Lost in Space: Improving Inference of IPv4 Address Space Utilization

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***Abstract*—One challenge in understanding the evolution of the Internet infrastructure is the lack of systematic mechanisms for monitoring the extent to which allocated IP addresses are actually used. In this paper we advance the science of inferring IPv4 address space utilization by proposing a novel taxonomy and analyzing and correlating results obtained through different types of measurements. We have previously studied an approach based on passive measurements that can reveal used portions of the address space unseen by active approaches. In this paper, we study such passive approaches in detail, extending our methodology to new types of vantage points and identifying traffic components that most significantly contribute to discovering used IPv4 network blocks. We then combine the results we obtained through passive measurements together with data from active measurement studies, as well as measurements from BGP and additional datasets available to researchers. Through the analysis of this large collection of heterogeneous datasets, we substantially improve the state of the art in terms of: (i) understanding the challenges and opportunities in using passive and active techniques to study address utilization; and (ii) knowledge of the utilization of the IPv4 space.**

***Index Terms*—Computer networks, Internet, IP networks**

I. Introduction

In September 2015 the American Registry for Internet Numbers (ARIN) exhausted its IPv4 address space, making it the fourth RIR unable to allocate new IP addresses. This historical event has been anticipated for decades, accompanied by intense debates over address management policy, IPv6 transition, and IPv4 address markets [1]–[4]. One thread in these debates is how many of the currently allocated IPv4 addresses are actually meaningfully "used" (we provide our definition of *used* in Section IV), and how effective different approaches could be to reallocate addresses to increase overall efficiency of usage. More generally, precise knowledge of IPv4 address space usage has applications in network security analysis (e.g., supporting detection of address squatting, informing host reputation systems), active measurement experiment design (e.g., selecting targets), and to estimate Internet evolution over time and across geographic regions.

However, only one project (Heidemann et al. [5]) presently measures – by collecting and analyzing responses to ICMP echo requests – which allocated addresses are actually being visibly used. Unfortunately, measurement campaigns based on Internet-wide active probing can only illuminate a portion of the used address space, because of (i) operational filtering of scanning or (ii) potential violation of acceptable usage policies, triggering either complaints or blacklisting of the measurement infrastructure. Recently, Dainotti et al. [6] proposed an approach based on passive measurements, which is complementary to [5] and promises significant improvement when surveying Internet address usage at /24 address-block (/24 blocks, in the following) granularity. Passive measurements may also compensate for active approaches' inability to scale for use in a future IPv6 census [7].

Building on Heidemann's landmark work and on the novel concepts introduced in [6], our goal in this study is to improve the science of Internet address usage inference in a systematic way. We contribute to this field from different angles:

- *Taxonomic*. We propose a taxonomy of address space utilization that pertains to the whole address space and we introduce metrics to analyze the results of census studies.
- *Methodological*. We extend the passive-measurement approach presented in [6] to vantage points and network measurements of different type. In total we consider: (i) full packet traces from a large darknet; (ii) NetFlow logs from a national academic network; (iii) sampled packet traces from one of the largest Internet exchange points (IXP) worldwide; (iv) traffic classification logs from residential customers of a European ISP. Thanks to the availability of these diverse datasets, we scrutinize the general applicability and limitations of this approach. We analyze how inferences of active address blocks can be influenced by characteristics specific to traffic observation vantage points, such as traffic composition, size of the monitored address space, and duration and

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time of the measurement. We find that all the four types of vantage points (VPs) are reasonably robust to variations in these characteristics and we provide insights to guide researchers in replicating our methodology on other VPs.

- *Knowledge and implications*. We combine seven passive and active measurement datasets to perform the first extended IPv4 Census using our taxonomy. We compare our results to the state of the art represented by the ISI census [5] and obtain an increase of 15.6% over ISI. In this process, we also learn novel insights about the views obtained through active and passive measurements (e.g., we identify special categories of address blocks that do not seem to generate traffic on the public Internet, unless solicited) which can inspire additional work in surveying address space utilization [8].

  We then analyze the results of our census, which estimates that *only 37% of the usable IPv4 space is used*, and that 3.4M assigned /24 blocks are not even visible in the global BGP routing system. We analyze how unused space is distributed across RIRs, countries, continents, and ASes and we infer that only 9.5% of the legacy /24 blocks are *used* and that most *unused* address blocks are in the U.S.

  Finally, we discuss how scientific studies of Internet-related phenomena might change if they used this extended dataset instead of other related data sets to estimate the address space of ASes or countries. As an example, we show the impact on CAIDA AS Rank [9].

Section II and Section III describe related work and the datasets we use in our study. Section IV introduces our new taxonomy for IPv4 address space utilization and provides a first insight in our findings. Section V extends and provides a detailed evaluation of our passive traffic methodology. Section VI combines passive and active measurement approaches and examines their different contributions. Section VII characterizes the utilization of the address space and the potential impact of using our dataset (shared through the PREDICT repository [10]) in other research studies. Section VIII offers promising directions for applicability and extension of this work.

II. Related work

Huston [2]–[4], [11] has provided a wealth of statistics and projections related to allocated and routed IPv4 address space, although he does not attempt to discern if allocated or routed addresses are actually *used* (for any definition). In a study of allocated and routed addresses, Meng *et al*. [12] found that most IPv4 prefixes allocated between 1997 and 2004 appeared in the global routing system within 75 days.

With respect to measurement to evaluate actual address usage, USC's long-standing effort [5], [13] periodically probes the entire IPv4 space with ICMP echo requests. Probing every routed IPv4 address over $\sim$30 days, repeated multiple times between 2005 and 2007, they observed only 3.6% of allocated addresses responding [5]. In developing their methodology, they compared ICMP and TCP probing to passive traffic observation of USC addresses on USC's own campus network, finding 14% more USC IP addresses visible to ICMP than to TCP, and 28% more USC IP addresses visible to passive traffic observation than to either ICMP or TCP active probing. But each method observed some IP addresses missed by other methods. Also, Bartlett *et al*. [14] found that passive traffic observation and active probing complemented each other for the purpose of discovering active network services on campus. In this work, we also find that active and passive methods are able to observe different subsets of addresses (Section VI), but unlike [5], we use our passive monitors to infer usage about the entire Internet instead of only hosts internal to a network we monitor.

However, passive measurements introduce their own challenges, most notably the presence of traffic using spoofed source IP addresses, which can badly pollute estimates if not removed. In [6], we introduced a methodology validated on two sources of traffic data available to us in 2012. In this work, we extend this approach to two additional types of data sources – the most challenging of which is sampled traffic captured at an IXP – and we then examine how resulting inferences can be influenced by characteristics specific to observation vantage points, such as traffic composition, size of the monitored address space, and duration and time of the measurement.

Others have also explored the use of passive data to estimate specific usage characteristics of IPv4 addresses. Zander *et al*. [15] estimated the *number* of used IPv4 addresses by applying a capture-recapture method for estimating population sizes on active and passive measurement logs of IP addresses collected from sources such as web servers and spam blacklists. This work is largely complementary to ours, since it does not focus on improving active and passive methodologies to collect census data and understand their complementarity, but rather proposes an approach to estimate the *size* of the used space that such methodologies fail to observe.

Durumeric *et al*. [16] explored the system challenges of active Internet-wide scanning in developing Zmap, a scanner that probes the entire IPv4 address space in under 45 minutes from a single machine. Accelerated scanning was also a goal of an Internet Census illegally (and anonymously) performed in 2012 from a botnet [17], although their methods were neither well-documented nor validated [18]. Finally, Cai *et al*. [13] explore (and undertake several) potential applications of clustering active probes to infer address usage, including understanding how efficiently individual address blocks are used, assessing the prevalence of dynamic address management, and distinguishing low-bitrate from broadband edge links.

III. Datasets

Table I summarizes the datasets we use, which include 4 types of passive traffic traces (from a darknet, an academic ISP, an IXP, and a residential ISP), 3 types of active measurements, BGP data, IPv4 address allocation data, and derived data about geolocations and ASes. They were collected between July and October 2013.

