

# Temporal and Spatial Classification of Active IPv6 Addresses

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## ABSTRACT

There is striking volume of World-Wide Web activity on IPv6 today. In early 2015, one large Content Distribution Network handles 50 billion IPv6 requests per day from hundreds of millions of IPv6 client addresses; billions of unique client addresses are observed per month. Address counts, however, obscure the number of hosts with IPv6 connectivity to the global Internet. There are numerous address assignment and subnetting options in use; privacy addresses and dynamic subnet pools significantly inflate the number of active IPv6 addresses. As the IPv6 address space is vast, it is infeasible to comprehensively probe every possible unicast IPv6 address. Thus, to survey the characteristics of IPv6 addressing, we perform a year-long passive measurement study, analyzing the IPv6 addresses gleaned from activity logs for all clients accessing a global CDN.

The goal of our work is to develop flexible classification and measurement methods for IPv6, motivated by the fact that its addresses are not merely more numerous; they are different in kind. We introduce the notion of classifying addresses and prefixes in two ways: (1) *temporally*, according to their instances of activity to discern which addresses can be considered stable; (2) *spatially*, according to the density or sparsity of aggregates in which active addresses reside. We present measurement and classification results numerically and visually that: provide details on IPv6 address use and structure in global operation across the past year; establish the efficacy of our classification methods; and demonstrate that such classification can clarify dimensions of the Internet that otherwise appear quite blurred by current IPv6 addressing practices.

## 1. INTRODUCTION

In 2015, we are in an era of production-quality, simultaneous operation of the Internet protocol version 4 (IPv4) and version 6 (IPv6). A number of observers have reported IPv6 traffic volume as doubling in the past year, and globally over 6% of clients having IPv6 connectivity [2, 26, 35]. In the fourth quarter of 2014, in some networks a significant pro-

portion of World-Wide Web (WWW) clients used IPv6 to access content that is available over both IPv6 and IPv4 via a global Content Distribution Network (CDN): in the United States, this proportion was 70% for Verizon Wireless, 30% for AT&T, and 27% for Comcast [3].

In this work, we study populations of active IPv6 addresses, *i.e.*, those observed to be sources of traffic rather than merely allocated or assigned. Like most censuses, ours involves counting members of groups or *classes*. IP addresses can be classified with respect to various dimensions. Historically, for IPv4, the initial address “classes” were determined *a priori* as classes A, B, C, *etc.* Following the introduction of classless inter-domain routing (CIDR), IPv4 addresses would more naturally be classified based on flexible aggregates in routing tables, such as that of their Border Gateway Protocol (BGP) prefix. Addresses can also be classified based on the set of reserved and special-use prefixes, *e.g.*, RFC1918 and multicast. However, operational needs have led to a broader notion of address class, even if not referred to as “class” *per se*, nor are classes mutually exclusive. Some example IPv4 address classifications of recent interest are based on client reputation, geolocation, assignment to a common network element (*e.g.*, router aliases), anycast, and proxy.

Most of these classes pertain to both IPv4 and IPv6 addresses. However, two dimensions are more significant with IPv6, and are the focus of this paper. The first we call “temporal” and is primarily motivated by the popularity of host privacy extensions whereby the vast majority of IPv6 addresses exist for short periods, *e.g.*, 24 hours or less, and in all likelihood will never be used again. The second we call “spatial” and pertains to the vastly greater number of possible areas (prefixes) and positions (addresses) in the IPv6 address space. Whereas scanning the full IPv4 address space is now routine, this is not feasible for IPv6, and one needs other techniques to discover

“where the action is.” IPv6, also, allows greater freedom in the use of the subnet prefix. We find a variety of practices employed by different network operators. Our goal is to detect the different types of IPv6 addresses in active use, with particular interest in (a) discriminating *stable*, persistent addresses from *ephemeral*, short-lived addresses and (b) discovering how addresses are arranged in the address space, thereby forming *sparse* and *dense* regions.

There are numerous potential applications of temporal and spatial address classification. Examples include: selecting targets for active measurements, *e.g.*, traceroutes, vulnerability scans, and reachability surveys; informing data retention policy to prevent resource exhaustion, *e.g.*, when encountering many ephemeral addresses or prefixes; informing host reputation and access control, *e.g.*, to mitigate network abuse; identifying homogeneous address aggregates, *e.g.*, for IP geolocation; and detecting changes in network operation or estimating Internet usage over time.

This paper makes the following contributions:

(1) We present census results based on a large-scale, longitudinal, passive IPv6 measurement study of *active addresses* used by active WWW clients in 133 countries and over four thousand autonomous systems. (2) We introduce a *temporal* classification technique for IPv6 addresses based on observation of address activity over time. (3) We introduce a complementary *spatial* classification technique for IPv6 addresses based on measurement of the sparsity or density of the address prefixes in which they reside. (4) We evaluate the temporal and spatial classifiers by utilizing them *in situ*, and show results of the classification of billions of active IPv6 addresses.

In addition, we introduce the Multi-Resolution Aggregate (MRA) plot, a visualization useful for examining populations of addresses. This plot is inspired by the work of Kohler *et al.* [27], and embellished for IPv6. MRA plots show structural detail and allow address space exploration without necessarily identifying specific addresses or blocks by number.

Highlights of our measurement and classification results include, as of early 2015:

- When autonomous systems (ASNs) are ranked by their WWW client address counts, the top 5 ASNs represent 85% of active /64 prefixes (“/64s”) and 59% of all active addresses. Of these ASNs, 2 are U.S.-based mobile carriers, *i.e.*, wireless Internet Service Providers (ISP); the others are a European, an American, and a Japanese ISP.

- Although the vast majority of IPv6 clients use native transport, 6to4 tunneling is still common. If not

segregated in measurement, the ASNs hosting 6to4 relays would be amongst the top 5 ASNs.

- 74% of the 153 million of the /64s observed as active during two weeks separated by 6 months are associated with just 1 ASN.

- Despite the vast IPv6 unicast address space and generous allocations to networks, many /64s are *reused*, *i.e.*, assigned to different users over time, certainly within a week.

- Of 1.81 million addresses observed as *stable* across 1 year, over half a million are associated with two mobile carriers which, in apparent contradiction, use *dynamic* values in network identifiers. Further investigation shows that many mobile devices simultaneously use the same fixed interface identifier. Combined with dynamic /64 assignment, this can result in an IPv6 address being reused by a different subscriber on a short timescale, *e.g.*, within days.

- While privacy addressing is common and brings randomness and sparsity to address values, there are many dense regions of IPv6 address space where addresses are well-ordered and tightly-packed. 49% of active IPv6 ASNs have BGP prefixes containing such regions, *e.g.*, /112 prefixes (64K address blocks) containing multiple active WWW client addresses. These blocks are natural targets if future, active scanning or probing is intended.

The remainder of this paper is organized as follows. In Section 2, we discuss related prior work. In Section 3, we give a brief introduction to IPv6 addresses. In Section 4, we describe the data used in our empirical study. In Section 5, we present our IPv6 address classification methods. In Section 6, we present results of our temporal and spatial classifications. In Section 7, we discuss results and future work, and subsequently conclude.

## 2. RELATED WORK

To our knowledge, our temporal classifier does not have a precedent in the research literature. The temporal characteristics of IPv4 addresses, however, became topical as scalability concerns arose with the Internet’s exponential growth in the 1990s. Carpenter *et al.* comment on this in RFC 2101 [9]. With respect to IPv6, Malone’s work [29] is similar to ours in that they also study active IPv6 addresses. They develop a technique intended to classify short-lived privacy addresses by examining only the address itself, but its accuracy is limited by design, expected to identify approximately 73% of all privacy addresses. Since it is very challenging to detect randomness in short strings, *e.g.*, 63 bits of an IPv6 address, we take the complementary approach and identify those

addresses that are stable and, thus, almost certainly *not* privacy addresses. In the end, Malone speculates that “[accuracy] might be improved accounting for the times addresses are observed and spatially/temporally adjacent addresses,” which seems exactly the notion at which we arrive independently, inspiring the strategies that we develop here.

Development of our spatial classifier is largely informed by the prior work of two teams: Cho *et al.* and Kohler *et al.* Cho *et al.* [11] introduce *aguri*, a traffic profiler that employs automatic aggregation based on addresses’ and prefixes’ observed traffic volume. As in their work, we find their Patricia/radix tree-based aggregation useful in dealing with resource constraints, however, we use it to discover *address structure*. We do this by aggregating to a threshold that is either (a) a percentage of total addresses or (b) a prefix density, rather than a percentage of total traffic volume. This aggregation method is useful because it generalizes to other metrics.

Kohler *et al.* [27] investigate the structure of the IPv4 address space based on passive traffic analysis. In a broad sense, our IPv6 investigation is similar and we employ two of their metrics as-is: active aggregate counts and aggregate population distributions. IPv6 addresses, however, present different challenges and opportunities to discern structure, so we develop new IPv6-specific metrics. Our work also differs in that we apply those metrics to classify addresses rather than to evaluate mathematical characterizations of the address space.

