

Whac-A-Mole: Six Years of DNS Spoofing

Lan Wei John Heidemann
{weilan, johnh}@isi.edu

University of Southern California/ Information Sciences Institute

ABSTRACT

DNS is important in nearly all interactions on the Internet. All large DNS operators use IP anycast, announcing servers in BGP from multiple physical locations to reduce client latency and provide capacity. However, DNS is easy to *spoof*: third parties intercept and respond to queries for benign or malicious purposes. Spoofing is of particular risk for services using anycast, since service is already announced from multiple origins. In this paper, we describe methods to identify DNS spoofing, infer the mechanism being used, and identify organizations that spoof from historical data. Our methods detect overt spoofing and some covertly-delayed answers, although a very diligent adversarial spoofer can hide. We use these methods to study more than six years of data about root DNS servers from thousands of vantage points. We show that spoofing today is rare, occurring only in about 1.7% of observations. However, the rate of DNS spoofing has more than doubled in less than seven years, and it occurs globally. Finally, we use data from B-Root DNS to validate our methods for spoof detection, showing a true positive rate over 0.96. B-Root confirms that spoofing occurs with both DNS injection and proxies, but proxies account for nearly all spoofing we see.

1 INTRODUCTION

The Domain Name System (DNS) plays an important part in every web request and e-mail message. DNS responses need to be correct as defined by the operator of the zone. Incorrect DNS responses from third parties have been used for ISPs to inject advertising [19]; by governments to control Internet traffic and enforce government policies about speech [15] or intellectual property [7]; to launch person-in-the-middle attacks by malware [8]; and by apparent nation-state-level actors to hijack content or for espionage [17].

DNS spoofing is when a third-party responds to a DNS query, allowing them to see and modify the reply. DNS spoofing can be accomplished by proxying, intercepting and modifying traffic (proxying); DNS injection, where responses are returned more quickly than the official servers [10]; or by modifying configurations in end hosts (§2). Regardless of the mechanism, spoofing creates privacy and security risks for end-users.

DNSSEC can protect against some aspects of spoofing by insuring the integrity of DNS responses [11]. It provides a

cryptographic signature that can verify each level of the DNS tree from the root. Unfortunately, DNSSEC deployment is far from complete, with names of many organizations (including Google, Facebook, Amazon, and Wikipedia) still unprotected [23], in part because of challenges integrating DNSSEC with DNS-based CDN redirection. Even for domains protected by DNSSEC, *client* software used by many end-users fail to check DNSSEC.

While there has been some study of how DNS spoofing works [10], and particularly about the use of spoofing for censorship [15], to our knowledge, there has been little public analysis of general spoofing of DNS over time. (Wessels currently has an unpublished study of spoofing [36].) Increasing use of DNSSEC [11], and challenges in deployment [5] reflect interest in DNS integrity.

This paper describes a long-term study of DNS spoofing in the real-world, filling this gap. We analyse six years and four months of the 13 DNS root “letters” as observed from RIPE Atlas’s 10k observers around the globe, and augment it with one week of server-side data from B-Root to verify our results. Our first contribution is to define methods to detect spoofing (§3.2) and characterize spoofing mechanisms from historical data (§3.3). We define *overt spoofers* and *covert delayers*. We detect overt spoofers by atypical server IDs; they do not hide their behaviors. We expected to find covert spoofers, but instead found covert delayers—third-parties that consistently delay DNS traffic but do pass it to the authoritative server.

Our second contribution is to *evaluate spoofing trends* over more than six years of data, showing that spoofing *remains rare* (about 1.7% observations in recent days), but *has been increasing* (§4.2) and is geographically widespread (§4.3). We also identify organizations that spoof (§4.4).

Finally, we are the first to validate client-side spoofing analysis with server-side data. We use one week of data from B-Root to show that our recall (the true-positive rate) is over 0.96. With the end-to-end check with B-root data, we are able to learn the fact whether or not a query reaches the server. Server-side analysis confirms that proxying is the most common spoofing mechanism. DNS injection [10] and third-party anycast are rare.

Our methodology builds on prior that used `hostname.bind` queries and the penultimate router [13, 16], but we provide the first longitudinal study of 6 years of all 13 root letters, compared prior work that used a single scan [13] or a day of DNS and traceroute and a week of pings [16]. In addition,

we are the first to use server-side data to provide end-to-end validation, and to classify spoofer identities and evaluate if spoofing is faster.

All data from this paper is publicly available as RIPE Atlas data [25–27] and from USC [4]. We will provide our tools as open source and our analysis available at no cost to researchers. Since we use only existing, public data about public servers, our work poses no user privacy concerns.

2 THREAT MODEL

DNS spoofing occurs when a user makes a DNS query through a recursive resolver and that query is answered by a third party (the *spoofer*) that is not the authoritative server. We call the potentially altered responses *spoofed*. We detect *overt spoofers* who are obvious about their identities. We look for *covert spoofers*, but find only *covert delayers* where DNS takes noticeably longer than other traffic. We look at reasons and mechanisms for spoofing below.

2.1 Goals of the Spoofer

A third party might spoof DNS for benign or malicious reasons.

Web redirection for captive portals: The most common use of DNS spoofing is to redirect users to a captive portal so they can authenticate to a public network. Many institutional wifi basestations intercept all DNS queries to channel users to a web-based login page (the portal). After a user authenticates, future DNS traffic typically passes through.

We do not focus on this class of spoofing in this paper because it is transient (spoofing goes away after authentication). Our observers (see §4.1) have static locations (e.g. home) that will not see captive portals. However, our detection methods would, in principle, detect captive portals if run from different vantage points (e.g. hotels).

Redirecting applications: DNS spoofing can be used to redirect network traffic to alternate servers. If used to redirect web traffic or OS updates, such spoofing can be malicious as part of injecting malware or exploits. Alternatively, it can reduce external network traffic.