Passive Data-plane Measurements. We apply our passive methodology for inferring used /24 blocks to the following four VPs, each of which retains traffic data in different formats

Dataset	Source type	Data format	Period
UCSD-NT [19]	Traffic: Darknet	full packet traces	July 23 to August 25, 2013
SWITCH [20]	Traffic: Live Academic Net.	Netflow logs	July 23 to August 25, 2013
IXP [21]	Traffic: IXP	sFlow packet samples	July 8 to July 28, August 12 to September 8, 2013
R-ISP [22]	Traffic: Residential ISP	Tstat [23] logs	July 1 to September 31, 2013
ISI [24]	Active Probing: ICMP ping	logs	July 23 to August 25, 2013
HTTP [25]	Active Probing: HTTP GET	logs	October 29, 2013
ARK-TTL [26]	Active Probing: traceroute	logs	July to September, 2013
BGP [27], [28]	BGP announcements	RIBs	July to September, 2013
Available Blocks [29]	IANA/RIRs	IP ranges	October 1, 2013
NetAcuity Edge [30]	IP Geolocation	IP ranges	July 2013
prefix2AS [31]	BGP announcements	prefix to ASN	July 2013

TABLE I: We infer used /24 blocks from passively collected traffic (UCSD-NT, SWITCH, IXP, R-ISP) and active probing (ISI, HTTP, ARK-TTL). The remaining datasets are used to infer both usable and routed prefixes, or label prefixes according to geolocation and AS.

and thus requires different approaches to filtering for use in a census (Section V). **SWITCH**: We collected unsampled NetFlow records from all the border routers of SWITCH, a national academic backbone network serving 46 single-homed universities and research institutes in Switzerland [20]. The monitored address range of SWITCH contains 2.2 million IP addresses, which correspond to a continuous block slightly larger than a /11. **R-ISP**: We collected per-flow logs from a vantage point monitoring traffic of about 25,000 residential ADSL customers of a major European ISP [22]. The VP is instrumented to run Tstat, an open source passive traffic flow analyser [23] that stores transport-level statistics of bidirectional flows, and uses internal network knowledge to label flows as inbound or outbound. **UCSD-NT**: We collected full packet traces from the /8 network telescope operated at the University of California San Diego [19]. Network telescopes, also called darknets, passively collect unsolicited traffic — resulting from scans, misconfigurations, bugs, and backscatter from denial of service attacks, etc. — sent to routed regions of the address space that do not contain any hosts. **IXP**: Our fourth VP is one of the largest IXPs in the world, which is located in Europe, interconnects $O(100)$ networks, and exchanges more than 400 PB monthly [21]. We have access to randomly sampled (1 out of 16K) packets, capturing the first 128 bytes of each sampled Ethernet frame exchanged via the public switching infrastructure of this IXP. A sample includes full Ethernet, network- and transport-layer headers, along with a few payload bytes.

Active Measurements. **ISI**: We used the ISI Internet Census dataset *it55w-20130723* [24], obtained by probing the routed IPv4 address space with ICMP echo requests[1] and retaining only those probes that received an ICMP echo reply from an address that matched the one probed (as recommended [32]). Note that the ISI Census experiment was designed to report at a /32 (host) rather than /24 (subnet) granularity, but we apply the resulting data set to a /24 granularity analysis. **HTTP**: We extracted IP addresses from logs of Project Sonar's HTTP (TCP port 80) scan of the entire IPv4 address space on October 29, 2013 [25]. For each /24 block, we stored how many IP addresses responded to an HTTP GET query from the scan. **ARK-TTL**: We processed ICMP traceroutes performed by CAIDA's Archipelago to each /24 in the routed IPv4 address space between July and September 2013 [26]. Specifically, we extracted the ICMP Time Exceeded replies sent by hops along the traceroute path.

[1]We did not use reverse DNS PTR scans of the IPv4 space for the same reasons articulated in [5], namely that many active IP addresses lack DNS mappings, and many unused IP addresses still have (obsolete) DNS mappings.

Address Allocation and BGP Data. We analyzed BGP announcements captured by all collectors (24 collectors peering with 184 peers) of the Routeviews [27] and RIPE RIS [28] projects. For each collector we took all routing tables (dumped every 2 hours by Routeviews and 8 hours by RIPE RIS) and built per-day statistics for each peer. For each /24 block, we computed the maximum number of peers that saw it reachable at any time within the full observation period of 92 days. To determine which address blocks are available for assignment, we used a dataset compiled by Geoff Huston [29], which merges the extended delegation files from the 5 Regional Internet Registries (RIR) [33]–[37] with IANA's published registries [38]–[43].

Mapping to ASes and Countries. To establish a mapping from /24 block to ASN, we merged all CAIDA's Routeviews Prefix to AS [31] mappings files for July 2013. For each /24 in the IPv4 address space, we identified the set of overlapping prefixes and chose the most specific. We found 116k /24s (out of more than 10M) that mapped to multiple ASNs (due to multi-origin ASes and AS sets), which we omitted from our per-AS computations (Sections VI and VII). We geolocated each /24 block using Digital Element's NetAcuity Edge [30] database from 6 July 2013. For each /24, we identified the unique set of country codes to which overlapping blocks map. We found 27k /24s (out of more than 14M) that map to multiple countries, which we excluded from the geographic visualization in Section VII.

IV. A TAXONOMY OF INTERNET ADDRESS SPACE UTILIZATION

How to to classify address space by usage? Of the unrouted space, which is assigned vs. available?

We propose a taxonomy of the IPv4 address space according to the tree in Figure 1, where blue labels set the terminology that we use throughout the paper and red annotations summarize the classification criteria. While this taxonomy is generally applicable, in this paper we analyze the IPv4 address space with /24 block granularity. There is no universal IP address segment boundary (due to sub-netting and varying size of administrative domains), but using a /24 granularity mitigates the effects of dynamic but temporary IP address assignment (e.g., DHCP), as well as having an intuitive relationship with both routing operations and address allocation policy.

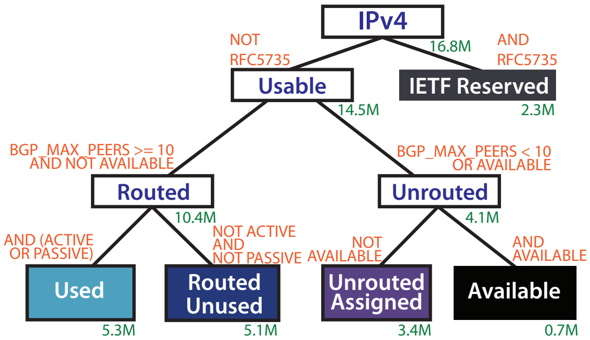


Fig. 1: IPv4 address space taxonomy. Nodes are annotated with the estimated /24 population of each category (Section VII) and the filter applied to arrive at the estimate (Sections IV through VI).

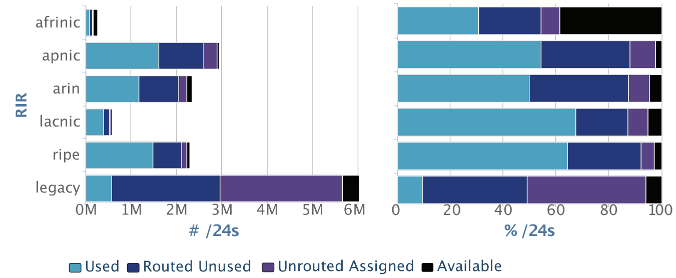


Fig. 2: Our final inferences classified by RIR-allocated (and legacy) address space. We identify legacy addresses per /8 [38], but include some /8s that are presently administered by RIRs. Only 9.5% of the legacy addresses are used.

All address blocks dedicated to special use (multicast, private networks, etc.) are *IETF reserved* and are covered by RFC5735 [44] (≈2.3M /24 blocks). To classify the remainder into *routed* and *unrouted*, we must distinguish legitimately routed address blocks from those that appear in BGP announcements due to router misconfigurations. We consider a /24 block as *routed* only if covered by a prefix visible by at least 10 BGP peers. RIPE recommends this threshold [45], which we believe is reasonable since it removed from BGP measurements 99.93% of the /24 blocks we previously determined were reserved by IETF or *available* (defined in the next paragraph) and thus could not be legitimately routed via BGP.

Of the 4.1M *unrouted* /24 blocks, we classified as *available* any /24 block (≈.7M) falling in address ranges marked in Geoff Huston's dataset (Section III) as either "available" (i.e., allocated to an RIR but not yet assigned to a Local Internet Registry (LIR) or organization) or "ianapool" (i.e., IANA has not allocated it to an RIR) [29]. This data does not have LIR granularity, thus we considered any block allocated to an LIR as assigned (i.e., not available). The remainder – the *unrouted assigned* category – is made of 3.4M /24 blocks that are assigned to organizations (many of whom announce other IPv4 address space) and yet are not routed. In other words, we find that **≈53 /8's worth of address space are not used for the purpose of global BGP reachability.**

Our filtering yields 10.4M *routed* /24 blocks that we further classify as *used* or *unused*. We define a /24 block as *used* if at least one of its IP addresses is assigned to a machine that will exchange packets on the public Internet with such address in the IP header. In Sections V and VI, we discuss the inference methodologies – based on both active and passive measurements – that we use for this purpose. Figure 2, provides an overview of our final results according to our taxonomy and breaking the space by RIR and legacy allocations. This visualization succinctly represents "where" in the allocation system, and how, large portions of address space appear unutilized.

