Cache Me If You Can: Effects of DNS Time-to-Live (extended)

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ABSTRACT

DNS depends on extensive caching for good performance, and every DNS zone owner must set *Time-to-Live* (TTL) values to control their DNS caching. Today there is relatively little guidance backed by research about how to set TTLs, and operators must balance conflicting demands of caching against agility of configuration. Exactly how TTL value choices affect operational networks is quite challenging to understand due to interactions across the distributed DNS service, where resolvers receive TTLs in different ways (answers and hints), TTLs are specified in multiple places (zones and their parent's glue), and while DNS resolution must be security-aware. This paper provides the first careful evaluation of how these multiple, interacting factors affect the effective cache lifetimes of DNS records, and provides recommendations for how to configure DNS TTLs based on our findings. We provide recommendations in TTL choice for different situations, and for where they must be configured. We show that longer TTLs have significant promise in reducing latency, reducing it from 183 ms to 28.7 ms for one country-code TLD.

CCS CONCEPTS

• **Networks → Network measurement**; **Naming and addressing**.

KEYWORDS

DNS, recursive DNS servers, caching

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1 INTRODUCTION

The Domain Name System (DNS) [33] is a core component of the Internet. Every web page and e-mail message requires DNS information, and a complex web page can easily require information from a dozen or more DNS lookups. The DNS provides a low-latency, distributed database that is used to map domain names to IP addresses, perform service location lookups, link distributed portions of the DNS together, including in-protocol integrity protection using in-protocol DNS key storage, linking and verification algorithms.

With this central position, often serving as the initial transaction for every network connection, it is not surprising that DNS performance and reliability is critical. For example, DNS performance is seen as a component of web browsing that must be optimized (for example, [50]), and DNS services providers compete to provide consistent, low-latency services around the world. Even in less-latency sensitive services, such as the authoritative service for the Root DNS, reducing latency is still a desired goal [47]. DNS *must* always work, and failures of major DNS resolution systems frequently makes public newspaper headlines. In 2016, when a Distributed Denial-of-Service (DDoS) attack led to problems at a DNS provider, it resulted in disruptions to multiple popular public services (including Github, Twitter, Netflix, and the New York Times) [41].

DNS is also often used to associate clients with near-by servers by large content providers [10] and in Content-Delivery Networks (CDNs) [12]. In this role, DNS helps both performance and reliability, associating clients to nearby sites [47, 54], and implementing load balancing, both to reduce latency, and to control traffic to support site maintenance and react to DDoS attacks [36].

It is not surprising that DNS has developed a complex infrastructure, with client software (the *stub resolver*, provided by OS libraries) that contacts *recursive resolvers* (a type of DNS server that can iterate through the DNS tree for answers), which in turn contact *authoritative servers* (which hold the answers being sought). Large-scale recursive and authoritative resolvers are often carefully engineered, with pools of servers operating behind load balancers, sometimes in multiple layers [48], often employing IP anycast [1].

Caching is the cornerstone of good DNS performance and reliability. A 15 ms response to a new DNS query is fast, but a 1 ms cache hit to a repeat query is far faster. Caching also protects users from short outages and can mute even significant DDoS attacks [36].

Time-To-Live values (TTLs) of DNS records control cache durations [33, 34] and, therefore, affect latency, resilience, and the role of DNS in CDN server selection. While caching DNS servers and anycast have been extensively studied, surprisingly, *to date there has been little evaluation of TTLs.* Some early work modeled caches as a function of their TTLs [26], and recent work examined their interaction with DNS [36], but no research provides *recommendations* about what TTL values are good.

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Determining good TTL values for DNS is surprisingly challenging. A fundamental tension exists between short and longer TTL values. Short TTLs allow operators to change services quickly, as part of regular operation for load balancing in CDNs, or perhaps to redirect traffic through a DDoS scrubber. Yet, long TTLs reduce latency seen by clients, reduce server load, and provide resilience against longer DDoS attacks.

Not only is there no "easy" optimal setting, but performance of modern DNS (with its effects on web browsing) is affected by *many* TTLs, since full resolution of a DNS name may require dozens of lookups across several organizations, all potentially using different TTLs. As a distributed database, TTLs are given in both the parent and child at a delegation boundary, and these may differ. In addition, responses come in different flavors, with some values labeled as authoritative, and others labeled as hints ("additional"). Finally, DNS records sometimes depend on the freshness of other records, which can be used as the basis of multiple points of attack. These concerns have been exploited as part of sophisticated DNS hijacking to open user accounts [28].

While there has be some study of what clients see (§7), there has been only limited academic study of operator options and their effects. Since operational requirements vary and choices are affected by components run by multiple parties, it is not surprising that, to our knowledge, *there is no operational consensus for what TTL values are reasonable.* Lack of consensus and an operational preference for "if it ain't broke, don't fix it", results in a large range of values in practice (§5), and offers new deployments limited guidance for choosing TTLs.

The goal of this paper is to fill this gap. First, we explore how these many factors influence what TTL is used by recursive resolvers (§2). Second, we provide recommendations about good TTL values to zone operators for different scenarios, in light of user experience and resilience. Our work complements prior work that studied how recursive resolvers handle caching (see §7). We use both controlled experiments and analysis of real-world data to make informed recommendations to operators.

Our first contribution shows what the *effective TTL* is as a result of TTLs stored in different places (§3) across multiple, cooperating records (§4). Second, we examine real-world DNS traffic and deployments to see how current use compares to our evaluation, and how operators choose TTL values and how their choices between short and long TTLs affect latency and operator flexibility (§5).

Finally, we show that DNS TTLs matter, since longer TTLs allow caching, reducing latency and traffic (§6.2). We outline the tradeoffs and provide recommendations (§6): those using CDNs or load balancers may require short TTLs (5 or 15 minutes), but most others should prefer longer TTLs (a few hours).

Discussion of our early results with operators prompted increase in their TTLs, and we show that the median latency drops from 183 ms with their earlier short TTLs, to only 28.7 ms now that longer TTLs enable better caching. While these specific results are from one ccTLD (`.uy`, §5.3), our crawls (§5.1) and discussion with operators (§5.2) suggest our results apply elsewhere.

We will make the majority of datasets available at no charge. Ripe Atlas datasets are public, and only data from `.nl` cannot be released. Our measurements are all about public network infrastructure and pose no ethical or privacy issues.

2 OUR QUESTION: WHICH TTLS MATTER?

DNS caching appears simple, with each record cached up to a given time-to-live. However, the reality is more complex: DNS records come from several places and resolution requires traversing multiple names and types. We next look systematically at each source of information and determine which, in practice, takes priority.

First, *records are duplicated in multiple places*, sometimes with different TTLs. Specifically, DNS records that cross delegation boundaries are in both the parent and the child zone and can have different TTLs. In §3 we examine if recursives in the wild prefer TTL values provided by the parent or child.

Second, *resolution of a fully qualified domain name (FQDN) requires identifying authoritative servers (NS records) and their IP addresses (A or AAAA records) for each part of the FQDN*. FQDN traversal raises two factors. First, communicating with an authoritative server requires knowing its IP address(es), but the NS and A/AAAA records for it may also have different TTLs. Second, records for it may be *in bailiwick* (when they are under the domain being served, so `ns.example.org` is in bailiwick of `example.org` [22]) or *out of bailiwick* (`ns.example.com` would not be in bailiwick of `example.org`). These factors interact: some recursive resolvers discard in-bailiwick A/AAAA records when the NS record expires, as we show in §4.