Faster responses: Some ISPs intercept DNS traffic to force DNS traffic through their own recursive resolver. This redirection may have the goal of speeding responses, or of reducing external traffic (a special case of redirecting applications, or implementing local content filtering (described next)).

Network Filtering and Censorship: DNS spoofing is a popular method to implement network filtering, allowing the ISP to block destinations to enforce local laws (or organizational policies, when done inside of an enterprise). DNS

spoofing has been used control pornography [1, 2], for political censorship [9], and to implement other policies. Spoofing for network filtering can be considered a beneficial technique or malicious censorship, depending on one’s point of view about the policy. Spoofing for traffic filtering can be detected by DNSSEC validation, if used.

Eavesdropping: Since DNS is sent without being encrypted, spoofing can be used to eavesdrop on DNS traffic to observe communications metadata [14].

2.2 Spoofing Mechanisms

Table 1 summarizes three common mechanisms used to spoof DNS: DNS proxies (in-path), on-path injection, unauthorized anycast, following prior definitions [10, 16]. We review each mechanism and how we identify them in §3.3.

3 METHODOLOGY

We next describe our active approach to observe probable DNS spoofing. This is challenging because, in the worst case, spoofers can arbitrarily intercept and reply to traffic, so we use multiple methods (§3.2). Moreover, we classify spoofing mechanisms (§3.3) from what we observe from historical data. Finally, we identify who are the spoofing organizations from the server IDs they returned (§3.4, and Table 6). We caution that our methods are best effort, and not fool-proof against a sophisticated adversary.

3.1 Targets and Queries

Our goal is to identify spoofing in a DNS system with IP anycast. In this paper we study the Root DNS system because it is well documented. Our approach can apply to other, non-root DNS anycast systems, provided we have access to distributed VPs that can query the system, and the system replies to server-id queries (e.g. DNS CHAOS-class), ping, and traceroute. In principle, our approach could work on anycast systems other than DNS, provided they support a query that identifies the server, as well as ping and traceroute.

We probe from controlled *vantage points* (VPs) that can initiate three kinds of queries: DNS, ping, and traceroute. We use RIPE Atlas probes for our vantage points since they provide a public source of long-term data, but the approach can work on other platforms that make regular queries. In practice, recursive resolvers communicate directly with nameservers on behalf of web clients, so these VPs represent recursive resolvers.

For each VP, we first examine basic DNS responses with *Server IDs* to detect *overt spoofers* with false-looking server IDs; Second, we test the timing of replies to search for *covert spoofers* and detect *covert delayers*, adversaries who process

mechanism	how	spoofers	spoofees
DNS proxies (<i>in-path</i>)	a device intercepts traffic and returns requests	ISPs, universities, corporations	users of the organization
<i>On-path</i> injection	a device observes traffic and injects responses	hackers, ISPs, governments	anyone whose traffic passes the device
Unauthorized anycast site (<i>off-path</i>)	a server announcing BGP prefix of the anycast service	ISPs, governments	anyone who accepts the BGP announcement

Table 1: Mechanisms for DNS spoofing.

and forward legitimate replies. Third, we combine information from all three types of query responses to distinguish the spoofing mechanisms used by the spoofer.

For each hour we observe, we analyze all three datasets (DNS, ping, traceroute). In that hour, DNS and ping have 15 observations, and traceroute has two observations. (See how we sample data over time in §4.1.)

Our targets are authoritative DNS servers using IP anycast. DNS has three methods to identify server ID: CHAOS-class `hostname.bind` [32], `id.server` [6], and NSID [3]. Each returns a server-specific string, which we call the *Server ID*. We use `hostname.bind` because it is supported on all root servers from 2014 to today.

We identify latency via ICMP echo request (ping) to the service address. We also identify penultimate hops of the destination from traceroute.

3.2 Finding Spoofed DNS responses

We examine server ID and ping and DNS latency to identify overt spoofers and covert delayers.

3.2.1 Detecting Overt Spoofers By Server ID. We detect covert spoofers because they use Server IDs that differ from what we expect.

DNS root operators use server IDs that follow an operator-specific pattern. Often they indicate the location, a server number, and the root letter. For example, A-root operators have a naming convention where the Server ID starts with *nnn1-* and then followed with three letters representing a site/city and end with a number, with examples like *nnn1-lax2* and *nnn1-lon3*. Other root letters follow similar patterns.

By contrast, overt spoofers use other types of names, often with their own identities. Examples include: *sawo*, *hosting*, or *chic-cns13.nlb.mdw1.comcast.net*, *2kom.ru*.

We build a list of regular expressions that match replies from each root operators, based on what we observe and known sites as listed at `root-servers.org`. We find server IDs defined by each DNS root operators provide a reliable way to tell spoofing, since our study on years of data shows operators tend to make the server IDs in similar formats across

multiple sites. Also, much fewer vantage points receive atypical server IDs than valid server IDs. In §5, we prove that recognizing spoofing with atypical server IDs are a reliable way to tell spoofing.

3.2.2 Detecting Covert Delayers with Latency Difference. Although regular expressions can identify spoofers that use obviously different Server IDs, *covert spoofers* could reused known Server IDs to hide their behavior.

We look for covert spoofers by comparing DNS and ping latency (as described below), assuming that a covert spoofer will intercept DNS but not ICMP. While we find delay differences, in all cases, we see that sites with delay difference actually pass the query to the authoritative server. We therefore call what we identify a *covert delayer*.

