ABSTRACT
Privacy-minded Internet service operators anonymize IPv6 addresses by truncating them to a fixed length, perhaps due to long-standing use of this technique with IPv4 and a belief that it’s “good enough.” We claim that simple anonymization by truncation is suspect since it does not entail privacy guarantees nor does it take into account some common address assignment practices observed today. To investigate, with standard activity logs as input, we develop a counting method to determine a lower bound on the number of active IPv6 addresses that are simultaneously assigned, such as those of clients that access World-Wide Web services. In many instances, we find that these empirical measurements offer no evidence that truncating IPv6 addresses to a fixed number of bits, e.g., 48 in common practice, protects individuals’ privacy.

To remedy this problem, we propose kIP anonymization, an aggregation method that ensures a certain level of address privacy. Our method adaptively determines variable truncation lengths using parameter k, the desired number of active (rather than merely potential) addresses, e.g., 32 or 256, that can not be distinguished from each other once anonymized. We describe our implementation and present first results of its application to millions of real IPv6 client addresses active over a week’s time, demonstrating both feasibility at large scale and ability to automatically adapt to each network’s address assignment practice and synthesize a set of anonymous aggregates (prefixes), each of which is guaranteed to cover (contain) at least k of the active addresses. Each address is anonymized by truncating it to the length of its longest matching prefix in that set.

1. MOTIVATION & INTRODUCTION
Protecting personally identifiable information (PII) in the form of IP addresses warrants special attention with IPv6 due both to nascent privacy concerns and mandates, e.g., in the European Union, and to increased IPv6 use, worldwide. Given today’s significant IPv6 deployment and dual-stack operation, the IPv6 address may be the identifier most likely to be unique to a client on the increasingly encrypted World-Wide Web (WWW). While individual IPv4 addresses are increasingly shared due to address exhaustion, this is neither intended nor commonplace with IPv6 which offers unique, globally-routed addresses end-to-end.

In this work we investigate but one Internet privacy measure: IP address anonymization by truncation. Address truncation means simply to delete a set of contiguous low (rightmost) bits, i.e., to remove a suffix from an input address. Typically the suffix’ bits are replaced with zeroes so that the anonymized output is an address-sized value. While more complex anonymization techniques have been implemented and are well-studied, they anonymize addresses in a way that prevents the result from being used for standard security, operations, and research tasks. Specifically, they prevent correlation with network topology, routing, service providers, and locations. For these purposes, truncation-based anonymization is ideal if, and only if, it can be guaranteed to improve privacy.

Such anonymization is typically performed by truncating input addresses to one fixed length. Consider, for instance, a WWW analytic system employing truncation-based IP address anonymization; e.g., zeroing the last 8 bits of a user’s IPv4 IP address and the last 80 bits of an IPv6 address. Essentially, this is equivalent to masking or aggregating to /24 and /48 prefixes, respectively, perhaps combining information about as many as 256 IPv4 addresses or 64K IPv6 /64 prefixes. Of course, the utilization of the IPv4 and IPv6 address spaces differ dramatically. While someone might believe that an IPv4 /24 prefix would aggregate individual users’ addresses, we ask two questions. First, can passive measurements inform decisions about anonymization? Second, is there reason to believe that any one IPv6 prefix length would perform satisfactorily?1

The key problem is how to decide at what prefix (bit) length(s) real addresses should be cleaved into a “public,” suitably anonymous prefix to be preserved and reported as is and a private suffix to be discarded or obscured. Note that prefix preservation in truncation-based anonymization, differs from “prefix-preserving anonym-

1Evaluating anonymization of IPv4 addresses by truncation is warranted as well, but it is not the subject of this work.
ymization” in the literature [5,15] which preserves prefix lengths amongst anonymized addresses but not the original prefix value. To tackle the problem of determining whether truncated prefixes or aggregates might effectively provide anonymity, i.e., to make an individual appear indistinguishable amongst a set of individuals (see Section 6.1.1. [3]), we count active addresses to determine how many they actually aggregate. Then, we use such counting as the basis for anonymization by variable length truncation or aggregation, resulting in different lengths to anonymize different areas of the address space.

