DNS Magnitude - A Popularity Figure for Domain Names, and its Application to L-root Traffic

Alexander Mayrhofer, Michael Braunöder, Aaron Kaplan - nic.at GmbH*

June 1, 2020

OPEN ISSUES: Conclusions are weak - new findings to be included, References and Bibliography is sluggish. Internal final review within nic.at is ongoing.

1 Abstract

When estimating the popularity of services on the internet, researchers often take simple surrogate measurements of that single service - most notable number of requests or number of "visitors". While this approach is simple, and usually works for a lot of services (for example web sites), it only considers that single service, and fails when it comes to measuring the popularity of a domain name as a whole, no matter what services are offered under that domain. To fill this gap, the following report defines a DNS-based metric for estimating the popularity of a domain name - the *"DNS Magnitude"*.

We start the report with a brief introduction to the Domain Name System (DNS), discuss weaknesses of domain popularity measures based on a simplistic number of requests measure (which usually ignores the TTL-effect) and look at previous work in this field. Next, we explain the design principles of DNS Magnitude and lay open our methodolgy. We then arrive at a formal definition of DNS Magnitude and discuss the contexts in which DNS Magnitude may be used, and its limits. We also give an informal reasoning why DNS Magnitude appears resilient to TTL variances amongst different domains. Manipulation attempts (for example via changes to the TTL values) or via spoofed source IP addresses are discussed, as are other aspects of DNS that might influence resulting magnitude values.

After these theoretical aspects, we apply the DNS Magnitude metric to the L-Root Traffic, explore the resulting distributions and time series, and dig deeper on some specific aspects of the DNS, most notable the very prevalent non-existing Domains. We conclude that DNS Magnitude based statistics can provide a valueable additional measurement in many cases where large volumes of DNS data are to be aggregated.

In this paper we reason that DNS Magnitude is a useful addition to the DNS researcher's toolbox, allowing to estimate the overall popularity of a domain, and express it in a meaningful, simple, human friendly single number.

Contents

[*] alexander.mayrhofer@nic.at, kaplan@nic.at, braunoeder@nic.at

2 Terminology

In addition to the common DNS terminology as defined in [14], we define the following terms:

Domain Within the scope of this paper, we define "Domain" as the Domain name and all of its Subdomains (both defined in [14]). Example: Domain "example.com" contains "example.com" itself, "www.example.com", "_sip._tcp.example.com" and all other Subdomains beneath the "example.com" label sequence.

Unique clients By this we mean the set of unique client IP addresses (or client IP networks, in case when aggregation is applied) a (recursive or authoritative) set of name servers receives queries from.

Domain Name Popularity The DNS query volume of domain d that is related to the popularity of services instigating queries (directly or indirectly) to d. See section 3.2.

DNS Magnitude A measurement for Domain Name Popularity of a Domain, as defined in Section 4.2 of this document.

Rank An ordinal number assigned to a Domain within a Context, based on its DNS Magnitude, as described in Section 4.3.

Context The parameters of the environment where measurements for calculation of DNS Magnitude are obtained. See section 4.4.

nxTLD Non-existing Top Level Domain: A label that is not delegated in the root zone.

3 Introduction

3.1 The Domain Name System

The Domain Name System (DNS) [19][20] is today's predominant naming infrastructure on the Internet. It is a distributed hierarchical scheme that is globally available. Since almost any transaction on today's internet starts with resolving a host name (which, in turn, triggers a query to the DNS), hundreds of billions of DNS transactions are performed each day [22].

The DNS hierarchy is structured into a single "root" node from which (as of November 04 2019) 1 583 Top-Level-Domains ("TLDs") [5] are administratively and technically delegated to organizations all around the world. These delegations form the "Root Zone". TLDs below the root zone then contain further levels of hierarchy, their structure depending on the local policy of the respective TLD. As of August 2019, about 355 millions of "Domain Names" were registered across all TLDs [25].

The root zone is hosted on 13 "Root Servers", named alphabetically *a.root-servers.net* to *l.root-servers.net*, and operated by 12 organizations as of Nov 2019 [4] (there's only 12 operators because Verisign, Inc. hosts two instances). By means of IP Anycast [1] the 13 root servers are hosted on a globally distributed set of 1 031 instances [24] (as of Dec 2019) to ensure ubiquitious and uninterrupted availability of the root DNS service. Similar infrastructure is in place for most TLDs [9].

3.2 Domain Name Popularity

Different names in the DNS hierarchy attract widely varying amounts and patterns of queries. The DNS is rarely the user desired end service itself, but rather a prerequisite for accessing any service that uses a name contained in the domain name's sub-tree. This leads to the first observation: the more often services under a domain are addressed, the more often name resolution within the respective domain name is required. In other words: the popularity of services offered is therefore related to the amount of query traffic that can be observed for the domain or any sub-tree of that domain name:

$$Pop(d) \sim \text{traffic}(d)$$

where $Pop(d)$ is the Domain Name Popularity function of domain d and traffic(d) is the set of DNS resolutions requests for d or any sub-tree of d.

We therefore define for the scope of this paper the *Domain Name Popularity* as a function of the query traffic observed for a domain name d or sub-tree of d:

$$Pop(d) = f(\text{traffic}(d))$$

where f is some to be discussed function.

3.3 Query traffic and the Time-to-Live

The most obvious method to measure popularity based on DNS query traffic would be to count the number of queries observed over a certain period of time for a specific name or sub-tree, and directly declare that figure to be the popularity of the domain. However, the DNS features an integral caching mechanism that constitutes one of the cornerstones of the efficient functioning of the DNS:

When a DNS client receives a response, that response is accompanied by "Time-to-live" (TTL) information, which, as described in RFC1035 [20] *"specifies the time interval that the resource record may be cached before the source of the information should again be consulted"*. This means that when the same client (such as a recursive resolver) receives a new downstream query for the identical resource while the the original response is still in cache, it will answer with the cached response, and not send another query to an upstream authoritative server for the domain. Shorter TTLs therefore incur earlier expiring of cached responses, earlier re-querying for identical resources, and create higher query rates.

TTLs are configurable by the administrator of a zone, and typical values span a wide range from a few seconds up to several weeks. In practice, this means that two domain names with identical popularity of their underlying services, but different TTL values will generate different DNS traffic volumes. This is undesireable for any query-based measurement of domain name popularity, as it introduces bias that a) reflects internal mechanisms of the DNS protocol, rather than an actual difference in service popularity and b) is subject to manipulation by modifying TTL values.

Note that there is also an important operational aspect: Assuming that there is a benefit associated with achieving higher (perceived) popularity, lowering TTL values would become very attractive for domain name administrators. However, lower TTLs also increase the load on recursive and authoritative DNS servers, and effectively reduce the resilience of the DNS [21] - a very undesirable consequence!

3.4 Previous Work & Development Timeline

Calculating/estimating popularity of domain names not novel. The internet community has well known estimates such as the Alexa top-1M list, but these don't extend to arbitrary domain names. Holmes et. al [15] discuss a domain popularity metric (in a Google patent), which goes far beyond looking at pure DNS traffic. And in addition, the domain investment industry has also come up with its own estimates of how popular (in the sense of reselling value) a domain is. None of these approaches try to estimate a domain names' popularity only on its DNS traffic.

To the best of our knowledge, the first such approach was presented by Sebastian Castro[8] in May 2016. He presented his revised popularity ranking based on term frequency-inverse document frequency to the CENTR R&D group. During that presentation, Castro first mentioned the idea that counting unique hosts rather than packets could be a strategy that offsets for variance of the DNS' caching TTL.

Inspired by that discussion, DNS Magnitude was developed by Alexander Mayrhofer over the course of the following months, and first presented by him to the CENTR R&D group[18] in Nov 2016.

In dec 2016, Cisco's Umbrella 1 Million list [16] was made public. Developed independently from DNS Magnitude, their ranking algorithm also seems to use host counts rather than query volume figures. Details are unavailable, as the actual algorithm is not publicly disclosed as of Nov 2019.

This very paper, developed in 2019/2020, to the best of our knowledge, represents the first formal definition of *DNS Magnitude*.

4 The "DNS Magnitude"

4.1 Design Principles and Reasoning

4.1.1 Client Address Cardinality instead of Query Counts

Because of the forementioned impact of TTL values on query volume (see section 3.3), DNS Magnitude relies on counting unique client addresses observed for a certain name or sub-tree, rather than the number of queries. This is expected to greatly reduce the impact of different TTL values for domains in identical contexts. An empiric observation that confirms this hypothesis is included in section 5.

> We propose that DNS Magnitude uses the number of unique client IP addresses (client cardinality), rather than the number of queries, as the basis for calculation.

4.1.2 Logarithmic Scale

As described in section 3, many contexts of DNS traffic have a high disparity between a few very busy domains, and many domains with very low traffic levels on the other end of the scale. Even when considering the number of unique hosts (rather than the number of queries), there is a high disparity amongst, for example, the set of second level domains below a TLD:

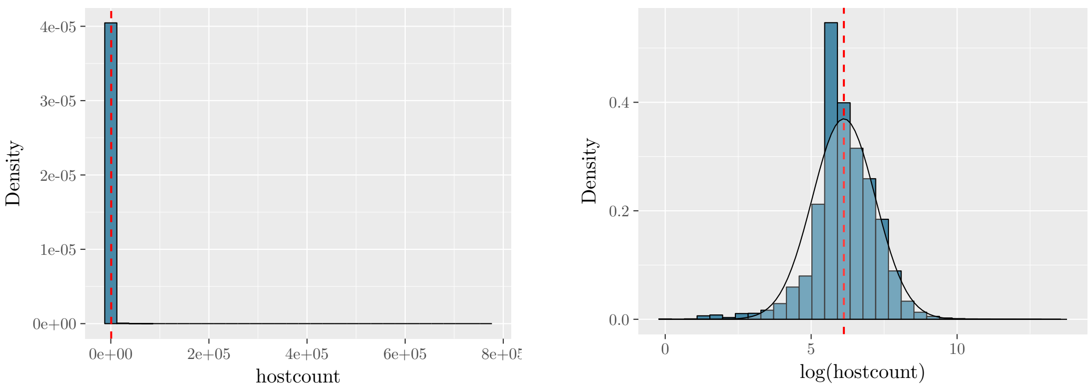
We investigate the disparity of unique hosts per second-level domain for the Austrian country code TLD (ccTLD) *.at*[1], based on traffic observed on authoritative nameservers. At the time of the investigation, the .at TLD is delegated to 8 different name server names. DNS traffic from the following subset of those nameservers is available for the investigation: *r.ns.at* (all 38 instances), *d.ns.at* ("Frankfurt" node only), *n.ns.at* ("Amsterdam" node only), *ns1.univie.ac.at* ("Vienna" node only) and *ns9.univie.ac.at* ("interxion Vienna" node only). We gather the traffic for the full month of August 2019 from those servers, which contains data for 5,45 billions of DNS queries. Out of those, 4,21 billions where responded with response code (Rcode) *0* (NOERROR), indicating that a delegation for the requested name exists. 989 millions of queries triggered Rcode 3 (NXDOMAIN), indicating that the requested name does not exist. The dataset contains 2 237 236 observed unique client IP addresses, and queries for 522 890 793 different second level domain names (Names under *ac.at*, *gv.at* and priv.at were excluded, because as they are delegated to a different set of servers, and hence 3rd-level names under those sub-trees always trigger a response code 0 (NOERROR) on the authoritative nameservers for .at. As the

[1] operated by nic.at, the employer of the authors

.at TLD during August 2019 contained only about *1.3* millions of delegated names, the vast majority of domainnames queried trigger NXDOMAIN.

We filter the data for *NOERROR* responses, and aggregate the data to a set of tupels containing the *domain name* the number of unique client IP addresses observed (*hostcount*) for each domain. Query names are aggregated to their 2nd level domain, or the 3rd level domain for names under *co.at* and *or.at*.