The answer to these questions should be given in the DNS specifications. Unfortunately early specifications were somewhat informal, and implementations varied in practice. The original DNS specifications left precedence unspecified [33, 34], while RFC2181 later gave the child zone's Authoritative Answers priority over the parent's glue [15], but did not require that both be fetched. DNSSEC [6, 7] confirms that authoritative TTL values must be enclosed in and verified by the signature record, which must come from the child zone. Thus our question is: *Do resolvers in the wild follow these specifications for TTL priorities?*

Answering these questions is also important to understand *who ultimately controls a zone's caching.*

3 ARE RESOLVERS PARENT- OR CHILD-CENTRIC?

We first examine how DNS handles *records that are served from multiple places*, to determine what controls caching. The DNS is a distributed database with portions of the hierarchy (*zones*) managed by different organizations through *delegation. Glue records* duplicate content from a child zone in the parent, either for convenience or out of necessity, if the authoritative server for the child zone is named only in that child's zone (*in-bailiwick*). A recursive resolver much choose which TTL it prefers (parent or child) based on several factors described below in §3.1.

We examine this question with a case-study and wild traffic observed from the edge and from authoritative servers for a country code TLD. We reach two key results of cross-zone TTLs: first, **most recursive resolvers are child-centric**, trusting the TTL in the child zone's authoritative server over the glue in the parent zone. Depending on the measurement technique, just 52% (§3.4, `.nl` from the authoritative) to 90% (§3.2, `.uy` from RIPE Atlas) of queries are child-centric.

Our second finding is that **enough queries are parent-centric, so parent TTLs still matter**. Although only 10 to 48% of queries are parent-centric, one *must* set TTLs the same in both parent and

Q / Type	Server	Response	TTL	Sec.
.cl / NS	k.root-servers.net	a.nic.cl/NS	172800	Auth.
		a.nic.cl/A	172800	Add.
		a.nic.cl/AAAA	172800	Add.
.cl/NS	a.nic.cl	a.nic.cl/NS	3600★	Ans.
		a.nic.cl/A	43200	Add.
		a.nic.cl/AAAA	43200	Add.
a.nic.cl/A	a.nic.cl	190.124.27.10/A	43200★	Ans.

Table 1: a.nic.cl. TTL values in parent and child (★ indicates an authoritative answer), on 2019-02-12.

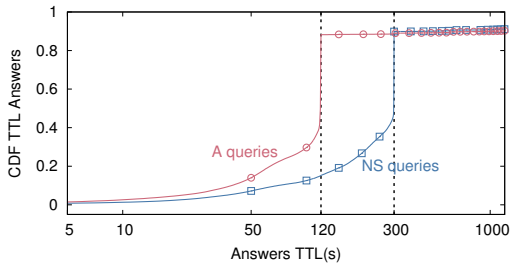


Figure 1: TTLs from VPs for .uy-NS and a.nic.uy-A queries.

child to accommodate this sizable minority. In cases where operator is *without control of the parent zone's TTL, resolvers will see a mix of TTLs for that zone.*

3.1 Parent and Child TTLs in Chile's .cl

To explore this question of whether the parent or child's TTL in the hierarchy is "believed more frequently", we first look at Chile's country-code TLD, .cl. Resolving this name involves three authoritative servers as shown in Table 1.

We see three *different* TTLs: 172800 s (48 hours) for NS and address records at the root, 3600 and 43200 s (1 and 12 hours) at the .cl authoritative servers, and 43200 s when we explicitly ask the name server itself for its own address record. Which TTL is used depends on the implementation of the recursive resolver; although RFC2181 [15] specifies the client's TTL should take priority, but it does not require recursive resolvers to actively fetch that value.

A second factor is that response components are returned in different DNS message sections [33], and may be treated differently by different implementations. Records are marked *authoritative* (.cl's NS record at the root), as *answer* (.cl's NS record at .cl), or *additional* (A records attached to the NS response at .cl).

Answers from the child have higher priority when the Authoritative Answer flag (AA flag) is set, though when a server resolves the domain example.cl, it may choose to never contact the child and instead may use the authority and additional records returned by the parent. (For example, to resolve example.cl, a resolver can use the A record of a.nic.cl as provided by the Roots in Table 1.) This question has been previously defined as resolvers' centricity [13, 17, 18, 42]: resolvers using the TTL provided by the parent authoritative (such as the Roots for .cl) servers are defined as *parent-centric*, while *child-centric* resolvers will use the child authoritative Original DNS specifications were unclear on which to prefer, and RFC2181 clarified child records (and their TTLs) as higher priority, but did not require resolvers to query for them [15]. Only DNSSEC validation requires fetching records from the child zone, but DNSSEC validating resolver deployment is incomplete today.

Resolvers employing in-resolver authoritative mirroring technologies, such as RFC7706 [29] or LocalRoot [20], or serving stale content [30] (*i.e.,* answering queries past TTL expiration only when the NS records for the given domain are unresponsive) will exhibit different perceived TTL caching behaviors. In the former case, resolvers implementing RFC7706 or LocalRoot, entire zones will be transferred into a pseudo-authoritative server that runs in parallel with a recursive resolver; no queries to these zones will likely be seen exiting the recursive resolver [20], though questions to their children will still be sent. For the latter case, resolvers serving stale content, outgoing requests will likely continue to be seen on the wire, but even when unanswered, resolvers will continue serving (expired) answers to clients.

This example illustrates the complexity of the TTLs used by different implementations. We next look at how these rules work in practice.

3.2 TTLs as Seen in the Wild with Uruguay's .uy top-level domain

We next consider Uruguay's country-code TLD .uy. We select Uruguay because it's ccTLD has two very different TTL values in its NS record: 172800 s at the root, and only 300 s in their own authoritative server (as of 2019-02-14), and 120 s for that server's A record.

These large differences allow us to study their effects on caching from "the wild". We use RIPE Atlas [44, 45], measuring each unique resolver as seen from their ~10k probes physically distributed around the world. Atlas Probes are distributed across 3.3k ASes, with about one third hosting multiple *vantage points* (VPs). Many Atlas probes have multiple recursive resolvers, sometimes at different locations, so we treat each combination of probe and unique recursive resolver as a VP, since potentially each represents a different perspective. We therefore see about 15k VPs from about 9k Atlas Probes, with the exact number varying by experiment to do small changes in probe and resolver availability. This definition of VP provides a dynamic view of what resolvers Atlas is using; it has some overlap, due to Atlas probes that share resolvers, and changes over time, due to complex recursive infrastructure [48]. It is also affected by non-uniform distribution of RIPE Atlas probes [9]; we report latency by region in Figure 10b to account for this distribution.

We make queries first for the NS record of .uy, then the A records of its authoritative server a.nic.uy. In each case, we query from each VP every 10 minutes (twice the shortest TTL of the NS records), for either two or three hours (for the NS or A records). For each query, we look for the TTL as seen in the answer section of the DNS response, obtaining about 190k and 280k valid responses from .uy-NS and a.nic.uy-A experiments, respectively. Table 2 summarizes the experiments (we disregard responses that did not return the answers we expected, typically from probes with hijacked DNS traffic [35]).

	.uy-NS	a.nic.uy-A	google.co-NS	.uy-NS-new
Frequency	600s	600s	600s	600
Duration	2h	3h	1h	2h
Query	NS .uy	A a.nic.uy	NS google.co	NS .uy
TTL Parent	172800 s	172800 s	900 s	172800 s
TTL Child	300 s	120 s	345600 s	86,400
Date	20190214	20190215	20190304	20190304
Probes	8963	8974	9127	8682
valid	8863	8882	9034	8536
disc	100	92	93	96
VPs	15722	15845	16078	15325
Queries	189506	285555	97213	184243
Responses	188307	282001	96602	184243
valid	188225	281931	96589	184209
disc.	82	70	3	34

Table 2: Resolver's centricity experiments. Datasets available at [43].

