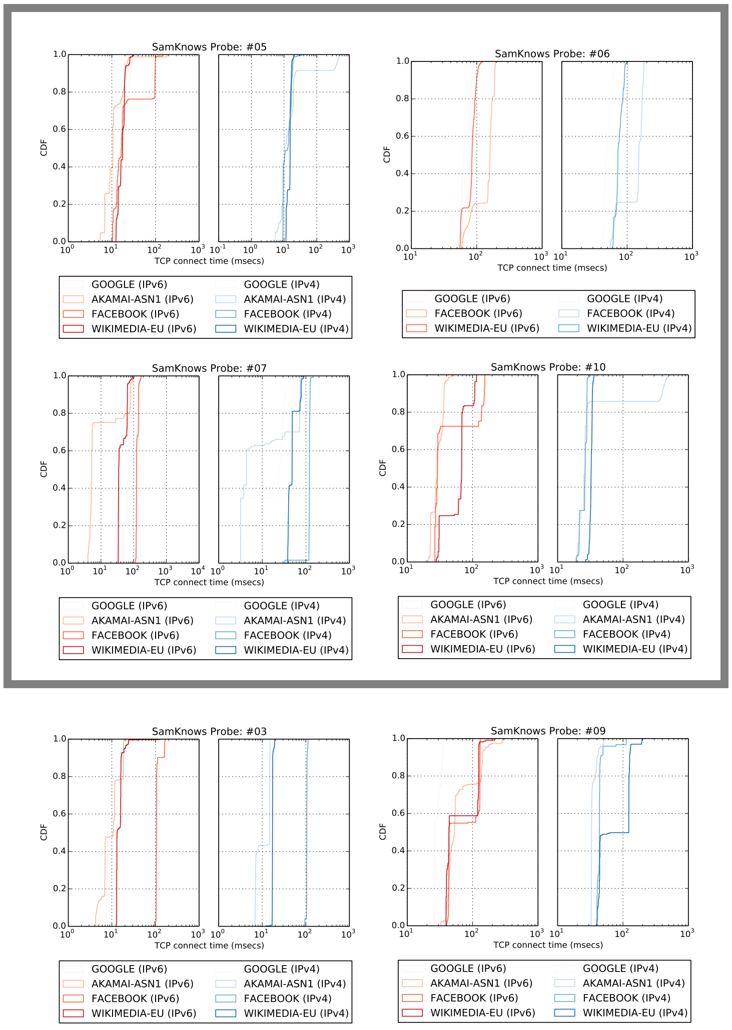


Fig. 10. *Distribution of TCP connect times (in log scale) over IPv4 (blue) and IPv6 (red) as seen by probes wired behind an operator's lab (boxed) and business network (unboxed) for 4 CDN deployments: Google, Akamai-ASN1, Facebook and Wikimedia-EU. The list of origin AS (IPv4 and IPv6) of each SamKnows probe is available in Fig. 4.*

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[8] *http://www.ripe.net/ris*