Our test for covert delayers is to compare DNS and ICMP latency for sites that have a good-appearing server ID. We compare DNS and ICMP latency by considering all measurements of each type for one hour. (We use multiple measurements to tolerate noise, such as from queuing delay, in any given observation.) For each group of RTTs, we take their median value ($median_{dns}$, $median_{ping}$), and median absolute deviations (mad_{dns} , mad_{ping}) in an hourly window. We exclude measurements that observe catchment changes (based on Server IDs that indicate another location) to filter out catchment changes, although we know they are rare [35]. We then define the difference as $\delta = |median_{dns} - median_{ping}|$, and require three checks:

$$\left\{ \begin{array}{l} \delta > 0.2 \times \min(median_{dns}, median_{ping}), \text{ and} \\ \delta > 3 \times \max(mad_{dns}, mad_{ping}), \text{ and} \\ \delta > 10 \text{ ms} \end{array} \right. \quad (1)$$

The comparison of medians looks for large (20%), stable differences in latency. The change also must exceed median absolute deviation to avoid overreacting to noisy measurements. Finally, the check for 10 ms avoids differences that are around measurement precision. These specific thresholds are based our evaluation of the data, and sense that 10 ms is well beyond normal jitter. Potentially, a sophisticated adversary could intentionally increase response latency in an effort

to bypass these three checks, however they cannot reduce latency.

While this test is designed to detect covert spoofing, in practice (details in §5) we see that most cases with large δ pass the query on to the authoritative server. The majority of such queries has a larger DNS latency rather than its Ping latency, implying the DNS queries being processed differently by a third-party. In this paper, we do not consider such interference as DNS spoofing, but consider them as covert delayers. We therefore count them as valid, non-spoofers in all of §4 and Table 4.

3.3 Identifying Spoofing Mechanisms

Once we detect a spoof, next identify the spoofing mechanism as anycast or non-anycast (injection or proxy, from §2.2).

Spoofers can use *anycast* to intercept DNS by announcing the same prefix as the official DNS servers. Anycast will affect not only DNS queries, but *all* traffic sent to the prefix being hijacked. Other spoofing mechanisms typically capture only the DNS traffic.

When we look at traceroutes to the site, a penultimate hop that differs from known legitimate sites indicates anycast-based spoofing. We use the list at root-servers.org to identify known sites. This method is from prior work [13]. We consider a VP is under influence of anycast spoof when it meets two conditions. First, the penultimate hop of its traceroute should not match that of any VP with an authentic reply, suggesting the site that the query goes to is not any authentic site. Second, its DNS RTT is the same as its Ping RTT, suggesting in fact anycast is capturing all traffic, not just DNS.

DNS injection is a second way to spoof DNS [9]. For DNS injections, the spoofer listens to DNS queries (without diverting traffic), then replies quickly, providing an answer to the client before the official answer sent from an authoritative server. The querying DNS resolver accepts the first, spoofed reply and ignores the additional, real reply.

DNS injection has two distinguishing features: responses are fast and doubled [30]. Without a platform that preserve multiple responses for one query, it is hard from historical data to recognize injection mechanism.

Proxies are the final spoofing mechanism we consider. A DNS proxy intercepts DNS traffic, then diverts it to a spoofing servers. Unlike DNS injection, the original query never reaches the official server because proxy simply drops the queries after returning the answer.

Using historical data collected from VP’s side, we can only differentiate mechanism between anycast vs. non-anycast. With further validation from Root DNS server-side data in

§5, we can differentiate mechanisms between injection vs. proxy.

3.4 Spoofing Parties from Server IDs

Spoofing is carried out by multiple organizations; we would like to know who they are and identify *unique spoofing parties*. We use patterns of Server ID to identify overt spoofers, and after knowing who they are, we classify them to seven categories based on their functions.

We identify unique spoofing parties through several steps. First, for Server IDs that have a recognizable DNS name, we group them by common prefix or suffix (for example, `rdit.ch` for `njamerson.rdit.ch` and `ninishowen.rdit.ch`). We handle Server IDs and IP addresses the same way, after looking up their reverse DNS name. We manually identify and group recognizable company names. Remaining Server IDs are usually generic (DNS13, DNS-expire, etc.), for which we group by the AS of the observing VPs.

We classify identifiable spoofing parties by examining their websites. Each class is based on the goal or function of the organization or the person. Table 6 shows seven class of different spoofing parties (ISPs, DNS tools, VPNs, etc.), with specific examples provided. Our work maintains a full table of spoofers seen in years and their responding webpages. An example table is at §4.4, with clickable example URLs showing the identity of spoofing organizations.

4 RESULTS

We next study six years and four months of Root DNS to look for spoofing. First, we study the quantity of DNS spoofing. We show it is uncommon but is getting more popular over time. Second we study the locations and identities of the spoofers. Finally we discuss whether spoofing always provides a faster response than authorized servers.

4.1 The Root DNS system and Datasets

We observe the Root DNS system using RIPE Atlas [24].

Background about Root DNS system: Root DNS is provided by 13 independently operated services, named A-root to M-root [28]. All of the root letters use IP anycast¹, where locations, typically in different cities, share a single IP address. The number of locations for each letter varies, from a few (2 for H, 3 for B, less than 10 for C, G, and 28 for A) to hundreds (D, F, J, and L all operate over 100) as in August 2019 [28]. We use the list of anycast locations at root-servers.org as ground truth.

RIPE Atlas: Our observations use public data collected by RIPE Atlas probes from 2014-02 to 2020-05 (six years and four months). RIPE Atlas has standard measurements of

¹H-Root’s sites are primary/secondary, so only one is visible on the general Internet at a time.

type	frequency
DNS	every 240s
Ping	every 240s
Traceroute	every 1800s

Table 2: Query detail

DNS server ID (hostname.bind), ICMP, and traceroute (UDP) to each Root Letter for most of this period. Exceptions are that G-Root never responds to ICMP, and E-Root data is not available from 2014-02 to 2015-01.

We show the frequency of each type of query in Table 2. In each part, we sample at a random one-hour window each of the three type of datasets. Over the multi-year period, we extract 4 observations each month. Each measurement is a randomly chosen hour in a different week of the month, with the first in the 1st to 7th of the month, the second in the 8th to the 14th, then 15th to the 21st, and finally 22nd to the end of the month (“weeks” are approximate, with the fourth week sometimes longer than 7 days). We choose the same hour for all letters, but the hour varies in each week to avoid bias due to time-of-day.