Dainotti *et al.* [15] investigate IPv4 address space usage by attempting to identify active and inactive /24 address-blocks using passive measurement. Our census of WWW client addresses similarly employs passive means, but we count aggregates of every possible prefix length. Also, because we determine address activity from the complete logs of all clients’ successful WWW transactions with a large CDN, we eschew complications introduced by spoofed addresses. While they propose that their method could potentially apply to measuring IPv6 address space usage, they do not discuss how it might treat persistent versus ephemeral addresses nor if it could count addresses in “small” address-blocks, *e.g.*, smaller than /64 prefixes. Our method would likely complement theirs, if applied to IPv6.

In 2012, Barnes *et al.* [7, 12] evaluated methods to map the vast IPv6 address space by probes in order to discover active addresses. Our work shares that goal but benefits from increased IPv6 activity and content-accessibility that make passive methods viable. The stable addresses and dense address re-

gions that we identify are feasible targets for active scans or probes, thus our method may repair or complement target selection heuristics employed in their early survey. Still, like Barnes *et al.*, our work is guided by operator practice with respect to IPv6 addressing.

There are a number of studies in the literature that measure and report on the deployment and adoption of IPv6. Recent examples of such work are those of Colitti *et al.* [13] and Czyn *et al.* [14] Our work differs in that we measure IPv6 by counting active addresses and prefixes, rather than by counting advertised prefixes or traffic hits and bytes. Each have different biases with respect to estimating usage. Internet-wide surveys of active IPv6 addresses are scarce in the literature, *e.g.*, Malone [29] circa 2008. However, Huston and Michaelson [25, 26], perform a significant ongoing measurement study involving IPv6 addresses; they observe activity by opportunistically running “interactive” advertisements that are crafted to elicit connection attempts from WWW clients to their own measurement service via both IPv4 and IPv6. Our study is limited to IPv6, but seems to offer different advantages. They observe the IPv4/IPv6 address pairs associated with WWW clients. We observe significantly more activity from mobile carriers, where the ads rarely run, and activity in a larger set of ASNs [31, 24].

### 3. IPV6 ADDRESSES

Here we present a brief introduction to IPv6 address assignment. An IPv6 address consists of a leading network identifier, *a.k.a.* subnet prefix, portion followed by an interface identifier (IID) portion. The network identifier is used to route traffic destined for this address to its Local Area Network (LAN) and the IID makes a host interface’s address unique on its local network segment. While superficially similar to the network and host identifier portions of IPv4 addresses, the vast IPv6 address space allows much more freedom.

There are many IPv6 addressing schemes and network operators are reminded to treat interface identifiers as semantically opaque [10]. In this work, however, we utilize address content, including IID, as a basis for classification and find correspondences with a variety of standards-defined address types. For instance, administrators have the option to use a /64 network prefix and a rather large IID, *i.e.*, 64 bits [21], or a larger network prefix, *e.g.*, /127, and a smaller IID, *e.g.*, only 1 bit [16, 28]. In the former case, with stateless address auto-configuration

(SLAAC), the host chooses a 64-bit IID suffix for itself. Consider the sample addresses in Figure 1. In increasing order of complexity, these addresses appear to be: (i) an address with fixed IID value (: :103), (ii) an address with a structured value in the low 64 bits (perhaps a subnet distinguished by : :10), (iii) a SLAAC address with EUI-64 Ethernet-MAC-based IID, and (iv) a SLAAC privacy address with a pseudorandom IID.

```
2001:db8:10:1::103
2001:db8:167:1109::10:901
2001:db8:0:1cdf:21e:c2ff:fec0:11db
2001:db8:4137:9e76:3031:f3fd:bbdd:2c2a
```

Figure 1: Sample IPv6 addresses in presentation format with the low 64 bits shown bold.

The first two addresses are similar to those created by traditional addressing schemes used in IPv4 while the latter two use standard IPv6-specific addresses schemes: EUI-64 [38] and privacy addresses [32], respectively.<sup>1</sup> Since one might reasonably expect these interface identifiers to be difficult to distinguish merely by their content, we employ temporal analysis to discriminate these from, at least, privacy addresses.

A number of transition mechanisms aid concurrent operation of IPv6 with IPv4 and affect IPv6 addresses themselves. These include: 6to4 relays [22] and Teredo [23], which employ global reserved prefixes; and ISATAP [37] which embeds IPv4 addresses in the IPv6 IID. Finally, there are additional *ad hoc* schemes by which an IPv6 address contains an embedded IPv4 address, *e.g.*, those used for some router and dual-stack host interfaces. This is typically a convenience rather than a requirement.

## 4. EMPIRICAL DATA

Our study requires data sources containing IPv6 addresses which are active, that is, addresses that exchange globally-routed Internet traffic.

### 4.1 WWW Client Addresses

We primarily rely on aggregated logs of WWW server activity in this study. These aggregated logs contain hit counts per client IP address. We select only the client IP addresses from log entries that represent successfully handled requests, thus avoiding spoofed sources. The aggregation interval is 24 hours, for

<sup>1</sup>Other IPv6 address schemes by which interface identifiers are generated include: Cryptographically Generated Addresses [4, 6], Hash-Based Addresses [5], and stable privacy addresses [19].

55,000 of the CDN’s IPv6-capable servers, and is processed roughly by the end of the subsequent day. Note that the aggregation does not include the timestamp from the individual log lines, used in separate processing for the CDN’s customers. Instead, we use the time epoch of the completion of processing of the aggregated logs, which might be offset by as much as a day from when the requests actually occurred. Our stability analysis, described in Section 5, uses a heuristic to accommodate this timestamp slew.

In March 2015, the dataset contains IPv6 addresses in 6,872 BGP prefixes originating from 4,420 ASNs (46% of those advertising IPv6 prefixes). These figures are an increase from March 2014 when there were 5,531 BGP prefixes originating from 3,842 ASNs (40%). Alas, we certainly do not see traffic from all the world’s WWW client addresses at this observation point, and our stability analysis shows that some specific long-lived active IPv6 addresses, *e.g.*, EUI-64, return as WWW clients only infrequently.<sup>2</sup>

Table 1 summarizes the IPv6 WWW client address activity observed across a year at 6 month intervals, March 2014 through March 2015; we report both daily and weekly counts. With daily counts, fewer ephemeral privacy addresses are observed, while with weekly counts there is increased opportunity to observe activity of WWW clients that visit the CDN less frequently than daily.

In Table 1, by March 2015, we see that the address count increased to over 318 million observed daily and over 1.8 billion observed in a week’s time. Correspondingly, 121 million /64 prefixes are observed daily and 307 million /64 prefixes in a week’s time.

We are careful to separate client addresses involving some IPv6 transition mechanisms from addresses involved in “native” IPv6 end-to-end transport; this is because those transition mechanisms’ addresses would skew results. Specifically, we cull addresses associated with the early IPv6 transition mechanisms, *i.e.*, Teredo, ISATAP, and 6to4. Of these, only 6to4 still shows significant use. Since these 3 particular transition mechanisms’ addresses are easily classified, we focus our classifiers on the “Other” addresses, *i.e.*, those involving native, end-to-end IPv6 transport. Newer transition mechanisms such as 464-XLAT [30] and DS-Lite [17, 8], *e.g.*, used by large mobile carriers, are included because they use IPv6 end-to-end, and thus represent native transport. These

<sup>2</sup>Some addresses that we label as EUI-64 are false positives or have invalid or duplicate MAC addresses, *e.g.*, MAC address 00:11:22:33:44:56 is the most prevalent and just in one mobile carrier’s network. Otherwise, examination suggests these outliers are modest in number.

Characteristic	Mar 17, 2014	Sep 17, 2014	Mar 17, 2015
Teredo addresses	1.98K (0.00%)	3.28K (0.00%)	20.1K (0.01%)
ISATAP addresses	90.2K (0.06%)	101K (0.04%)	133K (0.04%)
6to4 addresses	12.8M (7.97%)	12.5M (5.90%)	13.9M (4.19%)
<b>Other addresses</b>	<b>149M (92.0%)</b>	<b>199M (94.1%)</b>	<b>318M (95.8%)</b>
<b>Other /64 prefixes</b>	<b>61.4M</b>	<b>82.9M</b>	<b>121M</b>
ave. adrs per /64	2.41	2.40	2.63
EUI-64 addr (/16to4)	3.13M (1.94%)	3.66M (1.73%)	4.49M (1.35%)
EUI-64 IIDs (MACs)	2.85M	3.23M	3.81M

(a) Address characteristics per day

Characteristic	Mar 17-23, 2014	Sep 17-23, 2014	Mar 17-23, 2015
Teredo addresses	15.1K (0.00%)	24.5K (0.00%)	131K (0.01%)
ISATAP addresses	210K (0.02%)	238K (0.02%)	346K (0.02%)
6to4 addresses	64.9M (7.22%)	78.3M (6.34%)	64.2M (3.43%)
<b>Other addresses</b>	<b>833M (92.8%)</b>	<b>1.17B (94.9%)</b>	<b>1.80B (96.5%)</b>
<b>Other /64 prefixes</b>	<b>157M</b>	<b>207M</b>	<b>307M</b>
ave. adrs per /64	5.32	5.64	5.88
EUI-64 addr (/16to4)	8.88M (0.99%)	13.1M (1.06%)	16.2M (0.866%)
EUI-64 IIDs (MACs)	6.12M	8.16M	9.74M

(b) Address characteristics per week

Table 1: Active IPv6 WWW client address characteristics: March 2014 through March 2015.