We then plot (see Figure 1) the distribution of *hostcount* by domain in that aggregated data set, once with the *hostcount* unmodified (linear scale, Figure **??**), and once with the natural logarithm applied to *hostcount* (Figure **??**). We notice that the linear density exposes the extreme disparity between "busy" and "quiet" domains discussed above, even on the level of unique hosts. In comparison, we notice that the logarithmic scale exposes a much more natural distribution, and even shows a good match to a fitted normal distribution:



(a) Linear Distribution

(b) Logarithmic Distribution

Figure 1: Linear and logarithmic distributions of host cardinality for existing .at domain names

This is also reflected in the general "scale-free" architecture of the Internet. See also [6]. It is therefore no surprise that a logarithmic distribution fits the distribution of DNS traffic to domain names, since the popularity of nodes on the Internet is reflected by DNS traffic.

> For the reasons outlined in this section, we propose to use *the natural logarithm of unique client IP addresses per domain*, rather than a linear scale, as the calculation basis for DNS Magnitude.

4.1.3 Normalization

The number of queries and unique client addresses observed will vary greatly between different environments. A home or small enterprise network will typically see much fewer queries than the recursive resolver of their upstream internet service provider. However, in no environments can the number of unique client addresses querying a certain domain exceed the observed total number of unique client addresses. Given the goal of DNS Magnitude is to measure a relative popularity within a given context, it makes sense to normalize the resulting figure to the extent of that context.

When normalization is applied by means of dividing the observed unique clients per domain by the total unique number of observed client addresses, the resulting figure is in the range of 0 to 1.

However, as DNS Magnitude also has the goal to be human-friendly and -understandable (and humans are used to work in the decimal system, with digits ranging from 0 to 10), we propose to multiply that resulting figure by 10.

Because DNS Magnitude is - as explained above - normalized to a specific context, that also means that values cannot be compared cross-context.

We propose to use a scale of 0 to 10 for resulting DNS Magnitude values.

4.2 Formal Definition

DNS Magnitude is defined as follows:

Where A_d is the set of client addresses observed querying a specific Domain d (and therefore either the Domain name of d itself, or any of it Subdomains) in a given context (see 4.4) during a specific time interval, and A_{tot} is the total set of client addresses observed querying in the same Context during the identical time interval, DNS Magnitude $mag(d)$ for a Domain d in that Context is defined as the natural logarithm of the cardinality of A_d, divided by the natural logarithm of the cardinality of A_{tot}, normalized to the range $0 - 10$:

$$mag(d) = \frac{\ln(|A_d|)}{\ln(|A_{tot}|)} * 10 \tag{1}$$

Note that because $\forall A \forall d : |A_d| \leq |A_{tot}|$, $\forall d : 0 \leq mag(d) \leq 10$. For the empty set of client addresses $A_d = \{\}$, the respective DNS Magnitude $mag(d)$ is undefined.

For a prosa definition of DNS Magnitude, we propose the following text:

> DNS Magnitude is a logarithmic measure for the DNS popularity of a domain name, based on counting unique client addresses, normalized to 0-10 range"

4.3 DNS Magnitude based Rank

In some cases, the actual value of a measurement might be less important than comparing the value of different items against each other, as long as they are acquired in the same context (using the same methodology). One such method is to create a ranking, based on the order of the measurement values, and consider the rank of each item as the result, rather than the actual measurement value itself. DNS Magnitude can be used to create such a ranking of Domains within a specific Context. To assign a rank to each Domain, the set of Domains is sorted by their DNS Magnitude value in descending order, and ordinal numbers (starting from 1) are assigned to each Domain, starting with the Domain with the highest DNS Magnitude value.

Note that a Domain's Rank is specific to a Context.

4.4 Contexts

For the purpose of DNS Magnitude calculation, a *Context* is defined as the environment in which the DNS queries have been observed, including any filtering / truncation steps performed on the set of observed queries and addresses before the calculation in 4.2 is applied.

A specific context entails:

- The potential set of DNS clients
- The potential set and function of DNS servers
- Filtering performed on observed queries
- Aggregation performed on client IP addresses
- Aggregation performed on query names (Qnames)

Because DNS Magnitude values are always relative to such a Context, cross-context comparisons are potentially misleading and must be done with great caution. Such comparisons are only sensible if two Contexts expose significant correlation.

DNS Magnitude information is useless and invalid without the description of the respective Context.

An example of such a Context would be the set of recursive resolvers of an Internet Service Provider (ISP), their IP address ranges used for customers,together with the information that IPv6 addresses have been truncated to /56 prefixes (for example because this matches the local allocation policy for end customers), while IPv4 addresses have not been aggregated, and Qnames have been truncated to one additional level beyond the Public Suffix List, while no filtering for QTYPEs was performed.

Another example of a context would be a subset of authoritative servers for a TLD, the global IP address space as potential clients, queries filtered to NXDOMAIN type responses, QNAMEs aggregated to 2nd-level domains, and IP addresses truncated to /24 (IPv4) and /48 (IPv6).

5 Resilience against TTL variance

As described above, one of the main design goals of DNS Magnitude is resilience against traffic varieties which are based on TTL variance, rather then stemming from popularity differences of the underlying services. During preparation of an earlier study of DNS Magnitude (within the .at TLD), a specific domain was noticed to expose an much higher ratio of queries to Unique clients, compared to other domain names with similar client counts (See Table 1):

Domain	Unique clients	observed queries	queries / Unique clients ratio
univie.ac.at	543 437	41 428 395	76,23
anexia.at	**444 859**	**203 186 012**	**456,74**
telekom.at	336 942	11 178 255	33,17
google.at	295 864	4 940 158	16,70
nessus.at	283 206	12 850 393	45,37

Table 1: Query-to-Client ratio observed before TTL change

(Context / data set: Queries for the *.at* TLD to the authoritative nameservers *r.ns.at*, *n.ns.at* (Amsterdam node only), and *ns9.univie.ac.at*, observed between Mar 23 2019 and Mar 29 2019.)

Upon closer inspection of the properties of the affected domain *anexia.at*, it was discovered that some of the relevant TTL values were configured to unusually low values:

- *60 seconds* for the authoritative *NS* resource record set (RRSet)
- *120 seconds* for the *A/AAAA* RRSets of the glue record nameservers.

The domain name owner was notified of those low TTL settings, and subsequently changed all TTL values mentioned above to *10800 seconds.* Once the new TTLs had settled, new measurements (for a full week, again) were taken. The results of both measurements are compared in Table 2.

Measurement	Unique clients	Observed queries
(a) short TTLs	444 859	203 186 012
(b) long TTLs	422 278	21 409 529
relation b/a	94,94 %	10,53 %

Table 2: Comparison of client and query volume before and after TTL change

While the number of observed queries is reduced by 89,47 % of the original volume, the cardinality of the client IP addresses is only 5,06 % lower. This confirms that host cardinality is much more resilient against changes in TTL values than query counts, and hence more suitable for popularity measurements.

Note that the domain primarily serves as an ”infrastructure” domain, meaning that hosts under the domain serve as authoritative nameservers for a large number of other domains. Such infrastructure domains expose a high popularity, because these names need to be resolved before any of the hosted domain names can be resolved.

6 Manipulation potential and cost

DNS Magnitude may be used in situations where achieving a certain ranking might provide benefits to the owner of a domain name. Because of such benefits, owners could be tempted to explore the options to artificially influence the DNS Magnitude for their name. This section explores potential manipulation options and their associated cost.

As DNS Magnitude is derived from the DNS traffic for a certain name, the traffic volume and characteristics for a given name need to be manipulated in order to achieve a change of the DNS Magnitude value.

As described in section 4.1.1, DNS Magnitude is based on the cardinality of client IP addresses. Therefore, for manipulation of DNS Magnitude, that number of unique clients observed in a certain context is the target for manipulation. For example, by creating non-organic traffic from a set of IP addresses for a certain name, DNS Magnitude of a name can be artificially elevated. Artificially lowering the magnitude of a name is not directly possible, because this would require suppresing DNS queries from existing organic clients. However, Magnitude can be indirectly lowered by adding traffic for other names, hence increasing the based population used in the calculation, and reducing the relative fraction of hosts seen for a specific name.

Counting hosts is more resilient against modification than counting packets, because much more effort is required for introducing traffice from additional IP addresses rather than simply adding more queries. However, two properties of the current internet infrastructure relativize this:

6.1 IPv6 Allocations

In version 4 of the Internet Protocol (IPv4) the assignment to users and even small enterprises typically contains just a single IP address. However, when version 6 of the Internet Protocol (IPv6) is used, whole prefixes are assigned to end users [23]. The typical allocation size is /56 to /64, and any prefix of such size contains more IP addresses than the entire IPv4 space. Therefore, even a single IPv6 allocation could be used to increase the number of IP addresses observed on a server almost arbitrarily, and hence significantly change the set of client IP addresses used as the basis for DNS Magnituce calculation.

As a countermeasure, IPv6 addresses observed could always be truncated to /64, as this is a very common (and recommended) prefix allocated to a single host, and count each unique prefix as a single unique client, rather than each individual address.

6.2 Spoofed Source IP Addresses

The majority of DNS traffic today is transported using the User Datagram Protocol (UDP). Because UDP is stateless, and deployments do typically not verify whether the source adress used in a packet is actually assigned to the device (or routed to the network sourcing that packed, see BCP-38 [10]), sending packets with arbitrary source IP address is typically quite simple. Such packets can then be used to, again, artificially and almost arbitrarily increase the number of unique hosts observed for a name, even in the IPv4 space.

Spoofing of source IP addresses might not be possible in more controlled contexts (for example between the access plane of an ISP and the ISPs own recursive resolver). In such cases, DNS Magnitude is safe from manipuation by spoofed addresses. However, that level of control does not exist for the open internet.

One countermeasure would be to limit measurements to hosts seen via TCP-based DNS protocols. However, those protocols are currently not very prevalent nor available on the recursor-to-authoritative leg.

7 Applying DNS Magnitude to L-Root Traffic

The definition of DNS Magnitude was applied to traffic from the ICANN Managed Root Server System (IMRS), also known as *L-Root*. That practical part of the study was performed in two stages:

During the first (experimental) phase, we had access to traffic snapshots of 10 minutes for analysis. In that phase, we focused on exploring structure and properties of the data set, and developed software that performs the calculation of DNS Magnitude based on the given input format.

For the second phase, we were granted access to full traffic data of several months, as described in the following section.

7.1 L-Root Dataset Description

The dataset available for the study is based on pcap data gathered from the L-Root servers. For each 10-minute interval and each server instance, a seperate file is produced. Each incoming 10-minute fragment of pcap/cbor data was pre-processed by Roy Arends into a text format called *royparse*, and stored in gzip format, again producting seperate files for each 10-minute time slot and server instance.

The resulting files contain one line of text per DNS response sent to a client. Out of the fields included for each response, the destination of the response (client IP address) and the Query Name (QNAME) are relevant for the calculation of DNS Magnitude.

An average day of data consists of about 52 000 files, with a total (compressed) volume of about 120 GB. The average day sees traffic from a total of 3,5 million unique client IP addresses.

Based on the available curated data, we decided for the 5 months of April 2019 to August 2019 as the observation window. This resulted in a total count of 8 024 722 files with a total compressed volume of 17,95 TB (compressed).

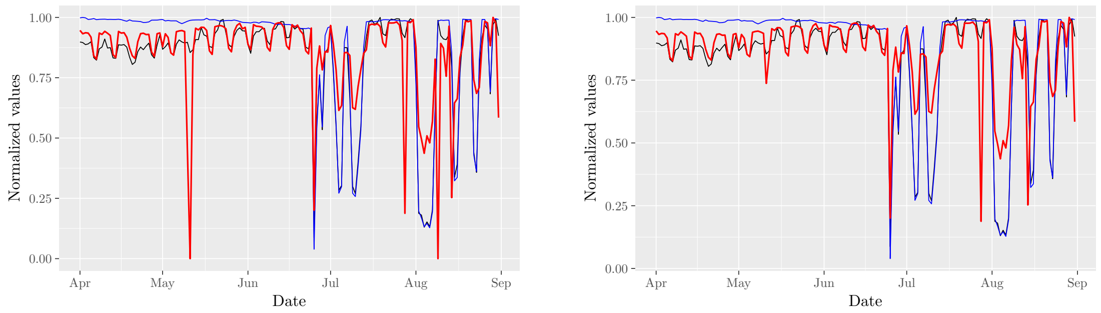
7.2 Data Completeness

During a late stage of the research, we noticed that some days exposed a significantly lower number of unique client IP addresses per day than average days. We performed a size based validation by comparing the number of unique client to the total number of data files and total data size of that day (See figure 2a). The irregularities observed fall into two different categories:

1. **Incomplete calculations:** Days with normal file counts and / or normal file sizes, but smaller than expected unique client counts indicate a problem with the calculation of DNS Magnitude for the given day. Specifically: 2019-05-10, 2019-05-11, 2019-07-28, 2019-08-09 and 2019-08-31.