Figure 1 shows the CDF of the valid TTLs from all VPs for .uy. Even though previous studies have shown that DNS TTLs are sometimes manipulated by resolvers [48], we found that such manipulation is very rare for TTLs shorter than 1h, at least as seen from RIPE Atlas VPs [36]. (These results are also not affected by recursive resolvers, shared, split, or existing caches, since our query intervals are longer than the TTLs: 600 s vs 120 s and 300 s.)

As such, the vast majority of responses in Figure 1 follow the child's value, not the parent's: 90% of .uy-NS are less than 300 s, and 88% of a.nic.uy-A are less than 120 s. We conclude that most resolvers are *child-centric*, preferring the TTL of the authoritative server (following RFC2181 §5.4.1 [15]).

Roughly 10% of resolvers appear to be *parent-centric*, following the 2-day TTL of the root zone (or these resolvers are manipulating TTLs [19, 36]). In fact, about 2.9% of .uy-NS and 2.2% of a.nic.uy-A show the full 172800 s TTL. Some of these resolvers include probes using the OpenDNS public resolvers [39]. Later queries sent to these resolvers confirm they are parent-centric for domains in the Root zone (likely implementing RFC7706 [29]), and when the child delegation's authoritative name server is unreachable (§4.4).

Besides, we also found only one VP that had TTL values larger than the parent delegation.

3.3 A Second-level Domain in the Wild

To confirm our observations that client-centric TTL preferences extend past top-level domains (RFC7706 does not apply to second-level domains [29]), we repeat the experiment from §3.2 for google.co, which is a popular second-level domain (SLD). The domain google.co has two TTL values for its NS records: 900 s from the parent servers (.co), and 345600 from the actual authoritative servers ns[1-4].google.com (as of 2019-03-05). We query every 600 s, for one hour (Table 2).

Figure 2 shows the CDF of observed TTLs for this second-level domain, for 16k VPs. About 70% of all answers have TTLs longer than 900 s—results that must come from the child authoritative server. About 15% of all answers, many using Google public DNS, have TTLs of 21,599 s, suggesting TTL capping. About 9% of all answers have a TTL of exactly 900 s, suggesting a fresh value from the parent authoritative server.

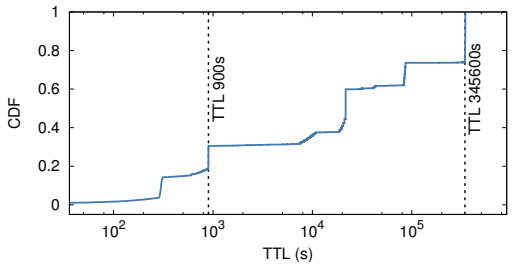


Figure 2: TTLs from VPs for .google.co-NS queries.

This experiment shows that resolvers querying second-level domains, are similar to those querying TLDs, most choosing child-centric TTLs.

3.4 Confirming Client-Centricity with Passive Observations of .nl TLD

Prior sections showed that specific domains are mostly client-centric, observing from the authoritative side, looking at *who is querying* and *what strategy they use* (parent- or child-centric). Here we study passive data for the the Netherlands zone, .nl, with about 5.8 million domain names in its zone [49].

At the time of this experiment (2019-03-06 to -07), the .nl ccTLD had four authoritative servers (sns-pb.isc.org and ns[1-3].dns.nl), each with multiple IP anycast sites [1]. We gather DNS data from ns[1,3].dns.nl servers using ENTRADA [57], which saw more than 6.5M queries for the two-day period. The ns[1,3].dns.nl A records are listed in the parent zone (the root zone) with glue records containing TTL values of 172800 s (2 days). The children's authoritative servers, however, contain only a 3600 s (1 hour) TTL for the same A records.

We examine query interarrivals for each resolver to classify that resolver as parent- or child centric. We find about 205k unique resolver IP addresses, providing 13× more VPs than our experiment using RIPE Atlas (§3.2 and §3.3).

We see 368k groups of *resolver, query-name* pairs, in which *query-name* is one of the four NS records for .nl pairs, and we compute the interarrival time between queries for each group. (In §3.2 we considered client-side VPs; here instead our authority-side considers resolvers instead of Atlas probes, and pairs them with query names since different records may have different TTLs in the cache.)

Figure 3 shows the CDF of the number of queries for each group for the aggregate queries (the solid blue "all" line), and for those queries where the interarrival time is more than 2 s (the red "filtered" line). This filtering aims at removing duplicate queries that are retransmissions, but we see that the curves are essentially identical.

More than half of the groups appear to be child-centric, since 52% send more than one query over the two days, suggesting they are following the shorter child TTL. Another possible explanation is that some recursive resolvers cap TTLs to less than 2 days (some versions of BIND [25], however, use one week as the default maximum caching time).

Just less than half (about 48%) send only one query during observation. Since we only observe two of the four authoritative servers, it is possible these resolvers made queries to non-observed

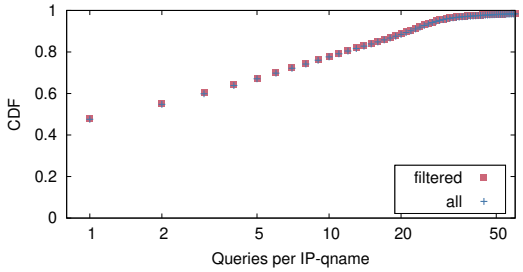


Figure 3: CDF of A queries per resolver/query name.

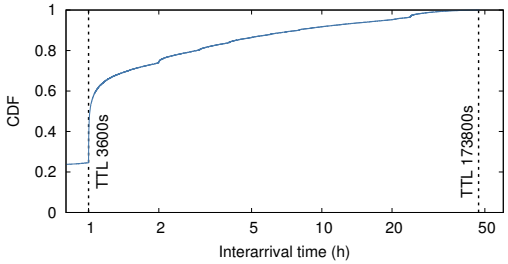


Figure 4: CDF of minimum interarrival time of A queries from each resolver/query-name.

authoritative servers. (It is known that resolvers tend to rotate between authoritative servers [37]). Another possibility is that these resolvers did not need to handle multiple queries for names under `.nl`.

To investigate if these resolvers, which sent only one query per query-name, are indeed parent-centric, we extract the unique source IPs from the groups that sent only one query; which gives us 122562 unique IP addresses. Around 14% of these IPs are also present in groups that sent more than one query for other names. For example, an IP that queries once for `ns1.dns.nl`, but queries 3 times for `ns2.dns.nl`. This suggests that at least 14% of the resolvers in this group behave as child centric as well.

We gain greater confidence how many resolvers are child-centric by looking at the minimum interarrival time for resolvers that send multiple queries for the same name in Figure 4. Even observing only two of the four authoritatives, we can conclude that most resolvers use the child TTL. We also see "bumps" around multiples of one hour. We believe that these bumps are resolvers returning to the same server after the TTL expires.

We conclude that, even when observed from the authoritatives, at least half recursive resolvers are child-centric.

4 THE MANY TTLS IN RESOLVING A FULLY-QUALIFIED DOMAIN-NAME

We next turn to the second problem from §2: how do the different parts of a FQDN, records (NS and A or AAAA), answer types (authoritative answer, authority, and additional), and server configurations (in and out-of-bailiwick) interact to influence the *effective* TTL lifetime of the originating request? Again, our goal is to understand *which* TTL or TTLs control caching.