The exact number of VPs we use varies, since VPs sometimes disconnect from RIPE Atlas infrastructure (VPs are individually owned by volunteers), and RIPE adds VPs over the measurement period. The number of VPs, ASes, and countries measured over time is show in Table 3. Our result is limited by the coverage of RIPE atlas VPs.

4.2 Spoofing Is Not Common, But It Is Growing

In this section, we talk about how much spoofing occurs today, and what is the trend of spoofing over the six years and four months.

4.2.1 Spoofing is uncommon. Spoofing today is uncommon: about 1.76%, 192 of the of 10882 responding VPs are spoofed. Table 4 shows on 2020-05-03: that about 95.85% of all VPs received valid answer (in which totally 19 (0.17%) VPs experience delayed DNS answers), 1.76% VPs are overtly spoofed. More VPs (2.39%) timeout than see spoofing.

Most spoofers spoof on *all* root letters. Fig. 1 shows the CDF of how many letters are spoofed for each VP, and of VPs that see spoofing, there are always more than 70% of VPs see spoofing of all root letters throughout the six years we observed. In year 2020, there are 83% of VPs experience spoofing across all root letters.

4.2.2 Growth. We see an increasing amount of spoofing over the six years and four months we study. Figure 2 shows the fraction of VPs that see *any* root servers spoofed (the thick black line), and for each root letter spoofed (colorful

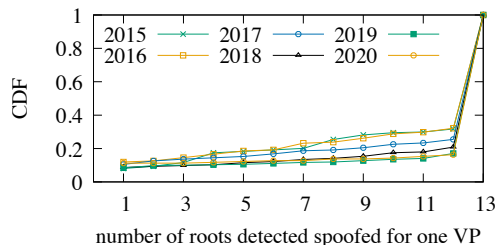


Figure 1: CDF of root counts seen overtly-spoofed (2014 not provided because of lacking E-root data)

dots). Although we see some variations from day to day, the overall fraction of spoofed VPs rises from 0.007 (2014-02-04) to 0.017 (2020-05-03), more than doubling over six years.

Because the set of active VPs changes and grows over time, we confirm this result with a fixed group of 3000 VPs that occur most frequently over the six years, shown in Figure 3. This subset also increased to more than twice over the six years, but from a slightly lower baseline (0.005) to 0.014, confirming our findings. In §4.3, we later show that location affects the absolute fraction of spoofing.

4.3 Where and When Are These Spoofers?

We next consider *where* spoofing happens. If spoofing is legally required in some countries, we expect spoofing to be concentrated there.

Figure 4 shows the fraction of VPs that see spoofing, by country (countries with less than 10 active VPs but are spoofed are listed as “insufficient” and are excluded from our ranking). From 2019-01 to 2019-08, we see spoofing is most common in the Middle East and Eastern Europe, Africa, and Southeast Asia. but we see examples of spoofing worldwide. The top ten countries by fraction of spoofing is in Table 5.

Most areas show spoofing activity over multiple years. Figure 5 shows our six years (without year 2020) of spoofing occurrence with different years in its last digit as symbols and in different darknesses. (Points in oceans are actually on islands.). Labels that overlap show VPs that are spoofed multiple times over different years.

4.4 Who Are the Spoofing Parties?

Goals of spoofers (§2.1) include faster response, reduced traffic, or censorship. With more than 1000 root instances, a strong *need* for spoofing for performance seems unlikely, although an ISP might spoof DNS. We next study the identification of spoofing parties and classify them to perhaps infer their motivation by using the methodology in §3.4.

Table 6 shows the spoofing parties we found. More than two-thirds, spanning 137 ASes, show generic Server IDs and

Year	2014	2015	2016	2017	2018	2019	2020
Vantage Points	7473	9223	9431	10311	10336	10492	10988
AS	2616	3322	3370	3633	3605	3590	3397
Country	168	184	186	183	181	180	175

Table 3: Data Coverage

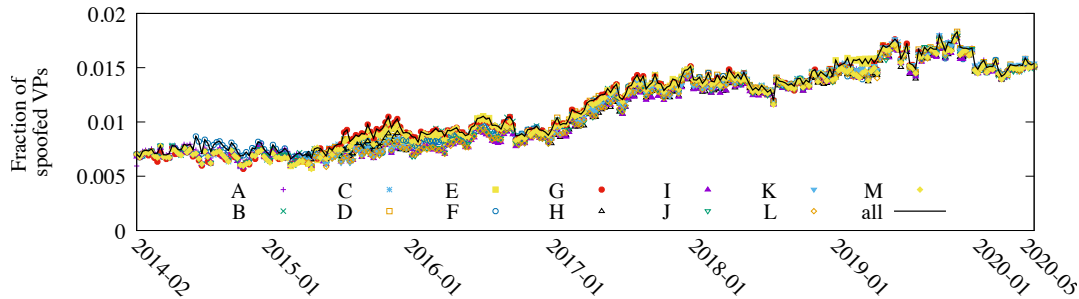


Figure 2: Fraction of spoofed VPs over all available ones at each date.

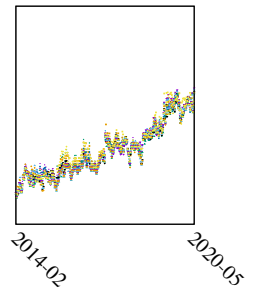


Figure 3: 3000 VPs

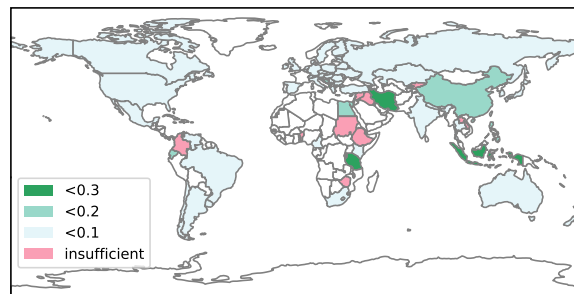


Figure 4: Fraction of spoofing per country (varied green shades), spoofed with under-sampled VPs (pink), not spoofed (white).