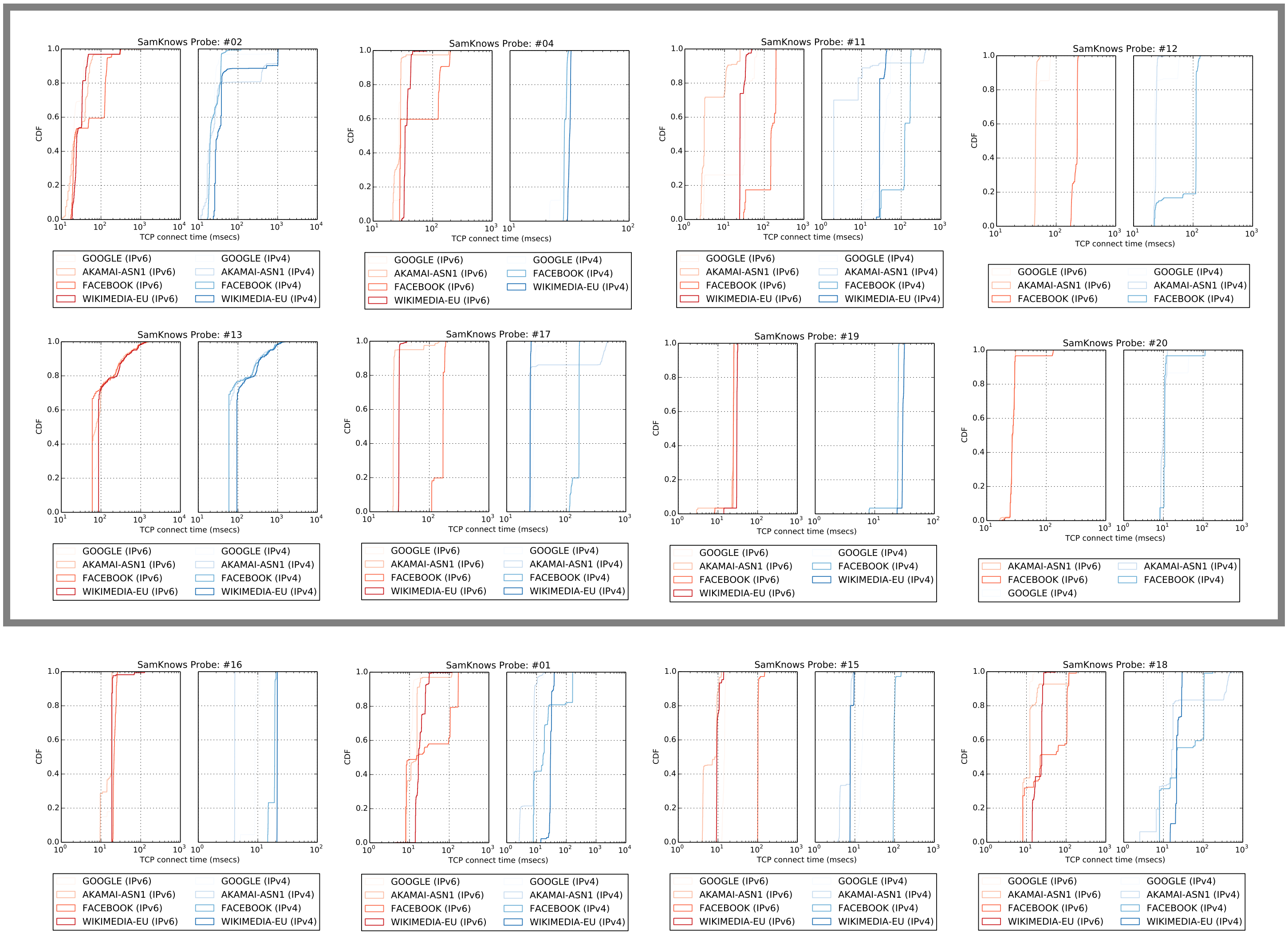

Fig. 11. *Distribution of TCP connect times (in log scale) over IPv4 (blue) and IPv6 (red) as seen by probes wired behind a residential gateway (boxed) and research network (unboxed) for 4 CDN deployments: Google, Akamai-ASN1, Facebook and Wikimedia-EU. The list of origin AS (IPv4 and IPv6) of each SamKnows probe is available in Fig. 4.*

DTAG networks (#04 and #19) do not reach out to websites served by Akamai CDN over IPv4, but instead are directly served by Akamai content caches deployed from within the DTAG network. It can also be seen how such content caches are largely absent over the IPv6 network. A probe connected to BELNET (the Belgian NREN) (#15) shows consistent behaviour across address families. A probe connected to the DFN (the German NREN) (#01) shows similar medians over the address families, however, the variation for the Facebook CDN over IPv6 is much higher. The probe connected to Kabel Deutschland (#02) shows very similar behaviour with a certain delay offset. This offset is likely due to the different access technology (cable). In general, it seems that IPv6 access to the Facebook CDN shows much higher variation compared to IPv4. Some of the probes occasionally also see very slow connect times (For instance, #13 connected to Jazz Telecom in Spain for all four CDNs and #02 connected to Kabel Deutschland for all except the Facebook CDN). It is not clear what causes this but at least these effects do not seem to be address family specific. A probe connected to ROEDUNET (the Romanian NREN) (#08) does not perform any IPv6 measurements due to a routing issue in the upstream network.