V. Analysis of Passive Traffic

Is the approach of passive measurement for inferring address space utilization generally applicable? How does it depend on different network types, trace types, and other parameters?

We first extend the method of [6], which used data from a darknet and an academic ISP, to work with the fundamentally different types of traffic collected at a residential ISP and an IXP, showing how to filter out spoofed traffic in different trace types (Section V-A). Second, we evaluate the impact on our inferences of varying aspects of the vantage points: traffic composition, size of monitored address space, duration and time of measurement (Section V-B).

A. Removing spoofed traffic

The main challenge in curating traffic data for use in a census is to remove spoofed traffic from the datasets, since it can severely distort estimates of address utilization. Since the R-ISP data retains bidirectional flow information and is guaranteed to see both directions of every flow, filtering out spoofed traffic is easy. For the IXP, the sampled data collection and the frequently asymmetric traffic flow (i.e., only one direction of a flow may traverse the IXP) mean that we cannot use the obvious and most reliable technique to infer spoofed traffic (i.e., failed TCP flow completion, variants of which we use for R-ISP and SWITCH data). Indeed, we see only one packet for the vast majority of flows in the IXP data. The IXP data also introduces a new challenge: filtering out packets with potentially unused destination addresses (e.g., scanning packets).

Although each VP's dataset requires its own technique, we tune and validate each technique using the same assumption: packets appearing to originate from [or destined to] *unrouted* blocks are likely spoofed [or scanning] packets. As an additional source of validation, we compare our results against other network blocks that we know to be unused. Specifically: (i) at the SWITCH, R-ISP, and IXP VPs we use the dark /24 blocks in the UCSD-NT address space [2] (62,838 /24 blocks); (ii) at the UCSD-NT VP, we use the /24 blocks from SWITCH that we infer to be dark because they did not generate a single bidirectional flow in the whole observation period (5,003 /24 blocks). We use these data only with UCSD-NT because their

[2]Some addresses within this "darknet" are actually used and their traffic is not collected.

Vantage Point	Original Traffic			After Applying Heuristics		
	/24 blocks	Unrouted	Dark	/24 blocks	Unrouted	Dark
UCSD-NT	10,884,504	1,284,219 (31.6%)	D-SWITCH: 4,553 (90.9%)	3,152,067	2,123 (0.05%)	D-SWITCH: 2 (0.04%)
SWITCH	4,679,233	35,585 (0.69%)	UCSD-NT: 429 (0.68%)	3,599,558	178 (0.004%)	UCSD-NT: 0 (0.00%)
R-ISP	5,233,871	344,188 (8.5%)	UCSD-NT: 7,287 (11.6%)	3,797,544	271 (0.006%)	UCSD-NT: 0 (0.00%)
IXP	14,461,947	4,068,232 (78.5%)	UCSD-NT: 62,838 (100%)	3,091,021	376 (0.009%)	UCSD-NT: 3 (0.004%)

TABLE II: Applying our heuristics to remove spoofed traffic reduces the number of unrouted and dark (i.e., likely spoofed) /24 blocks at all VPs. For each VP, we report the absolute number and percentage of all /24 blocks that are unrouted. For the dark category (4th and 7th column), we use the /24 blocks of SWITCH that did not generate bidirectional flows (D-SWITCH) to evaluate UCSD-NT, and the addresses monitored by UCSD-NT to evaluate all other VPs.

observation periods exactly match. Table II shows the numbers of /24s found by each VP before and after applying our heuristics.

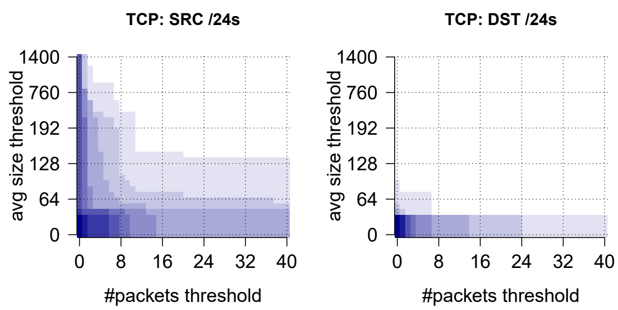
1) IXP (large IXP): For the IXP, we consider only TCP traffic and discard TCP packets with the SYN flag set, which reduces the number of observed /24s from 14.4M to 5.7M /24s. We then use a heuristic to filter out /24s observed due to spoofing (source addresses) or scanning (destination addresses).

Our heuristic is based on two metrics that correlate with the presence of spoofed and scanning traffic: the number of packets from and to a given /24 block and their average packet size. We obtain the left plot in Figure 3a by applying these metrics to source addresses of sampled packets observed at the IXP: for different threshold values (number of packets on x axis, average packet size on y axis), darker colors represent a larger number of unrouted blocks erroneously inferred as used. The diagram shows that by combining both filters it is possible to remove known errors while minimizing the respective thresholds.

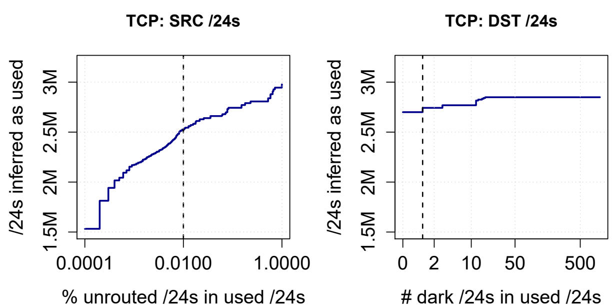
While the dataset of unrouted /24 blocks allows us to effectively reveal inference errors when applied to source addresses, we found it ineffective with destination addresses: we see almost no packets in the IXP traffic dataset destined to unrouted /24 blocks, perhaps because there are no default routes advertised across BGP peering (vs. transit) sessions at the IXP, so only explicitly routed addresses will be observed as destinations. Therefore, when examining destination addresses, we use dark but routed destination addresses as indicators of scanning traffic. The right plot in Figure 3a shows the number of dark /24 blocks inferred as used when considering the destination addresses of packets. The average packet size is highly efficient at removing scanning traffic.

Sufficiently high thresholds remove all traffic responsible for known erroneous inferences but dramatically reduce our ability to collect used /24 blocks. The left diagram in Figure 3b shows the number of /24 blocks that we infer as used (y axis) as a function of the corresponding fraction of unrouted source /24 blocks (x axis). Another way to read the graph is the following: for a given requirement on the x axis (e.g., "less than 0.1% unrouted inferred as used"), we find the combination of thresholds (minimum number of packets and minimum average packet size) that results in the largest set of inferred used /24 blocks (y axis). The right diagram in Figure 3b analogously refers to destination address blocks and dark /24 blocks inferred as used.

We select very conservative thresholds (shown as dashed vertical lines in Figure 3b) to achieve a low error due to either spoofing or scanning at the expense of detecting less used /24s. Table II shows the results obtained for the selected thresholds. Our antispoofing approach is efficient, reducing the number of unrouted and dark /24s dramatically, even for sampled traffic.



(a) Unrouted (left) and dark (right) /24s inferred as used for different threshold combinations.



(b) Trade off between introduced error (unrouted /24s, dark /24s) and the number of /24s inferred as used.

Fig. 3: IXP: Threshold selection for inference of used /24s.

We find similar behavior with UDP (as TCP) but we must set higher thresholds, particularly for average packet size. We do not include UDP-based inferences in our final dataset, since the additional gain in terms of /24s is not significant.

2) R-ISP (residential ADSL ISP): Unlike the other traffic data sources, the R-ISP's use of Tstat automatically removes essentially all TCP spoofed traffic, since to be logged a TCP flow must complete the 3-way handshake. For UDP traffic, our approach is to extract only bidirectional flows initiated locally with at least 1 packet with payload transmitted in both directions. We consider both source and destination addresses from the selected TCP and UDP flows. Table II confirms the accuracy of our approach.

3) UCSD-NT (a large darknet): In [6] we looked deeply into several *spoofing events* to derive filters that would allow

Spoofed Traffic Filter	Total /24s	Unrouted /24s
TTL> 200 and not ICMP	10,588,879	1,278,027
Least signif. byte src addr 0	45,382	7
Least signif. byte src addr 255	444,346	6,691
Non-traditional Protocol	56,502	2,209
Same Src. and Dst. Addr.	96	0
No TCP Flags	3,449	638
UDP Without Payload	545	114
All Specific Filters	10,587,049	1,280,826

TABLE III: Types of spoofed traffic observed and removed at UCSD-NT. Total and unrouted /24s seen in each traffic type. All non-general filters are grouped as “All Specific Filters”.