The key to our technique is to count a subset of simultaneously assigned, active IPv6 addresses given the likelihood that a given temporary privacy address must still be assigned in between two times at which the address’ activity was observed from a (possibly remote) vantage point. We rely on the ostensibly unique identifier present in temporary addresses that employ Stateless Address Autoconfiguration (SLAAC) with privacy extensions [11]. Far and away, this is the most common address assignment mechanism for World-Wide Web (WWW) clients. As of March 2017 by the 3-day stable definition, i.e., “3d-stable (−7d,+7d)” [13], we find 684 million (93%) ephemeral IPv6 WWW client addresses are active per day and 4.33 billion (97%) per week. While temporary privacy addressing aims to improve privacy by complicating the tracking of user activity beyond hours or days, we manage to use logs of sporadic activity of these short-lived addresses to calculate a lower bound on the number of simultaneously-assigned IPv6 addresses in a given prefix even during times when those addresses’ seem inactive, e.g., from a remote CDN vantage point.

To the best of our knowledge, prior works have not reported the privacy concerns we have with IPv6 address anonymization by truncation nor have they proposed privacy guarantees with such methods. Our goal is to develop IPv6 address anonymization that yields precise, useful results for operations and research while guaranteeing address privacy for users. Although this is a work in progress, we offer the following contributions: (i) an evaluation of IPv6 address anonymization by truncation; (ii) our kIP anonymization method (inspired by k-anonymity [15]) and early results on its performance.

2. METHODS

kIP anonymization involves three operations, namely: address classification, address activity matrix analysis, and anonymous aggregate (prefix) synthesis.

2.1 Address Classification

We employ address classification to identify SLAAC privacy addresses, i.e., those having pseudorandom values in their 64-bit IID. To do so, every input address is preprocessed by the addr6 tool which performs an initial stateless classification [10]. For example, consider the 16 IPv6 addresses in Figure 1(a) addr6 reports each of them as having a randomized IID because they do not have some other easily recognized IID type, e.g., EUI-64, nor an easily recognized pattern, e.g., only low-bytes being non-zero [6]. Next, we perform a stateful classification using our dendracron tool [13]. By “stateful,” we mean that we classify each address in: (a) space, relative to others addresses in a set, e.g., those within the same /64 prefix, and in (b) time, throughout an observation timeframe, e.g., a week. This yields two classification metrics for each address that we will use below: (1) its Discriminating Prefix Length (DPL) and (2) its number of Stable Days (SD) during which we’ve observed that address to be active and throughout which the address might have remained assigned. The DPL is simply the position of the first (left-most) bit at which the address differs from its nearest (observed) address. The SD is the number of days across which the address has been seen active. The smaller an address’ DPL (and SD) value, the more likely it is to have a randomized IID (and a temporary one at that) by the following rationale.

Identifying Plausible Randomness: Given a set of addresses in a /64 prefix, the following test for randomness in IIDs complements those above; it is based on the likelihood that a subset of bits at a given position is distinct across all of the IIDs assuming the bits were chosen randomly. For example, suppose there are 2 addresses, and consider the leading 6 bits of their IIDs. If these 6 bits were chosen randomly [11], then, out of the \(2^6 = 64\) possible 6-bit strings, the likelihood that these two IIDs have different values for these 6 bits is \(63/64 \approx 0.98\). More generally, given \(A\) addresses with candidate random IIDs in a /64 prefix, and a bit string of length \(N\) at a given position in the IIDs, then the number of possible bit strings is \(S = 2^N\), and the probability that the bit strings in those IIDs are distinct is:

\[
\frac{S}{S} * \frac{S-1}{S} * \frac{S-2}{S} * \cdots * \frac{S-(A-1)}{S}
\]