D. *Special Cases*

Our dataset from a distributed set of vantage points has allowed us to identify global events that have affected dual-stacked hosts. In this section, we discuss these events:

1) Bing: The website `www.bing.com` used to be dual-stacked. However, we witnessed how all of our SamKnows probes stopped performing measurements to `www.bing.com` over IPv6 starting September 2013. Fig. 13 shows the time series of TCP connection establishment times over IPv4 and IPv6 as seen from all and individual vantage points towards this website. There appears to be an abrupt cut-off of IPv6 hinting towards a network policy decision. We investigated the DNS entries returned for `www.bing.com` and found that the upstream resolvers have stopped providing `AAAA` entries for this website.

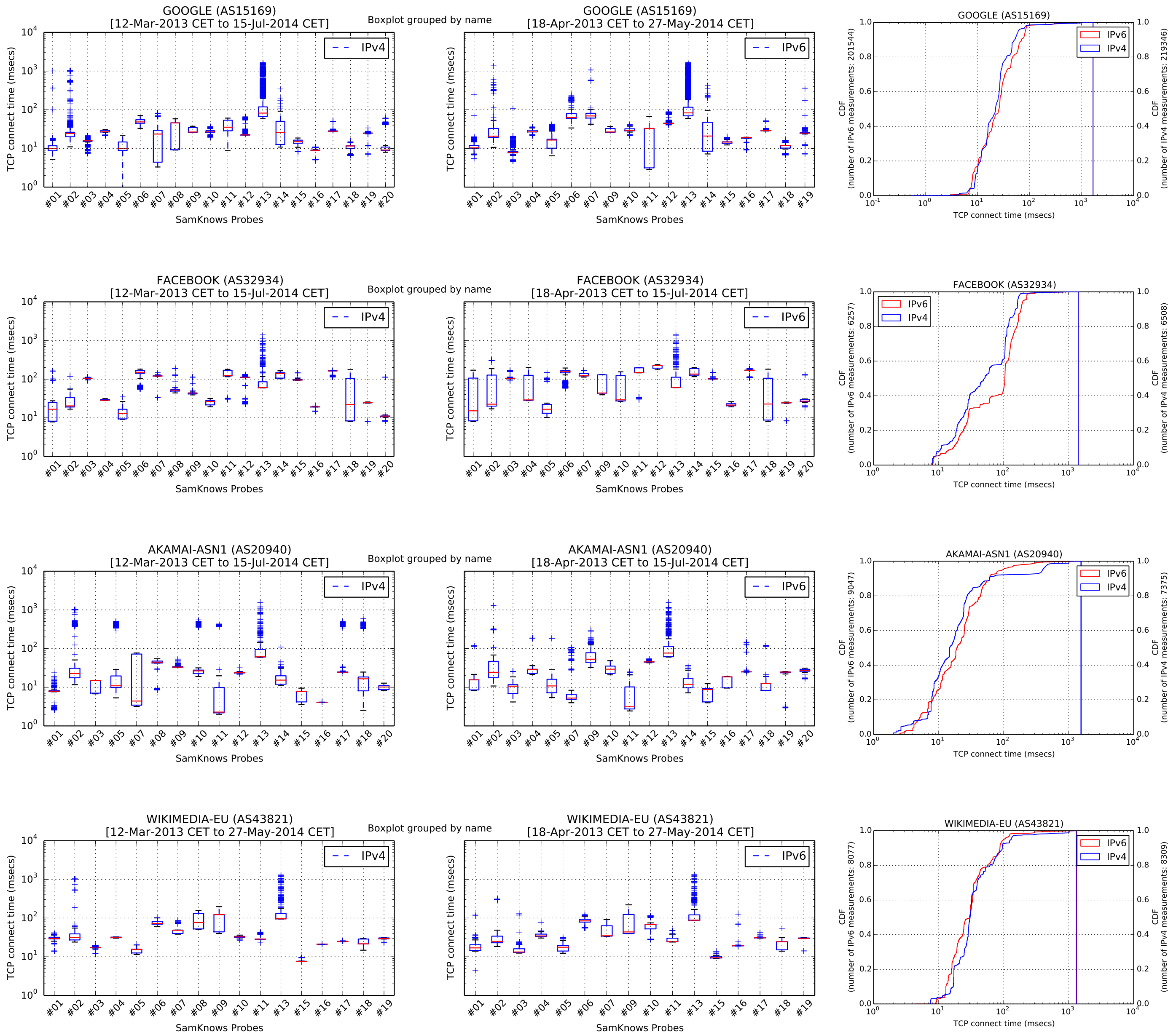

Fig. 12. *Box plots of TCP connection establishment times (in log scale) over IPv4 (left) and IPv6 (right) for 4 CDN deployments: Google, Akamai-ASN1, Facebook and Wikimedia-EU as seen by all vantage points. An associated CDF plot shows the distribution of TCP connection establishment times (in log scale) over IPv4 (blue) and IPv6 (red) aggregated over all SamKnows probes.*

2) Google: On another SamKnows probe (deployed in Japan) we noticed how there were no measurements being performed to any of the google websites. Fig. 14 shows BGP-based clusters formed from endpoints seen by this vantage point both over IPv4 and IPv6. The measurements appear to be active to Google CDNs over IPv4, but are completely absent for IPv6. The probe itself is also successfully able to measure against other websites over IPv6. We investigated the issue and found that this happens to be a network policy decision made by these content providers. For instance, Google used to perform `AAAA` prefix whitelisting to prevent users with broken IPv6 connectivity from requesting services over IPv6. Only the whitelisted DNS resolvers received `AAAA` records for Google services. This was an opt-in process, where an ISP explicitly signed up to receive Google services over IPv6. This helped ensure users had