“Other” addresses in Table 1 account for over 90% of the active addresses observed. Except for EUI-64 addresses, these can’t easily be classified by examination of address content based on standard formats. These “Other” addresses are subjects for the classifiers we introduce in Section 5 and are those for which we report results unless otherwise noted.

## 4.2 Router Addresses

In addition to periodic collection of active WWW client addresses, we also collect a set of IPv6 addresses that were the source addresses of ICMP “Time Exceeded” responses to our TTL-limited probes, similar to those generated by the *traceroute* tool. Based on collection in February 2015, this dataset consists of 3.2 million addresses that appear to be assigned to router interfaces. Three types of probe targets were used: (1) addresses of IPv6 recursive DNS servers, as observed by our authoritative DNS servers, (2) addresses of the CDN’s servers in approximately 500 locations world-wide, and (3) a selection of about 18 million WWW client addresses assembled since 2013, including a subset (12 million) of those addresses identified as stable in March and September, 2014 (Those reported in Table 2a in Section 6.) This dataset is used to identify additional dense prefixes as reported in Table 3 with the expectation that areas of the address space containing WWW clients differ from those containing routers.

## 5. ANALYSIS METHOD

### 5.1 Temporal Classification

Our temporal methods of IPv6 address classification are intended to determine address lifetime, primarily to separate those client addresses that are persistent or stable from those that are perhaps not. We refer to this as *stability* analysis. Let’s first consider a simple notion of stability. If one periodically logs sets of active addresses at some interval, *e.g.*, 6

months, it is easy to find which sets have addresses in common. For instance, if address  $x$  is observed as active in March 2015 as well as a year earlier, in March 2014, it can be considered stable. Our stability classes are named according to the length of time across which stability has been assessed. Thus we would say address  $x$  is “1 year stable,” when sampled across the past 1 year, and is classified as “1y-stable (-1y).” If  $x$  is observed in March 2015 and also 6 months earlier, in September 2014, it would also be classified as “6m-stable (-6m).” This notion of stability generalizes to prefixes of any length, not just full addresses; we similarly assess the stability of /64 prefixes extracted from the full addresses.

Since we wish to perform stability analysis on an ongoing basis, consider a slightly more complicated notion of stability. Let’s define more granular classes of stability, *e.g.*, daily. Definition: “ $nd$ -stable” is the class of addresses for which there exist observations of activity on two different days with an intervening time period of at least  $n - 1$  days. For example, a given address seen on March 17 and again on March 18 (for which there are no intervening days) is said to be “1d-stable.” Likewise, an address seen on March 17 and on March 19 (for which there is one intervening day) is said to be “2d-stable.” Note that since March 17 and March 19 have *at least* zero intervening days, then an address seen on these two days is also “1d-stable,” besides being “2d-stable;” the classes are *not* mutually exclusive. More generally, an address that is “ $nd$ -stable” is also “ $(n - 1)d$ -stable.”

Since a measurement study of client IP addresses that access a given service will typically capture only a portion of the addresses’ total Internet activity, and since that service may be accessed infrequently, even a long-lived client address, *e.g.*, using EUI-64, may appear to be ephemeral. Thus, we will simply label such addresses as “not stable,” meaning only that we do not know that address to be stable. Stability clas-

sification relies on, and is limited by, the opportunity for observation of activity from given vantage points.

In our daily stability analysis, we employ a sliding 15-day window centered on the day of observation and spanning 7 days prior through 7 days following. In such context, a 3d-stable address might be classified as “3d-stable (-7d,+7d).” For stability results herein, “(-7d,+7d)” is implied unless otherwise noted. Figure 4 in Section 6 shows the numbers of active addresses and /64s observed on each day as well as the subset in common between those also observed on the reference day (March 17 or March 23, 2015).

## 5.2 Spatial Classification

Our spatial methods of IPv6 address classification and prefix characterization are intended to both assess the proximity of addresses and prefixes and to visualize the address blocks in which they are contained. We develop two related metrics for use with IPv6: Multi-Resolution Aggregate (MRA) Count Ratios and Prefix Density, and a complementary visualization technique, the MRA plot. In the following, prefixes are characterized structurally, then addresses therein are classified according to the densities of their containing, non-overlapping sub-prefixes.

### 5.2.1 Multi-Resolution Aggregate Count Ratios

Our metric MRA Count Ratio is a generalization of a metric introduced by Kohler *et al.* With 128 bit addresses and IPv6 presentation format using hexadecimal characters, network operators have great flexibility to use segments of the address for internal purposes; *e.g.*, 16 bit and 4 bit segments are commonly used for subnetting. (See [20] and [34] for recommended operational guidelines.) Here we present an informal, high-level understanding of MRA ratios and an optional, formal definition. The latter is unnecessary for a general introduction.

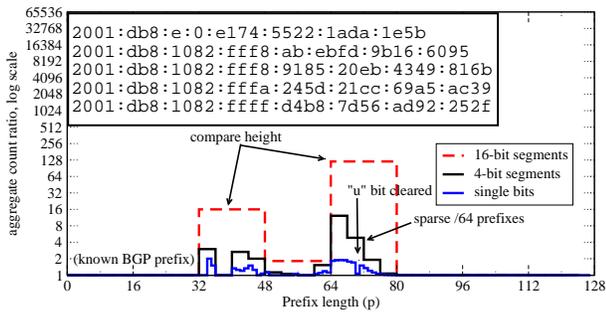
- *Informally*, in the following MRA plots, the height indicates how much that segment of the address is relevant to grouping a set of addresses into areas of the address space. Addresses aggregated further to the left (high order bits) are more distant from each other; addresses aggregated to the right are close to one another. MRA ratios for a set of addresses, when plotted, expose the density (or sparsity) of each segment of the addresses, whether bits, characters, or colon-separated segments.

- *Formally*, Kohler *et al.* introduce the metric of active aggregate (prefix) counts, and their ratio. Given  $N$  addresses, they can be grouped into prefixes of

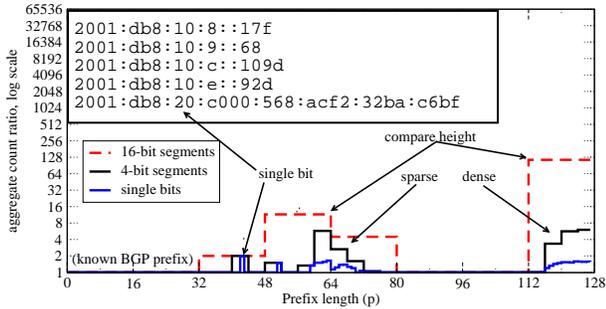
various sizes. For a given prefix size, say  $/p$ , there is a (smallest) set of prefixes of size  $/p$  that contains (covers) all  $N$  addresses. At one extreme, each IPv6 address is in its own  $/128$  prefix, at the other extreme the single  $/0$  prefix contains all of the addresses. Let the “active aggregate count”  $n_p$  be the number of  $/p$  prefixes that covers the given set of addresses. By definition  $n_p = 1$  for  $p = 0$  and  $n_p = N$  for  $p = 128$ . Often a more convenient metric is the ratio of active aggregate counts,  $\gamma_p \equiv n_{p+1}/n_p$ . The range of  $\gamma_p$  is 1 to 2. As an example, suppose that a set of addresses is covered by 100 prefixes of size  $/56$ ,  $n_{56} = 100$ . Now, consider one of these  $/56$  prefixes and what can happen when it is partitioned in two  $/57$  prefixes. Either all of the addresses in the  $/56$  are in one of the  $/57$  prefixes, or there is at least one address in each of the two  $/57$  prefixes. If the former pertains for *all* of the  $/56$  prefixes then the ratio  $n_{57}/n_{56}$  would be 1, and if the latter pertains for all, the ratio would be 2. Typically, the former pertains for some and the latter for others, in which case the ratio is between 1 and 2. Now, to examine 4-bit address segments, for instance, it is convenient to compute ratios of active aggregate counts where the mask has been incremented by values larger than 1 bit. Note that 4 bits is one hexadecimal character and 16 bits is a series of 4 hexadecimal characters that, when aligned, are colon-delimited in IPv6 presentation format; these are convenient segment sizes in IPv6 that are not convenient in IPv4 due to presentation format being in base 10. We consider the somewhat more general “MRA count ratio”  $\gamma_p^k \equiv n_{p+k}/n_p$ , where canonically  $p$  is a multiple of  $k$ , and  $k$  is 1, 4, 8, or 16. The range of  $\gamma_p^k$  is 1 to  $2^k$ . Note: The definition of the ratios implies that, for given resolution ( $k$ ), the product of the ratios is the total number of addresses in the set.