We see which depend on each other through two controlled experiments: one with an in-bailiwick server, `ns1cachetest.net`, and

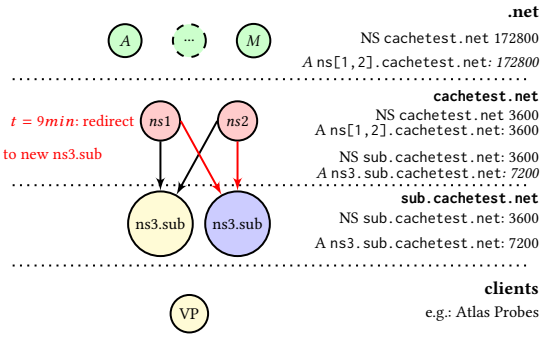


Figure 5: TTLs and domains for in-bailiwick experiment [43]. Italics indicate glue records.

the other with an out-of-bailiwick server. (We run these experiments on different days to avoid interference.)

The key results of this section are to show that it does matter where the authoritative server is located in the DNS hierarchy. For **in-bailiwick authoritative servers glue records drive cache lifetimes**, and the TTLs of the IP address and authoritative server are frequently linked (a still valid A record will still expire when its covering NS record expires). By contrast, **out-of-bailiwick servers use cached information about authoritative servers for the full TTL lifetime**.

4.1 Experimental Setup

Our experiments use a test domain (`cachetest.net`, from [36]) over which we have complete control. This domain has two authoritative servers: `ns[1,2]cachetest.net`, as can be seen in Figure 5, both running Debian and BIND 9.1 on EC2 in Frankfurt, Germany.

We add this domain to the parent `.net` zone, which requires adding both NS records in `.net` for our domain and glue records for the addresses of our authoritative servers (italic in Figure 5). By default, records in `.net` have a TTL of 172800 s, or 2 days.

Our `cachetest.net` one is run on authoritative servers running in EC2 VMs. (We run our own DNS servers in our own VMs and do not use Amazon's Route53 [5] hosted DNS.) We set the TTLs for the NS and A records in our zone to 3600 s.

As can be seen in Figure 5, recursive resolvers will find two different TTLs for the same record (at both parent and child). Even though most resolvers are expected to be child-centric (§3), for sake of precision, we decided to rule out this influence by creating the `sub.cachetest.net` zone. We configure this subzone in two different experiments using a third dedicated EC2 VM also in Frankfurt.

4.2 Effective TTLs for Servers *Inside* the Served Zone

We first look at how resolvers handle authoritative servers with names in the served zone—those that are *in-bailiwick*. We show that most recursives require both fresh NS and A records, and they re-fetch even valid A records when the NS record expires.

For this experiment, we configure `ns1.subcachetest.net` as an authoritative server for our subzone (`sub.cachetest.net`). We set the TTL of its NS record to 3600 s and its A record TTL to 7200 s. These TTLs are consistent in both the parent and child zones, so

	in-bailiwick	out-of-bailiwick
Frequency	600 s	600 s
Duration	4h	4h
Query	AAAA `probeid.sub.cachetest.net`	
Date	20190315	20190314
Probes	9131	9150
Probes (val.)	8864	9053
Probes (disc.)	267	97
VPs	15618	16103
Queries	367060	387037
Queries (timeout)	39471	10436
Responses	341707	368478
Responses (val.)	340522	366853
Responses (disc.)	1185	1625
Resolvers (VPs)	6364	6679
ASes	1629	1696
Resolvers(Auth.)	13187	14884
ASes	2474	2444

Table 3: Bailiwick experiments [43].

recursives will have the same cache duration regardless of which they prefer.

At $t = 9$ min., we *renumber* `ns3.subcachetest.net`, changing its IP address to a different EC2 VM. This new VM also serves this zone, but with some changes to the records so that old and new authoritative servers return different answers. This end-to-end check allows us to determine how caching works in between.

We test this potential dependency by querying the AAAA record of `PROBEID.sub.cachetest.net` from all RIPE Atlas VPs every 600 s, watching for the returned answer to change. Since the authoritative's NS and A records have different TTLs, the time at which the response changes reveals the caching behavior of the recursive resolver. We are looking to see if the NS and A records are independent, or if they are linked, causing the A record to expire earlier than it needs to, when the NS record times out. To ensure the test answer is not cached, Atlas probes make queries that include PROBEID in the identifier (see Table 3), and replies (AAAA records) have TTL of 60 s, one tenth our probe interval.

Table 3 shows the results of about 340k valid responses from 15.6k RIPE Atlas VPs. (We discard responses that included NS records, SERVFAIL, and others that did not include the answer we expected.)

Figure 6 is a timeseries chart of the AAAA answers received by our vantage points. We count how many responses were sent by each authoritative server (original and new), aggregated to 10-minute bins. In this figure, the first arrow down shows the time when we renumber the IP address of the authoritative server (after 9 minutes).

This figure shows that before renumbering (at 9 minutes), all queries are answered by the original server (due to edge effects around Atlas measurements, the very first round has fewer queries, but rounds after that include results for all VPs). From 9 to 60 minutes we see that some resolvers (the dark blue bars) continue to use the original server, showing they have cached and trust its A and NS records. Other resolvers (light yellow bars) switch to the new server, suggesting they re-fetched the new A record. We see that most resolvers trust their cache up to the 1-hour TTL.

After one hour the NS records begin to expire. Over the next hour we can test if the recursive resolver trusts its already-cached, yet-still-valid TTL for the A record, or if it drops it and refreshes it anyway and discovers the new server. We see that with an in-domain server, *very few recursives* continue to trust the cached A record—*in-domain servers have tied NS and A record cache times in practice*. Specifically, about 90% of the resolvers that queried on the first round (blue on $t = 0$) refresh both the NS and A records at $t = 60$ min., switching to the new server. We confirm this result from the authoritative side in §4.6.

After two hours, both the NS and A should expire, so we expect *all* recursives to switch to the new server.

We see that 305-390 VPs (about 2.25% of the total) continue with the old resolver, a phenomena known as "sticky resolvers" [37].

4.3 Effective TTLs for Servers *Outside* the Served Zone

We now move to what effective TTLs are seen when the authoritative servers are *outside* the served zone (*out-of-bailiwick* servers). In this case, the server's IP address is trusted even when the NS record is expired.

For this experiment, we replace both in-bailiwick authoritative servers with `ns1.zurrundeddu.com`. Since it is not with the `cachetest.net` domain, it is an out-of-bailiwick server. As before, the NS records in the glue has a TTL of 3600 s, and the A glue record has a TTL of 7200 s. As before, we renumber the A record of `ns1.zurrundeddu.com` after 9 minutes. (The `.com` zone supports dynamic updates and we verify this change is visible in seconds.) Finally, we query the AAAA record from 16k RIPE Atlas VPs, every 600 s and watch for changes (Table 3).

Figure 7 shows how VPs react to the changed records, and Table 3 provides details about the experiment. Comparing the in- and out-of-bailiwick cases (Figure 6 and Figure 7), we see that VPs trust the A record for the old authoritative server for nearly its full cache lifetime, out to 120 minutes, not just 60 minutes. This result shows that *most recursive resolvers trust cached A records when served from different zones (out-of-bailiwick)*, but not in-bailiwick servers.

4.4 Resolver's Infrastructure

What kind of resolvers exhibit the behaviors shown in this section so far? There are many kinds of resolvers today. Prior work has shown that clients often employ multiple levels of resolvers [36, 48], with local resolvers, forwarders, and sometimes replicated recursive resolvers. For example, in Table 3, Atlas VPs see 6.3k or 6.6k resolvers directly reachable from clients in 1.6k ASes for in and out-of-bailiwick measurements, respectively. However, analysis of traffic at authoritative servers shows 13.1k and 14.8k IP addresses of resolvers connect from 2.4k ASes (again, in- and out-of-bailiwick). This complex infrastructure affects what users see from what operators announce.