Figure 5: Location of spoofed VPs, slightly jittered. More recent years are darker colors, and each loation is the last digit of the year of the observation. Overlapping digits indicate spoofos over multiple years.

are unidentifiable. Of identifiable spoofers, most are end-user (eyeball) ISPs (32, about half) or network providers (24 providing cloud, datacenter, or DNS service).

Sometimes spoofing parties do not affect all VPs in the same AS. T-Mobile spoofs a VP in Hungary, but not elsewhere. In Comcast, 2 of the 322 VPs see spoofing, and in FrontierNet, 1 of the 28 VPs sees spoofing.

	2020-05-03	
active VPs	10882	100.00%
timeout	260	2.39%
answered	10622	97.61%
valid	10430	95.85%
covertly-delayed	19	0.17%
spoofed	192	1.76%

Table 4: DNS spoof observations.

Country	VPs		
	spf.	active	%
Indonesia	23	87	26
Iran	48	198	24
Tanzania	2	10	20
Albania	8	40	20
Philippines	4	26	15
Ecuador	2	15	13
Bosnia & Herz	2	18	11
China	3	27	11
Egypt	1	10	10
Lebanon	2	20	10

Table 5: Countries with largest fraction of VPs experiencing spoofing in 2019.

Types	Example URLs	Number of clustered spoofers
ISPs	skbroadband.com 2kom.ru	32 (16.16%)
network providers	softlayer.com level3.com	24 (12.12%)
education-purpose	eenet.ee	1 (0.5%)
DNS tools	dnscrypt.eu	1 (0.5%)
VPNs	nordvpn.com	1 (0.5%)
hardware	eero.com	1 (0.5%)
personal	yochiwo.org	1 (0.5%)
unidentifiable	DNS13 DNS-Expire	137 (69.19%)

Table 6: Classification of spoofing parties.

Identifying spoofing parties suggests possible reasons for spoofing: the ISPs may be improving performance, or they may be required to filter DNS. The 5 classes each with 1 example are likely spoofing for professional interest, because they work with DNS or provide VPNs.

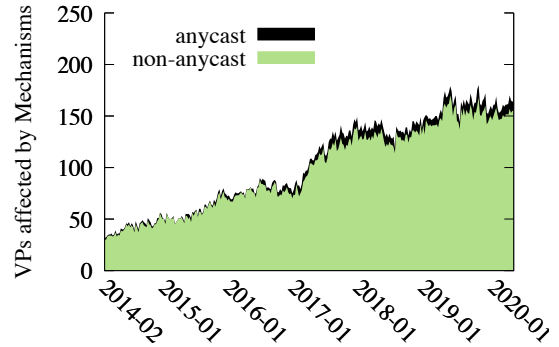


Figure 6: Number of VPs with different spoofing mechanisms over time.

4.5 How Do Spoofing Parties Spoof?

We next examine spoofing mechanisms, following §3.3.

Figure 6 shows how many VPs see non-anycast (injection or proxy, lightest area, on the bottom) or anycast spoofing (darkest, on top), from 2014-02 to 2020-05.

We see that non-anycast (injection or proxy) is by far the most popular spoofing mechanism, accounting for 87% to 100% of the VPs that see spoofing. We believe that non-anycast methods are popular because they do not involve routing, able to target at specific group of users; they can be deployed as a “bump-in-the-wire”. Anycast is the least popular one, since the anycast catchment relies on BGP, spoofers may not precisely control who to spoof.

We see 2 VPs that see alterations between overt spoofing and authentic replies, often with timeouts in between. We speculate these VPs may have a mechanism that sometimes fails, e.g. a slow DNS injection, or site change between the authoritative or the third-party anycast site.

4.6 Does Spoofing Speed Responses?

Finally, we examine if spoofing provides faster responses than authoritative servers, since most of our identifiable spoofing parties are ISPs.

For each overt spoofer, we compare the median values of DNS response time with ping-time to the authoritative root on 2019-08-24. In Figure 7, we see that spoofing is almost always faster: there can be about 15% of all VPs that see equal or worse latency performance in spoofed answers. This result is consistent with spoofing occurring near the VP. In general, the amount of performance improvement is the inverse of the size of root letter’s anycast footprint. Letters with more anycast sites see less improvement, while for letters with only a few anycast sites (e.g. H-root, B-root), spoofing tends to be much faster. This result is as one would expect for anycast latency [29], and is consistent with the statement

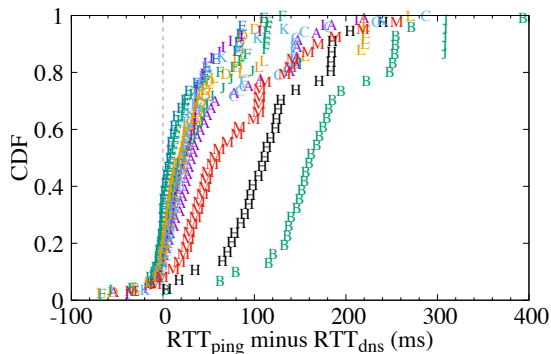


Figure 7: CDF of RTT_{ping} minus RTT_{dns} from spoofed VPs on 2019-08-24

that overt spoofer are improving user performance. Except A-, B-, H-, and M-root, we also see that half of the VPs only see less than 20 ms latency improvement from spoofer. This shows even though spoofer improve performance but half of the VPs may still be good without them.

5 VALIDATION

In this section, we validate the spoofing detection by the fact of whether the query has an answer from the authoritative B-root server or not. First, we show our detection method can promise a true positive rate over 0.96. Second, we show that other than the spoofing we detected, there are about 13 (0.14%) VPs that may experience covert delay over their DNS queries, and most of the cases, the DNS reply is slower than the Ping reply. Third, we show that in recent days proxy is far more popular than injection is used, packets of about 98% of spoofed queries are dropped on 2019-01-10.