2. **Incomplete source data:** Days with fewer than expecte unique client counts, but also fewer than expected data files (or smaller than expected total source data size) indicate missing source data (but correct DNS Magnitude calculations. For example, first few days of August 2019.

Based on these findings, we were able to correct some of the incomplete calculations (namely 2019-05-10, 2019-05-11, 2019-08-09), but none of the ”incomplete source data” cases, as the original data was unavailable. We do, however, believe that this allows to examine the resilience of DNS Magnitude against imcomplete measurement data, and consitutes an interesting research aspect. Figure 2b illustrates data completeness post corrections - this data was used for the subsequent findings. For data focusing on a single day, we used 2019-08-30 (last complete, non-weekend day of the observation period).



(a) Before corrections

(b) After corrections

Figure 2: Size based Validation of Dataset

7.3 Supplementory Datasets

Besides the L-root traffic data described in section 7.1, we used the following datasets to augment the calculated DNS Magnitude results:

- **Historic root zones:** In order to identify whether or not a label existed as a delegation in the root zone on a given day, we use a private root zone archive managed by Arsen Stasic from the University of Vienna. This archive was created using a nightly cron job to perform a zone transfer from *b.root-servers.org*. For the dates of 2019-05-21, 2019-07-29, and 2019-08-06 no root zone could be acquired. For these dates, we used the root zone files of the respective preceding day for analysis.
- **ICANN new gTLD Application List:** To identify whether or not a TLD is part of ICANN’s new gTLD Program, we used a CSV file of new gTLD applications[11], published by ICANN itself.

7.4 Description of Data Processing

Based on the data set described in section 7.1, we created daily lists of DNS Magnitude per TLD. That analysis was performed directly on ICANN’s Office of the CTO *OCTO* infrastructure, which removed the necessity to copy any privacy sensitive information off ICANN’s servers. Each day of calculation required about 5 hours of run time.

As a compromise between file size and extent of the analysis, we truncate the DNS Magnitude lists to TLDs which receive queries from at least 100 unique IP addresses during the respective day. Depending on the specific day, this censors the data to TLDs with a minimum DNS Magnitude of about 3,2, but still yields about 160k data rows for each day. The minimum number of 100 unique clients was chosen so that (on most days), all delegated TLDs are contained in the result files.

8 L-Root Dataset Results

We initially use the data from a single day, August 30 2019[2], calculate the DNS Magnitude for each TLD, and sort the results by DNS Magnitude in descending order to create a ranking of TLDs[3] by the observed DNS Magnitude. We augment the results with information from the supplementory datasets (See section 7.3).

The result file contains 169 507 TLDs for which at least 100 unique clients have been observed. Given that 1 528 TLDs existed in the root zone on that day, 99,1 % of rows represent non-existing TLDs (nxTLDs).

8.1 Top 20 TLDs by DNS Magnitude

We first look at the TLDs with the highest DNS Magnitude values. For brevity, we truncate the data to the top 20 (see Table 3).

	Rank	TLD	DNS Magnitude	Unique clients	TLD exists	new gTLD
1		com	9.50	1861869	TRUE	FALSE
2		.	9.48	1825446	TRUE	FALSE
3		net	9.45	1735329	TRUE	FALSE
4		org	9.03	917320	TRUE	FALSE
5		uk	8.82	666371	TRUE	FALSE
6		info	8.75	595804	TRUE	FALSE
7		au	8.68	538117	TRUE	FALSE
8		de	8.64	502903	TRUE	FALSE
9		arpa	8.59	471062	TRUE	FALSE
10		eu	8.56	444635	TRUE	FALSE
11		biz	8.55	443072	TRUE	FALSE
12		local	8.45	376781	FALSE	FALSE
13		br	8.43	368388	TRUE	FALSE
14		cn	8.43	365896	TRUE	FALSE
15		io	8.35	326590	TRUE	FALSE
16		it	8.32	310880	TRUE	FALSE
17		jp	8.31	305900	TRUE	FALSE
18		ru	8.31	305562	TRUE	FALSE
19		co	8.26	282390	TRUE	FALSE
20		pl	8.24	273454	TRUE	FALSE

Table 3: Top 20 TLDs by DNS Magnitude for 2019-08-30

We see that the set of top 20 TLDs contains widely known, long-established TLDs with a high number of registrations on subsequent levels, so those TLDs correlate with the empiric observation that these are indeed "busy" TLDs. The *.local* TLD is the only non-existing label in the top 20, with a popularity similar to larger country code TLDs. This is not surprising, however, as the popularity of that invalid TLD is well known, and has been described before [7]. We further examine the prevalence of non-existant (invalid) TLDs in section 8.4.

8.2 Distribution of DNS Magnitude of delegated TLDs

We filter the results described in section 8.1 so that it contains only data for the 1 528 TLDs which existed that day[4]. When we plot a histogram of the resulting data we see that the distribution exposes bimodal characteristics (see Figure 3a).

[2] Last non-weekend day of the observation period that has complete data

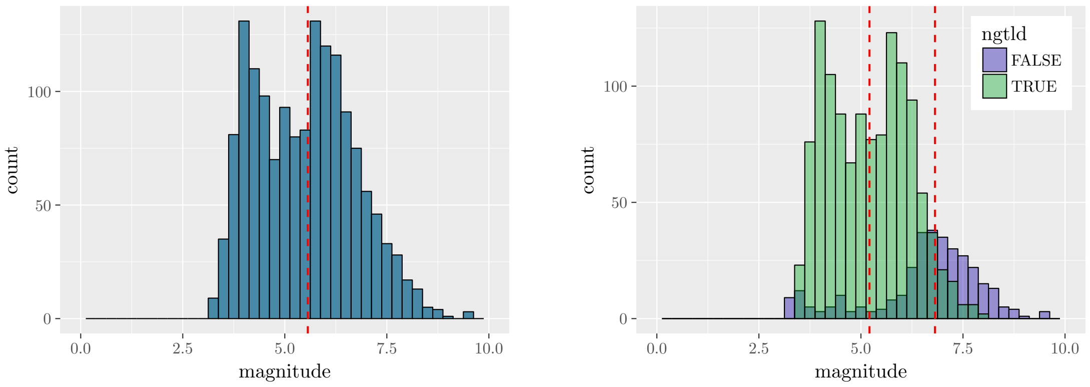
[3] Note that we include the root zone itself as well, even strictly speaking it does not constitute a "TLD"

[4] The whole file contains data for 169 507 root labels

Because a manual review of the data suggests a high concentration of new gTLDs in the bottom 50% of the scale, We initially suspect that bimodality to originate from the introduction of new gTLDs (as the Top 20 shown above contains exclusively ”legacy” TLDs). We split the histogram into two groups: TLDs introduced by ICANN’s new gTLD program (*”ngtld”*), and others (TLDs pre-dating the new gTLD program, and IDN ccTLDs) (*”legacy”*). The resulting distributions (see Figure 3b) refutes that hypothesis:

The *legacy* group exposes a relatively unimodal distribution - the slight peak of low-magnitude TLDs contains apparently unused IDN ccTLDs. The *ngtld* group itself shows a significant bimodality, indicating that this group itself contains two groups with disjoint magnitude values.

We conclude that neither group of domains is uniform, and both the *legacy* and *ngtld* groups contain sub-groups of ”busy” and ”idle” TLDs. We can show, however, that the *legacy* group exposes a higher median popularity than the *ngtld* group.



(a) Ungrouped Distribution

(b) Grouped: New gTLDs vs. legacy TLDs

Figure 3: Distribution of DNS Magnitude from August 30 2019 for delegated TLDs. Dashed red line reflects the median DNS Magnitude

8.3 Temporal Fluctuation of DNS Magnitude

As we calculate DNS Magnitude values for each TLD on a per-day basis, and the observation period spans several months, we can also investigate the fluctuation of the measurement values of each TLD over time. This investigation can be done fore each TLD’s DNS Magnitude values, but also for the Ranks (see Section 4.3) derived from those values. The observation period contained 153 days, so splitting the data by TLD yields a time series with 153 data points each for Magnitude and Rank. This allows us to inspect the stability of the DNS Magnitude values over time for each TLD.

We calculate the median DNS Magnitude for each TLD, and select the Top 20 TLDs to plot their daily DNS Magnitude values over time (See Figure 4).

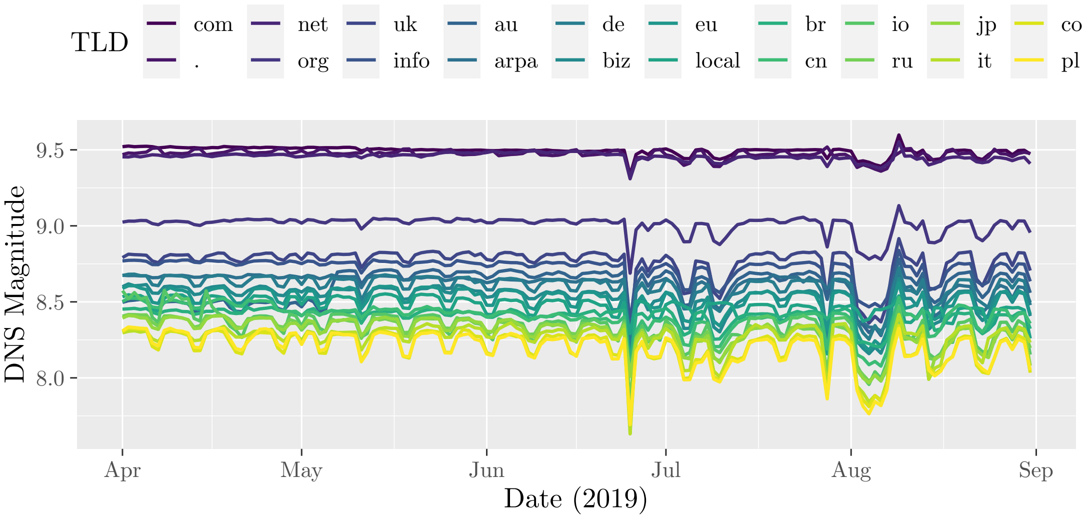


Figure 4: DNS Magnitude values of Top 20 TLDs over time

We observe that:

- DNS Magnitude values for those very busy TLDs are generally very stable over time, at least up to the last week of June.
- Values for some TLDs fluctuate weekly, exposing a visible difference between working days and weekends. This effect appears to be more pronounced in ccTLDs. Note that a similar effect is also visible for May 1st, which is a holiday in many countries.
- The period of instability of DNS Magnitude value (starting in last week of June) correlates with our observation of incomplete data (See section 7.2). We therefore assume that those fluctuations of DNS Magnitude are an effect of the incomplete data, rather than actual changes of popularity of the respective TLDs.

We also observe that in periods with missing data, absolute DNS Magnitude values are visibly lower. However, all TLDs in the chart appear to be affected to a similar degree, so differences between Magnitude values (and therefore Ranks) seem to be more stable than actual values.

To verify that assumption, we create a bump chart of Ranks of those same 20 TLDs (See figure 5). We do indeed observe that the periods of missing data are not immediately visible and the chart, and fluctuation of Ranks in such periods is much less affected than the fluctuation of actual values.