Sample MRA plots are shown in Figure 2, annotated with sample addresses (inset) and arrows marking features to aid the reader’s interpretation. In Figure 2a, consider the portion of the plot for the “single bits” (blue) line at  $x \geq 64$ . This portion of the plot initially approximates 2, then slopes downward to the right, but with a drop to 1 at a particular bit: this is the signature of a scenario where each  $/64$  contains many addresses and where, within each prefix, the majority of the addresses have IIDs determined by the end host according to the pseudorandom privacy extension as specified in RFC 4941 [32].

- *Details on the signature for privacy extension:* Consider one of the  $/64$  prefixes. Given that the 65th bit is chosen randomly, and that there are many addresses in the  $/64$  prefix, *e.g.*,  $x$  addresses, then it is very likely (probability =  $1 - (1/2)^{x-1}$ ) that at least



(a) US university



(b) JP telco

Figure 2: MRA plots for active IPv6 WWW client addresses (a) 7.22K adrs and (b) 12.8K adrs.

one of the addresses will have a 0 for the 65th bit and, likewise, that at least one of the addresses will have a 1. Thus the ratio  $n_{65}/n_{64}$  for this prefix is very likely to be 2. If this pertains for all /64 prefixes, the ratio for the whole set of addresses will also be 2. In turn, given that each /65 prefix also has a large number of addresses, the above logic repeats, and thus we expect the ratio to remain close to 2. However, as we continue to split prefixes in half, each prefix has a decreasing number of addresses and an increasing chance that those addresses will all have the same next bit. Once they are all the same, the ratio for such prefixes will be 1 and the overall ratio will begin to decline from 2. Moreover, even if the original set contained a billion addresses, it would still be very sparse in the space of  $2^{64}$  possible IIDs. As we continue to consider ever smaller prefixes, eventually, each will contain just one pseudorandom-IID address, and the overall ratio will flat line at 1. In the presented plot, this occurs at about the 80th bit. Finally, as a defining feature of the present scenario, note that the ratio drops to almost 1 at the 71st bit, shown at 70 on the horizontal axis. This is consistent with end hosts that determine the IID according to RFC 4941, which specifies that the “u” bit be set to 0, meaning that an IID is not necessarily universally unique, as opposed to a MAC address.

Now consider Figure 2b in contrast to Figure 2a. These two organizations appear to have significantly different address assignment policies. In Figure 2b, we see a prominence between bits 112 and 128. This indicates that there are many active addresses that differ in only those least-significant bits, *i.e.*, addresses are clustered within smaller prefixes, and thus such prefixes are more dense address blocks.

If one were interested in searching for additional active IPv6 addresses, these denser address blocks would be natural targets. A /112 prefix covers  $2^{16}$  addresses, the same as a /16 in IPv4, and is easily scanned, whereas scanning across a /64 is not practical.

Now consider Figure 2a with respect to the plotted ratios for 4-bit segments, *a.k.a.* *nybbles*, in the plot (black line). Here we consider changes on a per-nybble, hexadecimal character basis. This provides a more aggregated view, summarizing details of changes on a per-bit basis. Our first-order interest is network operator practice with respect to subnetting. In particular, we assume this network subnets their /32 BGP prefix, so we consider segments of the address down to the /64, *i.e.*, across the canonical network identifier. The jump up for the plot at 32 indicates that addresses have differing (character) values at that nybble, but not, in turn, at the subsequent nybble at 36. The subsequent two nybbles could also be used to discriminate many addresses, and then much less so for the subsequent three nybbles. In contrast to Figure 2a, note that the addresses in Figure 2b have many different (character) values in the last nybble within network portion of the address at 60. In Section 6, *e.g.*, Figure 5, we examine aggregation ratio across the advertised BGP prefixes, *i.e.*, operator-defined address blocks in the unicast portion of the IPv6 address space.

While this introduction to Multi-Resolution Aggregation ratio focussed on visual recognition of IPv6 features in MRA plots, the underlying  $x, y$  values offer a convenient basis to classify prefixes, and the addresses therein. While defining MRA-based address classes is left for future work, we begin by developing spatial classification by identifying dense prefixes.

### 5.2.2 Prefix Density

Kohler *et al.* [27] introduces the metric of the number of active addresses in a prefix, and examine the distribution of this number across prefixes of a given size. They consider IPv4 and are interested in the variability of population densities for prefixes of a given size, *e.g.*, /8 or /16, and how well their models

match with measurements. They comment, “aggregate population distributions are the most effective test we have found to differentiate address structures.”

We plot the aggregate population complementary cumulative distribution function for all IPv6 addresses and /64 prefixes active during a 7-day period in Figure 3. For the curve showing the 112-aggregate of addresses (the lowest curve), only  $10^{-5}$  of the /112 prefixes contained 10 or more observed addresses; for the 48-aggregate of addresses, fewer than one in ten of the /48 prefixes contained 10 or more observed addresses, hence, a few prefixes must contain most of the addresses. Approximately  $10^{-4}$  of the 48-aggregate of addresses contain  $10^5$  or more addresses, which clearly illustrates the sparsity of the IPv6 address space and the concentration of observed addresses in a small subset of prefixes.

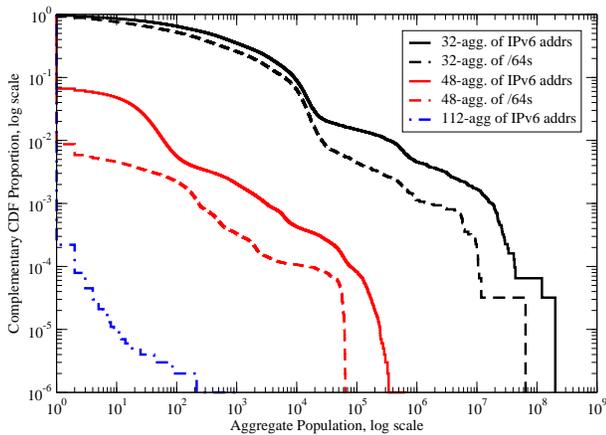


Figure 3: Aggregate population distributions for 1.87B IPv6 addr, 358M /64s, March 17-23, 2015.

Kohler’s aggregate population considers the observed *count* of addresses in a prefix. A related measure is obtained by dividing that observed count by the number of addresses spanned by the prefix, yielding the *percentage* of the addresses of the prefix that were observed.

Cho *et al.* [11] use a percentage as a criterion in an aggregation-based traffic profiler, *however*, their percentage is obtained by dividing an observed count by a total observed count across all prefixes. In their implementation, prefixes are nodes in an *aguri tree*, with observed addresses added as leaf nodes. Aggregation is kind of “pruning,” and is performed by aggregating a node’s count to its parent (and removing that node), unless that node’s count meets or exceeds a target minimum percentage.

Consider an IP network prefix such as  $2000::/3$  or  $2001:db8::/32$ . A prefix might contain “addresses of interest” by arbitrary criterion, *e.g.*, addresses for which activity was observed. A simple notion of a prefix’s *density*, then, is the fraction of its addresses that are active. Both the prefix and its addresses can be said to have a density of  $d$ , where  $d$  is a fraction with a value greater than 0 and less than or equal to 1.

If we restrict desired minimum densities to the fraction  $n/2^{p'}$ , where  $p'$  is a number of bits in the range 0 through 128, there is a simpler solution that does not require base-10 math with large numbers, *i.e.*, greater than 64 bits. We use this restriction, and choose densities based on two parameters:  $n$  and  $p$ , where  $p = 128 - p'$ .

Now, let’s define our spatial address classes based on prefix density. Definition: “ $n@/p$ -dense” is the class of prefixes of length  $p$  that contain at least  $n$  addresses for which there exist observations of activity. It is also the class of those addresses contained therein. For example, let’s say the IPv6 addresses  $2001:db8::1$  and  $2001:db8::4$  are both active, but no others. If the desire is to identify /112 prefixes that are dense, then  $2001:db8::/112$  is the sole  $2@/112$ -dense prefix. There is also one  $2@/125$ -dense prefix, but no  $2@/126$ -dense prefixes.

### 5.2.3 Computing Dense Prefixes

We would like to identify the dense prefixes based on observed active addresses. We start by choosing a desired minimum density, and then compute the set of dense prefixes, if any.

Given a set of IP addresses and a desired minimum density, we compute a corresponding set of prefixes that (a) contain a subset of those addresses, (b) have the desired density, and (c) have prefix length up to 127. The dense subset are the least-specific, non-overlapping prefixes that are dense, *i.e.*, contain the requisite fraction of addresses.

