

Bootstrapping Active IPv6 Measurement with IPv4 and Public DNS

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ABSTRACT

The IPv4 address space is small enough to allow exhaustive active measurement, permitting important insight into Internet growth, policy, and evolution. The IPv6 address space, on the other hand, presents the problem that we can no longer perform exhaustive measurements in the same way, inhibiting our ability to continue studying Internet growth. Access to private datasets (*e.g.*, HTTP access logs on content servers, flow data in ISP networks, or passive DNS traces) solves some problems but may not be feasible or desirable. This paper describes IPv6 address collection by exhaustively sweeping the reverse DNS domain for the IPv4 address space and performing AAAA queries on the results. Subsequent ICMP and TCP measurements are conducted to measure the responsiveness of the resulting set. Key outcomes include: the PTR sweep discovers 965,304 unique, globally routable IPv6 addresses originating from 5,531 ASNs. 56% of the addresses are responsive, across 4,571 ASNs. Upon inferring pairs of IPv4 and IPv6 addresses that are likely associated with the same device, the data indicates a trend toward IPv4 addresses being more responsive than their IPv6 counterparts, with a higher incidence rate of TCP connections being refused, and wide disparity on where TCP connections or ICMP echo requests fail silently when comparing IPv4 and IPv6. The disparity in IPv4 and IPv6 responsiveness is highly variable, and indicative of distinct host configuration and network policies across the two networks, presenting potential policy or security gaps as the IPv6 network matures.

1. INTRODUCTION

Exhaustive active measurement of the Internet’s IPv6 address space is infeasible: the current global allocation defines up to 2^{125} addressable hosts and 2^{61} addressable networks [2]. Individual IPv6 BGP advertisements are intractably large for exhaustive scans: BGP tables from February 29th 2016, 43.5% of advertisements were /48s (*i.e.*, 2^{16} individual /64s); 25.3% were /32s. The pace of growth in the IPv6 network necessitates additional sources of addresses for direct measurement, or to augment existing heuristics used to constrain the search space for active measurement.

The problem for active measurement in an IPv6 Inter-

net, therefore, is how to derive subsets of the IP space to use in measurement studies. There is no direct address mapping mechanism to determine the IPv6 address of a known-reachable IPv4 address. Traffic data is often used to understand the IPv6 address space: HTTP access logs at content servers, passive DNS traces, or network flow data, all of which can reveal subsets of the active address space. However, gaining access to these datasets may not be feasible or desirable, and often the data cannot be released publicly. Public sources will be used to locate IPv6 hosts for measurement or more nefarious purposes; it is important that the nature of publicly discoverable devices be understood.

This paper describes a study in which reverse DNS queries are made against all publicly routable IPv4 addresses advertised on February 29th 2016. The resulting names are then used to perform forward AAAA queries in order to derive a large set of around 1 million unique IPv6 addresses. This technique relies on the assumption that there is often physical and naming overlap with IPv4 for reasons of minimising costs and simplifying network management; it is likely to commonly produce IP addresses assigned to infrastructure in addition to end-hosts and servers. The types of addresses returned, and the results of active ICMP and TCP measurements, are presented. Finally, a conservative pairing of IPv4 and IPv6 addresses is constructed; key to this part of the study is whether there is disparity, indicating immature network policy, or differing host configuration.

The contributions of this work include an evaluation of using the IPv4 space and DNS to discover IPv6 addresses for active measurement, an analysis of the liveness of those addresses using ICMP and TCP metrics, and an attempt at pairwise comparison of IPv4 and IPv6 addresses likely assigned to the same device to determine whether there are gaps in network or host configuration or policies.

This paper is structured as follows: Section 2 covers background and related work. Sections 3 through 5 cover the collection of PTR records, the collection of AAAA records, then active measurement against those addresses respectively. Section 6 summarises the paper.

2. BACKGROUND

Other work has studied aspects of IPv6 deployment and maturity. Czyz *et al.* studied various metrics IPv6 deployment metrics [8], including nameservers with IPv6 connectivity, IPv6 glue records, queries arriving at nameservers, and others including active measurement on the top 10,000 domains listed in the Alexa top-million popularity index. The study shows that IPv6 is maturing by all metrics, though not all at the same pace.

Plonka and Berger contributed traffic measurements from Akamai’s content delivery network, and characterised the temporal stability of the IPv6 space in [8]. Their study features IPv6 addresses collected from HTTP access logs, and shows how hosts or ISPs use that space.