reliable IPv6 connectivity before trying to reach Google services over IPv6 [8]. Since the World IPv6 Launch Day in 2012[9], Google has changed their policy. The whitelist has been replaced by a blacklist[10]. This eliminates the opt-in process and increases the chance of a dual-stacked host reaching Google services over IPv6. However, if a host is behind a resolver from a blacklisted prefix, it will not receive Google services over IPv6 even though the host may enjoy perfect IPv6 connectivity from the network provider. The pie

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[9] *http://www.worldipv6launch.org*

[10] *http://www.google.com/ipv6/statistics/data/no_aaaa.txt*

chart in Fig. 15 shows a country-based distribution of the blacklisted prefixes. The geolocation of the prefix is fetched from the MaxMind[11] database. It appears, a large number of blacklisted prefixes appear to originate from Japan. These are ISPs whose DNS resolvers explicitly started filtering `AAAA` records after World IPv6 launch day and are now blacklisted. We checked and our probe appears to be behind such a blacklisted resolver.

V. CONCLUSION

We have performed a study using a metric that measures TCP connection establishment times to 100 dual-stacked websites from SamKnows probes connected behind both residential and NREN. Using a year-long dataset derived from these measurements we showed how popular websites cluster around CDN deployments. We showed how multiple websites are served from CDN caches deployed within access networks. We also witnessed cases where these CDN caches were present for IPv4, but were largely absent for IPv6 leading to relatively higher TCP connection establishment times. We also showed how CDN clusters and number of websites within each cluster vary depending on the used address family. The distributions of connection setup times revealed how IPv6 connectivity to popular CDN deployments have improved over time. We showed how `www.bing.com` stopped providing websites over IPv6 since Sep 2013 and how Google employ blacklists to block some hosts from receiving their services over IPv6.