One way to implement this “densification” is by using an aguri tree, [11] (a base-2 radix tree, *a.k.a.*, Patricia trie) augmented with a new “densify” operation that works as follows:

(1) Populate the tree by adding each of the addresses with a count of 1. If dense prefixes of just that one length are desired, add each address with a “/ $p$ ” and skip to step 3.<sup>3</sup>

<sup>3</sup>When prefixes of just one length are desired, the aguri tree is unnecessary; it is just accumulating counts and sorting output. An alternative is to print addresses in a fixed-width 32-character hex format, one per line, and use: `sort [-m] |cut -c1-$(($p/4)) |uniq -c [1]`

(2) Perform a post-order traversal of the tree; when visiting a node that has children and the sum of counts for the current node and its children would make the current node’s prefix of the desired density, aggregate the node’s children into the current node, by accumulating the count and removing the children.

(3) Now the least-specific dense prefixes, of at least the desired length  $p$  (if specified), are nodes in the tree. However, addresses in sparse regions remain unaggregated, so they are present as well, *e.g.*, /128s. To report only the dense prefixes, perform an in-order traversal, skipping those with a count that is less than  $n$ , *e.g.*, 2, and print others as they are dense prefixes.

## 6. RESULTS

### 6.1 Temporal Classification

Table 2 summarizes the temporal classifications for the “Other” addresses in Table 1 of Section 4.

Based on our temporal classification method as described in Section 5.1, Figure 4 shows stability of active addresses and /64 prefixes observed on March 17 and 23, 2015, by 15-day sliding window. Consider the values for “March 17 active” (red) in Figure 4a. Here we see that about 320 million WWW client IPv6 addresses were observed on March 17. Of those addresses, about 75 million were also seen the previous day, about 20 million the day before that, about 10 million the day before that, and so on, in stepwise fashion. The same is true, approximately symmetrically, for the days following March 17. Ultimately, this assessment yields 30.1 million 3d-stable addresses (9.44%), as listed in the “Mar 17, 2015” column of Table 2a.

Now consider the corresponding stability of /64 prefixes shown in Figure 4b. A larger proportion of /64 prefixes are stable than that of full addresses: 109 million 3d-stable /64s (89.8%), as listed in the “Mar 17, 2015” column of Table 2b. (The upper limit on the number stable addresses is the number of stable /64s, or stable prefixes of any length.)

See Tables 2c and 2d for the stability results of addresses and /64s, respectively, over a week’s time. For each of the seven days, the 3d-stable addresses are determined, and the table reports the count of the unique 3d-stable addresses seen over those days. Likewise for the “not 3d-stable.”

On examining the values highlighted (bold) in Table 2, we make two notes: (a) in a relative sense, there are not many very long-lived WWW client IPv6 addresses, only 1.81 million (0.1%) observed over the course of a year; and (b), there are many long-

lived /64 prefixes for active WWW clients: 153 million 6m-stable /64s, and even 116 million 1y-stable /64s. Consider Figure 5a, where we plot the CCDF of various counts by ASN. We see that a single ASN accounts for over 100 million /64s (dashed black) as observed across 6 months, indicating that most long-lived /64s (dashed blue) are in only a few networks. We explore this further in Section 6.2.1.

#### 6.1.1 Discussion of Temporal Results

One motivation for identifying 3d-stable addresses is the proposal that they would be good targets for subsequent active probing to discover network infrastructure. We tested this hypothesis by using a randomly selected subset of 3d-stable IPv6 addresses as targets for TTL-limited probes. We discovered 129% (1.8 million) more active IPv6 router addresses than using a simpler, long-standing target-selection strategy that works well with IPv4. (The IPv4 strategy is based only on selecting target addresses of recursive name servers that query the CDN’s authoritative servers and randomly selected addresses of active WWW clients.)

As for the “not 3d-stable” addresses, we expect that the vast majority are hosts using a privacy-extension IID, as the default timeout is 24 hours. [32] However, other types of addresses are present as well. Note that, although the IID of EUI-64 addresses is static, the subnet prefix can vary, as when the device is moved between networks, or when a given operator implements a policy of assigning another subnet prefix each time the device connects to the network. (See Section 6.2.1 for further discussion.) We investigated EUI-64 addresses in the Sept. 17-23, 2014 dataset that were classified as “not 3d-stable.” In 62% of them, the IID appeared in more than one address. Also, for 14% of them, the IID also appeared in an address that was classified as 3d-stable.

While the temporal class “3d-stable (-7d,+7d)” is useful when applied to target selection for active measurements, more research is warranted in order to determine what specific temporal classes may be most useful, *e.g.*, varying the number of days or the sliding window size, and in combination with addressing practices.

One wonders whether or not any of our counts of active or stable /64s could be an approximate lower-bound on the actual number of subscribers or instances of IPv6-capable Internet connections in the world today. Consider the highlighted (bold) counts in Table 2d; is the 116 million 1y-stable /64s observed March, 2015, a reasonable lower-bound? We discuss this in the forthcoming Section 7, but first, we ad-

dress spatial classification results in order to better understand how network identifiers such as /64 prefixes are assigned by ISPs.

## 6.2 Spatial Classification

### 6.2.1 Multi-Resolution Aggregate Count Ratio

Here we turn to results based on MRA plots that we introduced in Section 5.2.1. With myriad possible MRA plots but limited space, a data-driven exploration methodology that directs our attention to ASNs and prefixes of interest is called for. To this end, we first examine Figures 5a and 5b, distributions of aggregate count ratios across all active IPv6 ASNs and BGP prefixes.

Consider Figure 5b. This is a set of box plots, each showing the distribution of aggregation ratios across all IPv6 BGP prefixes for each of the 16-bit segments of each prefixes' set of active IPv6 addresses. Unlike a typical box plot showing just the median, middle 50, and whiskers to, say, the 1st and 99th percentiles, these also show middle 90% and whiskers extend to the absolute maximum, as annotated. Overall, we can see that most aggregation takes place across the three 16-bit segments between bits 32 and 80. We also see that about 20% of the prefixes (the 75th through 95th percentiles (transparent portion of the box) have significant aggregation in the 112-128 bit segment, thus we include an MRA plot for just such a prefix in Figure 5g.

In Figure 5a, by the solid black line near the lower righthand corner, we see that there is an exceptional ASN with 500 million active addresses in a week's time, thus we include its MRA plot as Figure 5e. This happens to be the ASN of the prefix with the highest aggregation in the 48-64 bit segment in Figure 5b.

Figures 5c through 5h are the resulting selected MRA plots for active WWW client addresses observed March 17-23, 2015. Let's tour the active IPv6 address space through these plots, discovering their features of interest. Coincidentally, the networks represented in these plots happen also to be diversely located in the world. Figure 5c is the MRA plot for all active WWW client addresses observed in the entire IPv6 unicast address space, the proverbial "30,000 foot view." The 0-32 bit segment is roughly governed by the Regional Internet Registries (RIRs) via their allocations and assignments to ISPs and end users (though some allocations are much larger than a /32), and remaining bits down to /64 are within the area that a network operator uses for subnetting in routing protocols. Figure 5c shows that there is greater use of the bit space in the 32-64 range than

the 0-32, with the greatest use of a 16-bit segment in the 32-48 bit range. Within the 16-32 bit range, the RIRs partition more frequently by the higher-order bits, while in the 32-48 bit range, network operators partition more frequently by the lower-order bits. Lastly, the 64-128 bit segment is clearly different, as expected given the prevalence of ephemeral addresses presumably due to SLAAC and privacy addressing. While we can't see fine details at this level, prefix aggregation here happens near bit position 64; this is because this segment is mostly sparsely populated with random values such that the majority of hosts' addresses share at most short runs of leading bits of their IIDs in common with other active addresses in their /64.

Figure 5d is the MRA plot for 6to4 clients. Here we witness the significant difference between IPv6 and IPv4 aggregation. For addresses in the /16 prefix reserved for 6to4, IPv4 addresses are embedded in bits 16 through 48, as is clearly evident in the plot. (The single bits plotted (blue) in the 16-48 segment are essentially that which Kohler *et al.* studied years ago and plot in [27].) This 32-bit IPv4 address segment has much higher aggregation than any similar segments of IPv6 in Figure 5c.

Figure 5e is the MRA plot for a U.S.-based mobile carrier. Its most unusual feature is that the 44-64 bit segment is nearly 100% utilized when observed over one week's time. This is evidenced by the 16-bit segments value (dashed red) and the 4-bits segments value (black) nearly reaching their maximum possible heights of 64K and 16, respectively. By experiment as a subscriber, we know that user equipment (UE) in this mobile service receives a different /64 prefix on each association, and by comparison to the same plot over only 1 day (not shown), we can deduce that this network seems to dynamically assign /64s from pools of addresses in this 44-64 bit segment. This dynamic assignment has consequences when trying to estimate subscribers because it can cause the count of active /64s observed to over-represent the number of subscribers. Corroborating evidence for a dynamic address component in the 44-64 bit segment is that this carrier's BGP advertisements consist of over 400 /44 prefixes. The MRA plot for another top mobile carrier that advertises tens of /40 prefixes (not shown due to limited space) is strikingly similar.