For classification, we start with the number of addresses and a desired probability, i.e., 0.99, and compute the number of bits. In particular, given \(A\) addresses with candidate random IIDs, we compute the smallest number of bits, \(N\), such that the probability is at least 0.99 that all \(N\)-bit strings at a given position in the IIDs are distinct. Given this \(N\), we examine the IIDs in the /64 to see whether the given bit strings are all distinct. If all bit strings are distinct, then we infer that there is further evidence that the IIDs are pseudorandom. If they are not all distinct, then the IIDs may still be pseudorandom, but we choose to not make the inference. Lets consider the candidate random bit string to begin at the
first bit of the IID. RFC4941 dictates that the 7th bit be set to zero in an otherwise randomized IID, so, if the bit string spans that bit, we need to allow an additional DPL bit. Conveniently, this makes 64 + 1 + N the 99%-probable maximum DPL of each address in a set of addresses, of size A, having candidate random IIDs. We implement this additional test for randomness using a precomputed lookup table in dendracron, for A ranging from 2 to about 1 million. For example, for 16 addresses such as those in Figure 1(a), the 99%-likely maximum DPL is 64 + 1 + 14 = 79, since all the actual DPL values (in the second column of the figure) are less than 79, we classify these addresses as having plausibly random IIDs as a basis for assignment inferences, next.

2.2 Address Activity Matrix Analysis

Richter et al. [14] employed an IP address activity matrix, with time on the horizontal axis and address space on the vertical axis, to visualize daily activity over months and to calculate IPv4 address space utilization. At finer timescales, we use an enhanced address matrix to handle the sheer size and sparsity resulting from IPv6 assignment practices, e.g., SLAAC with privacy extensions. Figure 1(a) is an activity matrix capturing activity per hour for 16 active IPv6 addresses, sorted by address value, in one /64 prefix during 24 hours. An address is active sometime during each hour marked with “#” and inactive other hours from the CDN’s vantage; see legend in Figure 1(d). The address matrix has temporal parameters that allow the analysis and method to operate on other timescales: i, the time interval used to aggregate activity and w the time window of observation. Here i = 1 and w = 24 in hour units.

Figure 1(b) is a resorted activity matrix that contains the same activity information, but with the address’ rows in order of initial activity time (earliest first) rather than by address value. This makes clearer which of the addresses might be active simultaneously. (Also, when the IID is random, sorting by address value is meaningless.) We see, for instance, that two addresses were both active in interval (hour) 3, but we can not conclude that they were active simultaneously, since interval-binned summaries e.g., hourly, do not record durations of transactions.

In Figure 1(c), we rewrite Figure 1(b)’s activity in four ways: address’ activity in just one interval i (within window w) is marked “x” address’ activity in multiple, contiguous intervals have the first interval marked “>” and the last “<”; intervals between those at which we infer that the given temporary privacy address is assigned throughout and are marked “o”.

Address Assignment Inference: The ability to infer address assignment between moments of activity is the key to our method. Critically, we assume that IPv6 host implementations that support privacy extensions choose good pseudorandom values when building their IIDs. This allows one to infer that a given host’s temporary SLAAC address with randomized IID must still be assigned between (any) two instances of observed activity since it is ridiculously unlikely that host or any other will choose the same pseudorandom value for the IID on any subsequent reconfiguration of its network interface(s).

Now that we have inferred the intervals in which each address is assigned, we can count the simultaneously assigned addresses. To do so, we perform special arithmetic to “sum” the marks in each hour column (column): (1) Each of a column’s “o” marks increment its total by 1; this is because those addresses were assigned at every moment during the interval and the moments between the previous and next intervals. (2) Either (a), each of a column’s “>” marks can increment its total by 1 because we know that the moment between this interval and the next had that additional address assigned; or (b) each of a column’s “<” marks can increment its total by 1 because we know that the moment between this interval and the next had that additional address assigned. Of (a) or (b), we choose whichever column total would be larger. (3) All of a column’s “x” marks, taken together, increment its total by 1 only in column’s having no “>” or “<” marks; this is because we know there was some specific moment amidst that interval when (at least) one of those addresses was assigned that wasn’t a moment between the previous and next intervals. This process is performed for each column to come to a sum, for example, shown totaled below the matrix in Figure 1(e). These totals, single digits with whitespace removed here: “001001111233232122100”, are the lower bounds on the number of simultaneously assigned addresses in each interval (hour). Their minimum is 0 and maximum is 3, meaning we are confident at least 3 addresses were simultaneously assigned within this /64 prefix at some moment during this day.