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[11] *http://www.maxmind.com*

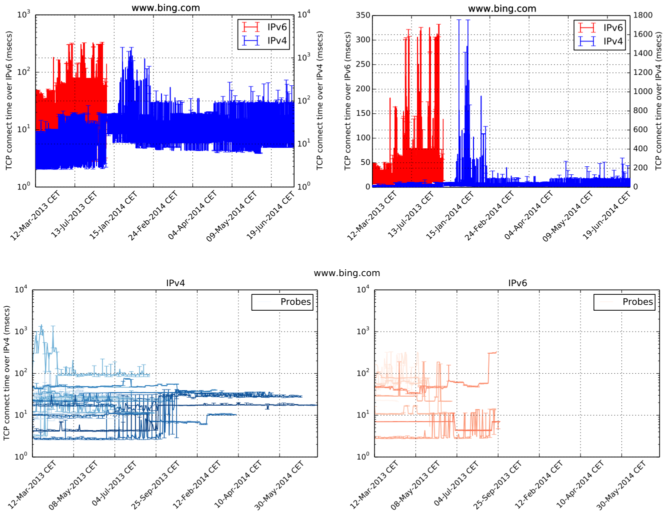

Fig. 13. *Time series of TCP connect times to www.bing.com over IPv4 (blue) and IPv6 (red) as seen from all (above) and each (below) vantage point. The measurements over IPv6 stopped for all probes starting Sep 2013.*

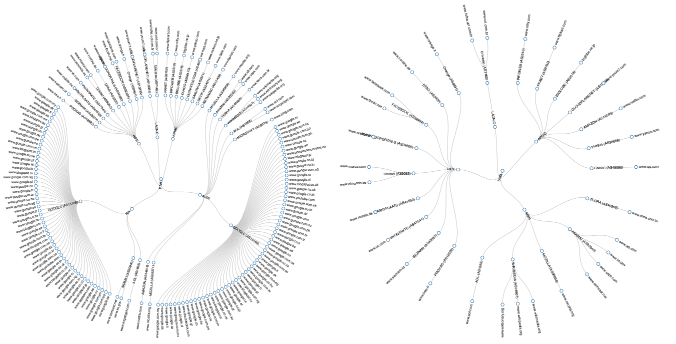

Fig. 14. *An IPv4 (left) and IPv6 (right) BGP-based aggregation of websites as seen by a SamKnows probe deployed in Japan connected via BIGLOBE NEC [AS2518, AS2516]. The probe does measurements to Google websites over IPv4, but not over IPv6. Its IPv6 connectivity is not broken, since it does perform measurements to rest of the websites over IPv6.*

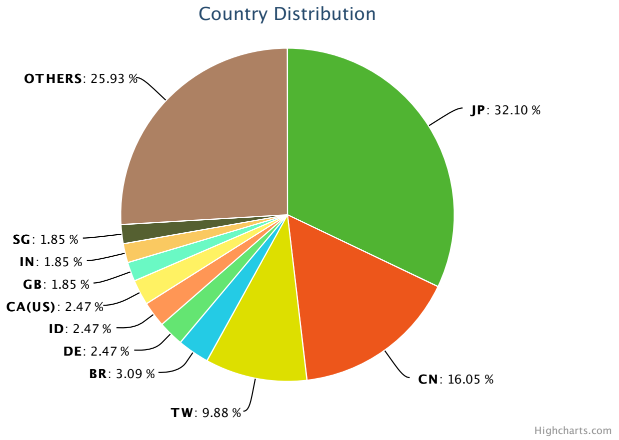

Fig. 15. *A distribution of prefixes blacklisted by Google over IPv6. A large number of resolvers in Japan appear to be blacklisted.*

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