R-ISP Traffic Class	/24 Blocks	Unique	Volume
P2P[a]	3,172,439 (91.2%)	610,438	34.1%
Teredo	914,533 (26.3%)	1,467	1.4%
VoIP (RTP,RTCP)	892,488 (25.7%)	3,619	0.5%
HTTP/HTTPS	234,586 (6.8%)	20,274	57.7%
Other[b]	196,503 (5.7%)	62,406	1.9%
Unknown[c]	2,691,300 (77.4%)	115,869	4.5%

[a] eMule, ED2K, KAD, BitTorrent, PPLive, SopCast, TVAnts, and PPStream
[b] DNS, POP3, SMTP, IMAP4, XMPP, MSN, RTMP, SSH
[c] Flows unmatched by the classification engines.

TABLE IV: At the R-ISP VP, P2P traffic contributes almost 3.2M /24 blocks, including 610K unique (only observed through P2P traffic). HTTP/HTTPS is a smaller component, despite accounting for 57.7% of the volume.

Darknet Traffic Class	/24 Blocks		Unique
BitTorrent	2,210,257	(70.2%)	321,474
Encrypted[a]	1,349,578	(42.8%)	34,290
UDP Qihoo 360 bug	1,343,911	(42.7%)	115,951
Other P2P (eDonkey,QQLive)	834,657	(26.5%)	5,361
Encapsulated IPv6 (Teredo,6to4)	745,092	(23.7%)	11,322
Conficker	604,877	(19.2%)	61,836
Backscatter	388,095	(12.3%)	53,277
Scanning (non-Conficker)[b]	194,649	(6.2%)	4,269
Other	2,038,150	(64.7%)	143,066

[a] Packets where entropy(payload)≈$\log_2$ len(payload).
[b] Meeting Bro's definition of a scanner: sent same protocol/port packets to at least 25 destinations in 5 minutes [46].

TABLE V: At UCSD-NT, BitTorrent traffic contributes the most /24 blocks, instead of activities traditionally observed in darknets (scanning, Conficker, backscatter). For each class of traffic less than 15% of /24 blocks are unique (only observed through the class).

us to filter such events from darknet traffic in general. Two phenomena that we found to be indicators of a spoofing event were: (i) spikes in the numbers of both unrouted and overall /24 blocks per hour, and (ii) traffic using the same ports and protocols with a high fraction of unrouted source /24 blocks. We developed general filters (properties of the traffic that always indicate spoofing), and filters specific to individual events. Many types of spoofing captured by our generic filters in our 2012 study [6] were also present in 2013 (see [6] for details on methodology and filters). In addition, we added two general filters: TCP packets with no flags set and UDP packets without payload. Table III reports the number of /24 blocks matching each filter.

After applying our filters, we observe more than 3 million /24 blocks. Table II shows that our filtering heuristics reduce traffic appearing to originate from unrouted or dark networks to around 0.05% (compared to 31.6% and 90.9% unrouted and dark blocks, respectively, before filtering).

4) SWITCH (academic network): To filter spoofed traffic, we use the same heuristic we introduced in [6], which extracts from Netflow records bidirectional TCP flows with at least 5 packets and 80 bytes per packet on average and we use both source and destination addresses. We performed a sensitivity analysis on these thresholds in [6], and found that they diminish the probability that the remote IP address is spoofed. Using this heuristic leads us to infer as used only 0.004% and 0% of the unrouted and the UCSD-NT /24 blocks, respectively (Table II).

B. Effect of vantage points characteristics: traffic, network address segment, time, duration

After filtering spoofed traffic, we analyze the impact of four characteristics specific to a given vantage point on the number of /24s observed: type of traffic, size of address space monitored, and duration or specific time of monitoring. We find that all four VPs are reasonably robust to variations in these characteristics, i.e, we observe a substantial fraction of address space at all VPs or when observing from smaller fractions of the address spaces (where we could test that), and each VP saw a consistent number of /24 blocks over a two-year period.

1) Influential Traffic Components: How do traffic characteristics specific to a VP influence its contribution to the inferences?

Characterizing traffic at our VPs assists with two objectives: (i) highlighting how the VP contributes to the census; and (ii) ensuring that traffic components specific to a VP do not skew our findings or make them not generally applicable. That is, to legitimately use passive traffic data for a census, we need to convince ourselves that a given VP is not observing a special set of /24 blocks. For objective (i), SWITCH's popular services attract users from many /24 blocks, while R-ISP and UCSD-NT contribute many /24 blocks as the result of P2P traffic. However, for each VP, when we exclude the traffic generated by the top component, we still observe at least 69.9% of the totals reported in Table II, implying that traffic composition at a particular VP does not skew our results (i.e., objective ii). We could not analyze traffic composition from the IXP due to the sampled packet capture.

SWITCH. SWITCH hosts many popular services that attract end users to the monitored address space, including: a website hosting medical information (exchanging traffic with hosts in 1.8M /24 blocks), a SourceForge mirror, PlanetLab nodes, university web pages, and mail servers. The top 100 most popular IP addresses (i.e., the top services) in SWITCH each observe over 70K /24 blocks, and collectively contribute 91.2% of the /24 blocks observed at this VP. Compared to the UCSD-NT and R-ISP vantage points, SWITCH's value as a VP depends more on popular IP addresses. If SWITCH did not host its top 1000 most popular IP addresses, it would observe only 69.9% of the /24 blocks it otherwise observes, compared to 89.7% and 97.5% at R-ISP and UCSD-NT respectively. This finding can be easily explained: the top services at SWITCH tend to attract large, varying client populations, while at R-ISP and UCSD-NT we capture /24 networks generating P2P traffic (the largest component for each VP) via multiple monitored IP addresses.

R-ISP. Table IV aggregates the Tstat-identified traffic categories observed at R-ISP into five traffic components accounting for 97% of /24 blocks observed at the ISP. While HTTP and HTTPS account for 57.7% of the traffic volume, they contribute only 6.8% of the /24 blocks observed at the VP. Instead, the largest source of /24 blocks comes from client-to-client communication (e.g., P2P and VoIP). P2P is a key contributor, as 610k /24 blocks are only observable through P2P traffic.

UCSD-NT. Surprisingly, P2P also plays a key role at the UCSD-NT VP, where we observe 2.2M /24 blocks (357k unique) from traffic with a BitTorrent payload (see Table V), probably caused by index poisoning attacks [47]. Qihoo 360 updates using a P2P network [48] and a byte-order bug in the software results in traffic from sources in over 1.3M /24 blocks, 40% of which geolocate to China. To a lesser extent, networks with end users are exposed through malware-infected hosts (e.g., Conficker and scanning). Alternatively, the backscatter traffic (a result of spoofed DoS attacks) reveals networks likely hosting services. In [49], we present a thorough analysis of (unspoofed) traffic reaching large darknets.

2) Impact of Vantage Point Size: We analyze vantage point size (the number of IP addresses monitored) to determine the extent to which our results depend on access to large datasets. Unfortunately, the analysis of vantage point size is not straightforward due to the non-uniform nature of the monitored address space. Notwithstanding the extraordinary popularity of some IP addresses, as well as non-uniform assignment of hosts within an address subnet, we found an interesting correlation: for each vantage point, the median number of /24 blocks observed is roughly proportional to the log of the number of monitored IP addresses. Consistent with this observation, the utility of a monitored IP address declines as the size of the vantage point increases. While our results benefit large datasets, halving or doubling the size of our vantage points is unlikely to have a substantial impact on the number of /24 blocks we infer as used.

3) Impact of Time: How does the duration or time of collection affect the inference of which /24s are used?

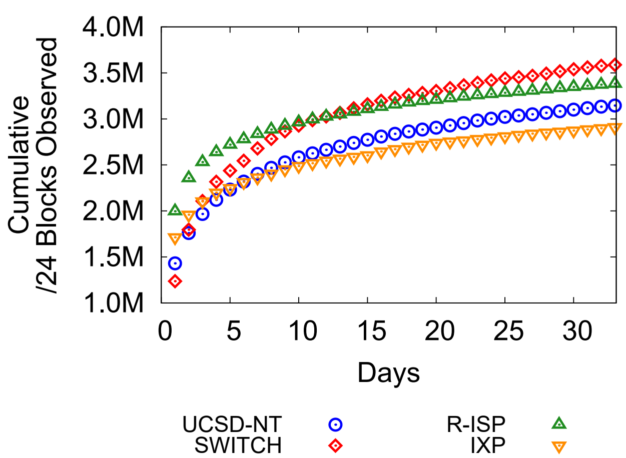


Fig. 4: The cumulative number of /24 blocks observed grows sublinearly at each vantage point.