5.1 Validation Methodology

Our spoof detection looks at traffic from VPs as DNS clients §3. We validate it by looking at the destination side, from the authoritative server. We expect queries from VPs that are intercepted and spoofed to not reach the server, while regular queries will appear in server traffic (unless there is packet loss or timeout). For DNS injection, we expect the query to reach the server and two replies to return to the VP (first from the injector, then from the authoritative).

To validate our spoof detection we use server-side data from one week (2019-01-10 to -16, the only week available) of B-Root [4]. That dataset uses host-only anonymization where the low-8 bits of the IPv4 address are scrambled, so we look for matches that have the same query type (DNS) and field name (hostname.bind) from the same IPv4 /24 prefix as the public address of each VP. We also require that the timestamps are within 4 minutes as the RIPE Atlas querying

2019-01-10T03:52:49Z

	sent	received	true positive rate
active VPs	8981	8449	-
timeout	241	47	≥ 0.81
spoofed	142	3	≥ 0.98
non-anycast	140	3	≥ 0.98
anycast	2	0	1
not spoofed	8598	8399	-

Table 7: How many queries reach B-root based on spoof detection, for a sample hour.

interval. (There are always multiple queries per second, so we cannot match by timestamp only.). We use RIPE queries that are made directly to B-Root’s IP address, not querying through the VP’s recursive resolvers.

We apply our detection method during the same week to match the B-Root dataset period. Following §4.1, we select four random full hour, each starting with a random offset (smaller than 3600 seconds) over the day from each day of the week. We evaluate each full hour. We compare queries sent from the RIPE Atlas VP that get a response or timeout to those seen at B-Root. For each VP in the hourly window where some queries timeout and some succeed, we examine only successes. With all queries timeout we classify that VP as timed-out. We classify a timeout or spoof as correct if it does not show up at B-Root, and any other query as correct if it does appear in B-Root traffic.

A false positive is a query that is detected as spoofed where we can see that it actually reaches B-Root. If a query does not reach B-Root and receives an answer, this query is definitely spoofed (a true positive). Because of DNS injection, though, a spoofer may reply quickly to a query, but allow it to proceed to B-Root where it then generates a second reply. The scenario of DNS injection means that we cannot get a definitive count of false positives spoof detections, even with server-side data. These potential false positives therefore place an upper bound on the actual false positive rate of spoofer; that upper bound is 0.02 ($1 - 0.98$) in Table 7.

5.2 Validation of Overt Spoof Detection

We first verify detections of overt spoofer (§3.2.1). We expect queries that see overt spoofing to *not* reach B-Root. Since overt spoofing is obvious with atypical server IDs, we expect a high true positive rate.

Table 7 shows a representative hour (other sample hours are similar), and Table 8 shows the range of true positive rates for all 28 sample hours over the week.

The week of samples in Table 8 shows that spoofing detection is accurate, with a true positive rate consistently around 0.97. Examining a sample hour starting at 2019-01-10 3:52:49

detection	True-Positive Rate			
	range	quantile		
	[min, max]	0.25 th	0.50 th	0.75 th
timeout	[0.79, 0.84]	0.8071	0.8198	0.8249
spooft	[0.96, 0.99]	0.9719	0.9787	0.9859
not spoof	[0.90, 0.99]	0.9138	0.9297	0.9534

Table 8: The range of true positive rate of spoof detection from 2019-01-10 to 2019-01-16

2019-01-10T03:52:49Z				
	detected	received	$RTT_{dns} - RTT_{ping}$	
covert-delayers	13	13		-
$RTT_{dns} > RTT_{ping}$	12	12		40.52ms
$RTT_{dns} \leq RTT_{ping}$	1	1		-10.25ms

Table 9: Covert delay validation: how many reached B-Root, with the mean difference for each DNS or ICMP faster.

GMT in Table 7, 142 of the 8981 VPs see spoofing. For almost all VPs that see spoofing (139 of the 142), their queries do not arrive at B-Root, making a true positive rate over 0.98. For mechanism, 140 of the 142 VPs experience either proxy or injection, and only 3 out of 140 VPs reached B-root, suggesting potentially DNS injection (the proxy drops the packets, so the query cannot reach B-root). The rest 2 VPs suggest third-party anycast, and we confirm their queries are not seen at B-Root.

When examining VPs that timeout, the true positive fraction is around 0.82, with a wider range from 0.79 to 0.84 (see Table 8). Some queries that timeout at the VP still reach B-root. It is possible that a query reached B-Root and is answered, but the VP still timed out, perhaps because the reply was dropped by a third party. The timeout default of RIPE Atlas probe is 5 s. In our example hour (Table 7), we see that out of 241 VPs that timeout, 47 of them has queries reach B-root, making a true positive rate of 0.81.

There are 199 VPs (about 2%) VP in Table 7 that neither were spoofed nor timeout, but for which we did not find a match on the B-Root side. It is possible the metadata of the IP address of those VPs is outdated or those VPs is multi-homed, so their queries arrive at B-Root from an IP address we do not know about.

5.3 Validation of Covert Delayers

We now examine covert delayers (§3.2.2). Table 9 shows analysis from one sample hour (other hours were similar).

First, we see that in all cases with a large delay, the queries *does* get through to B-Root. We originally expected differences in time indicated a covert spoofer, but these networks

are passing the query to the authoritative server and not interfering with it.

However, we see there is a very large delay for the DNS replies. Most of the time (12 of 13 cases) DNS is longer than ICMP, and the median difference is 40 ms. This consistent, large delay suggests that this difference is not just queueing delay or other noise in the network, and it is possible that a third-party is processing the traffic.

Although we do not have server-side data for other letters, we do see that about one-third of VPs that experience covert-delaying for B-Root also see covert-delaying with at least one other letter.

Finally, in one case we see a 10 ms delay of ICMP relative to DNS. it is possible that this delay is due to a router processing ICMP on the slow path.