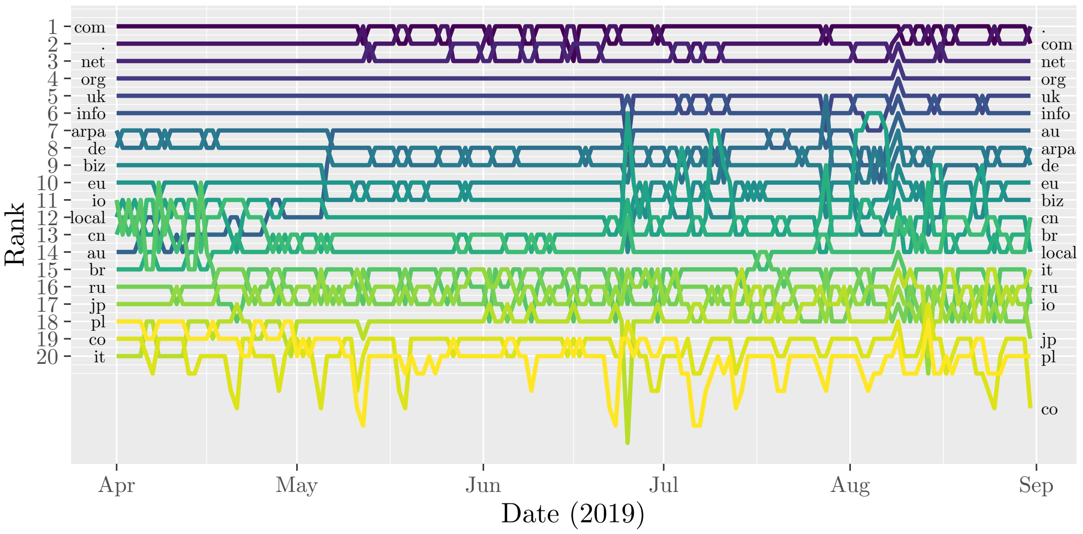


Figure 5: DNS Magnitude based Ranks of Top 20 TLDs over time

We therefore conclude that when there's risk of incomplete data, comparisons should be performed on a Rank basis, rather than actual DNS Magnitude values of individual Domains.

8.4 Prevalence of Non-Existing TLDs by DNS Magnitude Ranking

As described in section 8.1, even the list of top 20 TLDs (ranked by DNS Magnitude) contains a non-existant (invalid) TLD. This poses the question how those TLDs are distributed amongst a more extensive ranking list. More specifically, we are interested whether *.local* represents a notable exception amongst the busiest delegated TLDs, or whether nxTLDs are more prevalent amongst the top-ranking delegated TLDs.

We take the existing result file for 2019-08-30, and create bins of 200 TLDs, starting from the top ranked TLD. The first bin therefore contains TLDs with ranks #1 to #200, while the second bin contains TLDs ranked #201 to #400, etc. We count the number of delegated TLDs in each of the bins, and plot the results on a bar chart (see Figure 7). We initially truncate the chart to the top 5 000 TLD, in the naive believe that this would contain almost all delegated TLDs.

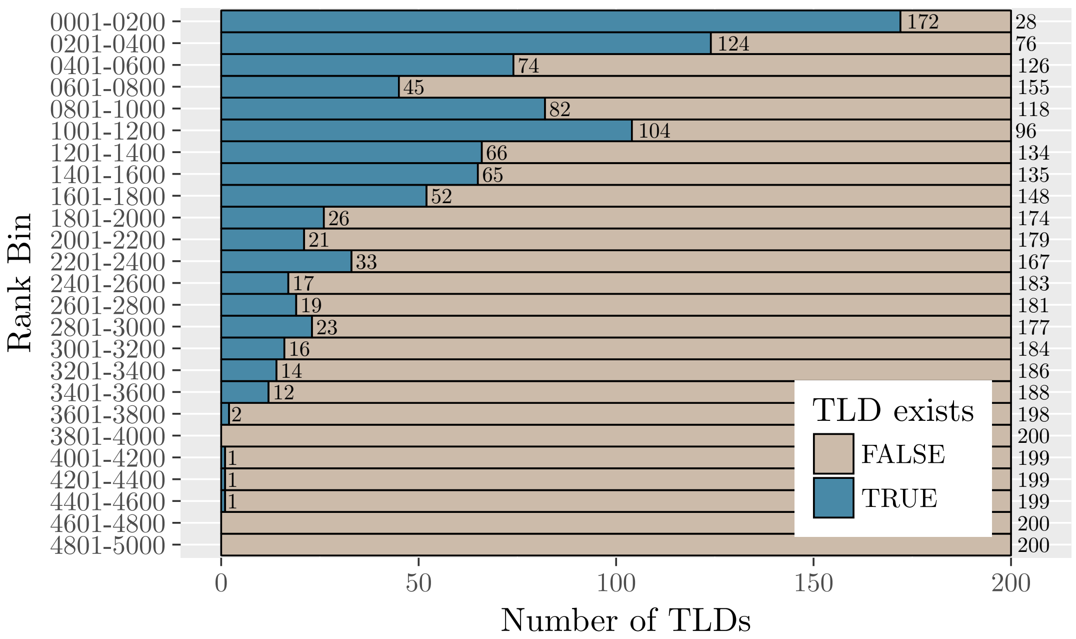


Figure 6: Number of delegated and non-existant TLDs by binned rankings

However, we find that only 970 out of the total 1 528 delegated TLDs are contained in the top 5 000 TLDs. Even the top 2000 TLDs are literally infested with 1 190 nxTLDs (59,5 %).

We therefore create another chart with a bin size of 5 000, representing the entire dataset. All 970 delegated TLDs represented in figure are hence contained in the first bin. The chart exposes a surprisingly long tail of TLDs with low-ranking DNS Magnitude values.

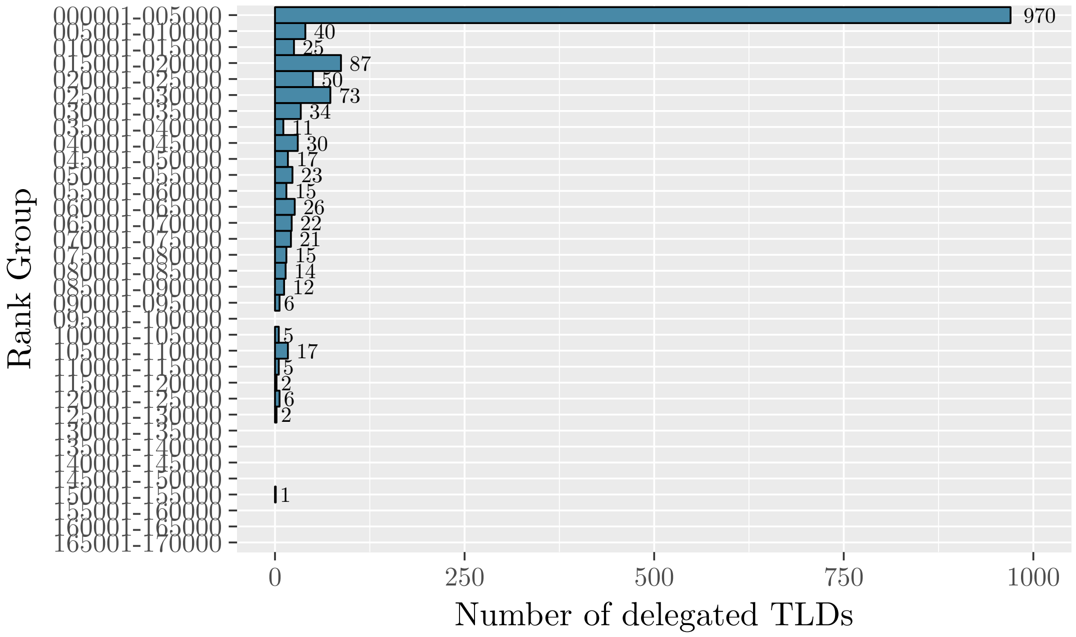


Figure 7: Number of delegated and non-existant TLDs by binned rankings

The IDN ccTLD *xn–mix891f* had the lowest DNS Magnitude value of all delegated TLDs on August 30 2019. It ranked 151 243 out 169 507 labels with at least 100 unique clients observed during that day. This means that on that day, there were 149 714 nxTLDs with a higher popularity than this specific delegated TLD. The position of that TLD was fairly constant during the observation period, Its rank fluctuated between 140 000 and 170 000.

8.5 A Deeper Dive into nxTLDs

In Section 8.4 we discussed the prevalence of nxTLDs amongst top-ranking labels. Because of this prevalence, we take a closer look at the properties of DNS Magnitude values of nxTLDs. To identify the top-ranking nxTLDs, we filter the daily DNS Magnitude result files for non-existing labels, and calculate the median of the DNS Magnitude values for each nxTLD across the observation period. Results truncated to the Top 20 ranking rows are included in Table 4. Besides the Rank amongst nxTLDs, the table also includes the ranking of each TLD in the full, unfiltered list of TLDs observed.

Rank	nxTLD	DNS Magnitude	Rank across all TLDs
1	local	8.48	12
2	localdomain	7.86	45
3	_ta-4f66	7.71	64
4	home	7.70	65
5	lan	7.65	71
6	tcs	7.56	81
7	gif	7.47	91
8	internal	7.41	105
9	invalid	7.41	106
10	com/	7.38	107
11	wpad	7.37	112
12	1	7.34	116
13	corp	7.29	125
14	null	7.28	130
15	1]	7.20	145
16	_tcp	7.15	155
17	com_1	7.07	164
18	2	7.06	177
19	loc	7.05	183
20	_msdcs	7.03	186

Table 4: Top-ranking 20 nxTLDs by DNS Magnitude

To understand whether popularity of nxTLDs fluctuates differently than that of delegated TLDs, we create a chart of daily DNS Magnitude values across the observation period for those 20 nxTLDs (See figure 8).

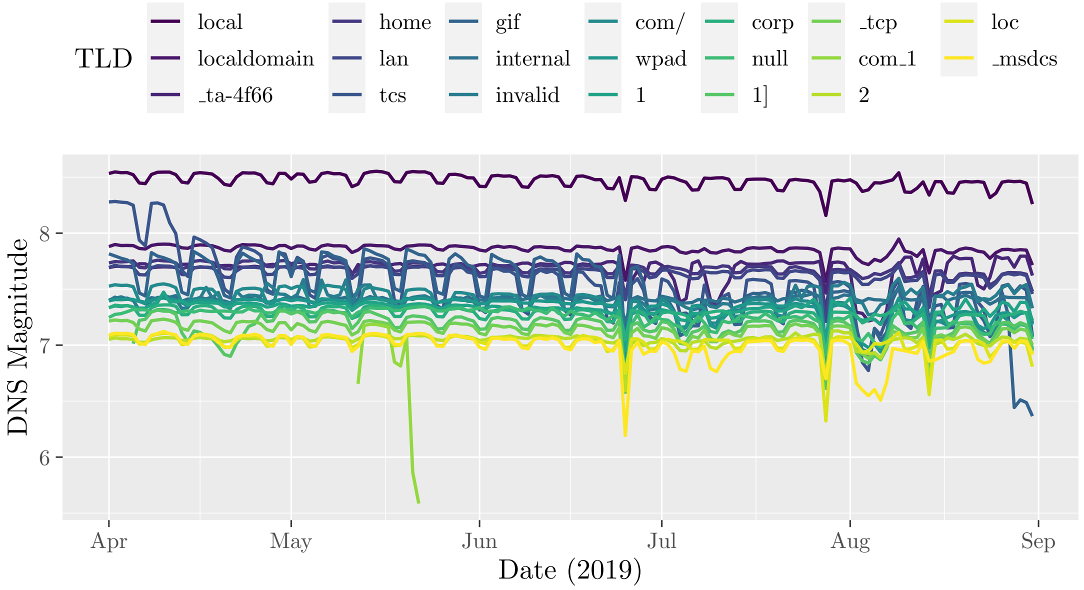


Figure 8: DNS Magnitude values of Top 20 nxTLDs over time

Comparing figure 8 with the similar figure 4 (containing the Top 20 TLDs, regardless of whether they exist or not) exposes a similar basic structure. However, some TLDs in the nxTLD chart appear to have a higher fluctuation in DNS Magnitude values.