On network maturity, Livadaria *et al.* [16] compare aspects of IPv4 and IPv6 network stability, including routing stability and the effect on data-plane stability. Their findings suggest that the IPv6 network is proportionally less stable than the IPv4 network. Beverly *et al.* also recently studied router availability, albeit without a contrast to IPv4 stability [6]; much earlier work attempted to perform global topology discovery [20, 15]

Understanding the structure of the IPv6 Internet, and the means by which anybody may be able to conduct network measurement or by which attacks may be staged, is important; for example, how the IPv6 network structure may be used to launch malicious traffic [5]. Other work has listed speculative approaches or concerns around to active IPv6 measurement [12].

Some work has attempted to use the *ip6.arpa* DNS domain to locate public IPv6 addresses [10], though the approach may not return many responses [14]. Nikkiah *et al.* also used the Alexa top-million index to feed DNS queries to locate A and AAAA records to perform active measurements on connectivity and throughput [19].

Earlier work suggested that stateless addressing (SLAAC) or addressing that placed a device’s IPv4 address into the bottom 32-bits of its IPv6 were commonplace [17]. Since then, privacy extensions for autonomous host addressing were specified [18] and have become common primarily in end-hosts. RFC 7721 [7] provides an overview of privacy, and address generation mechanisms.

3. SWEEPING *IN-ADDR.ARPA*

The first step of this work is to collect DNS names from which AAAA records can be queried. The starting point is understanding that, first, the IPv4 space is currently under high utilisation and, second, that performing queries to retrieve PTR records for all IPv4 addresses is feasible and cheap. The *in-addr.arpa* domain is used as a means to perform a query against an IPv4 address, returning one or more names for a host if the owner of the address space has provided one.

The principle caveat is to note that there is no operational requirement for network administrators to config-

ure PTR records for their address space. While coverage will not be complete, the practice is currently common enough to provide a large set of names. In many cases, a successful query for a PTR record is likely to return a name that refers to a single network device.

3.1 Approach

To conduct all the DNS queries presented in this section and the active measurements presented in Section 5, four virtual hosts hosted by DigitalOcean were deployed in the UK. Each VM runs a local instance of *bind*, reachable only by processes on the localhost.

Each host ran a program dedicated to performing the DNS queries presented in this study (A, AAAA, and PTR), issuing and handling multiple DNS queries asynchronously with the assistance of *libevent*.

For each IPv4 address derived from a full routing table collected by Route Views on February 29th 2016 [3], a PTR query was sent and the responses, including error codes, stored for inspection. This table includes 2,814,910,336 global IPv4 addresses, each of which is used to create a reverse DNS query for this study. The AAAA responses are covered in Section 4.

DNS PTR queries took place between March 8th and March 17th 2016. DNSSEC was not used during this initial study, but should be enabled for future work. In cases where the DNS response is too long for a UDP datagram, queries are reissued over TCP.

3.2 PTR Responses Obtained

A summary of responses is outlined in Table 1(a). 1.19 billion queries returned names (around 42.8%). 1.4 billion return an NXDOMAIN error, with no configured subdomain for the address space. Around 200 million returned a server failure code, and another 3 million where the domain is configured but no record is found. A small number of queries failed with timeouts. From the set of 1.4 billion queries that returned an answer, a short breakdown of obvious misconfigurations of bad data is presented in Table 1(b).

24,945 names returned multiple PTR records. A partial distribution of the larger answer sets is shown in Figure 1, indicating that after the common convention of one record per name, the most common PTR sets, though rare, are 15-20 records in size. The largest set observed from a PTR query was 1,248 records associated to one IPv4 address. Breaking out the records that returned multiple responses, we have a full set of 1,190,767,539 names.

The names revealed through this process often identify infrastructure nodes (routers, middleboxes, firewalls, etc) in addition to hosts intended for use as public servers. Common strings surface: “static”, “customer”, “gw”; numeric strings and two or three-character codes. The set of names is therefore distinct from datasets

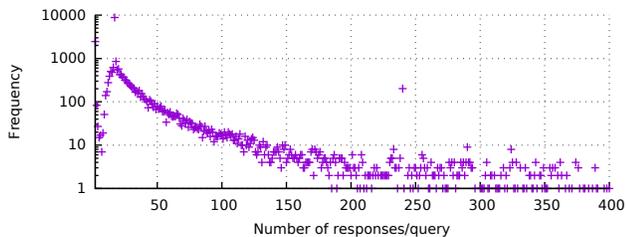


Figure 1: Partial range of PTR response sets larger than one record; full range includes sets with over 1,000 records.