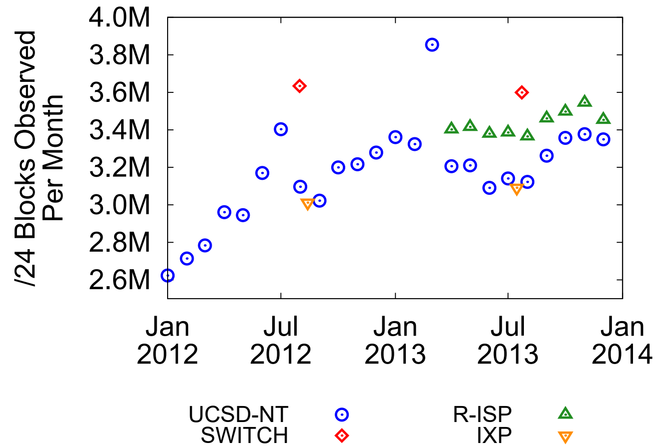


Fig. 5: In our data, taken over two years, every VP observed at least 2.6M /24 blocks per month. The fluctuations in UCSD-NT data are the result of changes in the traffic components comprising IBR.

Figure 4 shows sublinear but varied growth of the number of /24 blocks collected over time for our four VPs. For all VPs, a period of few (e.g., 10) days is enough to capture a the majority of the sources that are observed at each VP within the considered time frame. SWITCH, which initially captures the fewest /24 blocks has the fastest growth rate; while the R-ISP and IXP VPs capture more /24 blocks initially but they grow more slowly. Other factors that can influence inferences are strong changes in traffic composition, e.g., flash events. Our traffic datasets all had low (max 2%) standard deviation in the number of /24 blocks observed per week, with no abnormal events observed. However, when observing measurements from a broader time frame, we found evidence of flash events and changes in traffic. For example, in August 2012 (the year preceding our datasets), SWITCH web sites hosting content about shark protection experienced a sharp increase in visits (and thus observed /24 blocks); the Discovery Channel's Shark Week aired that month.

Figure 5 shows per-month sample measurements using our methodology over a period of two years. The SWITCH and IXP VPs observed a similar number of /24 blocks approximately one year prior to our census. R-ISP consistently observed between 3.4M and 3.6M /24 blocks for nine consecutive months. At UCSD-NT, changes in the phenomena responsible for IBR resulted in a corresponding increase in visible /24 blocks. Specifically, (i) in July 2012, there was an increase in BitTorrent traffic; (ii) in March 2013, there was a large increase in the darknet's backscatter category, likely related to the DDoS attacks on Spamhaus [50]. Such events may increase the number of /24 blocks inferred as used, but our technique does not appear to significantly depend on one-off events: in our data, every VP observed at least 2.6M /24 blocks per month.

VI. Combining Active and Passive Approaches

In this section, we first combine our seven datasets obtained from active and passive measurements to break down the *routed* node in Figure 1 into *used* and *routed unused* categories (we filtered all the datasets used in this section to include only /24 blocks marked as *routed* according to Section IV). We then compare our results to the state of the art represented by the ISI census (Section VI-B).

A. Active vs Passive Measurements

What are the respective strengths and limitations of active and passive measurements? Are passive measurements from multiple VPs useful?

The top half of Table VI shows the number of /24 blocks discovered by each active approach and their unique contribution. The large number of /24 blocks found by ISI and HTTP, and their distinct contributions within the set of active measurements, are unsurprising because we know that ICMP and TCP port 80 probing are among the most effective active probing methods that capture different but overlapping populations [5], [51]. More surprising is the 40k additional /24 blocks that we obtain from the ARK-TTL dataset; we speculate that routers may be sending TTL exceeded packets using a different source address from what they use in ICMP echo responses.

Dataset	**# /24s**	**# Unique /24s within same family**	**# Unique /24s among active + passive**
Active			
ISI	4,589,213	1,319,283	398,334
HTTP	3,161,064	189,831	76,189
ARK-TTL	1,627,363	40,284	24,533
All Active	4,837,056		
Passive			
SWITCH	3,599,380	147,220	54,905
UCSD-NT	3,149,944	61,443	24,134
R-ISP	3,797,273	176,721	59,278
IXP	3,090,645	195,328	55,155
All Passive	4,468,096		
Total	5,306,935		

TABLE VI: Each data set used to infer address space utilization offers a unique contribution. Unrouted /24 blocks are not represented here. The third column is the number of /24s observed in the data set that were not also observed in the (top) other active data sets or (bottom) other passive data sets; the fourth column is the number of /24s observed that were not observed in any other data set. The final total is the number of /24s we infer as *used* (lower left node of tree in Figure 1).

The bottom half of Table VI compares the contribution of our passive measurements. The merged results from our four passive VPs do not entirely cover the set observed by active measurements, missing about 840k /24 blocks. However, the same data includes 470k /24 blocks not observed through active measurements, demonstrating the value of combining active and passive datasets.

Each passive vantage point offers a unique contribution, shown in the third and fourth columns of Table VI, suggesting that these measurements are not exhaustive and that using more vantage points could improve the coverage. In particular, when we examine the portion of the address space observed exclusively by passive approaches (470k /24 blocks, not shown in the table), we find that only 17% of it was visible by all four vantage points, while $\approx 41\%$ came from the sum of each unique contribution (4th column in Table VI).

	% of newly discovered /24 blocks	per-continent % increase of /24 blocks
Europe	32.44%	11.11%
North America	26.54%	9.08%
Asia	25.31%	7.64%
South America	8.56%	10.85%
Africa	4.65%	30.18%
Oceania	4.33%	29.24%

TABLE VII: Absence of significant geographical bias in passive vs active measurements: of the number of /24 blocks discovered by passive approaches and not seen by active ones, a slightly larger portion is geolocated to Europe (where 3 of our 4 passive VP are). But on a per-continent basis (right colum), the increase is more even across continents (Southern continents have little address space so any increase will be relatively large in percentage terms.)

Since 3 out of 4 vantage points are in Europe, we test for the possibility of geographical bias in the passive measurements. Table VII shows the percent increase of /24 blocks discovered by merged passive+active data vs. active measurements alone. The larger increase in European coverage vs. other continents (middle column) is consistent with a slight bias from the European vantage points, but on a per-continent basis the marginal increase spreads more evenly across continents (right column, noting that the lower three continents have so much less address space that any increase will be relatively large in percentage terms.)

We also explored why a significant portion of space is discovered only by the active measurements in our data sets. On one hand, there are limitations in passive approaches, some of which will be subject of future work: (i) some of our heuristics to remove spoofed traffic may be too conservative and remove much legitimate traffic; (ii) for IXP and SWITCH, we included only TCP traffic which could have limited our view; curating UDP and other traffic would probably improve coverage; (iii) as discussed, adding more VPs would also bring an improvement. On the other hand, our results also reveal fractions of IPv4 space that does not seem to spontaneously generate traffic on the public Internet, since visible only by active measurements and showing special properties. For example, we found that most /24 blocks from the ISI dataset with a single responding address whose last octet was 0, 1, or 255 (*isi_special* column in Table VIII) were not observed in our passive measurements. Table VIII shows the distribution of the number of passive vantage points that saw such /24 blocks

# Passive VPs	# ISI-special /24s	# single-IP /24s without ISI-special
0	94,266	58,132
1	13,057	19,414
2	9,674	19,115
3	4,959	27,185
4	2,465	13,091

TABLE VIII: Most /24 blocks in the ISI dataset with only a single IP address ending in .0, .1, .255 are not observed by any of our passive measurements (first row and middle column). In contrast, if a /24 in the ISI dataset had only a single responding address ending in another octet, it was more likely to be through our passive datasets (3rd column). We conclude that most /24s represented in the middle column likely do not send traffic to the public Internet.

(2nd column), as well as all /24s in the ISI data that had only a single non-special responding IP address (3rd column). The progression from /24 blocks observed by 1 to 4 VPs shows a rapid decay for *isi_special* blocks (middle column), while there is almost no trend for /24s in the right column. We conclude that most of the /24s represented in the middle column likely do not send traffic to the public Internet. This finding poses the question of wether such addresses – even if matching our definition of *used* – are actually utilized for the purpose of global reachability, which suggests to extend our taxonomy in the future by defining *used* subcategories to provide additional insight.

We manually investigated other cases of network blocks only visible to active probing, identifying special cases that suggest that they are not used on the public Internet, including clusters of /24 blocks apparently used as internal CDNs by large service providers. In a study led by the Naval Postgraduate School [8], we also identified network *tarpits* (a form of defensive cyber-deception, whereby a single host or appliance can masquerade as many fake hosts on a network and slow network scanners) as large as /16, polluting Internet census data. We plan a thorough investigation of all these behaviors (and their taxonomization) as future work.