8.5.1 nxTLDs with strong Fluctuation of DNS Magnitude Values

To identify the nxTLDs with stronger popularity fluctuation, we calculate the standard deviation of the DNS Magnitude value per nxTLD across the observation period (see Table **??**). We also extend the list of nxTLDs to the Top 70, as this includes more Domains with ”interesting” shape.

TLD	Standard deviation of DNS Magnitude value
com_1	0.56
gif	0.30
tcs	0.30
zervdns	0.28
***	0.23
adsl	0.18
com/	0.15
_ta-4f66	0.13

Table 5: nxTLDs with largest standard deviation in DNS Magnitude values

To inspect the fluctuation characteristics of those, we highlight the respective nxTLD in seperate plots, set against the whole array of 70 time series. Interestingly, even that small set of nxTLDs exposes very different shapes:

nxTLD ’com_1’ (see figure 9) suddenly jumps into the Top 70 nxTLDs around mid May, retains a fairly constant DNS Magnitude for about a week, and then drops back as quickly as it appeared. Because it appeared and disappeared so abruptly, we believe that this was a misconfiguration in a single popular service or software (or a small set thereof).

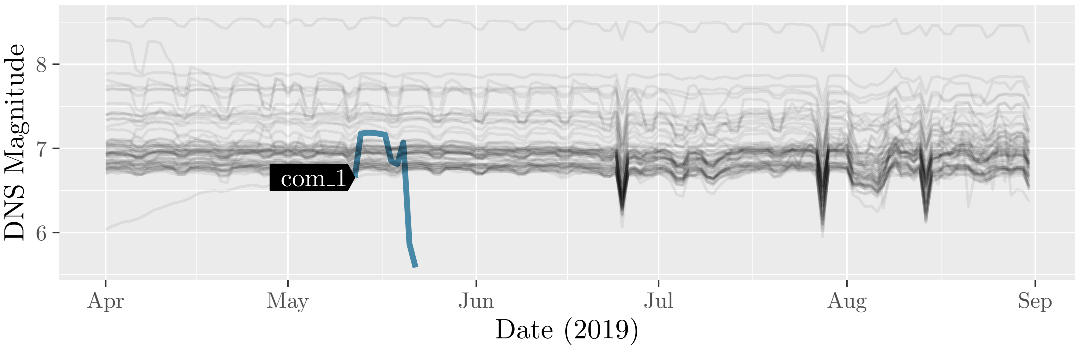


Figure 9: DNS Magnitude time series of 'com_1' nxTLD

nxTLD 'gif' (See Figure 10) has significant, constant popularity with a strong weekly periodicity. It appears to lose some of its popularity from the beginning of July, and then again in the last week of August. As the change in popularity roughly coincides with the start of the "incomplete data" period, we're cautious on any conclusions regarding the decrease of popularity. As "GIF" (Graphics Interchange Format) is a popular image format on the Web, our (unconfirmed) hypothesis is that the source of the queries for this nxTLD is incorrectly authored Uniform Resource Locators, creating host parts ending in ".gif".

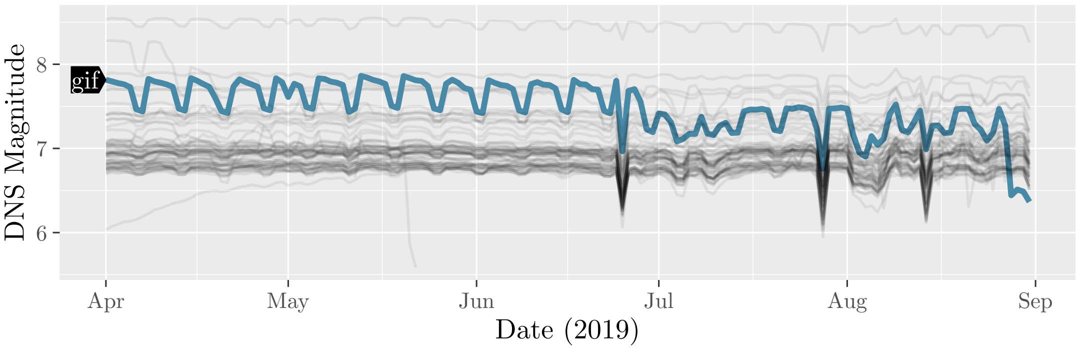


Figure 10: DNS Magnitude time series of 'gif' nxTLD

nxTLD 'tcs' (See Figure 11) exposes weekly periodicity that is similar to that of 'gif', but starts with a much higher initial DNS Magnitude. It does consistenly lose some of its popularity over time, and there's no noticable step at the beginning of the period of incomplete data. An uninformed web search for the string yields "Tata Consulting Services" as the first result (whose symbol on the New York Stock Exchange is also 'TCS'). Our (again unconfirmed) hypothesis here is that a potential source for queries for this nxTLDs could indeed be leaked internal queries from said enterprise. The string 'tcs' was not applied for under ICANN's new gTLD program in the 2011 round.

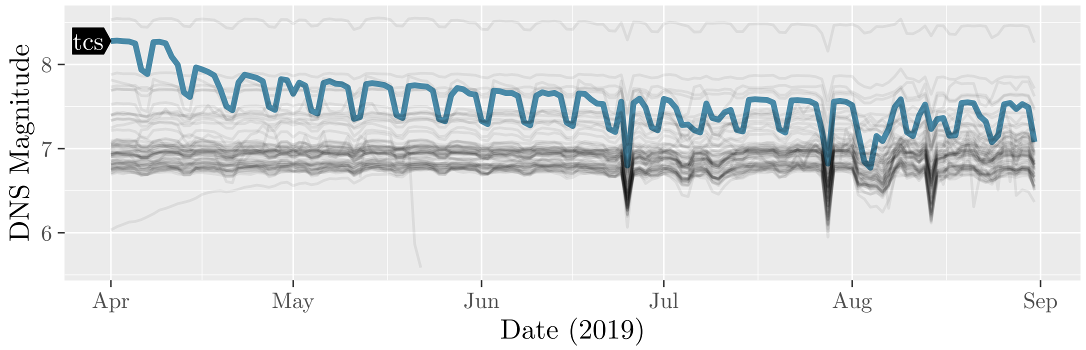


Figure 11: DNS Magnitude time series of 'tcs' nxTLD

nxTLD 'zervdns' (See Figure 12) suddenly appears with relatively high DNS Magnitude in the last week of July. Our hypothesis here is that the reason for these queries lies in incorrectly configured Pointer (PTR) records in some networks[5]. Subsequently, when servers receive traffic from those networks, and attempt to verify the reverse DNS by performing a correlating forward lookup, they trigger a query for said nxTLD.

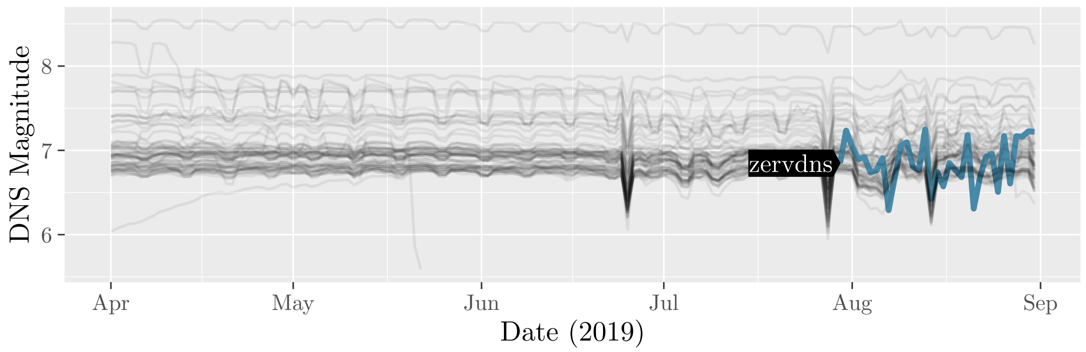


Figure 12: DNS Magnitude time series of 'zervdns' nxTLD

nxTLD '*'** (See Figure 13) steadily rises in DNS Magnitude value in the first month of the observation period, with a slower increase during the remaining month. We fail to come up with an hypothesis for the source of those queries, but can observe that the chart follows the weekend / workday pattern observed with other nxTLDs of similar Magnitude.

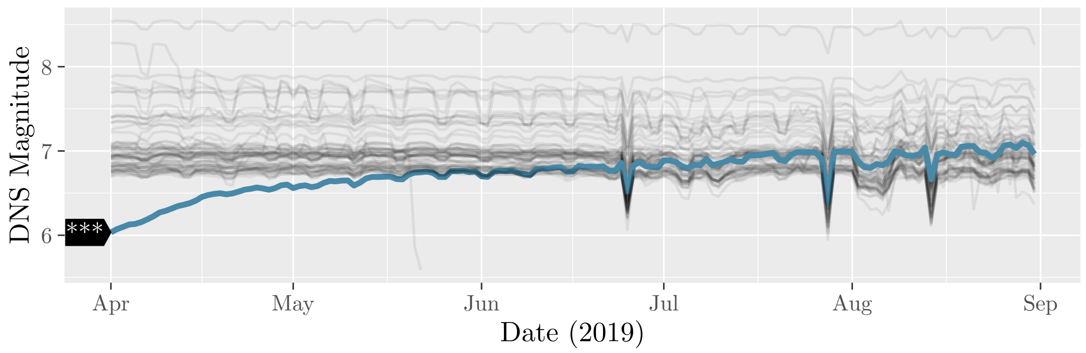


Figure 13: DNS Magnitude time series of '***' nxTLD

[5] For example, as of 2020-05-25, the PTR record for *22.38.118.92.in-addr.arpa.* resolves to *ip-38-22.ZervDNS.*

nxTLD 'adsl' (See Figure 14) does not expose a visible trend in DNS Magnitude, but varies for individual days in a pattern that looks more random than the common workday / weekend pattern. The source of those queries is unclear, though the name hints to some relation to end subscriber lines / customer premises equipment.

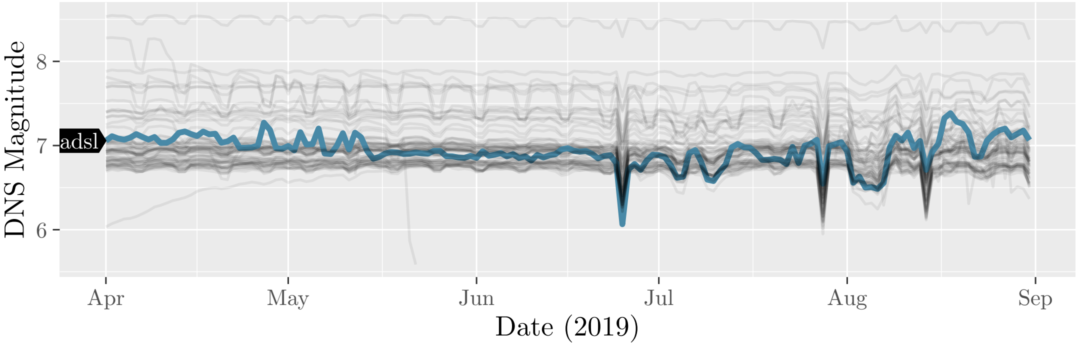


Figure 14: DNS Magnitude time series of 'adsl' nxTLD

nxTLD 'com/' (See Figure 15) exposes both a clearly visible workday / weekend pattern as well as a slight downward trend of Magnitude. Due to its similarity with the largest TLD 'com', the use of the character '/' in URLs, and its slight downward trend, our (unconfirmed) "best guess" for the reason for these queries is a malfunctioning client software that gradually gets partly replaced during the period of measurements.