Type	Count	String	Count
No domain	1,421,766,914	localhost	2,401,398
Serv failure	199,697,905	empty string	965,114
No data	3,055,458	IPv4 addr	184,858
Other	32,112	127.0.0.1	1,517
No Error	1,190,362,811	0.0.0.0	10
Total	2,814,915,200		

(a) Response types

(b) Notable results

Table 1: PTR query response overview.

based on common web accesses or DNS requests. In addition, many of the names resolve directly to one network device, rather than a name that points into a geo-based DNS load balancer.

“localhost” is associated with 2.4M addresses, and various other strings that appear to be configuration error are returned; the empty string is associated with almost 1 million IPv4 addresses, and often the PTR record is a string of the IPv4 address used to create the query. These are summarised in the right-hand column of Table 1.

4. IPV6 ADDRESS SWEEP

The names discovered in the previous section form the basis for the next stage, querying for AAAA records.

4.1 Approach

Using the same infrastructure as the name collection stage, a AAAA query was issued for each of the 1,190,767,539 names, and the responses were collected. These queries were conducted between March 24th and March 28th. Results from the previous section were not de-duplicated, but *bind* was configured to cache results to minimise the number of duplicate queries emitted.

4.2 Results

An overview of the responses in this stage is shown in Table 2(a); 4,742,818 queries (0.4%) returned AAAA records, with particular responses shown in Table 2(b): for example, 2.4 million responses were the result of querying the “localhost” string from the PTR sweep, and a further million came from a common string

Type	Count	Type	Count
No data	856,923,311	::1	2,401,386
No domain	315,419,165	level3	1,024,600
Server failure	13,678,831	prefix::	7,715
Timeout	3,414	::	84
No error	4,742,818		
Total	1,190,767,539		

(a) Response types

(b) Notable results

Table 2: Overview of results to the AAAA queries.

Network Name	ASN	#	Country	Count
SURFnet (NL)	1103	93,649	DE	237,896
Deutsche Tele. (DE)	3320	79,903	US	222,528
1&1 (DE)	8560	51,326	EU	123,423
Comcast (US)	7922	43,384	RU	43,679
GMO (JP)	7506	40,672	GB	40,082
Yandex (RU)	13238	35,109	FR	33,733
Host Europe (DE)	20773	23,522	NL	28,547
Hetzner Online (DE)	24940	19,404	CZ	15,949
Contabo (DE)	51167	15,516	NO	11,355
CloudFlare (US)	13335	14,387	SG	11,198

(a) ISPs

(b) Country Codes

Table 3: Networks and countries with the greatest number of unique IPv6 addresses discovered.

“unknown.level13.net”, which all resolved to 2001:1900:2300:2f00::ff at the time of the study. This leaves 1,316,832 AAAA responses. After removal of duplicates and non-routable addresses with no corresponding ASN in the BGP table, 965,304 unique, globally routable IPv6 addresses remain. These occupy 328,134 /64s, and originate from 5,531 ASNs.

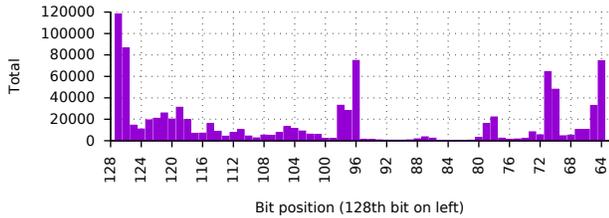
The number of addresses matching each origin ASN is heavily skewed: 3,132 are small, returning fewer than 10 IP addresses; 717 IPv6 addresses are the only address from that ASN; 626 ASNs have two IPv6 addresses; 412 have three. 1,826 return 10 or more, but fewer than 100 IPv6 addresses, and 573 ASNs return more than 100 IP addresses. The largest of these have tens of thousands of IP addresses in the DNS.

Table 3(a) enumerates the top 10 ASNs from the data, given unique occurrences of IP addresses. The geographic diversity of the networks is evident; notable is the variety of providers listed: domestic ISPs are present, but so too are virtual hosting companies, research networks, and content delivery networks. The range of networks is of particular importance: passive address collection from content networks has a tendency to skew towards collecting address sets from domestic ISPs, and not a wider variety of networks. Table 3(b) indicates the country-level distribution, according to the country code for the ASN registered by the regional internet registries.