5.4 Non-Anycast Mechanism: Proxy or Injection?

Server-side data also allows us to distinguish DNS proxies from DNS injection. DNS injection will respond quickly to the query while letting it pass through to the authoritative server (on-path processing), while a DNS proxy will intercept the query without passing it along (in-path processing).

In Table 7, shows that we see 139 out of 142 (98%) of VPs that detected as spoofed never reach B-root, suggesting a DNS proxy instead of injection. The remaining 3 VPs (only 2%) are likely using DNS injection. (Unfortunately we cannot confirm injection with a double reply at the receiver because we cannot modify the RIPE Atlas software.)

6 RELATED WORK

Our work is inspired by prior work in improving DNS security, anycast location-mapping, and DNS spoofing detection.

Several groups have worked to improve or measure DNS security. DNSSEC provides DNS integrity [11]. Recent work of Chung et al. [5] shows under-use and mismanagement of the DNSSEC in about 30% domains. This work indicates that securing DNS involves actions of multiple parties. Several groups explored DNS privacy and security, suggesting use of TLS to improve privacy [37], and methods to counter injection attacks [10]. Others have identified approaches to hijack or exploit DNS security [21, 31, 33, 34], or studied censorship and multiple methods to spoof DNS [12, 15]. Our work considers a narrower problem, and explores it over more than six years of data: we study who, where and how DNS spoofing occurs. Our work complements this prior work by motivating deployment of defences. Liu et al. looks at DNS spoofing when users use public DNS servers [18]. This work points out that interception happens about 10 times more than injection in TLD DNS queries. This finding agrees with our conclusion that proxies (interception) account for nearly

all spoofing we see. Our work goes beyond their work to characterize who third-parties are, and to study longitudinal data.

Several groups have studied the use of anycast and how to optimize performance. Fan et al. [13] used traceroute and open DNS resolvers to enumerate anycast sites, as well as Server ID information. They mention spoofing, but do not study it in detail. Our work also uses Server ID and traceroute to study locations, but we focus on identifying spoofers, and how and where they are. Other prior work uses Server ID to identify DNS location to study DNS or DDoS [20, 29, 35].

Work of Jones et al. [16] aims to find DNS proxies and unauthorized root servers. They study B-root because it was unicast at the time, making it easy to identify spoofing. Our work goes beyond this work to study spoofing over all 13 letters over more than six years, and to identify spoofing mechanisms.

Closest to our work, the Iris system is designed to detect DNS manipulation globally [22]. They take on a much broader problem, studying all methods of manipulation across all of the DNS hierarchy, using open DNS resolvers. Our work considers the narrower problem of spoofing (although we consider three mechanisms for spoofing), and we study the problem with active probing from RIPE Atlas. Although our approach generalizes, we analyse only the DNS Root.

Finally, we recently became aware that Wessels is studying currently spoofing at the DNS Root with Ripe Atlas [36]. His work is not yet generally available and is in progress, but to our knowledge, he does not look at spoofing mechanisms and has not considered six years of data.

7 CONCLUSION

This paper developed new methods to detect overt DNS spoofing and some covert delayers, and to identify and classify parties carrying out overt spoofing. In our evaluation of about six years of spoofing at the DNS Root, we showed that spoofing is quite rare, affecting only about 1.7% of VPs. However, spoofing is increasing, growing by more than 2× over more than six years. We also show that spoofing is global, although more common in some countries. By validating using logs of authoritative server B-root, we prove that our detection method has true positive rate of at least 0.96. Finally, we show that proxies are a more common method of spoofing today than DNS injection.

We draw two recommendations from our work. First, based on the growth of spoofing, we recommend that operators regularly look for DNS spoofing. Second, interested end-users may wish to watch for spoofing using our approach.

REFERENCES

- [1] ABC. Australia bans 220 video games in 4 months as government adopts new classification model. <http://www.abc.net.au/news/2015-06-30/australia-bans-220-video-games-in-four-months/6582100>. 2015-06-30.
- [2] ABC. Internet companies forced to block The Pirate Bay, bittorrent websites in Australia, Federal Court rules. <http://www.abc.net.au/news/2016-12-15/federal-court-orders-pirate-bay-blocked-in-australia/8116912>. 2016-12-15.
- [3] R. Austein. DNS Name Server Identifier (NSID) Option. RFC 5001, Aug. 2007.
- [4] B-root. B-root server logs. Contact B-root operators.
- [5] T. Chung, R. van Rijswijk-Deij, B. Chandrasekaran, D. Choffnes, D. Levin, B. M. Maggs, A. Mislove, and C. Wilson. A longitudinal, end-to-end view of the dnssec ecosystem. In *26th USENIX Security Symposium USENIX Security 17*, pages 1307–1322, 2017.
- [6] D. R. Conrad and S. Woolf. Requirements for a Mechanism Identifying a Name Server Instance. RFC 4892, June 2007.
- [7] S. Crocker, D. Dagon, D. Kaminsky, D. McPherson, and P. Vixie. Security and other technical concerns raised by the DNS filtering requirements in the PROTECT IP bill. Technical report, RedBarn, May 2011.
- [8] T. Cymru. SOHO pharming. Technical report, Team Cymru, Feb. 2014.
- [9] A. Dainotti, C. Squarcella, E. Aben, K. C. Claffy, M. Chiesa, M. Russo, and A. Pescapé. Analysis of country-wide internet outages caused by censorship. In *Proceedings of the 2011 ACM SIGCOMM Conference on Internet Measurement Conference, IMC '11*, pages 1–18, New York, NY, USA, 2011. ACM.
- [10] H. Duan, N. Weaver, Z. Zhao, M. Hu, J. Liang, J. Jiang, K. Li, and V. Paxson. Hold-on: Protecting against on-path DNS poisoning. In *Proceedings of the Workshop on Securing and Trusting Internet Names (SATIN)*, Teddington, UK, Mar. 2012.
- [11] D. Eastlake. Domain Name System security extensions. RFC 2535, Internet Request For Comments, Mar. 1999. obsoleted by RFC-4033.
- [12] R. Ensafi, D. Fifield, P. Winter, N. Feamster, N. Weaver, and V. Paxson. Examining How the Great Firewall Discovers Hidden Circumvention Servers. In *Proceedings of the 2015 Internet Measurement Conference, IMC '15*, pages 445–458, New York, NY, USA, 2015. ACM.
- [13] X. Fan, J. Heidemann, and R. Govindan. Evaluating anycast in the Domain Name System. In *INFOCOM, 2013 Proceedings IEEE*, pages 1681–1689. IEEE, 2013.
- [14] S. Farrell and H. Tschofenig. Pervasive monitoring is an attack. RFC 7758, Internet Request For Comments, May 2014. (also Internet BCP-188).
- [15] P. Gill, M. Crete-Nishihata, J. Dalek, S. Goldberg, A. Senft, and G. Wiseman. Characterizing web censorship worldwide: Another look at the opennet initiative data. *ACM Transactions on the Web*, 9(1), Jan. 2015.
- [16] B. Jones, N. Feamster, V. Paxson, N. Weaver, and M. Allman. Detecting dns root manipulation. In *International Conference on Passive and Active Network Measurement*, pages 276–288. Springer, 2016.
- [17] B. Krebs. A deep dive on the recent widespread DNS hijacking attacks. Krebs-on-Security blog at <https://krebsonsecurity.com/2019/02/a-deep-dive-on-the-recent-widespread-dns-hijacking-attacks/>, Feb. 2019.
- [18] B. Liu, C. Lu, H. Duan, Y. Liu, Z. Li, S. Hao, and M. Yang. Who is answering my queries: Understanding and characterizing interception of the DNS resolution path. In *27th USENIX Security Symposium (USENIX Security 18)*, pages 1113–1128, 2018.
- [19] C. Metz. Comcast trials (domain helper service) DNS hijacker. The Register, July 2009.