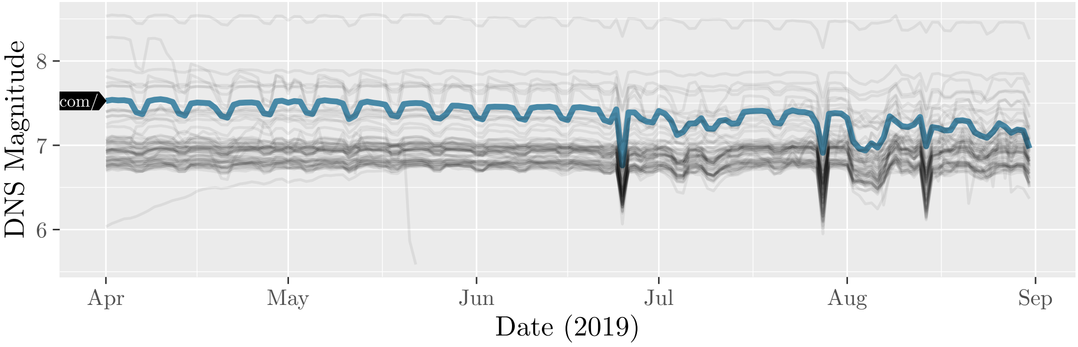


Figure 15: DNS Magnitude time series of 'com/' nxTLD

nxTLD '_ta-4f66' (See Figure 16) is a very special case amongst the discussed labels. The label is an effect of "Signaling Trust Anchor Knowledge in DNS Security Extensions" specified in RFC 8145 [26]. By means of that protocol, resolvers indicate the list of DNSSEC trust anchors they support to authoritative servers. For the measurement period with complete data (up to last week of june), the nxTLD has an almost constant DNS Magnitude value. We believe that this can be explained by the fact that queries for this label are created by resolvers automatically (rather than by user interaction with a service), and DNS Magnitude hence reflects the number of resolvers supporting this protocol, rather than the popularity of services. The fact that DNS Magnitude exposes very slight but regular upward weekend bumps indicates that more such resolvers are active on weekends than on working days.

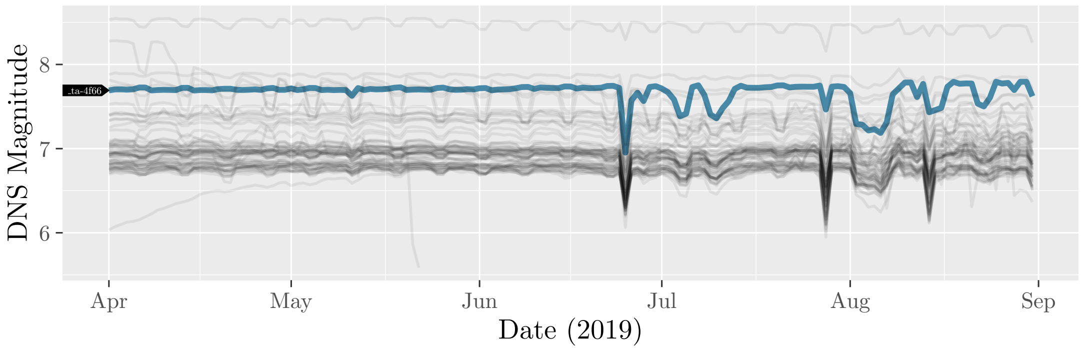


Figure 16: DNS Magnitude time series of '_ta-4f66' nxTLD

OPEN ISSUES: Conclusions are weak, references / bibliography is sluggish

8.5.2 Name Collision Management Framework 'High-Risk' Strings

Over the course of the first round of applications for new gTLDs in 2012 [11], there was concern about "Name Collision" between applied-for gTLD labels and existing use of those DNS names, for example by configuration of those names in local networks. Several studies were conducted (see "Name Collision in the DNS" [13] and "Mitigating the Risk of DNS Namespace Collisions" [2]), and the ICANN Board subsequently approved the "Name Collision Management Framework" [12], declaring "home", "corp" and "mail" as "high-risk strings" whose delegation should be deferred indefinitely.

These "high-risk" strings were primarily identified by their volume of DNS queries to the root. Even though about 6 years have passed between the reports and the data gathering for the DNS data for this paper, it is interesting to explore whether those strings still expose significant DNS Magnitude values.

Using the data created for Table 4, we extract the rows for the three strings Table **??** lists the Rank of those three nxTLDs across all nxTLDs as well as their overall rank (excluding the root itself). For illustration, the table furthermore includes name and DNS Magnitude of the delegated (existing) TLD with the popularity closest to the respective "high-risk" string. We see that there is still significant query traffic observed for these strings, comparable to that of medium-sized ccTLDs.

nxTLDs	Rank (nxTLDs)	DNS Magnitude	Rank (all strings)	comparable to
home	4	7.70	65	pt (7.70)
corp	13	7.29	125	ml (7.29)
mail	54	6.79	284	tm (6.79)

Table 6: Rankings of "High-Risk" gTLD application strings

When we plot the time series of DNS Magnitude values highlighted against the remaining Top 70 nxTLDs (See Figure 17), we observe that these TLDs are very stable across the observation period, expose no obvious general trend, and follow the working day / weekend pattern.

The Interisle report describes that, in 2013, the two strings "home" and "corp" *"occur with at least order-of-magnitude greater frequency than any others"* (See Page 4 of [13]). As many of the gTLD strings have been delegated and put into service in those 6 years, we set the "high-risk" strings against all applied-for gTLD strings (see Table 7).

While the data is not directly comparable (Interisle primarily used queries rather than unique clients in their study), we see that quite a few new gTLDs now exceed the popularity of the "high-risk" strings. As we have shown above, both "corp" and "home" expose stable popularity, so we assume that the reason that those strings have been "overtaken" meanwhile is mainly due to the rising popularity of the new gTLDs since their delegation, rather then the sinking popularity of the "high-risk" strings.

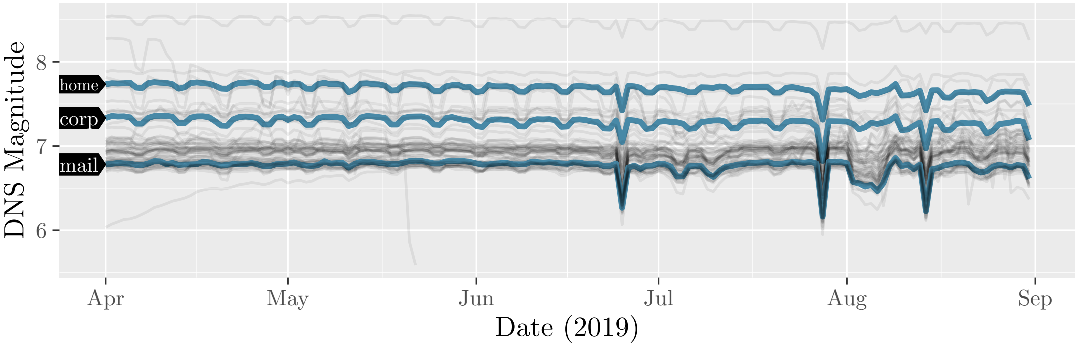


Figure 17: DNS Magnitude time series of home, corp, mail nxTLDs

Rank (across gTLD strings)	TLD	DNS Magnitude	Rank (all strings)
1	cloud	7.99	36
2	google	7.81	46
3	xyz	7.77	51
4	works	7.74	54
5	**home**	**7.70**	**65**
6	goog	7.68	67
7	tech	7.63	71
8	network	7.59	77
9	link	7.59	78
10	online	7.57	80
11	site	7.55	83
12	club	7.53	89
13	top	7.49	95
14	host	7.43	101
15	business	7.34	114
16	technology	7.33	117
17	media	7.31	123
18	**corp**	**7.29**	**125**
19	space	7.28	127
20	live	7.28	128
...	...	...	...
61	tools	6.80	278
62	**mail**	**6.79**	**284**
63	press	6.76	294

Table 7: Top-ranking gTLD strings by DNS Magnitude

We conclude that DNS Magnitude based exploration show that the "high-risk" strings identified in 2013 still carry significant (and stable) popularity similar to that of medium-sized ccTLDs or top-ranking new gTLDs. DNS Magnitude could therefore be a useful input into future similar assessments.

Also, the JAS Report includes in RECOMMENDATION 11 that some form of *"medium-latency, aggregated summary feed describing queries reachings the DNS root"* should be explored. We believe that for the reasons layed out in this document, per-TLD DNS Magnitude values could be a valuable component of such a summary feed.

8.5.3 ISO3166-1 User-Assigned Code Elements

The list of ISO3166-1 2-letter codes [17] forms the basis for the assignment of country code TLDs (ccTLDs). Out of the 676 two-letter combinations, 42 are "User-assigned code elements" ('aa', 'qm' to 'qz', 'xa' to 'xz', and 'zz'). These are not delegated in the root zone, and hence constitute nxTLDs.

In November 2019, Arends and Lewis published an Internet Draft [3] that proposes the use of those as strings for private internets ("Private TLDs"). A previous version of the draft recommended designating "zz" as a single private-use TLD, but the version current as of May 2020 proposes that any of them can be used by a network or application for private use.

While there is no risk that name collision may happen (due to the fact that those TLDs are not planned to be delegated), it is interesting to investigate the DNS Magnitude characteristics of these 42 strings at the root level.

We filter the Magnitude data across the observation period for the 42 user-assigned code elements, and calculate the median DNS Magnitude as well as its standard deviation. Using the data for all 676 ISO3166-1 code elements, we also assign a Rank amongst all 676 code elements for the 42 user-assigned values (see Table 9).

We observe that that the 4 most popular user-assigned values (in terms of DNS Magnitude) are those where first and second letter are identical. Our hypthesis is that these are more attractive to humans, and are therefore configured more frequently than other combinations. The least popular code is 'qv', which ranks 673 out of 676 possible combinations (only 'qj', 'vq', and 'zv' rank lower).

Figure 18 contains a plot of the time series of DNS Magnitude values of all 42 user-assigned code elements, with the TLDs 'aa' (as the most popular), 'qv' (as the least popular), and 'zz' (as the TLD poposed in the first version of the Arends & Lewis draft) highlighted. Many user-assigned strings (except the top-ranked) experience a notable upwards trend in Magnitude over the first three months of the observation period, though the reason for that is unclear. This appears to affect all proposed Private TLDs equally, as a plot of the Rank time series shows no visually obvious trends (See Figure 19).