The last step in our matrix analysis is to infer precise moments that the /64 prefix, itself: 2001:db8::/64, must be assigned to some host’s interface, given when the addresses it covers were known assigned. We do so by inferring address assignment at “fenceposts,” i.e., the moments between our “fence sections” (intervals) in time. Because these are the moments between intervals, they number 1 fewer than intervals in the window: f = w − 1 = 23. The /64 prefix is inferred to have been assigned at the fencepost trailing each interval where there is a ! (exclamation point) mark. We now have a time series array of size f, temporarily encoded: “--------1!!!!!!!!!1-!!!!!!-?,” that indicates the precise moments (between intervals) when the prefix must have been assigned. Translating the ! marks to 1 (and others to 0) makes them time series values suitable for accumulating across an entire network (or
the entire Internet) to compute \( f \) (hourly) lower bounds on the count of simultaneously assigned /64 prefixes.

### 2.3 Synthesizing Anonymous Aggregates

Our synthesis of aggregates, i.e., larger, covering prefixes that coalesce individuals’ SLAAC prefixes for privacy, is inspired by Cho et al. [2,13] who developed “aguri” which recursively aggregates prefixes based on activity counts until a stopping condition is met. We augment the aguri tree with an array (size \( f \)) of time series counters in each node and with a new stopping condition for active prefixes per day or week, which can far exceed the number of IPv6-capable clients that actually exist in a given network. Thus, more careful counting is warranted as the basis for guaranteed anonymity in aggregates.

In our results below, we used the full ISP data sets in Table 1 meaning \( w = 168 \) (overall window of time) and \( f = 167 \) (fencepost moments) in units of \( i = 1 \) hour (intervals). Thus, min is the minimum of the 167 lower bounds counts of simultaneously-assigned /64 prefixes, i.e., 167 hours (one week’s time). Likewise, max and median are of the 167 (hourly) lower bound counts.

### 3. RESULTS

We offer two early results based on logged IPv6 addresses of active WWW clients from real networks: (1) an evaluation of current practice for truncation-based anonymization and (2) a characterization of the anonymous aggregates produced by kIP anonymization. Both these use real WWW client addresses found in the activity logs of a large CDN as input data. Consider Table 1 which characterizes our active WWW client address data sets. We chose these specific networks for the variety of address assignment practices they demonstrate, rather than, e.g., their country. We first show the Meeting Network used in Figure 2 in Section 2. Note the lower bounds for simultaneously assigned /64 prefixes and addresses and their plausibility with 1000 attendees, a subset of whose wired and wireless hosts (apparently) use SLAAC.

Table 1 also shows three ISP networks, one each from Europe (EU), Japan (JP), and the United States (US). Seen over the 7 days of observation, the three ISP’s have wildly varying numbers of active /64 prefixes (up to \( \sim 10 \times \) different) and /48 covering prefixes (up to \( \sim 300 \times \) different). This strongly suggests that either (a) their subnet and address assignment practices differ greatly or (b) their WWW client population sizes differ greatly. However, note that they share similar lower bounds on number of simultaneously assigned /64 (SLAAC) prefixes and addresses calculated by our method, each being in the low single-digit millions. These intermediate results, i.e., estimated counts of each network’s IPv6-capable WWW clients, suggests that our method can mitigate bias in counting caused by some networks’ address assignment practices and is a basis of ongoing work. In networks whose IPv6 addresses’ network identifiers (in addition to IIDs) contain pseudorandom segments or have short assignment periods from very large pools, simple counts, e.g., active prefixes per day or week, can far exceed the number of IPv6-capable clients that actually exist in a given network. Thus, more careful counting is warranted as the basis for guaranteed anonymity in aggregates.