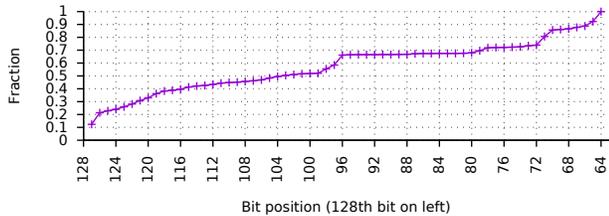
Table 4 describes sets of IPv6 addresses discovered that match the blocks defined in the IANA special-

Class	Count	Class	Count
6to4	109,078	::	84
v4-mapped Addr	5,080	Teredo	72
::1, not "localhost"	4,350	Documentation	18
Link-local	981	IETF	5
IPv4-v6 Translat.	555	Direct, AS112	3
Unique-Local	553		

Table 4: Overview of special-purpose addresses.



(a) Frequency of first bit set in IID (note: reverse x-axis)



(b) Cumulative form of (a).

Figure 2: Bit patterns in the addresses returned.

purpose IPv6 registry. 103,928 queries of those returned one or more of the same *class* of special-purpose address, outlined in Table 4.

Figure 2 indicates structure in the lower 64 bits, the Interface ID (IID) portion, of the addresses. The IID can be generated by various mechanisms; for fixed infrastructure, these are often statically assigned and likely to follow well-defined patterns. Using the addresses obtained, these plots show how frequently each bit is the first bit set in the IID portion; that is, they are a measure of the string of zeros before any set bits. Note that the least significant bit of the address space is on the left-hand side of the plots. In these addresses, Figure 2(a) indicates clearly that the 127th and 128th bits are commonly the only bits set in the addresses discovered in this study, but there are other bumps near some byte boundaries. Figure 2(b) shows the same data in cumulative form. We can see that for 50% of these addresses, the first bit set is the 104th bit or later, and for two thirds of the addresses, the first bit is the 96th bit or higher. Such indicators are useful in constraining the speculative measurement space.

Other notable address counts are as follows:

All-zeros: 7,715 returned addresses have an IID set to zero; in 84 returned addresses, *all* bits are zero.

Stable IIDs: 73,532 addresses were returned with bits 7 and 25 – 39 (“*ff:fe*”) set in the IID, indicating a SLAAC address generated from a MAC address. 72,888, are globally routable, associated with hosts from 1,007 different ASNs. RFC 7043 [4] states that these static addresses should not be published in the DNS because of the the privacy concern they present.

Special-Purpose Addresses: Table 4 lists the number of names that resolve to special-purpose IPv6 address ranges [1]. In all, 120,780 queries returned a special-purpose address. Some 304 names returned *both* globally routable addresses and special-purpose addresses.

Non-standard Addresses : 28,889 unique responses fall outside the standard IANA allocations. Many of those are the origin IPv4 address in the bottom 32-bits without the network portion set, much like the deprecated IPv4-Compatible IPv6 Addresses [13]. Many others are 32-bit values padded into the most significant bits of the returned address, which do not appear to match the origin IPv4 address.

::1: The origins of the *localhost* strings in Table 2 is largely constrained to a small set of ASNs, primarily registered in Vietnam; the largest contributors are ASNs 45899, 7552, and 7643.

4.3 Pairing IPv4 and IPv6 Addresses

Next, we attempt to consider IPv4 and IPv6 addresses in pairs. Attempting to pair addresses across protocol families offers scope for direct like-for-like measurement of performance or network policy, against infrastructure which is not as heavily monitored as, say, content servers. It may be possible to determine the gaps in host configuration and security policies between the IPv4 and the IPv6 networks.

To pair IPv4 and IPv6 addresses, the following approach was used: in each of the cases where an AAAA query returned at least one result which was a globally routable address with an ASN in the routing table used throughout this paper, an additional A query was attempted on the same domain name. There are of course many cases where names may resolve to multiple addresses (for either family); to pair addresses, I have conservatively retained only IP addresses following the following criteria: addresses resolve from the same name, originate from the same ASN, and where no address resolves against any other name with a contradictory result. Note that this could be expanded in cases where the same *organisation* uses multiple ASNs.

This process leads to 673,108 *pairs* of unique IPv4 and IPv6 addresses originating from 5,228 ASNs.

Note there is no requirement that A and PTR records transpose: querying the PTR record for a given IP ad-

dress then the A record of the resulting name need not return the original IPv4 address. Further, the name in the PTR record may have A and AAAA records, but without any requirement that they map onto the same network device. In the common case, however, it is likely that there is a strong correlation of A records and AAAA records mapping onto a single device or interface, not least to reduce management complexity.