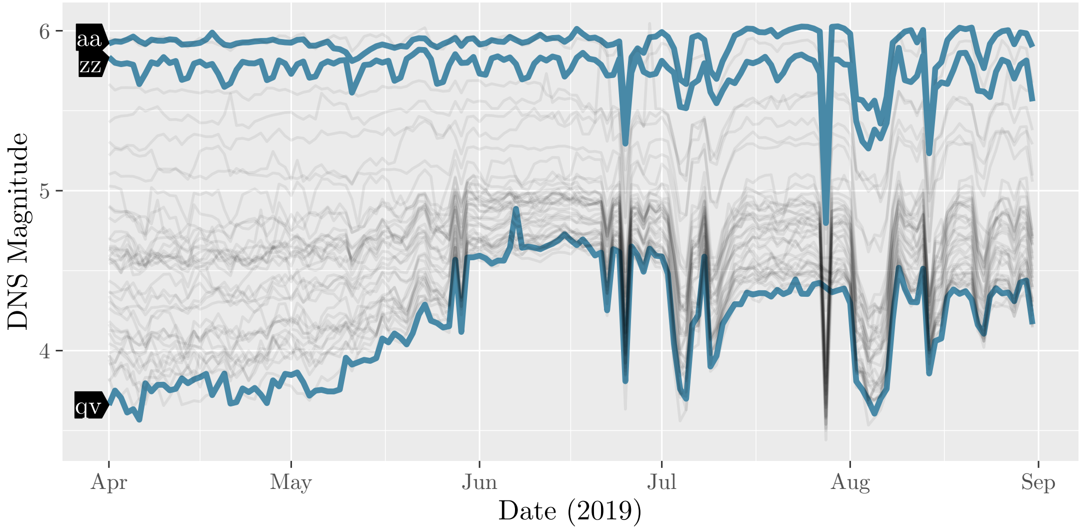


Figure 18: DNS Magnitude time series of ISO3166-1 User-assigned code elements

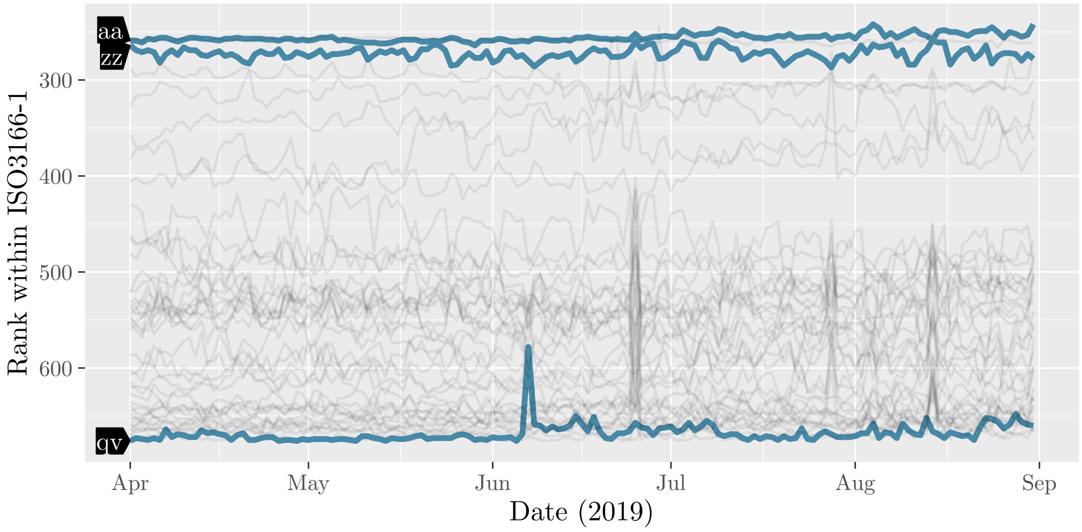


Figure 19: "Private Use" TLDs ranked amongst all ISO3166-1 strings

Further, we note that the user-assigned TLDs are almost perfectly segregated from the delegated ccTLDs. Across all 676 strings, Only 13 existing ccTLDs rank lower in terms of DNS Magnitude than the highest-ranking user-assigned ISO3166-1 string 'aa' (See Table 8).

We believe that the findings could be a valuable input to the decision whether or not the approach described in the Internet Draft shall proceed in standardization. If (and once) the draft proceeds, DNS Magnitude could be a tool to monitor adoption in the wild, and also assist in selecting a specific Private Use TLDs for certain applications.

ccTLD	DNS Magnitude	Rank across all ISO3166-1
er	5.87	261
gn	5.82	264
gf	5.82	265
aq	5.73	275
kp	5.70	282
mq	5.66	289
gu	5.63	293
ss	5.51	306
mh	5.48	310
gb	5.40	333
bv	5.24	377
sj	5.19	389

Table 8: ccTLDs with lower DNS Magnitude than the 'aa' TLD

8.6 From the Cradle to the Grave

Another interesting aspect of the root zone is that set of delegated TLDs is not static. While new TLDs historically have been added in severals waves to the root zone, the removal of a TLD from the root is a relatively novel and rare event. However, even the relatively short observation period of May 2019 to August 2019 includes several such events (and one addition - see Table 10):

TLD	date	event type
honeywell	2019-06-07	*removal*
bnl	2019-07-29	*removal*
starhub	2019-08-02	*removal*
iselect	2019-08-05	*removal*
gay	2019-08-09	*addition*
duns	2019-08-30	*removal*

Table 10: TLDs added and removed from the root zone during the observation period

Note that all TLDs listed above stem from ICANN's *New Generic Top-Level Domains Program* [**?**], and - with the exception of the *gay* TLD - they constitute "Brand" TLDs.

The interesting question here is whether these events - the "birth" and "death" of the TLD in the DNS - have any impact on on the DNS Magnitude of the respective TLD.

We therefore extract daily DNS Magnitude values for each of these TLDs, and inspect the resulting time series for discontinuities around the dates of their respective addition or removal events.

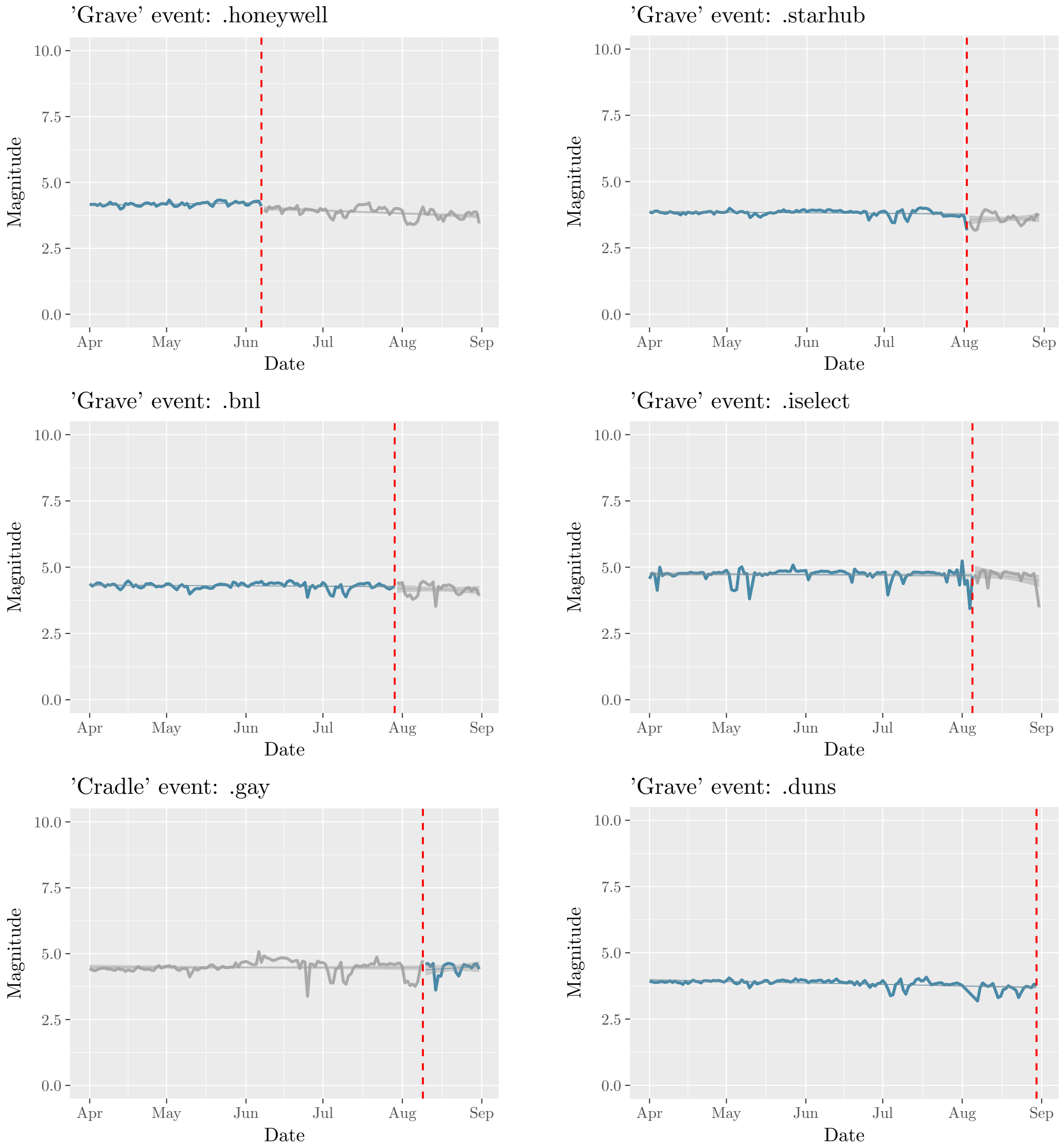


Figure 20: DNS Magnitude for TLDs added or removed from the root zone during observation period

We see that the introduction (or removal) of an (empty) TLD does not appear to significantly influence the DNS Magnitude of the respective TLD immediately. Although the data for the TLD *.honeywell* exposes a slight downward slope post removal, this effect is not apparent in the other TLDs. It might be attributed to the limited observation period, and therefore should be taken with a grain of salt.

The fact that the introduction of the TLD *.gay* into the root does not appear to increase its popularity (DNS Magnitude) immediately is surprising. Whether this effect is consistent with additions of other TLDs is - due to the limited observation period - unclear.

On the other hand, this suggests that DNS Magnitude indeed reflects the popularity of the services under a TLD, as the event of delegation of a fresh TLD (or the removal of empty, unused TLDs) does not significantly change the amount of services offered by that TLD.

8.7 Effects of IP Address Aggregation

DNS Magnitude uses client IP addresses as the basis of calculations. However, using the full address might not be desireable or possible: (a) Section 6.1 describes that aggregating addresses can be a countermeasure against artifically inflated numbers of unique clients by using IPv6 prefixes. Furthermore, (b) full IP addresses are considered Personally Identifyable Information (PII) in many legislations, and policies might require anonymization before DNS query logs can be analyzed. Aggregation of IP addresses to their prefixes is a well-known, accepted, and widespread measure of anonymization.

As aggregation of IP addresses into prefixes influences the number of observed unique clients, it influences DNS Magnitude calculations based on such aggregated data - both the total number of unique clients as well as the per-TLD count.

It is desirable that the effects of aggregation are minimal on the resulting DNS Magnitude values - in other words, that DNS Magnitudes are stable, irrespective of whether or not aggregation was performed. For the purpose of assessing the level of stability, we look at the following two metrics

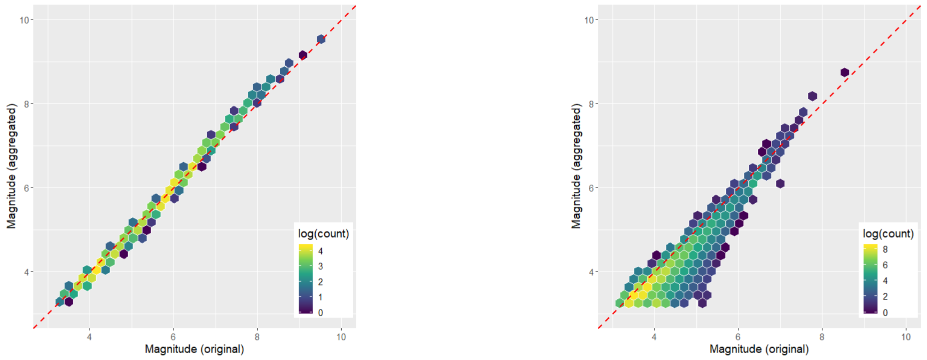
- The correlation between DNS Magnitude values based on unaggregated and aggregated versions of identical data
- The set stability of lists of TLDs ranked by their DNS Magnitude, again comparing results from unaggregated and aggregated versions of identical data

We investigate the effects using the data set d containing the L-Root traffic from a single day (2019-08-30). From that set, we create a derived aggregated data set $d' = agg(d)$ using the aggregation function $agg()$, which replaces each client IP address with its respective /24 (for IPv4) or /48 (IPv6) prefix. We then perform DNS Magnitude calculations for both data sets, and compare the resulting sets against each other.

We define M_{tld} as the DNS Magnitude of the TLD tld calculated from the full (unaggregated) data d, and M'_{tld} as the DNS Magnitude of the same TLD calculated from the aggregated data set $d' = agg(d)$.

Value based Correlation:

Looking at a two-dimensional density plot of M' versus M, we find that - again - delegated TLDs and nxTLDs appear to behave differently: Existing TLDs (see Figure 21a) expose a near-perfect correlation between M' and M (Pearson 0,998), while correlation is weaker for nxTLDs (see Figure 21b) witha Pearson correlation factor of 0,921.



(a) Density of existing TLDs

(b) Density of nxTLDs

Figure 21: Density chart of TLDs by DNS Magnitude values before and after aggregation

We therefore believe that (a) the impact of aggregation on actual DNS Magnitude values of existing TLDs is negligable (at least for this data set); and (b) that while the impact on the

DNS Magnitude values of nxTLDs is slightly bigger, aggregated data still provides an excellent approximation even for those data points.