Sticky resolvers: We show in Table 4 a classification of the resolvers as seen from VPs. First, we address sticky resolvers, which are the ones that both send queries on the first round of measurements (blue bar at $t = 0$) *and* always contact the same authoritative name server, even when TTLs expire. For the in-bailiwick experiment, we see that only a minority of VPs (207) have this behavior, while for out-of-bailiwick we see this number reaching 1.6k VPs

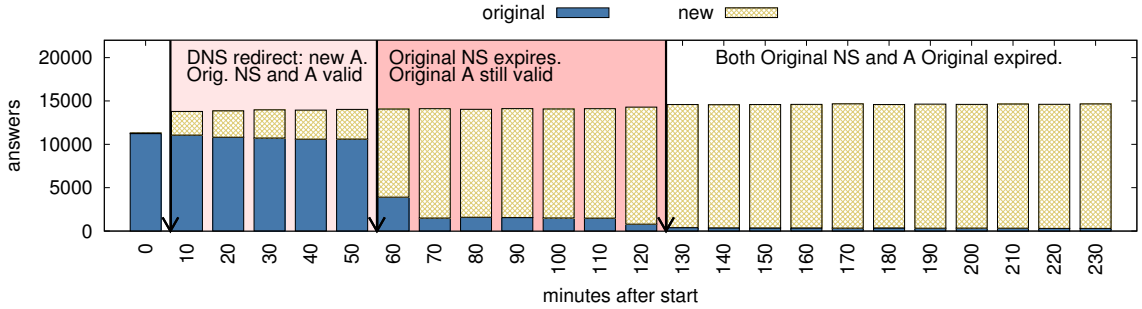


Figure 6: Timeseries of answers for in-bailiwick experiment

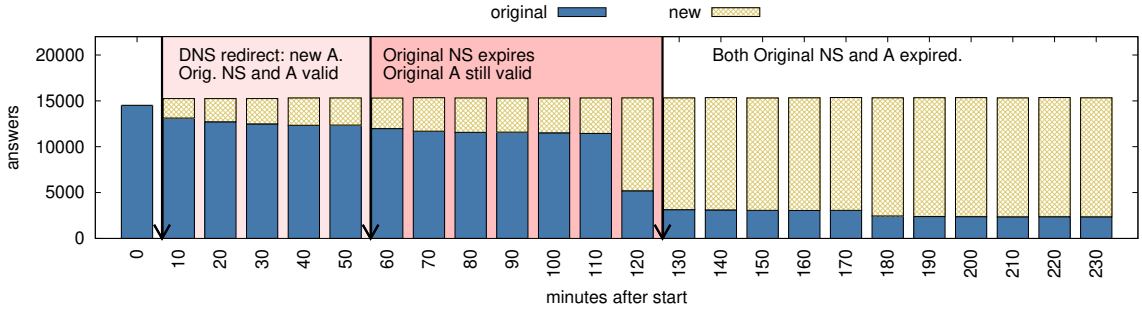


Figure 7: Timeseries of answers for out-of-bailiwick experiment

	Sticky Resolvers	
	in-bailiwick	**out-of-bailiwick**
VPs	196	1642
Resolvers	146	997
ASes	51	378

Table 4: Resolver classifications from bailiwick experiments.

(17.8% of the valid VPs, Table 3). These 1.6k VPs, in turn, query 997 unique resolvers, from 378 ASes.

Of these 997 resolvers, 291 use reserved addresses (private ranges or local interfaces). The remaining distribution is quite sparse: 16 resolvers are announced from an European NREN, 13 from another NREN, 10 from Hurricane Electric and 8 from OpenDNS [39], which provides a public DNS resolver.

To confirm the case of OpenDNS, we repeated the out-of-bailiwick configuration and send queries from a single VP (a VM located at EC2 Frankfurt) which sent queries to one of the public resolvers of OpenDNS (208.67.222.123), every 300s. Even though this experiment was carried in July 2019 (2.5 months later), we still found evidence of this behavior: out of 161 DNS responses received by our client, 13 contained answers which were from the original server after the expired TTLs. By analyzing the pcap files, we found that this is *not* due to OpenDNS being sticky resolver, but that OpenDNS servers seems to be *parent centric*, trusting the TTL of NS `zurrundeddu.com` from the .com zone (2 days), and, as such, it does not update the A record values after we renumber it. We confirm that because our authoritative servers have received no queries for NS `zurrundeddu.com`, therefore they could have only trusted the parent.

In fact, we confirm this hypothesis by running an experiment with Ripe Atlas VPs to query for NS of `zurrundeddu.com`, while keeping the *child authoritative servers offline* (zurrundeddu-offline in [43]). We see that VPs that employ OpenDNS receive a valid answer, while most others either time out or receive SERVFAIL code [33] (indicating that their local resolver could not reach the child authoritative servers).

However, we do not mean that all VPs that use OpenDNS behave this way. In fact, 252 VPs use OpenDNS public DNS directly (listing an OpenDNS address as a local resolver) in the out-of-bailiwick experiment, and 225 of these VPs send the expected 24 queries each. Out of these 225 VPs, 186 have *more queries* answered by the old server, but some also answer by the new server, perhaps due to cache fragmentation and use of different resolver backends [36].

4.5 Same VP, different behavior

In this section we focus on VPs that exhibit distinct behavior for the in and out-of-bailiwick experiments. To do that, we focus on VPs that are "sticky" in the in-bailiwick experiment—the 1642 VPs from Table 4. Our goal is to identify *how* they behave in the in-bailiwick experiment.

Out of the 1642 sticky VPs, 1395 were also employed on the in-bailiwick experiment. Figure 8 shows the distribution of these 1395 VPs and their respective ratio of DNS responses from the new server, for the in-bailiwick experiment. As can be seen, the same VPs that were "sticky" for the out-of-bailiwick scenario, mostly behave as expected, retrieving most responses from the new server.

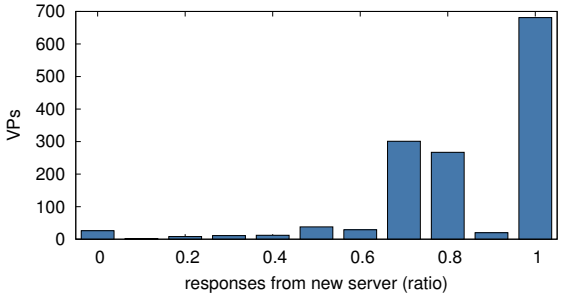


Figure 8: Responses from new server for matched VPs.

These results show that same VPs can behave differently depending on how DNS zones are configured.

4.6 Confirmation from the Authoritative Side

We investigate in this section *why* results from in-bailiwick and out-of-bailiwick differ that much. We analyze traffic obtained at the authoritative servers.

First, we compare the responses for the queries issued by RIPE Atlas VPs. The responses sent to RIPE Atlas for the in-bailiwick scenario had, besides the AAAA records in the *answers* section and NS record in the *authority section*, an A record (glue) of the NS records found in the *additional*. In comparison, the out-of-bailiwick scenario had no *additional* section, as the zone had no glue.

For out-of-bailiwick servers, the resolver must explicitly fetch the address of the authoritative servers. This difference affects *who* provides that information: for in-bailiwick, it comes from the parent based on the glue records, while for out-of-bailiwick it is from NS's authoritative server. Resolvers therefore get different TTLs because parent and child provide different TTLs.

5 TTLS IN THE WILD

While there is limited guidance for setting TTLs, we can look at how TTLs are set *in the wild* to see if there is consensus. We look both at top-level and popular second-level domains, and report on our discussion of these results with operators.

5.1 Crawling TLDs and Popular Domains

To evaluate how TTL values are used in the wild, we study five data sources; the root zone, the country-level domain of the Netherlands, and "top" lists from Alexa [3], Majestic [32], and Umbrella [52]. We use root data from 2019-02-13, and all other data from 2019-02-06. While it is known that top lists show considerable churn [46], our results provide a snapshot of one instant, and the diversity of sources allows us to evaluate trends.