The last row of Table VI shows the final number (5.3M) of /24 blocks we infer as *used* combining our 7 active and passive datasets (leftmost leaf in Figure 1). We subtract this from the total amount of BGP-routed space (10.4M) to arrive at an estimate of **5.1M *routed unused* /24 blocks, an impressive quantity of unused but BGP-reachable IPv4 space**. Zander *et al.* [15] corroborate this finding: using a capture-recapture methodology they estimate that about 40% of routed /24 blocks are unused.

B. Coverage

What is the improvement of our combined approach to infer utilization in the routed space with respect to the state of the art (ISI census)?

We consider the ISI Census [5] to be the state of the art in inferring address space utilization within the routed space. Since there is no global ground truth available about which routed space is actually utilized, we present our results in terms of additional IPv4 space coverage we obtain when combining our 7 datasets (which include ISI). We define coverage at three different levels: (i) the percentage of routed /24 blocks inferred as used (*global coverage*); (ii) the percentage of ASes announcing the /24 blocks inferred as used out of the ASes that announce at least one BGP prefix (44,628 ASes) (*AS-level coverage*); (iii) for each AS, the percentage of routed /24 blocks inferred as used (*intra-AS coverage*). AS-level coverage is the only case in which we expect the upper bound to approximate ground truth (i.e., it is reasonable to assume that an AS announcing prefixes through BGP uses at least one /24 block).

We found 718k previously undiscovered used /24 blocks (difference between last and 1st row of Table VI), bringing global coverage from 44% to 51%. Our AS-level coverage is 98.9% versus 94.9% found by ISI. We manually analyzed whois and BGP data for the 489 ASes for which we did not infer a single used /24 block. We found that 37 ASes associated with U.S. military organizations accounted for 79% of the (17,080) /24 blocks advertised by these 489 unobserved ASes. We suspect such networks do not transmit ICMP, TCP or UDP traffic over the public Internet (but they may be tunneling traffic using, e.g., IPSEC, which we did not capture in our passive measurements). The vast majority of the remaining ASes (399 out of 452) announce 10 or fewer /24 blocks.

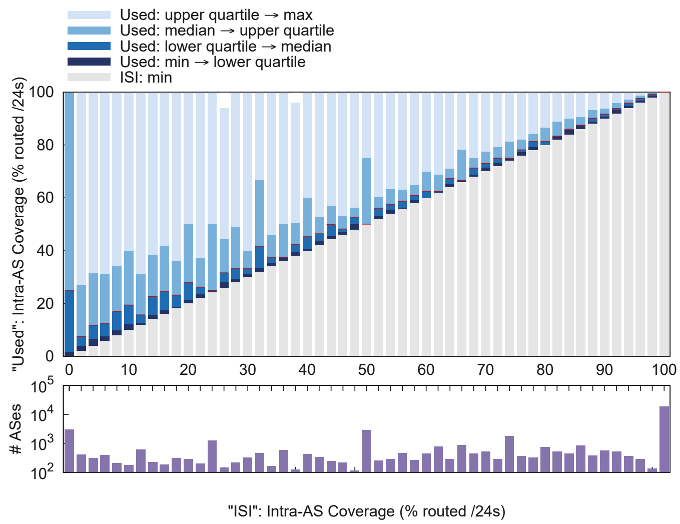


Fig. 6: Comparing the intra-AS coverage of our combined approach ("Used") against ISI's. The graph is sorted by increasing intra-AS coverage in ISI's data, with bins of 2%. The bottom graph shows the number of ASes per bin. In the top graph, the bottom grey bar represents the intra-AS coverage obtained by ISI for ASes in the bin, whereas the remaining 4 (colored) bars refer to the intra-AS coverage obtained by our combined approach (which includes ISI data). Each of these 4 bars represents a quartile of the ASes in the bin. For each bar, its bottom and top show on the y axis, respectively, the lower and upper bound of the coverage we obtain for ASes in that quartile (e.g., in the first bin, the bar from the median to the upper quartile shows intra-AS coverage between 23% and 100%).

Figure 6 shows the intra-AS coverage obtained with our combined approach as a function of results obtained by ISI (the graph is sorted by increasing ISI intra-AS coverage, with bins of 2%). For example, in the first bin, the bar from the median to the upper quartile shows intra-AS coverage between 23% and 100%. The graph shows visible increments across the whole x axis (decreasing as ISI intra-AS coverage approaches 100%). This result shows that even for ASes which responded to ISI's pings ($x! = 0$), our additional datasets reveal new /24 blocks (i.e., ASes do not exhibit a uniform behavior across their used subnets with respect to ICMP echo requests). In most of the bins, for half of the ASes (i.e., two bottom quartiles) we obtain a few percentage point increase. The two upper quartiles show more significant increments, e.g., up to $x = 20$, for ASes in the upper quartile we see about 20% more /24 blocks (at least). The first bin shows different behavior, with at least 25% of ASes covered entirely by our method (although most of these ASes announce only one /24).

We can derive better reference data for SWITCH (rather than simply using the 100% upper bound): from 23 July to

25 August 2013, all 9,271 /24 blocks within SWITCH were announced in BGP, but only 49% of these blocks generated bidirectional flows. Assuming these are the only used /24 blocks in SWITCH, we should not infer an intra-AS coverage above 49% for this AS (instead of considering 100% of the routed /24 blocks according to our definition of upper bound). ISI's infers 20.9% intra-AS coverage for this AS; our combined approach (without data from the SWITCH VP) reaches 33.1%. Still almost 16% of the blocks of the AS (which are used) are not discovered by our approach, showing space for further improvement. However, for all other ASes we would include the SWITCH VP in our analysis (thus using 4 VPs instead of 3), potentially resulting in a higher intra-AS coverage.

VII. IPv4 Census 2013: Results and Implications

How is (un)used space distributed across RIRs, ASes, countries and continents? Which ASes or countries make the worst use of the space they have been assigned? Would previous scientific studies of Internet-related phenomena change if they used this dataset instead of other related data sets?

While our results expand our knowledge of which portions of the space are used, they establish only a lower bound on the amount of address space we believe is used. They do not provide a lower bound on the amount of unused space, except for the obvious lower bound – the amount of unrouted space. However, this is the first IPv4 census dataset available to researchers [10] that includes ASes and network blocks that are not responsive to ICMP probing. In addition, a recent estimate of the used space that ICMP-based methodologies fail to observe [15] suggests that our estimates are quite close to the actual amounts of unused and used space. [15]. All our data is from approximately the same time frame (from July 2013 through Oct 2013). In the following analysis, we assume that usage of the address space does not change significantly within a period of 4 months.

Figure 7 illustrates[3] a Hilbert map of IPv4 address space utilization based on our results, taxonomized in Figure 1. The *IETF reserved* space accounts for 2.3M address blocks, or 13.7% of the entire IPv4 address space (grey). The remaining usable 14.5M address blocks consist of 5.3M (37%) *used* (light blue), 5.1M (35%) *routed unused* (dark blue), 3.4M (23%) *unrouted assigned* (purple), and 0.7M (5%) *available* (black). It is striking that most of the usable address space is actually unused. An enormous amount of IPv4 address space is assigned to organizations that do not even announce it on the Internet (i.e., there is no need to perform inference through additional active/passive measurements to sketch this phenomenon). In addition, since we verified that several of these organizations announce on BGP other address blocks they have been assigned, such number also suggests that our inference of large unused routed space is realistic.

A. View by allocation, geographic area, and AS

Figure 2 classifies IPv4 addresses by their RIR region, or as *legacy* addresses if they were allocated before the RIR system

[3]Full resolution of this image and other visualizations from this work are available at [52].