- [20] G. C. M. Moura, R. de O. Schmidt, J. Heidemann, W. B. de Vries, M. Müller, L. Wei, and C. Hesselman. Anycast vs. DDoS: Evaluating the November 2015 root DNS event. In *Proceedings of the ACM Internet Measurement Conference*, Nov. 2016.
- [21] G. Nakibly, J. Scholnik, and Y. Rubin. Website-Targeted False Content Injection by Network Operators. In *25th USENIX Security Symposium (USENIX Security 16)*, pages 227–244, Austin, TX, 2016. USENIX Association.
- [22] P. Pearce, B. Jones, F. Li, R. Ensafi, N. Feamster, N. Weaver, and V. Paxson. Global measurement of DNS manipulation. In *26th USENIX Security Symposium (USENIX Security 17)*, pages 307–323, Vancouver, BC, 2017. USENIX Association.
- [23] J. Purra and T. Cuddy. DNSSEC Name-and-Shame. website <https://dnssec-name-and-shame.com>, 2014.
- [24] RIPE Atlas. <https://atlas.ripe.net/>, May 2020.
- [25] RIPE NCC. RIPE Atlas root server dns data. <https://atlas.ripe.net/measurements/ID>. ID is the per-root-letter experiment ID: A: 10309, B: 10310, C: 10311, D: 10312, E: 10313, F:10304, G: 10314, H: 10315, I: 10305, J: 10316, K: 10301, L: 10308, M: 10306.
- [26] RIPE NCC. RIPE Atlas root server ping data. <https://atlas.ripe.net/measurements/ID>. ID is the per-root-letter experiment ID: A: 1009, B: 1010, C: 1011, D: 1012, E: 1013, F: 1004, G: 1014, H: 1015, I: 1005, J: 1016, K: 1001, L: 1008, M: 1006.
- [27] RIPE NCC. RIPE Atlas root server traceroute data. <https://atlas.ripe.net/measurements/ID>. ID is the per-root-letter experiment ID: A: 5109, B: 5010, C: 5011, D: 5012, E: 5013, F: 5004, G: 5014, H: 5015, I: 5005, J: 5016, K: 5001, L: 5008, M: 5006.
- [28] Root Operators. <http://root-servers.org>, Apr. 2019.
- [29] R. d. O. Schmidt, J. Heidemann, and J. H. Kuipers. Anycast latency: How many sites are enough? In *Proceedings of the Passive and Active Measurement Workshop*, page to appear, Sydney, Australia, May 2017. Springer.
- [30] K. Schomp, T. Callahan, M. Rabinovich, and M. Allman. Assessing DNS vulnerability to record injection. In *International Conference on Passive and Active Network Measurement*, pages 214–223. Springer, 2014.
- [31] S. Son and V. Shmatikov. The hitchhiker’s guide to DNS cache poisoning. In *International Conference on Security and Privacy in Communication Systems*, pages 466–483. Springer, 2010.
- [32] D. B. Terry, M. Painter, D. W. Riggie, and S. Zhou. The Berkeley Internet Name Domain Server. Technical Report UCB/CSD-84-182, EECS Department, University of California, Berkeley, May 1984.
- [33] T. Vissers, T. Barron, T. Van Goethem, W. Joosen, and N. Nikiforakis. The wolf of name street: Hijacking domains through their nameservers. In *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security*, pages 957–970. ACM, 2017.
- [34] N. Weaver, R. Sommer, and V. Paxson. Detecting Forged TCP Reset Packets. In *NDSS*, 2009.
- [35] L. Wei and J. Heidemann. Does Anycast Hang up on You? In *IEEE International Workshop on Traffic Monitoring and Analysis*, page 9, Dublin, Ireland, July 2017. IEEE.
- [36] D. Wessels. About DNS Spoofing. Private communication, Apr. 2019.
- [37] L. Zhu, Z. Hu, J. Heidemann, D. Wessels, A. Mankin, and N. Somaiya. Connection-oriented DNS to improve privacy and security. In *Proceedings of the 36th IEEE Symposium on Security and Privacy*, pages 171–186, San Jose, California, USA, May 2015. IEEE.