Methodology: For each list, we retrieve TTLs of several DNS records (NS, A, AAAA, MX, and DNSKEY) directly from both the *parent* and *child* authoritative servers, measuring from Amazon EC2 in Frankfurt, querying the parent or the child authoritative server directly for the measurement (without using shared recursive resolvers). Here we report results only for the child zone, since that reflects the operator's intent, and most recursives are child-centric (§3).

These results are necessarily incomplete. A full comparison of parent and child is future work, but we know that the TTL of `.nl` is 1 hour, so we know that about 40% of `.nl` children have shorter TTLs, as can be seen in Figure 9a. In addition, we study only one third-level zone for each domain, although actual services may employ many internal names with different TTLs.

	Alexa	Majestic	Umbre.	.nl	Root
format	2LD	2LD	FQDN	2LD	TLD
domains	1000000	1000000	1000000	5582431	1562
responsive	988654	928299	783343	5454833	1535
discarded	11346	71701	216657	345479	27
ratio	0.99	0.93	0.78	0.94	0.97
Date	2019-02-06				2019-02-13
NS	2479257	2430773	855147	14184460	7289
unique	269896	234356	106475	74619	4169
ratio	9.19	10.37	8.03	190.09	
A	1247139	1069314	1126842	5389560	4145
unique	572689	539301	451220	274920	3188
ratio	2.18	1.98	2.50	19.60	
AAAA	282818	215935	287069	2127664	3740
unique	106235	97545	139456	134751	2951
ratio	2.66	2.21	2.06	15.79	
MX	1697001	1532026	522089	7494383	88
unique	480787	435455	130751	2157676	35
ratio	3.53	3.52	3.99	3.47	
DNSKEY	42950	38262	11731	3800612	–
unique	26274	25275	6838	3597613	–
ratio	1.63	1.51	1.72	1.06	
CNAME	45228	2493	344500	10666	–
unique	3592	1512	166230	3509	–
ratio	12.59	1.65	2.07	3.04	

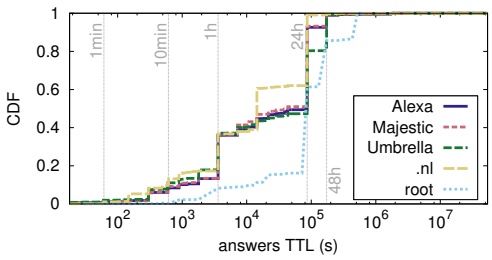
Table 5: Datasets and RR counts (child authoritative)

Results: Table 5 shows the sizes of each crawl, and how many replies we see each record and list. Most lists have high response rates, with Umbrella as an exception with only 78% responding. The Umbrella list includes many transient names that point to CDNs or cloud instances (for example, wp-0f21050000000000.id.cdn.upcbroadband.com). We report the number of unique records, and higher ratios of unique records show greater levels of shared hosting. (The top lists reflect diverse users and diverse hosting, while `.nl` reflects a large number of static domains with relatively little use that use low-cost shared hosting.)

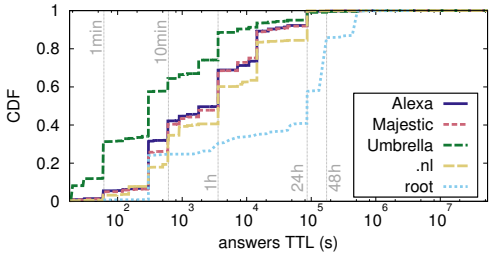
Figure 9 shows the CDFs of TTLs of authoritative answers for each record type. There are no A or AAAA records for TLDs in root zone, so there we report the A and AAAA records of their respective NS servers. For other lists of SLDs or full names, we do not do this indirection and report only A records for the given name. Our first observation is that *TTLs show a large variation in values*, from 1 minute to 48 hours, for all lists and record types.

Second, we see some trends in different lists. In general, the times reflect human-chosen values (10 minutes and 1, 24, or 48 hours). In the root, about 80% of records have TTLs of 1 or 2 days. For Umbrella, on the other hand, 25% of its domains with NS records are under 1 minute. This difference reflects the list populations—the root is slowly changing, and changes are carefully monitored and managed. Umbrella instead reflects many cloud and CDN names, that are often transient and changing as load comes and goes and cloud instances are created and discarded.

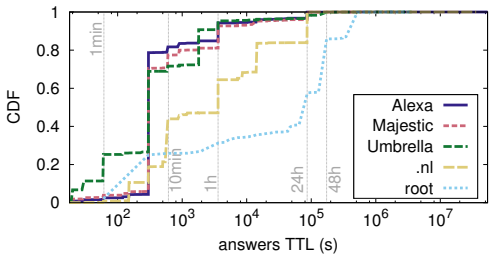
We also see variation across record type. NS and DNSKEY records tend to be the longest-lived (Figure 9a), while IP addresses are the shortest (Figure 9b and Figure 9c). These reflect service dynamics: changing authoritative servers is an administrative action with



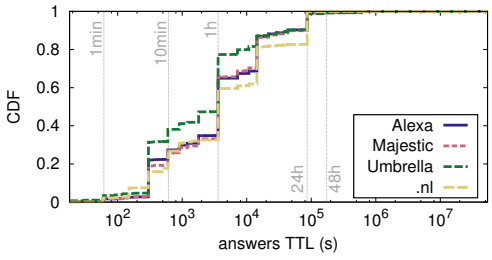
(a) NS-TTL



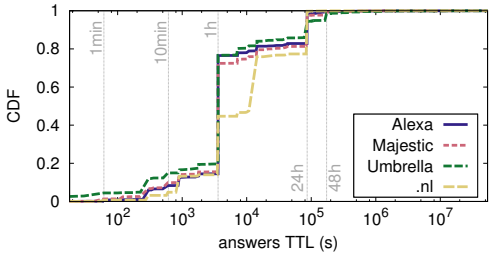
(b) A-TTL



(c) AAAA-TTL



(d) MX-TTL



(e) DNSKEY-TTL

Figure 9: CDF of TTLs per record type, for each list.

Categories	*#*	*Meaning*	*Example*
Placeholder	1199152	Landing page	`k-man.nl`
E-commerce	148564	Shop cart presence	`monsfietsen.nl`
Parking	127551		`coffeebar.nl`
Total	1475267		

Table 6: `.nl` classified domains by DMap

	Ecommerce	Parking	Placeholder
NS	4.0	24.0	4.0
A	1.0	1.0	1.0
AAAA	0.1	1.0	4.0
MX	1.0	1.0	1.0
DNSKEY	1.0	24.0	4.0

Table 7: Median TTL values (hours) for `.nl` domains

	Alexa	Majestic	Umbrella	.nl	Root
NS	4524	4187	1365	3414	0
A	896	575	529	673	0
AAAA	244	1549	116	45	0
MX	506	374	211	266	0
DNSKEY	0	2	12	15	0
unique	5385	6202	1955	4047	0

Table 8: Domains with TTL=0 s, per Record Type

careful planning, while server addresses are often dynamic with automated creation in clouds and CDNs.

This diversity in TTL choices of major domains suggests some combination of differing needs and lack of consensus in TTL choice.

5.1.1 TTLs and content type. Besides using our DNS crawler on the `.nl` zone, we use data collected using DMap [56], an open-source multi-application crawler for domain names (it crawls HTTP, DNS, SMTP, TLS, among other applications). We focus on (i) domains that have a web page (that is, when the IP address also responds on port 80 or 443), and (ii) that can were classified by DMap into one of its categories. In total, on 2019-01-25, there were 58310209 domain names in `.nl` zone. Out of these, 4846496 (83.1%) had both an A record and an web page.