Ranking Set Stability

DNS Magnitude values can be used to rank TLDs by their popularity. As aggregation affects the DNS Magnitude values of TLDs, it may also impact their position (rank) on popularity lists. We amend the information presented in Table 3 with DNS Magnitude and ranking information created from the aggregated data, and calculate the Ranking gain/loss as well as the difference in Magnitude (see Table 11).

We see that even in the Top 15 TLDs, aggregation does indeed shift rankings of 8 of the 15 TLDs. However, looking at the set stability, only 1 out of 15 TLDs dropped entirely from the Top 15 list (.br; new rank is 16) - and that entry was near the bottom of the original list. We repeat that analysis for larger Top lists (See Table 12):

	Set Size	Retained in set	Percentage	Median rank dropped
1	15	14	93,33 %	13
2	100	98	98 %	95
3	200	192	96 %	196.5
4	500	448	89,6 %	447
5	1000	932	93,2 %	932
6	2000	1848	92,4 %	1813.5
7	5000	4344	86,8 %	4220
8	10000	8738	87,38 %	7943

Table 12: Ranking set stability impact of IP Address aggregation on various set sizes

While we see that larger sets also have a smaller number of retained (stable) TLDs, the median of dropped TLDs shows that entries dropped are typically near the end of the list, while entries towards the top of the list might switch rankings, but rarely drop off the list entirely.

9 Limitations and further research

During the research and creation of the paper, we came up with many ideas and research questions which could not be answered in this paper, mainly due to lack of time, but sometimes also due to lack of data. This section summarizes some of those research questions for eventual further study.

- **Effects of 'Controlled Interruption'**: During ICANN's first round of the new gTLD program, a range of TLDs was subjected to 'Controlled Interruption' by adding a special wildcard A and AAAA resource record to the freshly delegated TLD for 90 days. The research question here would be whether that process affected the DNS Magnitude of the TLDs during the 90 day period.
- **DHCP-churn**: The formal definion of DNS magnitude assumed static IP addresses. While it can be argued that most recusors are static and hence DHCP churn does not influence DNS magnitude in the contexts of authoritative DNS servers, the same can not be claimed for recursive DNS servers. A large ISP's recursive DNS server might see the same host querying the same domain d multiple times (even though it might have changed IP address in the mean time). The question is: did our metric mis-calculate in this case? We have a strong belief that DNS magnitude will still work in these cases[6], this is something which should be explored and proven.

[6] Mainly because a host on dynamic IP address will appear in both the nominator as well as the denominator of the formula.

- **Calculations with DNS Magnitude values**: As DNS Magnitude relies on set cardinalities, merging of magnitude values (eg. single days to whole weeks) is not directly possible. While we believe that the mean or median of the values (as long as the context is identical) serves as a usefull approximation of the precise magnitude for the longer time interval, it would be interesting to empirically calculate the difference.
- **Correlation of TLD age and Popularity**]: While we explored the distribution of DNS Magnitude amongst *legacy* and *ngtld* groups seperately, this could not explain the bimodality of either group. Our hypothesis is that one factor in this bimodility is the age of the TLD. Other factors might include the fact whether a new gTLD is a "brand" TLD, or a TLD is a IDN ccTLD. The research question here is "What is the source of the bimodality in each of the groups?".
- **More "Cradle and Grave" events**: In addition to what is outlined above, it would be interesting to understand the impact of non-gTLD additions to the root. The recently added greek ccTLD for the European Union might be an interesting candidate, but it's delegation data was outside of the available data. Furthermore, a successful General Availabilty even (in terms of registration volume) of a new gTLD might also be an interesting event. For example, the .app GA event saw more than 200 000 registrations in a single week - but again, that event was outside of the study's observation period..
- **TTL values vs. query volume**: To the best of our knowledge, there's no broad study about the correlation of TTL values and the query volume of a domain seen at recursive and authoritatve servers. If such data would be available, the query volume could be normalized based on the findinds of the study, and used as a secondary popularity figure along with (or compared with) DNS Magnitude.

10 Conclusions

We presented *DNS magnitude*, a simpel but novel metric for estimating the popularity of a domain name d and its subdomains. DNS magnitude can be calculated in differnet *contexts* and within these contexts the magnitude values can be compared amongst each others. DNS magnitude can be used with DNS traffic of recursive name servers or authoritative name servers. It is resilient against different TTL settings of different domains and still accurately predicts the popularity of a domain name on a logarithmic scale. We analysed how DNS magnitude might be gamed (for example via spoofed IP addresses or IPv6) and how to deal with such manipulation attempts.

We also used the DNS magnitude metric in the context of L-Root Server traffic to calculate the importance of TLDs.

11 Acknowledgements

The study of the L-Root traffic and the creation of this paper was supported by ICANN Org's Office of the CTO. Roy Arends provided access to L-Root data, extensive advice and review during the creation of the paper.

Sebastian Castro initially inspired the work on DNS Magnitude. Michael Braunöder created the software to analyse L-Root traffic, and performed most of the data analysis work. Arsen Stasic from the University of Vienna provided historic root zone files.

References

[1] J. Abley and K. Lindqvist. Operation of Anycast Services. RFC 4786 (Best Current Practice), December 2006.

[2] JAS Global Advisors. Mitigating the risk of dns namespace collisions. https://www.icann.org/en/system/files/files/name-collision-mitigation-study-06jun14-en.pdf, 2014.

[3] Roy Arends and Ed Lewis. Top-level domains for private internets. Internet-Draft draft-arends-private-use-tld-01, IETF Secretariat, May 2020. http://www.ietf.org/internet-drafts/draft-arends-private-use-tld-01.txt.

[4] Internet Assigned Numbers Authority. Root servers.

[5] Internet Assigned Numbers Authority. Root zone database.

[6] Albert-Lszl Barabsi. *Linked: The New Science of Networks.* Perseus Books Group, 2002.

[7] Nevil Brownlee, Kimberly C Claffy, and Evi Nemeth. Dns measurements at a root server. In *GLOBECOM'01. IEEE Global Telecommunications Conference (Cat. No. 01CH37270)*, volume 3, pages 1672–1676. IEEE, 2001.

[8] Sebastian Castro. Domain popularity ranking revisited. https://www.centr.org/members-library/library/centr-event/r-d8-castro-domain-popularity-ranking-revisited-20160517.html, 2016.

[9] Xun Fan, John Heidemann, and Ramesh Govindan. Evaluating anycast in the domain name system. In *2013 Proceedings IEEE INFOCOM*, pages 1681–1689. IEEE, 2013.

[10] P. Ferguson and D. Senie. Network Ingress Filtering: Defeating Denial of Service Attacks which employ IP Source Address Spoofing. RFC 2827 (Best Current Practice), May 2000. Updated by RFC 3704.

[11] Internet Corporation for Assigned Names and Numbers. List of new gtld applications.

[12] Internet Corporation for Assigned Names and Numbers. Name collision occurence management framework. https://www.icann.org/en/system/files/files/name-collision-framework-30jul14-en.pdf, 2014.

[13] Interisle Consulting Group. Name collision in the dns. https://www.icann.org/en/system/files/files/name-collision-02aug13-en.pdf, 2013.

[14] P. Hoffman, A. Sullivan, and K. Fujiwara. DNS Terminology. RFC 8499 (Best Current Practice), January 2019.

[15] Alexander Holmes, Andrew Simpson, Karthik Shyamsunder, Srinivas Sunkara, Eyal Lanxner, Nir Zohar, Leonard Orentas, Matt Larson, Mark Kosters, Yona Mankin, et al. Domain popularity scoring, December 9 2014. US Patent 8,909,760.

[16] Dan hubbard. Cisco umbrella 1 million.

[17] ISO. *ISO 3166-1:1997: Codes for the representation of names of countries and their subdivisions — Part 1: Country codes.* 1997.

[18] Alexander Mayrhofer. Dns magnitude - another approach on domain name popularity. https://www.centr.org/members-library/library/centr-event/r-d9-mayrhofer-dns-magnitude-20161129.html, 2016.

[19] P.V. Mockapetris. Domain names - concepts and facilities. RFC 1034 (Internet Standard), November 1987. Updated by RFCs 1101, 1183, 1348, 1876, 1982, 2065, 2181, 2308, 2535, 4033, 4034, 4035, 4343, 4035, 4592, 5936, 8020, 8482.

[20] P.V. Mockapetris. Domain names - implementation and specification. RFC 1035 (Internet Standard), November 1987. Updated by RFCs 1101, 1183, 1348, 1876, 1982, 1995, 1996, 2065, 2136, 2181, 2137, 2308, 2535, 2673, 2845, 3425, 3658, 4033, 4034, 4035, 4343, 5936, 5966, 6604, 7766, 8482, 8490.

[21] Giovane C. M. Moura, John Heidemann, Moritz Müller, Ricardo de O. Schmidt, and Marco Davids. When the dike breaks: Dissecting DNS defenses during DDoS. In *Proceedings of the ACM Internet Measurement Conference*, October 2018.

[22] Sridhar Muppidi. How to use dns analytics to find the compromised domain in a billion dns queries, 2018.

[23] T. Narten, G. Huston, and L. Roberts. IPv6 Address Assignment to End Sites. RFC 6177 (Best Current Practice), March 2011.

[24] Root Server Operators. root-servers.org.

[25] Inc. Verisign. The domain name industry brief.

[26] D. Wessels, W. Kumari, and P. Hoffman. Signaling Trust Anchor Knowledge in DNS Security Extensions (DNSSEC). RFC 8145 (Proposed Standard), April 2017. Updated by RFC 8553.

	TLD	DNS Magnitude	Rank across all ISO3166-1	Standard Deviation
1	aa	5.93	257	0.14
2	xx	5.92	258	0.16
3	zz	5.79	272	0.14
4	qq	5.60	300	0.17
5	xy	5.50	307	0.16
6	xl	5.36	343	0.15
7	xn	5.26	369	0.20
8	qt	5.15	402	0.15
9	xp	5.02	445	0.25
10	xo	4.90	484	0.20
11	xm	4.89	486	0.20
12	xd	4.86	495	0.21
13	xi	4.80	512	0.20
14	xa	4.77	519	0.21
15	qu	4.77	520	0.22
16	xf	4.76	528	0.19
17	xz	4.74	532	0.22
18	xc	4.72	534	0.21
19	xu	4.71	542	0.19
20	qw	4.71	543	0.21
21	xv	4.69	548	0.23
22	xe	4.64	562	0.22
23	qr	4.63	566	0.23
24	xs	4.59	583	0.23
25	xh	4.56	596	0.23
26	xj	4.53	606	0.23
27	qs	4.49	618	0.25
28	xk	4.47	621	0.23
29	qm	4.43	635	0.27
30	xr	4.40	637	0.27
31	xt	4.36	644	0.26
32	qz	4.36	646	0.26
33	xq	4.34	649	0.26
34	xb	4.33	651	0.28
35	xw	4.33	654	0.28
36	xg	4.31	658	0.28
37	qp	4.29	659	0.29
38	qy	4.27	662	0.31
39	qx	4.26	664	0.30
40	qn	4.21	668	0.30
41	qo	4.20	670	0.34
42	qv	4.19	673	0.34

Table 9: DNS Magnitude data for the proposed ”Private TLD” strings

	TLD	Rank (full)	Rank (agg.)	gain/loss	Mag. (full)	Mag. (agg.)	Mag. Diff.
1	com	1	2	-1	9.50	9.58	0.09
2	.	2	1	1	9.48	9.59	0.10
3	net	3	3	0	9.45	9.52	0.07
4	org	4	4	0	9.03	9.19	0.16
5	uk	5	5	0	8.82	9.02	0.20
6	info	6	6	0	8.75	8.96	0.21
7	au	7	7	0	8.68	8.92	0.24
8	de	8	9	-1	8.64	8.84	0.21
9	arpa	9	8	1	8.59	8.84	0.25
10	eu	10	12	-2	8.56	8.75	0.20
11	biz	11	11	0	8.55	8.78	0.22
12	local	12	10	2	8.45	8.78	0.34
13	br	13	16	-3	8.43	8.59	0.16
14	cn	14	14	0	8.43	8.61	0.18
15	io	15	13	2	8.35	8.67	0.32

Table 11: Unaggregated / aggregated ranking comparion