4.4 Summary

Although the yield on this form of collection is low, the range of addresses obtained and the location of those (by ASN, registered country, and set of ISPs) is broad. As a data source for forming sets of addresses for measurement, range is important. Broad coverage such as this helps us to understand the subnets actually in use as a subset of what is visible in BGP, and to better understand static address allocation patterns within networks. The addresses found here are used in the following section.

5. ACTIVE MEASUREMENT

In this section, we will use a limited set of active measurements to better understand how active the set of addresses is. These measurements are intended as a lightweight first attempt at characterising the addresses, rather than anything that may be construed as invasive port scanning or flooding.

While tools exist specifically for either port scanning (*nmap*) or rapid measurement of the IPv4 address space (*zmap* [11] and *masscan*), tooling for large-scale scanning is weaker for IPv6. *scan6* attempts to speculatively search IPv6 networks with various heuristics; in this work, we have a fixed set of target addresses.

The two broad tests conducted on these addresses were ICMP echo requests, and TCP connection attempts to various well-known port numbers. These tests used the same virtual machines as used for the DNS queries, employing GNU Parallel with standard tools: *ping* and *ping6* for the echo requests, and the standard OpenBSD release of *netcat* for TCP connections.

The set of unique IPv6 addresses was reordered using the GNU tool *shuf*, and the paired IPv4 addresses identified in Section 4.3 were inserted adjacent to their IPv6 counterpart. This list was divided across the four virtual machines, and each individual step scheduled to take approximately 24 hours. The intention here is to be deliberately lightweight, taking measurements against apparent pairs at approximately the same time but otherwise attempting to stage the work such that consecutive runs of addresses are avoided.

5.1 Ethical Considerations

The measurements for this study were all conducted against IP addresses publicly listed in DNS: no brute-

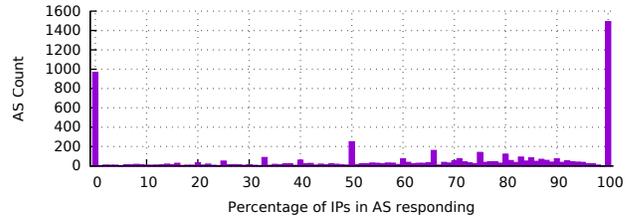


Figure 3: Histogram showing distribution of ASNs responding to echo requests.

force or speculative measurement was attempted. The measurements relied on no unusual TCP or IP options, didn't send any data aside from packets required for echo requests, TCP handshakes, and TCP teardowns. TCP connections were closed immediately if successful, and no data from the connection was read or stored. Nothing other than the outcome of an echo request or a connection attempt is stored (packets, payload, etc, are all discarded immediately).

The hosts running the measurements also each ran a webserver, configured to serve an informational page on the study with contact details. Five networks requested, via DigitalOcean, that the measurements cease. In these cases, all addresses advertised from the ASN identified in the report from future measurements.

5.2 ICMP Echo Requests

Three ICMP echo requests were sent to each target address, the address marked active if any responses were received. Timeouts of 3s were recorded.

544,156 addresses (56.7%) responded to echo requests, across 4,573 ASNs (82.7% of the ASNs discovered in Section 4). The range of responses by ASN, as a percentage of the set of IP addresses per ASN, is indicated in Figure 3; the clear bimodal pattern is generated by ASNs with small sets of hosts either all responding or not responding at all, while the ASNs with larger address sets offer a much more varied response.

5.3 TCP Measurements

TCP connections were attempted to the addresses discovered in the previous section, on a range of port numbers: 21, 22, 53, 80, 443, and 8080. The purpose is not to be exhaustive, merely to investigate common port numbers to determine if there are gaps in policy or configuration. The full list of addresses was tested against one port before progressing to the next. Connections were staged slowly, paced at around 85,000 addresses an hour. When a TCP connection timed out (using a 3s timer), no retry was attempted.

Broadly, on port 80, around 21.1% of connections were made successfully, and 13.3% were refused; on port 22, 18.5% were successful and 9.4% refused. In all cases, around 60% of requests were silently dropped.