To explore this more broadly, Figure 3 plots the distribution of prefix lengths necessary to aggregate 2 simultaneously assigned active /64 prefixes together. (IPv6 hosts have a 64-bit subnet prefix [18], thus an ISP commonly provides at least a /64 prefix to each customer or subscriber.) This is based on our empirical measurements and lower bounds on numbers of simultaneously-assigned IPv6 /64 prefixes as described in Section 2. In this figure, note the JP ISP’s (red) \( k = 2 \) min and max prefix lengths always plot left of bit 48 on the horizontal axis; as above, this confirms that aggregation to /48 would never aggregate any individual customer’s SLAAC prefixes together, thus truncation to /48 does not improve privacy to subscribers. The figure also shows (solid blue) that the EU ISP’s \( k = 2 \) min
Figure 1: (a) Initial Activity Matrix: 16 addresses in 1 /64 prefix
(b) Time Sorted Activity
(c) Inferred Assignment

- = every 24th interval in the matrix, e.g., first hour of day, UTC
+ = every 8th interval in the matrix, e.g., 8 hours
# = activity logged during the given hour
X = activity started and ended during the given hour, i.e., a "short" episode
> = activity started during the given hour, i.e., beginning of an episode
< = activity ended during the given hour, i.e., end of an episode
@ = infer address assigned throughout the given interval, e.g., hour
! = infer /64 prefix assigned at trailing edge of given hour, i.e., the "fencepost" moments between intervals
? = the last "fencepost" moment is discarded since address assignment can't be determined (yet)

(d) matrix legend

Figure 2: A 3-step method to calculate anonymous aggregates using a binary PATRICIA tree, for example, the Meeting Network in Table 1. (a) First, a tree is populated with active /64 prefixes (the 3 nodes with solid lines), each with a time series showing assignment, on or off. (b) Next, the tree is aggregated and the arrays added to their parent until the min count of k = 2 is reached. Here, the first two /64s have been aggregated to their parent, but the third has not yet been visited. (c) Finally, after aggregation is complete, we report only the anonymous aggregates with (at least) the desired number of simultaneous addresses (2): only the one prefix shown in a solid box.
Table 1: Characteristics of the active IPv6 WWW client address data sets. Counts determined by our method, as described in Section 2 are shown bold. The others are simple activity counts during the 7 days of observation.

| Data set    | 7-day date range | Total active /48 prefixes | Total active /64 prefixes | Lower bound simultaneously assigned /64 prefixes maximum (median) | Lower bound simultaneously assigned addresses maximum (median) | Total active addresses |
|-------------|------------------|---------------------------|---------------------------|---------------------------------------------------------------|----------------------------------------------------------------|-----------------------|
| Meeting Network | Mar 25-31 2017   | 1                         | 3                         | 3 (2)                                                         | 309 (84)                                                      | 15.4K                 |
| EU ISP      | Sep 17-23 2016   | 163K                      | 21.5M                     | 2.02M (1.52M)                                                 | 3.80M (2.63M)                                                 | 12.8M                 |
| JP ISP      | Mar 17-23 2017   | 2.46M                     | 2.46M                     | 1.21M (0.897K)                                                | 2.26M (1.54M)                                                 | 72.2M                 |
| US ISP      | Mar 17-23 2017   | 8.16K                     | 2.42M                     | 1.81M (1.660)                                                 | 4.71M (3.82M)                                                 | 84.5K                 |

more than 25% of the prefixes needed prefix lengths less than 48, i.e., not even two /64s are aggregated by /48s therein. Moreover, we presume no one would settle for such a weak notion of anonymity as \( k = 2 \), which would be equivalent to truncating only 1 bit in IPv4, or aggregating to /31. Both in the past and today with IPv4, it is common to truncate or aggregate to /24 prefixes, presumably with the intention of aggregating up to 256 (max) individuals’ addresses together. We consider more reasonable values of \( k \) for privacy, next.