Next, let's consider the MRA plots of a European ISP, in Figure 5f, and a Japanese ISP, in Figure 5h, for one of each of their advertised BGP prefixes. The careful observer will note that the prefixes are at least of size 19 and 24 bits, respectively, as evidenced

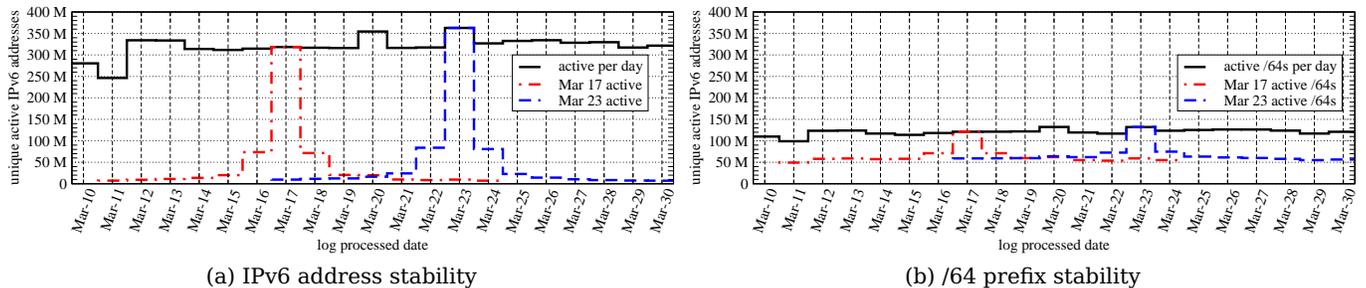


Figure 4: Stability study of active IPv6 WWW client addresses and prefixes observed per day, March 2015.

addr class	Mar 17, 2014	Sep 17, 2014	Mar 17, 2015
3d-stable	13.7M (9.22%)	13.6M (6.84%)	30.1M (9.44%)
not 3d-stable	134M (90.8%)	185M (93.2%)	288M (90.6%)
6m-stable (-6m)		588K (.296%)	1.08M (.340%)
1y-stable (-1y)			328K (.103%)

(a) Stability of IPv6 addresses per day

/64 class	Mar 17, 2014	Sep 17, 2014	Mar 17, 2015
3d-stable	55.8M (91.0%)	74.6M (89.9%)	<b>109M (89.8%)</b>
not 3d-stable	5.53M (9.01%)	8.33M (10.1%)	12.3M (10.2%)
6m-stable (-6m)		23.4M (28.2%)	32.4M (26.7%)
1y-stable (-1y)			21.8M (18.0%)

(b) Stability of /64 prefixes per day

addr class	Mar 17-23, 2014	Sep 17-23, 2014	Mar 17-23, 2015
3d-stable	37.0M (4.44%)	34.0M (2.91%)	69.0M (3.82%)
not 3d-stable	796M (95.6%)	1.13B (97.1%)	1.74B (96.2%)
6m-stable (-6m)		3.25M (.280%)	3.66M (.202%)
1y-stable (-1y)			<b>1.81M (.100%)</b>

(c) Stability of IPv6 addresses per week

/64 class	Mar 17-23, 2014	Sep 17-23, 2014	Mar 17-23, 2015
3d-stable	131M (83.7%)	169M (81.8%)	<b>246M (80.3%)</b>
not 3d-stable	25.5M (16.3%)	37.7M (18.2%)	60.6M (19.7%)
6m-stable (-6m)		120M (58.1%)	<b>153M (49.9%)</b>
1y-stable (-1y)			<b>116M (37.8%)</b>

(d) Stability of /64 prefixes per week

Table 2: Stability of active IPv6 WWW client address and prefix counts, not 6to4 or Teredo, March 2015.

by the left-most of the single bits (blue) values. Their numbers of active addresses are similar and both sets appear to primarily consist of privacy addresses, sparsely distributed in the 64-128 bit segment. However, the leading 64-bit portions (left side) of the plots differ starkly, suggesting very different address plans are in use. Most notably, in Figure 5f, the 40-64 bit segment is populated with many values over a week’s time, with heavier usage of the higher order bits of this range. Note that bit 40 seems to be constant and that there is a subtle perturbation in the single bits (blue) aggregation ratios at position 56. After examining the distribution (not shown) of values in bits 40-55, we posit that this segment contains an oft-changing, pseudorandom 15-bit number beginning at bit 41. This is followed by an 8-bit value in bits 56-63 of unknown construction, with all 256 possible values observed, but non-uniform and most often 0x00 or 0x01. By contrast, in Figure 5h, the 48-64 bit segment exhibits seemingly no aggregation, suggesting that each /48 has the same 16-bit value in every address it contains. Further, by examining the distribution (not shown) of /64 counts per IID (or Ethernet MAC address) for the JP ISP’s 185K active EUI-64 addresses, we see that 99.6% of them were observed in just one /64 in a week’s time; this figure

is 67.4% for the EU ISP. We discuss a reason for this in Section 6.2.3.

Figure 5g is the MRA plot for one /64 prefix for one department at a European university. We selected it for consideration because it contains multiple 2@/112-dense prefixes, identified in the forthcoming results in Section 6.2.2. Consequently, the structure shown is markedly different from other plots. The WWW client addresses are densely packed, as evidenced by the values at all resolutions (dashed red, black, and blue) being most prominent in the 112-128 bit segment; this indicates that these client addresses are numerically close together, as one might expect, e.g. when assigning static addresses to hosts or when assigning addresses via DHCP. There don’t appear to be any SLAAC addresses, which require a 64-bit network identifier. Aggregation seen in the 72-80 bit range and none in bits 80-120 suggests network identifier lengths are between 80 and 120.

### 6.2.2 Dense Prefixes and Addresses

Table 3 summarizes the dense prefixes discovered, by the method described in Section 5.2.3, using the router addresses dataset described in Section 4. Here we perform a limited search of the parameter space to determine what combinations of  $n$  and  $p$  (where  $n$

is the number of hosts that must be observed within a prefix of length  $p$  for the prefix to be considered dense) yield a reasonable number of targets for active measurements. As we see, manipulating these two parameters gives significant control over the prefixes classified as dense and, therefore, the number of possible target addresses that result.

Density Class	Dense Prefixes	Router Addresses	Possible Addresses	Router Address Density
2 @ /124	43.1K	116K	689K	0.1678459119
3 @ /120	8.28K	81.0K	<b>2.12M</b>	0.0382372758
2 @ /120	64.2K	193K	16.4M	0.0117351137
2 @ /116	207K	568K	852M	0.0006670818
64 @ /112	187	41.2K	12.3M	0.0033593815
32 @ /112	509	54.8K	33.4M	0.0016417438
16 @ /112	3.06K	105K	201M	0.0005259994
8 @ /112	21.5K	290K	1.41B	0.0002057970
4 @ /112	101K	681K	6.63B	0.0001026403
2 @ /112	367K	1.29M	24.1B	0.0000534072
2 @ /108	289K	1.72M	303B	0.0000056895
2 @ /104	108K	1.84M	1.81T	0.0000010171

Table 3: Dense prefixes identified at various densities for 3.2M router addrs collected February 2015.

Finally, for active WWW client addresses observed March 17, 2015, we identify 128 thousand 2@/112-dense prefixes and 1.38 million WWW client addresses contained therein. This yields 8.39 billion possible target addresses. Given that it is feasible to survey the entire IPv4 address space by active probing in only minutes [18], we propose that it is similarly feasible to survey these dense regions of the IPv6 address space. Other IPv6 address datasets could yield additional sets of dense prefixes to survey.

### 6.2.3 Discussion of Spatial Classification

To evaluate the interpretation of our MRA plots, we contacted operators pertaining to networks in Figure 5 and received the following information. (1) The high utilization of the 40 - 64 bit address segment in Figure 5e coincides with their subscribers being assigned /64s, *e.g.*, by least recently used, from a pool sized according to the connection capacity of a gateway. Thus the /64s are reused by other subscribers. Our results suggest this reuse can occur in just days. (2) The university of Figure 2a provided us with their full IPv6 address plan, and the implication from the figure that we observe only 3 hex character values matches their address plan. Two of these indicate “customer networks” and “large customer networks,” which are the portions of their prefix that one would expect to see WWW clients.

After we posited that the IP addresses plotted in

Figure 5f contain a pseudorandom value in the network identifier, we learned that a European ISP does just that. As a supposed privacy-enhancing feature, they allow service subscribers to have their IP addresses’ network identifier changed on demand, at the press of a button [36].

Regarding the subnet shown in Figure 5f, we found a pertinent IPv6 address allocation plan available on the web; this indicates the university to which the containing /48 is assigned. Furthermore, we found that every active address had an ip6.arpa PTR record in the DNS and, thus, were able to collect names for each of these hosts of which 92 began with “dhcprv6-.” This is evidence that the department uses a single /64 to provide IPv6 addresses to a set of about 100 active hosts.