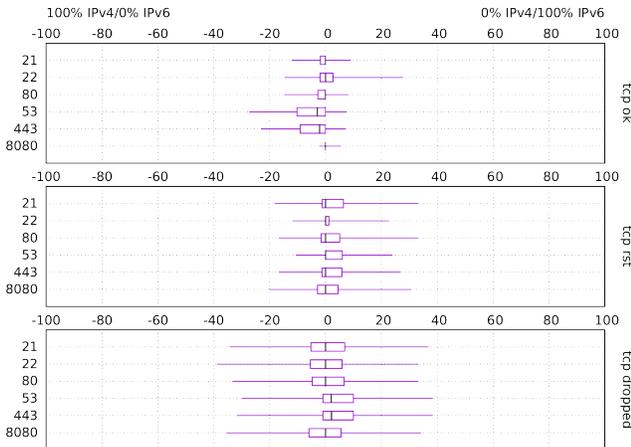
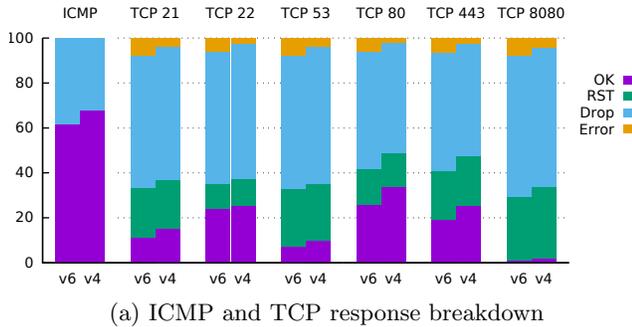


Figure 4: ICMP and TCP response rates.

Notably, 31,527 addresses accept or reset a TCP connection (on at least one of the ports tested) in cases where ICMP echo requests were not returned. This may be intentional, if network administrators have decided to drop ICMP traffic to or from hosts against the current practice specified in [9].

5.4 Evaluating the IPv4-IPv6 Pairing

Here, we will refer to the pairs of addresses identified in Section 4.3. Figure 4(a) presents an overview of the response rates for echo requests and TCP connection attempts on the port numbers tested. First, note that on this smaller set of addresses, the ICMP echo response rate is slightly higher than the full set of addresses available, with 61.7% of the paired IPv6 addresses responding. The response or success rates on all tests was lower on IPv6 than IPv4, however: 67.8% of the IPv4 addresses responded to echo requests.

Figure 4(b) attempts to break down the distributions of the response rates in each ASN according to the type of the response. In all cases, IPv4 hosts are more likely

to respond to ICMP echo requests, and are more likely to accept connections on the ports tested, while the IPv6 devices are more likely to reject connections, implying services are configured to listen on IPv4 but not yet on IPv6. TCP drop ratios are, on average, equivalent for IPv4 and IPv6 traffic, though the spread in individual networks is wide. These trends are not universal, and there is wide disparity in responses across networks. The data presented here suggests there are gaps in host or network policy between IPv4 and IPv6; in some cases this may be intentional, for example if server software isn't deemed stable with IPv6 traffic.

6. CONCLUSIONS/IMPLICATIONS

This paper has presented an approach for discovering IPv6 addresses that can be used for public measurement. By sweeping PTR records of the IPv4 address space as advertised in BGP then performing AAAA queries against the returned names, 965,304 unique IPv6 addresses are located in 5,531 autonomous systems. 56.7% of those respond to ICMP echo requests from 82.7% of those autonomous systems.

On attempting to pair IPv4 and IPv6 addresses, 673,108 pairs of unique IPv4 and IPv6 addresses originating from 5,228 are discovered in ASNs. 61.7% of the IPv6 addresses respond to echo requests compared to 67.8% of the IPv4 addresses. Performing TCP measurements against these addresses exposes a similar trend: devices are more likely to respond over IPv4 than over IPv6. The causes of this are unclear, but a slightly higher proportion of IPv6 hosts refusing connections implies host configuration for services lagging network policies.

While this approach relies on the IPv4 space to locate IPv6 addresses on which measurements can be attempted, the IPv4 network is a resource that we should not ignore while it is still dominant. Obviously, approaches must change in future when IPv6 becomes the dominant protocol family.

This study highlights some configuration, privacy, or security concerns. For example, SLAAC addresses in the DNS may be intentional or accidental. Similarly, dropped ICMP traffic may be intentional, or indicative of immature network security policies.

Finally, this study has shown some structure evident in the IPv6 addresses collected. Bit patterns from real IPv6 deployments, especially for fixed infrastructure, is useful to help improve existing heuristics for speculative active measurement studies. Such heuristics are by definition not exhaustive, but may allow active measurement studies of the IPv6 space similar to the large body of existing IPv4 active measurement work.

7. ACKNOWLEDGEMENTS

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