Table 6 shows the results of DMap classifications for the `.nl` zone. We only consider domains that do not redirect to other domains, either using CNAME records or HTTP redirects. The reason for that is redirection implies the use of other domains – which therefore have their own DNS records.

We see that about 1.1M pages are placeholders (domains with their hosting provider default web page), followed by e-commerce (148k, which are domains that have webpages with shopping carts in it), next to parked domains (127k) [53].

Table 7 shows the median TTL value (in hours) per each type of page, and type of DNS records. We see that Parking has the the longest median TTL for NS records (24 h), while e-commerce and placeholders share the same median value (4 h). Their median A record TTL is the same (1 h).

5.1.2 TTL 0 s. TTL values may range from 0 s to years [34], but in practice most TTLs measured in-the-wild are under two days (Figure 9).

	Alexa	Majestic	Umbre.	.nl	Root
responsive	988654	928299	783343	5454833	1535
CNAME	50981	7017	452711	9436	0
SOA	12741	8352	59083	12268	0
respond NS	924932	912930	271549	5433129	1535
Out only	878402	873447	244656	5417599	748
percent out	*95.0*	*95.7*	*90.1*	*99.7*	*48.7*
In only	37552	28577	20070	12586	654
Mixed	8978	10906	6823	2941	133

Table 9: Bailiwick distribution in the wild.

While not an error per se, a TTL of 0 s effectively *undermines caching* at the resolvers. We show in Table 8 the counts of domains with TTL equal zero. We see that few domains are configured with 0 s TTLs. We recommend against eliminating caching by setting TTL values to zero, since it increases latency to users and reduces resilience (such in cases against DDoS attacks [36]).

5.1.3 Bailiwick configuration in the wild. We have seen in §4 how bailiwick affects the choice of TTLs for a given record. We now investigate how many domains in-the-wild are in-bailiwick.

Table 9 summarizes the results. We start with the *responsive* domains (obtained from Table 5), which are domains that responded to at least one of our queries (in regardless of query type). To evaluate how domains are configured, we consider only NS queries that had NS records in the answers (we disregard domains that either returned a CNAME or SOA records to NS queries). We see that the majority of domain names remain (the "respond NS" row), for all datasets except the Umbrella list, which uses long FQDNs, often from clouds and CDNs.

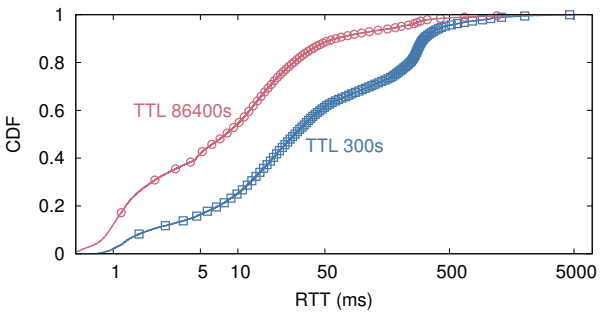
We next evaluate what baliwick these domains use. For the popular lists, we see that the *nearly all* (more than 90%) are configured with out-of-bailiwick NSes *only*. The exception to that is the list of TLDs (Roots), which roughly half are out-of-bailiwick and the other half are either only in-bailiwick or mixed.

5.2 Discussions with Operators

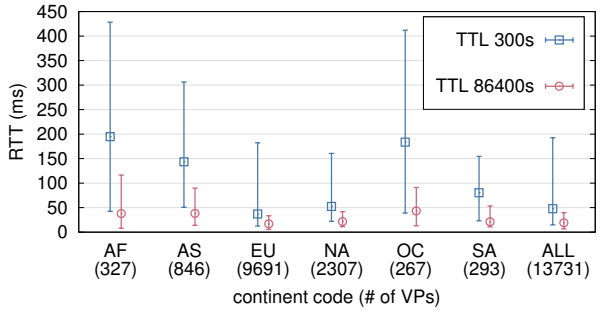
Our crawl of the root zone (§5.1) showed 34 TLDs (including 8 country-code) with NS TTLs less than 30 minutes, and 122 TLDs with NS TTLs under 120 minutes. These short TTLs are only partially effective because of parent-centric resolvers (§3), and they prevent caching which can help latency (§6.2), and increase DDoS vulnerability [36].

We reached out to the operators of the eight ccTLDs, asking them why they chose such short TTLs. Five of them responded, with three stating that they had not considered the implications of such short TTLs. After our contact, three operators *increased their NS records TTL* to 1 day: Uruguay's .uy increased it from 300 s, a middle-eastern ccTLD increased it from 30 s, and an African ccTLD increased their TTL from 480 s, both to one day. We report in §5.3 the implications of this increase in TTL for .uy. Two other operators said the short TTLs were intentional to account for planned infrastructure changes. Another reply was from a large operator who stated they kept the TTL values in place when they took over service ("if it ain't broke don't fix it" approach we discussed in §1).

One should be cautious in drawing conclusions from such a small sample but while some operators intentionally use small TTLs, many appear to have not carefully considered the implications and are interested in considering longer TTLs.



(a) VPs combined



(b) Median and quantiles of RTT as seen by RIPE Atlas VPs per region (AF:Africa, AS:Asia, EU:Europe, NA:North America, OC:Oceania, SA:South America); Halo symbols (left) are for TTL 300s and filled for TTL 86400s

Figure 10: RTT from RIPE Atlas VPs for NS .uy queries before and after changing TTL NS records.

5.3 Early Feedback from Uruguay's .uy

Our study of Uruguay's ccTLD shows that in early 2019 they had very different TTLs between their parent and child, with authoritative TTLs of only 5 minutes while the root zone defaults to 2 days (300 s vs. 172800 s!). During the time of our analysis, .uy had 8 NS records (5 in-bailiwick, 3 out). After sharing our early results with them, on 2019-03-04 they changed their child NS records TTLs to one day (86400 s).

Uruguay's .uy change provides a natural experiment to test the effects of different TTLs on DNS latency. Our studies had measurements from RIPE Atlas VPs both *before* and *after* this change (see uy-NS and uy-NS-new in Table 2). We measure the response time for a .uy/NS query from around 15k VPs, querying for two hours every 600 s. Since .uy is a country-level TLD, it may be cached, so this study reflects a dynamic snapshot remaining TTL.

Results: Figure 10a shows the CDF of query response times for .uy before, with a short TTL (the top, red line), and after, with long TTLs (the bottom, blue line). With short TTLs, .uy often falls out of the cache, and the median response time is 28.7 ms. With long TTLs .uy remains in the cache and so many queries are handled directly by the recursive, providing an 8 ms response time.

Differences in tail latency are even larger: at the 75%ile, longer TTLs have median of 21 ms compared to 183 ms with short TTLs; at the 95%ile, longer TTLs have a median of 200 ms compared to 450 ms, and, at 99%ile, these values raise to 1375 ms and 678 ms, respectively.

To confirm these differences are not biased by geographic distribution of RIPE probes, we evaluate RTT changes by continent based on each probe's self-reported geolocation. Figure 10b shows the distribution of RTT per continent as seen by more than 13.7k VPs worldwide. We see that all regions observe latency reduction after changing TTL; higher reductions are seen for those with larger range of latency.

This natural experiment shows the large benefit to user latency from increased caching and long TTLs. We do not have access to authoritative traffic at .uy, so we cannot evaluate traffic reduction, but it too is likely substantial (we evaluate traffic reduction due to longer TTLs in §6.2) .

Besides .uy, two other ccTLDs also increased their NS records TTL to one day after our initial contact, from 30 s and 480 s ,respectively. Their users can also expect similar perform gains as from .uy users.