We evaluate the application of our dense prefix results by performing ip6.arpa PTR queries for the 2.12 million possible addresses prefixes of the 3@/120-dense class, highlighted (bold) in Table 3. This yielded an additional 47K domain names more than performing queries for just the active WWW client addresses. (DNS names are valuable hints to IP geolocation software because domain names sometimes contain physical location information; this is especially true for routers. [33])

Overall, although our results are based on only a few months of data across a year-long period, we claim they demonstrate that both temporal and spatial address classifications can reasonably be performed at large scale, and that the results are useful in choosing targets for active measurements and in discovering network-specific addressing practices.

## 7. DISCUSSION AND FUTURE WORK

### 7.1 Counting IPv6

If one assumes a 1:1 correspondence between /64 prefixes and IPv6 subscribers or “user connections,” the numbers of /64 prefixes are candidate surrogates for IPv6 “user” counts. However, this assumption is rather crude. It is difficult to say whether numbers of active and stable /64 prefixes are low or high estimates. Some networks employ addressing schemes which cause the count of /64s (active or stable) to overestimate the number of subscribers, *e.g.*, the U.S. mobile carrier in Figure 5e. Other networks use a plan by which the number of active /64s seems a reasonable estimate of active subscribers, *e.g.*, the Japanese ISP in Figure 5h. Still other networks place many users in the same /64, or more specific subnet, causing the count of active /64s to underestimate the number of user connections, *e.g.*, the network in Fig-

ure 5g. Evidence shows that the number active /64s observed in a week's time can miscount IPv6 WWW client devices by a *factor of 100* in either direction.

This challenging situation leads us to conclude that estimating IPv6 user or device counts should be informed by addressing practice on a per-network or per-prefix basis. This likely requires either inside information from network operators, or a reliable measurement method to determine addressing practices from outside. We've had success in reverse engineering addressing practice by examining the network identifiers of EUI-64 addresses over time. These persistent, unique IIDs serve as guides that help find our way in areas of the IPv6 address space.

## 7.2 Longest Stable Prefixes

Having achieved some success reverse engineering network structure "manually," as just described, we propose that one could automatically discover stable portions of network identifiers, defined as the set of *longest stable prefixes* in a dataset recording many address observations over time. By combining aspects of our temporal and spatial classification techniques, we claim that it is possible to identify a set of such prefixes, perhaps without relying on inspection of addresses with long-lived IIDs, *e.g.*, EUI-64. These longest stable prefixes are likely to be significant aggregates within a network's routing tables, thus this presents a passive means by which one might glean a network's address plan. We've begun to explore this prospect and it is a focus of our future work.

## 8. CONCLUSION

In this paper, we present a methodology to classify IPv6 addresses. We employ two techniques: (1) temporal analysis to determine prefix and address stability over time, and (2) spatial analysis to determine the structure in which prefixes and addresses are contained. We develop classifiers and demonstrate their efficacy in an empirical study of active IPv6 addresses observed at a large CDN across a year's time, involving billions of WWW client addresses. The results of our analyses expose operator addressing practices that impact the interpretation of Internet measurements. Finally, we propose that the classifications we develop are applicable, and likely necessary, to comprehensively survey or census the IPv6 Internet by passive and active means.

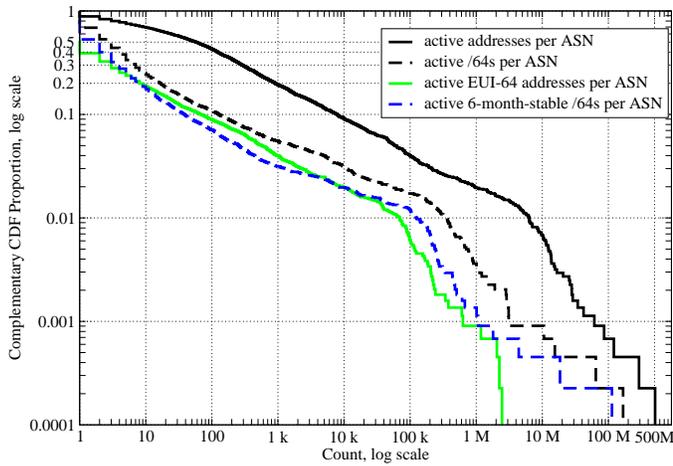
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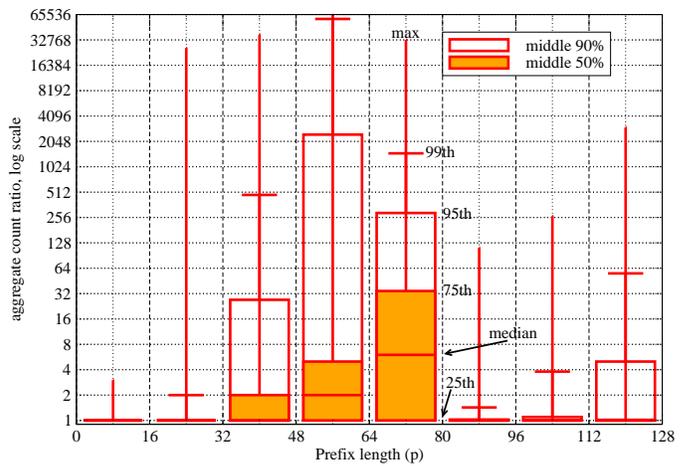
## 9. REFERENCES

- [1] GNU core utilities. <http://www.gnu.org/software/coreutils/>, 2003.
- [2] Google IPv6 Statistics. <http://www.google.com/intl/en/ipv6/statistics.html>, 2015.
- [3] State of the Internet: IPv6 Adoption Trends by Country and Network. <http://www.stateoftheinternet.com/ipv6>, April 2015.
- [4] T. Aura. Cryptographically Generated Addresses (CGA). IETF RFC 3972, March 2005.
- [5] M. Bagnulo. Hash-Based Addresses (HBA). IETF RFC 5535, June 2009.
- [6] M. Bagnulo and J. Arkko. Support for Multiple Hash Algorithms in Cryptographically Generated Addresses (CGAs). IETF RFC 4982, July 2007.
- [7] R. Barnes, R. Altmann, and D. Kerr. Mapping the Great Void: Smarter scanning for IPv6. [http://www.caida.org/workshops/isma/1202/slides/aims1202\\_rbarnes.pdf](http://www.caida.org/workshops/isma/1202/slides/aims1202_rbarnes.pdf), Feb 2012.
- [8] F. Brockners, S. Gundavelli, S. Seicher, and D. Ward. Gateway-Initiated Dual-Stack Lite Deployment. IETF RFC 6674, July 2012.
- [9] B. Carpenter, J. Crowcroft, and Y. Rekhter. IPv4 Address Behaviour Today. IETF RFC 2101, February 1997.
- [10] B. Carpenter and S. Jiang. Significance of IPv6 Interface Identifiers. IETF RFC 7136, February 2014.
- [11] K. Cho, R. Kaizaki, and A. Kato. Aguri: An Aggregation-Based Traffic Profiler. In *Proceedings of the Workshop on Quality of Future Internet Services (QofIS '01)*, Coimbra, Portugal, September 2001.
- [12] k. claffy. The 4th Workshop on Active Internet Measurements (AIMS-4) Report. *ACM SIGCOMM Computer Communication Review (CCR)*, 42(3):34–38, Jul 2012.
- [13] L. Colitti, S. H. Gunderson, E. Kline, and T. Refice. Evaluating IPv6 Adoption in the Internet. In *PAM*, pages 141–150, 2010.
- [14] J. Czyz, M. Allman, J. Zhang, S. Iekel-Johnson, E. Osterweil, and M. Bailey. Measuring IPv6 Adoption. *SIGCOMM Computer Communication Review*, 44(4):87–98, August 2014.
- [15] A. Dainotti, K. Benson, A. King, k. claffy, M. Kallitsis, E. Glatz, and X. Dimitropoulos. Estimating Internet Address Space Usage Through Passive Measurements. *ACM SIGCOMM Computer Communication Review (CCR)*, 44(1):42–49, Jan 2014.
- [16] R. Droms, J. Bound, B. Volz, T. Lemon, C. Perkins, and M. Carney. Dynamic Host Configuration Protocol for IPv6 (DHCPv6). IETF RFC 3315, July 2003.
- [17] A. Durand, R. Droms, J. Woodyatt, and Y. Lee. Dual-Stack Lite Broadband Deployments Following IPv4 Exhaustion. IETF RFC 6333, August 2011.
- [18] Z. Durumeric, E. Wustrow, and J. A. Halderman. ZMap: Fast Internet-Wide Scanning and its Security Applications. In *Proceedings of the 22nd USENIX Security Symposium*, August 2013.
- [19] F. Gont. A Method for Generating Semantically Opaque Interface Identifiers with IPv6 Stateless Address Autoconfiguration (SLAAC). IETF RFC 7217, April 2014.
- [20] C. Grundemann, A. Hughes, and O. Delo. Best Current Operational Practices - IPv6 Subnetting. <http://bcop.nanog.org/images/6/62/BCOP-IPv6-Subnetting.pdf>, 2011.
- [21] R. Hinden and S. Deering. IP Version 6 Addressing Architecture. IETF RFC 4291, February 2006.
- [22] C. Huitema. An Anycast Prefix for 6to4 Relay Routers. IETF RFC 3068, June 2001.
- [23] C. Huitema. Teredo: Tunneling IPv6 over UDP through Network Address Translations (NATs). IETF RFC 4380, February 2006.
- [24] G. Huston. Personal correspondence, April 2015.
- [25] G. Huston and G. Michaelson. Measuring IPv6. <http://www.potaroo.net/presentations/2013-05-16-ipv6-measurement.pdf>, May 2013.
- [26] G. Huston and G. Michaelson. March 2015 Update on Measuring IPv6. <http://www.potaroo.net/presentations/2015-03-16-ipv6-measurement.pdf>, March 2015.