### 3.2 Anonymous Aggregates

We now apply kIP anonymization to addresses for each of the three ISPs. Figure 4 characterizes the resulting prefixes in histograms for \( k = 32 \) and \( k = 256 \). (Essentially, these are equivalent to aggregating a fully-utilized IPv4 network to /27 or /24, respectively.) At these levels of anonymization, we find that, the JP ISP and EU ISP almost always required more aggregation than /48 (more than 80 bits truncated) for us to guarantee that the aggregation meets our desired \( k \) on lower bounds for median counts of simultaneously-assigned addresses. The kIP anonymous aggregate prefixes reported here vary from /25 to /58. In CDF plots (not shown) for the US ISP’s customer’s, we find that /48 aggregation guarantees \( k = 32 \) anonymization for 90-95% (min-max) of those customers, but guarantees \( k = 256 \) anonymization for only 30-40% of those customers. By comparing the resulting kIP anonymous aggregate prefixes counts to fixed-length /48 prefix counts, as shown parenthetically in the legends in Figure 4 and Figure 1, we see that kIP anonymization (with \( k = 256 \) or even \( k = 32 \)) can yield a much smaller set of anonymous prefixes while guaranteeing significant aggregation of individuals’ /64 prefixes.

Figure 3: CDF of aggregate prefix lengths, \( k = 2 \).

Figure 4: Anonymous aggregate prefix lengths.

### 4. LIMITATIONS & FUTURE WORK

In offline operation, e.g., anonymizing addresses of clients that access a worldwide CDN as we report here, the guarantee of anonymization is strong because every address observed is used as input to the anonymization. However, in online operation, e.g., anonymizing addresses on the fly, the guarantee is unclear because the anonymous aggregate set was determined \textit{a priori}, based on addresses active in the past. Thus, online operation of this method entails \textit{forecasting}, wherein the anonymizer likely assumes that past activity is suitably representative.

Lets consider attacks and situations that might call our claimed privacy guarantee into question. In this work, we treat an address’ /64 prefix and anything more specific, e.g., the IID, as private. While it’s common for ISPs to provide a /64 prefix to a customer, some ISPs will honor requests for a larger prefix, e.g., a /60 or /56 [10][17]. Then, the customer’s router can advertise SLAAC prefix(es) to their hosts. In this case, it is possible for an individual customer to have a set of simultaneously-assigned /64 prefixes, resulting in an anonymous aggregate where the number of distinct cus-
tomers could be much less than $k$. To combat this, an anonymizer wants to know the customer’s prefix length, so that it might increase $k$ accordingly. Discovering this prefix length automatically (via the activity matrix) is ongoing work. Similarly, if a malicious party generates traffic from what would be quiescent source addresses in many unique /64 prefixes, they might cause $k$-IP-anonymization to report more specific anonymous aggregates allowing them to determine what their neighbors’ nearest active prefixes might be. For this reason, it may be important to keep time series of simultaneously assigned address counts (as we do here), so that anomalous counts, e.g., during flash crowds, or attacks, can be identified and/or ignored.

In conclusion, we evaluate IPv6 address anonymization and demonstrate that truncation to a single prefix length of 48 bits, Internet-wide, fails to anonymize information associated with individuals’ IP address identities, e.g., /64 prefixes, in the face of some common addressing practices used today. We develop a technique to compute lower bound counts on simultaneously-assigned addresses and an improved anonymization method that truncates to variable prefix lengths guaranteeing a desired degree of address privacy. Our results show that $k$-IP anonymization, e.g., with $k = 32$, outperforms IPv6 address anonymization by 80-bit truncation. Thus, we propose this as preferred privacy practice in research and operations and invite community feedback.

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