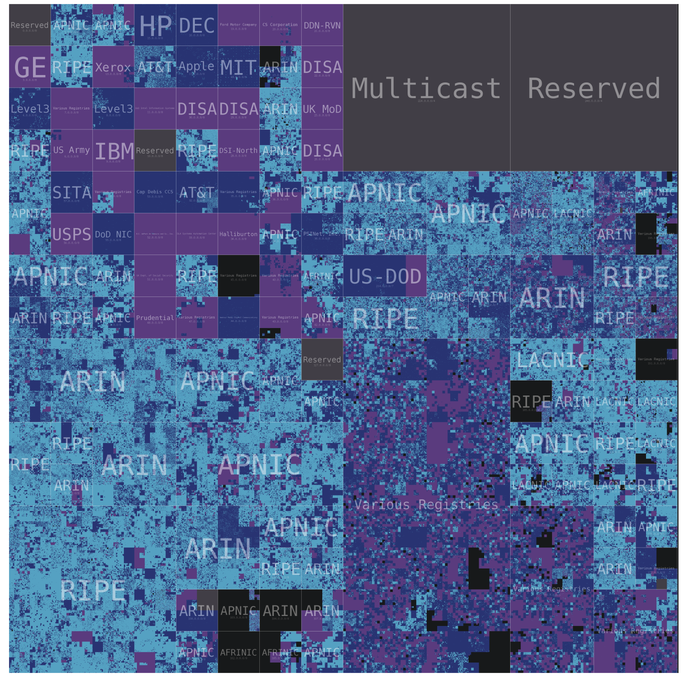


Fig. 7: Hilbert map visualization showing the utilization of the address space according to our taxonomy. The IPv4 address space is rendered in two dimensions using a space-filling continuous fractal Hilbert curve of order 12 [53], [54]. Each pixel in the full-resolution image [52] represents a /24 block; light blue indicates used, dark blue routed unused, purple unrouted assigned, black unassigned, and grey reserved by RFC blocks.

began. Legacy addresses were allocated by the central Internet Registry prior to the RIRs primarily to military organizations and large corporations such as IBM, AT&T, and Apple. Some of this space is now administered by individual RIRs. We use the IANA IPv4 address space registry [55], which marks legacy space and its designation at a /8 granularity. The figure shows that 42% of the usable address blocks are legacy; these blocks are more lightly utilized (9.5% of the legacy) and include more *unrouted assigned* (45% of the legacy) addresses than the RIRs (56% and 7.7% of the RIR address blocks, respectively). Interestingly, the combined set of legacy *routed unused* and *unrouted assigned* addresses is similar in size (5.1M /24s) to the entire *used* address space (5.3M /24s)! ARIN, RIPE, APNIC, and LACNIC have 50%, 65%, 54% and 68% of their address blocks *used*, respectively, in contrast to AFRINIC which has fewer of their blocks *used* (31%) and many more *available* (38%) address blocks than other RIRs (6.7% of other RIR addresses are *available*).

Table IX(a) lists the top-5 continents and countries in *routed unused* and *unrouted assigned* /24s. 52.2% of the *routed unused* space and 72% of *unrouted assigned* space is in North America, primarily in the U.S., where most legacy allocations were made. Asia follows, with China owning 8.79% and 5.7% of the global *routed unused* and *unrouted assigned* space, respectively, and then Europe. Other continents (South America, Oceania, and Africa) have between 0.93% and 2.13% of the global *routed unused* and *unrouted assigned* space.

Top Continents			
By Routed Unused /24s		By Unrouted Assigned /24s	
North America	52.2%	North America	72.0%
Asia	22.3%	Asia	13.1%
Europe	19.7%	Europe	12.1%
South America	2.13%	Oceania	0.97%
Oceania	1.92%	Africa	0.93%
Top Countries			
By Routed Unused /24s		By Unrouted Assigned /24s	
USA	49.8%	USA	67.5%
China	8.79%	China	5.70%
Japan	6.22%	United Kingdom	5.39%
Germany	4.85%	Japan	4.21%
South Korea	2.72%	Canada	3.73%

(a) Top continents and countries in unused and unrouted assigned /24s.

Top ASes in unused /24s	
AS Name & Number	Routed Unused /24s (%)
DoD NIC (721)	190k (3.82%)
Level 3 (3356)	157k (3.16%)
HP (71)	126k (2.54%)
China Telecom (4134)	106k (2.13%)
UUNET (701)	105k (2.12%)

(b) Top ASes in routed unused /24s

TABLE IX: Top continents, countries, AS names, and AS numbers in unused and unrouted assigned /24s. North America and USA have a large fraction of the assigned, but unused or unrouted address space.

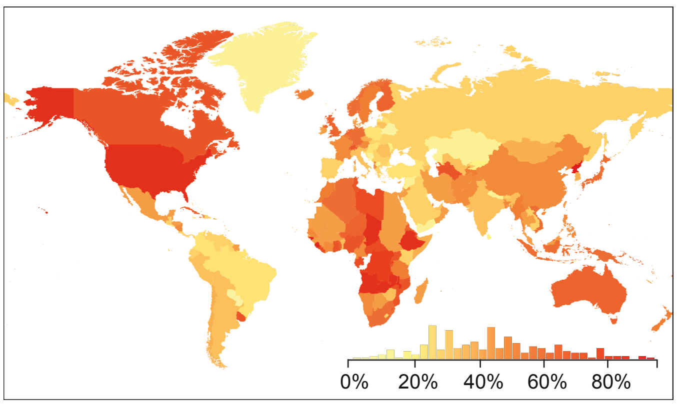


Fig. 8: Per-country percentage of unused space (*routed unused* + *unrouted assigned*) out of the assigned. The U.S. is red in this map due to a few very large allocations heavily unutilized, while some African countries are red because they use a very small fraction of their (also small) assigned space.

Figure 8 visually illustrates the per-country ratio of *assigned unused* (the sum of *routed unused* and *unrouted assigned*) over *assigned* (that is, *usable* minus *available*) space, suggesting which regions are using space most and least efficiently. The U.S. is red in this map due to a few very large allocations, while some African countries are red because they use a very small fraction of their (also small) assigned space.

Figure 9 compares address space assigned to countries to per-country population [56] and Gross Domestic Product (GDP - we used "purchasing power parity" from CIA's World Factbook [57]). We observe notable disparities between used /24s and population. For example, USA has 25% of the used /24s, but only 4.44% of the population. In contrast, African countries have only 1.8% of the used /24s, but 16% of the world population. The per-country used /24s correlate much better with the distribution of GDP (0.960 correlation), than with population (0.517 correlation), suggesting that economic inequalities could explain the differences in the used /24s. We can also observe disparities in the distribution of used and unused addresses: due to legacy allocations USA holds 49.8% of the *routed unused* and 67.5% *unrouted assigned* space, but 25% of the used space. The distribution of the *unrouted assigned* space is more uneven than of the *routed unused* space. These superficial but interesting observations demonstrate that our data and methods could enable economists and social scientists to pursue lines of inquiry not previously possible.

Table IX(b) lists the top ASes by *routed unused* /24s (we do not have per-AS data for *unrouted assigned* space). The top ASes are the Department of Defense (DoD) Network Information Center (NIC), followed by Level 3, HP, China Telekom, and finally UUNET.

B. Implications for scientific and commercial research applications

The characteristics of this census dataset also have implications for a range of scientific research of the Internet, as well as the now active commerical market for IPv4 addresses. The most notable scientific applications of our methodology and results are projects that incorporate routed address space metrics into estimates of the size, degree, type, or maliciousness of ASes [9], [58]–[61]. As an illustration, Figure 10 shows the overestimation error one would make by using a canonical *BGP-routed address space* metric to reflect how much address space an AS is actually observably using, for five types of network providers of various sizes. For each AS, we calculate overestimation error as the fraction of routed /24 blocks we infer as unused out of the routed /24 blocks. Median overestimation error generally increases with the size of the AS, perhaps due to large ASes under-utilizing their allocations. Large Enterprise ASes (>1k /24s) result in the most dramatic overestimation, with a median overestimation error of 96%. Figure 11 shows the overestimation error when using the same (*BGP-routed address space*) to reflect each country's Internet footprint. Both figures also show that there is no simple formula to translate between routed address space and actually used address space – the difference varies widely by AS and country, independently from the number of routed /24s.

We use CAIDA'S AS Rank [9] to illustrate a concrete example of how switching from BGP data to our census dataset can impact scientific analysis of Internet structure. CAIDA uses publicly available BGP data to infer business relationships among ASes and provides a ranking of ASes based on a measure of their role in the global Internet routing system. The specific measure AS Rank uses is based on the AS customer cone, which is the number of /24 blocks that the AS can reach via its customers, i.e., by (recursively) crossing only customer links. To capture more complex peering relationships than those inferred from the simple provider/customer/peer model, CAIDA refines this definition of AS customer cone,