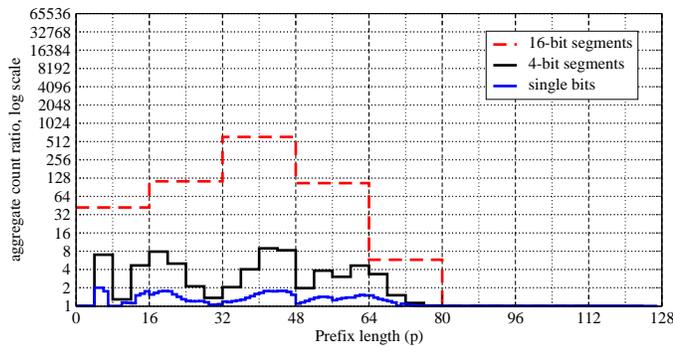
- [//www.potaroo.net/presentations/2015-03-22-ipv6-stats.pdf](http://www.potaroo.net/presentations/2015-03-22-ipv6-stats.pdf),  
March 2015.
- [27] E. Kohler, J. Li, V. Paxson, and S. Shenker. Observed Structure of Addresses in IP Traffic. In *Internet Measurement Workshop*, pages 253–266, 2002.
  - [28] M. Kohnno, B. Nitzan, R. Bush, Y. Matsuzaki, L. Colitti, and T. Narten. Using 127-Bit IPv6 Prefixes on Inter-Router Links. IETF RFC 6164, April 2011.
  - [29] David Malone. Observations of IPv6 Addresses. In *Passive and Active Network Measurement, 9th International Conference, PAM 2008, Cleveland, OH, USA, April 29-30, 2008. Proceedings*, pages 21–30, 2008.
  - [30] M. Mawatari, M. Kawashima, and C. Byrne. 464XLAT: Combination of Stateful and Stateless Translation. IETF RFC 6877, April 2013.
  - [31] G. Michaelson. Personal conversation, July 2014.
  - [32] T. Narten, R. Draves, and S. Krishnan. Privacy Extensions for Stateless Address Autoconfiguration in IPv6. IETF RFC 4941, September 2007.
  - [33] V. N. Padmanabhan and L. Subramanian. An Investigation of Geographic Mapping Techniques for Internet Tools. In *Proceedings of ACM SIGCOMM 2001*, San Diego, CA, August 2001.
  - [34] SURFnet. Preparing an IPv6 Address Plan. <http://www.ripe.net/lir-services/training/material/IPv6-for-LIRs-Training-Course/Preparing-an-IPv6-Addressing-Plan.pdf>, September 2013.
  - [35] Akamai Technologies. State Of The Internet Q3 2014 Report. <http://www.akamai.com/dl/akamai/akamai-soti-q314.pdf>, 2014.
  - [36] Deutsche Telekom. Deutsche Telekom offers anonymous surfing with IPv6. <https://www.telekom.com/media/company/93184>, Nov 2011.
  - [37] F. Templin, T. Gleeson, and D. Thaler. Intra-Site Automatic Tunnel Addressing Protocol (ISATAP). IETF RFC 5214, March 2008.
  - [38] S. Thompson, T. Narten, and T. Jinmei. IPv6 Stateless Address Autoconfiguration. IETF RFC 4862, September 2007.



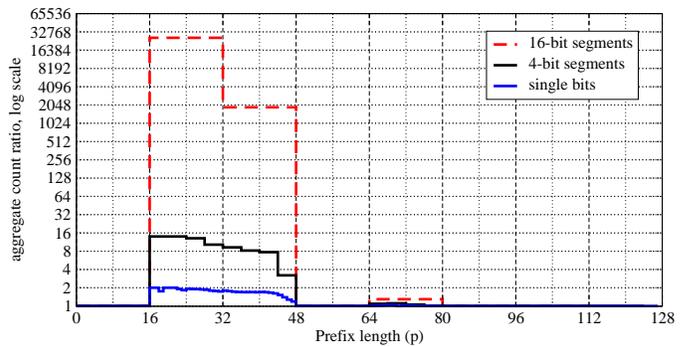
(a) Distribution of active addrs and /64 counts, 4.42K ASNs



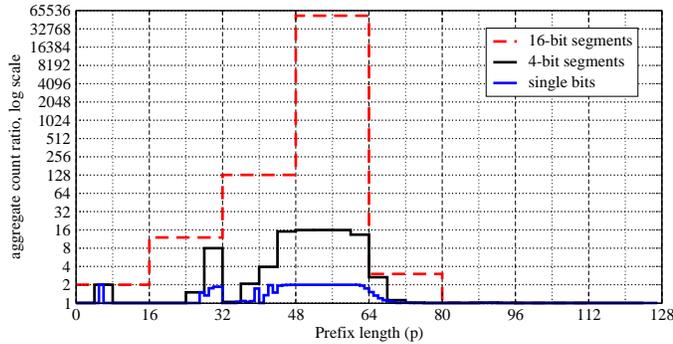
(b) 16-bit segment agg. distributions, 6.87K BGP prefixes



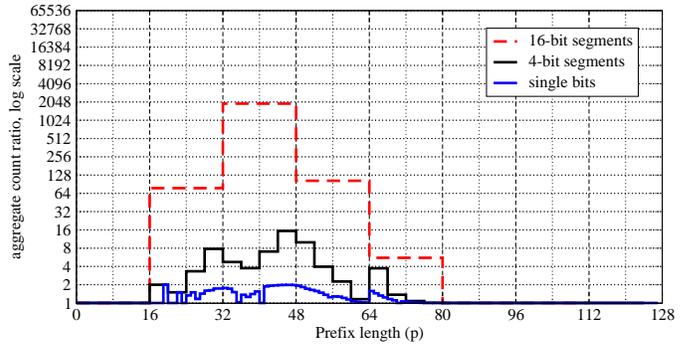
(c) All: 1.81B active IPv6 client addrs, not 6to4 or Teredo



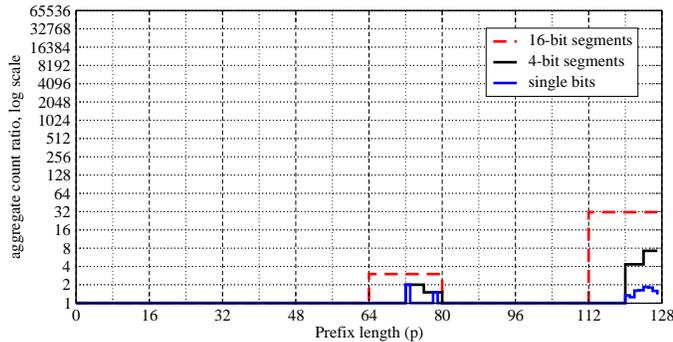
(d) 6to4: 64.2M active IPv6 (49.3M IPv4) client addresses



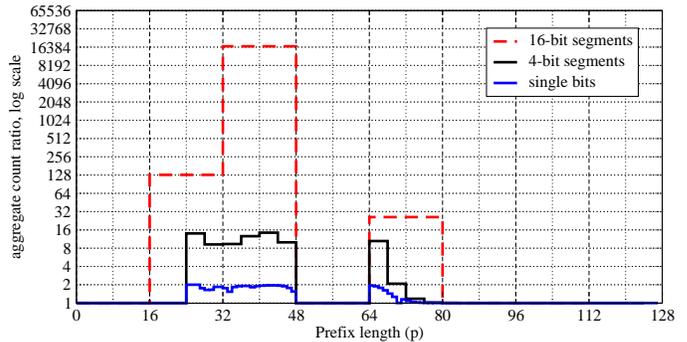
(e) US mobile: 510M active IPv6 client addrs, 167M /64s



(f) EU ISP prefix: 86.2M active IPv6 client addrs, 15.5M /64s



(g) EU univ. dept. prefix: 94 active IPv6 client addrs, 1 /64



(h) JP ISP prefix: 57.0M active IPv6 client addrs, 2.18M /64s

Figure 5: Distribution and MRA plots for active IPv6 addresses observed during 7 days, March 17-23, 2015.