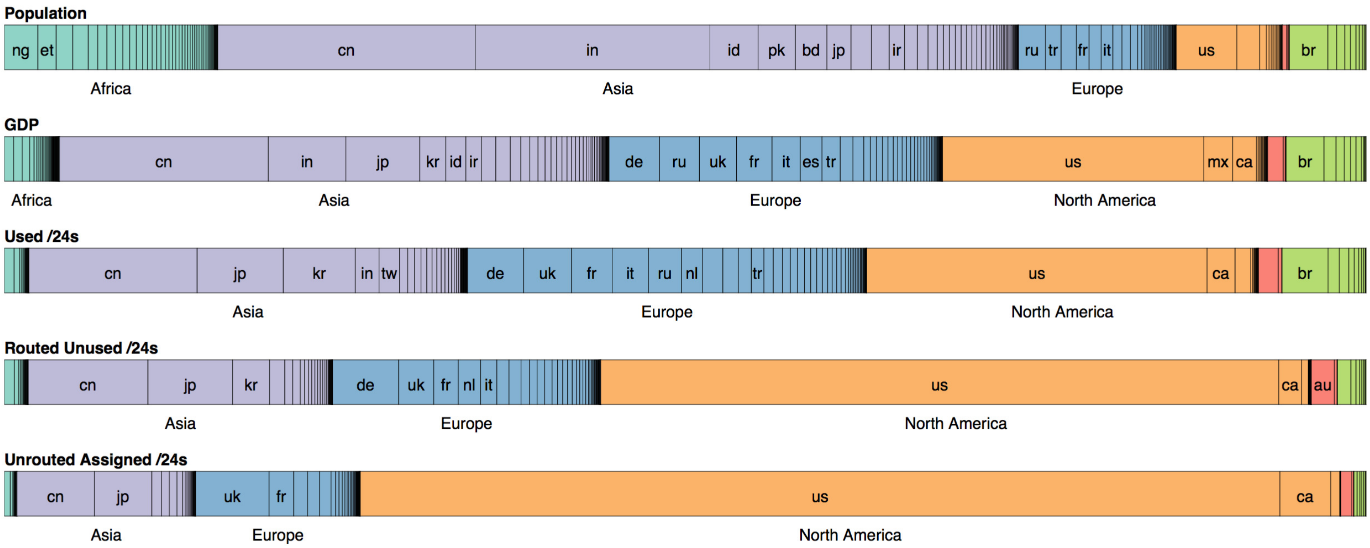


Fig. 9: Comparison of address space assigned to countries with per-country population and GDP. The width of a country (and continent) represents its relative size within a dataset. E.g., the top bar shows the percentage that each country contributes to the global population, with China (*cn*) contributing the most (1.36B, 18.9%). The correlation between datasets can be observed by comparing bars. We observe that there is not a strong correlation between population (top bar) and number of *used* /24 blocks of a country; in large part due to high usage by the USA. There is however, a strong correlation between the GDP (2nd from top) and number of used /24 blocks of a country (3rd bar). Not only does the USA dominate /24 block usage, it also represents a significant portion of both the *routed unused* and *unrouted assigned* bars, with 49.8% and 67.5% respectively. An interactive version of this visualization is available at [52].

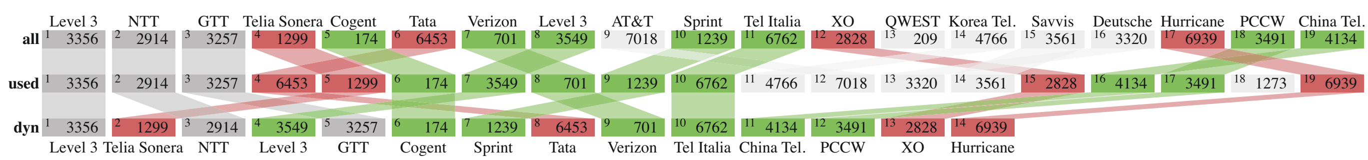


Fig. 12: ASes ranked by: the number of /24 blocks in their customer cone (**all**), *used* /24 blocks in their customer cone (**used**), and Dyn's transit addresses (**dyn**). AS color is dependant on if **used** or **all** rank was closer to **dyn**. *Green* means **used** was closer to **dyn**'s ranking. *Red* means **all** was closer to **dyn**'s ranking. *Dark grey* means they are at the same distance from **dyn**'s ranking. *Grey* means **dyn** provided no ranking. **Used** ranked 7 ASes closer to their **dyn** ranking, while **all** had only 4.

restricting it to only blocks from the set of prefixes that the AS is observed announcing to its peers or providers [9].

Recomputing the AS customer cones by filtering out /24 blocks that are *routed unused* (leaving only *used* blocks) significantly changes the AS ranking order. The resulting ranking (Figure 12, described further at [62]) makes CAIDA'S AS rank closer to Dyn's *IP Transit Intelligence AS ranking*, which is inferred with proprietary techniques to estimate actual transit traffic [63].

In a more recent commercial context, exhaustion of IPv4 space has motivated the emergence of an entire industry focused on brokering IPv4 address markets [64]–[67]. Precise knowledge of which addresses are unused or lightly used is a competitive advantage on this market. Specifically, it could improve the accuracy of analysis of (or prediction of likely future) address blocks transfers in the grey market, but also provide brokers with marketing information to target potential customers. Furthermore, improved understanding of how address utilization increases as a result of market activity can inform research and potential regulatory oversight.

VIII. Future Directions

In addition to the applications of census measurements that have been well articulated by [13], there are many possible future directions for this work. To enhance our methodology, we would like to further improve our ability to infer spoofed traffic and validate such inferences, perhaps by responding to darknet traffic. We would also like to investigate the use of UDP or other protocol traffic at R-ISP and IXP vantage points, and analyze in more detail what addresses are less visible to traffic measurement e.g., internal CDNs or quiet networks. As always, additional vantage points and ground truth information from operators would help improve the integrity of the method.

For a periodic global Internet census that tracks changes over time, we imagine a hybrid approach that first infers used IP address blocks based on passive measurements from one or more (live or dark) traffic vantage points, then probes only those address blocks that cannot be confidently inferred as in use. This approach could dramatically improve coverage over state of the art methods, while minimizing measurement overhead and potential irritation of network operators with aggressive firewalls. When performing a periodic census, our proposed taxonomy and definitions of coverage will help to

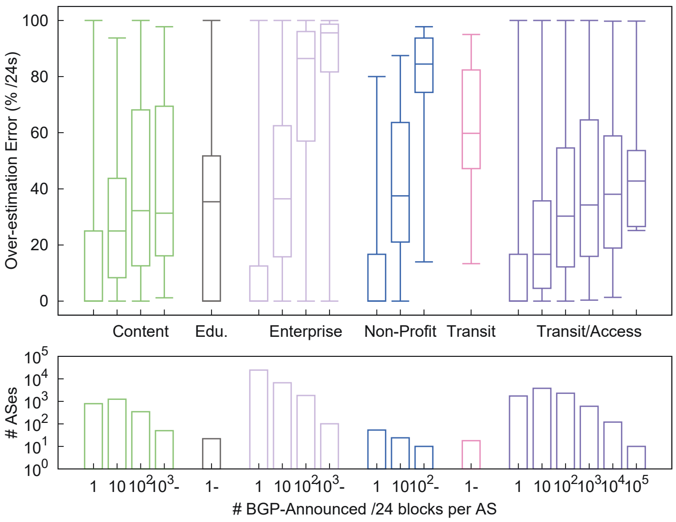


Fig. 10: Overestimation error (top graph) when using *routed address space* instead of our census as a rough metric for AS size. ASes are grouped according to the classification scheme proposed by Dhamdhere et al. [60] and sorted by number of routed /24 blocks (the x label indicates the minimum value in the bin). The bottom graph shows the number of ASes per bin. Median overestimation error generally increases with the size of the AS, perhaps due to large ASes under-utilizing their allocations.

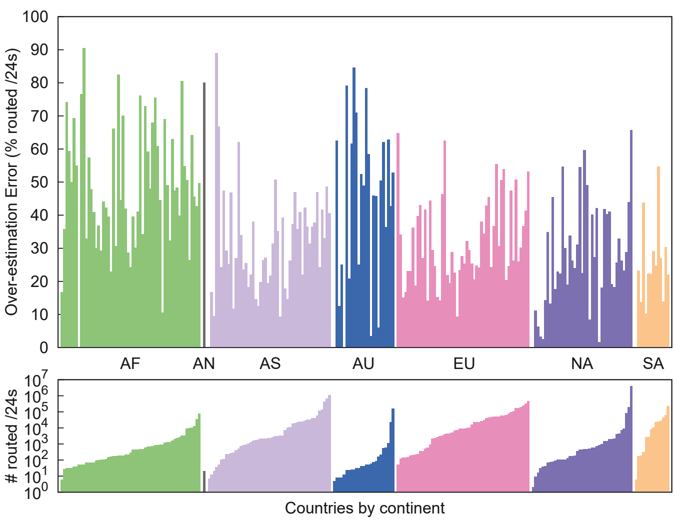


Fig. 11: Overestimation error when using *routed address space* instead of our census as a rough metric for a country's footprint of activity on the Internet. Countries are grouped by continent and sorted by number of routed /24 blocks (y value on bottom graph). The top graph shows the overestimation error for each country. As is also evident in Figure 8, activity in African countries would be significantly overestimated using *routed address space*. Most importantly, there is no significant correlation between the the number of per-country routed /24s and the resulting overestimation error.

quantify and track changes in space utilization over time. Finally, the unscalability of active scanning to the IPv6 address space was one motivation to explore our hybrid apporach, but we do not know how well distributed passive traffic observation alone could effectively support a future IPv6 census.

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