6 RECOMMENDATIONS FOR DNS OPERATORS

We next consider recommendations for DNS operators and domain owners, about TTL durations and the other operational issues.

6.1 Reasons for Longer or Shorter TTLs

TTLs in use range from as short as 5 minutes, to a few hours, to one or two days (§5.1). This wide range of time values seen in TTL configurations is because there are many trade-offs in "short" vs. "long", and which factors are most important is specific to each organization. Here are at least factors operators consider:

Longer caching results in faster responses: The largest effect of caching is to enable queries to be answered directly from recursive resolvers. With a cache hit, the resolver can respond directly to a client, while a cache miss requires an additional query (or queries, in some cases) to authoritative servers. Although a query to the authoritative is usually fast (less than 100 ms), a direct reply from the recursive resolver is much faster. While caching has long been recognized as important, we are the first to show how important it is, both for Uruguay's .uy in §5.3, and through controlled experiments in §6.2.

Longer caching results in lower DNS traffic: caching can significantly reduce DNS traffic. However, DNS queries and replies are quite small, and DNS servers are relatively lightweight. Therefore, costs of DNS traffic are likely smaller than costs of web hosting or e-mail. We evaluate this effect in §6.2.

Longer caching results in lower cost if DNS is metered: Some DNS-As-A-Service providers charges are metered, with a per query cost (often added to a fixed monthly cost). Even if incremental costs are small relative to fixed charges, caching can reduce this cost.

Longer caching is more robust to DDoS attacks on DNS: DDoS attacks on a DNS service provider [21] harmed several prominent websites [41]. Recent work has shown that DNS caching can greatly reduce the effects of DDoS on DNS, provided caches last longer than the attack [36].

Shorter caching supports operational changes: An easy way to transition from an old server to a new one is to change the DNS records. Since there is no method to remove cached DNS records, the TTL duration represents a necessary transition delay to fully shift to a new server, so low TTLs allow more rapid transition. However, when deployments are planned in advance (that is, longer than the TTL), then TTLs can be lowered "just-before" a major operational change, and raised again once accomplished.

Shorter caching can help with a DNS-based response to DDoS attacks: Some DDoS-scrubbing services use DNS to redirect traffic during an attack [38]. Since DDoS attacks arrive unannounced, DNS-based traffic redirection requires the TTL be kept quite low at all times to be ready to respond to a *potential* attack.

Shorter caching helps DNS-based load balancing: Many large services use DNS-based load balancing (for example, the Akamai CDN [12] and Bing search engine [10]). Each arriving DNS request provides an opportunity to adjust load, so short TTLs may be desired to react more quickly to traffic dynamics. (Although many recursive resolvers have minimum caching times of tens of seconds, placing a limit on agility.)

Organizations must weigh these trade-offs to find a good balance, after considering other factors such as server load and maintenance.

6.2 Caching Reduces Query Volume and Latency

Latency is not the only factor to consider; one should also consider query volume. Caching reduces query volume at the authoritative server, reducing load and indirectly improving latency. Exactly how much depends on the workload: who queries, when, and from where. We saw a significant reduction in latency for Uruguay in in §5.3. We next study those questions with a controlled experiment.

Methodology: We carry out five experiments listed in Table 10. We use DNS servers at Amazon EC2 in Frankfurt, with short (60 s) and long (84,400 s) TTLs, and we use anycast (Route53, with 45 global sites at experiment time) with 60 s TTLs.

We place queries to a test domain (unique to this experiment) from 15k Atlas VPs to different types of DNS configurations. We use either unique names (the left two columns) or a common name (the right three).

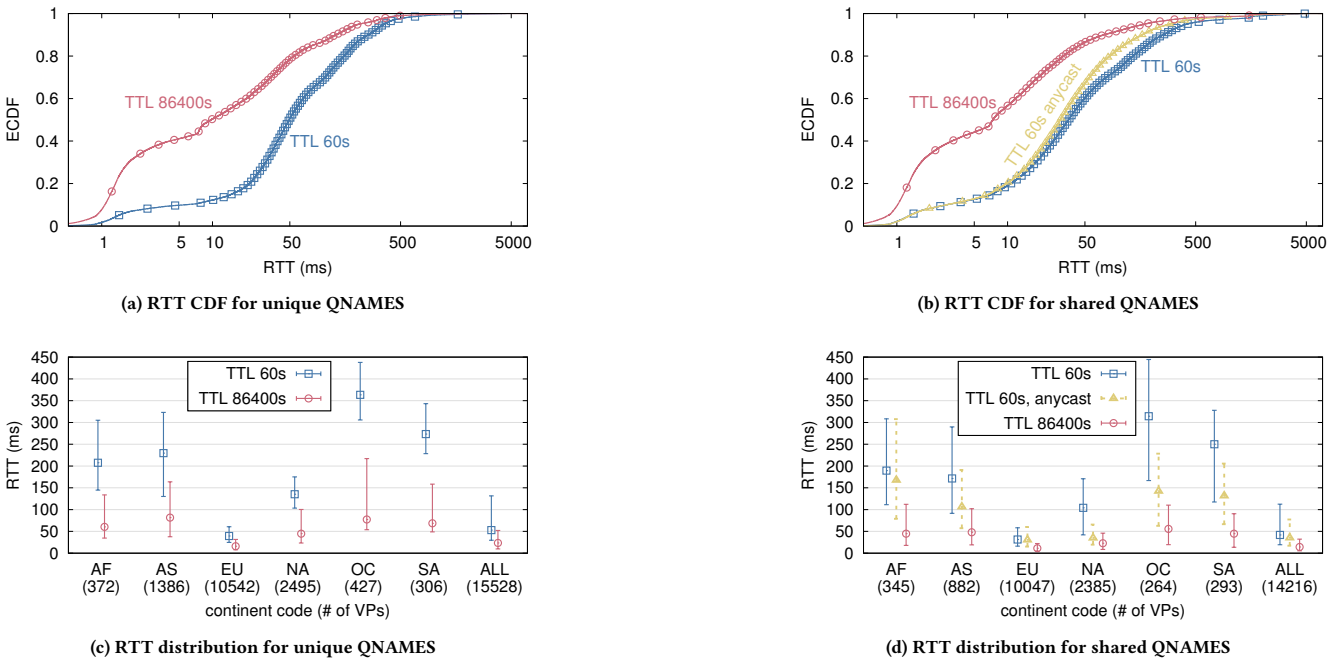
Longer TTL reduces authoritatives load: We see that the traffic to authoritative servers is reduced by about 77% with the long TTL (from 127k to 43k with unique names, and from 92k to 20k with shared names). Similarly, in 2016, when .nl reduced the TTL of the A records of its NS records from 7200 to 3600 s, it saw a traffic increase by 22 to 30% in two of its authoritative servers [55]. Our controlled experiment shows the economic savings when DNS is provided as a metered service [5].

Longer TTL improves response time: Figure 11 shows latency distributions, comparing short TTLs with long TTLs. We can see that for unique queries (Figure 11a), using a TTL of 60 s leads to a median RTT of 49.28 ms, while a TTL of 84600 s reduces the median to 9.68 ms.

For shared query names (Figure 11b), the median RTT for a TTL60 s is 35.59 ms, and 7.38 ms for TTL86400, which can be explained that some VPs benefit from caches being warmed by others

	unique QNAME		shared QNAME		
	TTL60-u	TTL86400-u	TTL60-s	TTL86400-s	TTL60-s-anycast
Frequency	600s	600s	600s	600s	600s
Duration	60min	60min	65min	65min	60min
Query	PID.mapache-de-madrid.co		1.mapache-de-madrid.co	2.mapache-de-madrid.co	4.mapache-de-madrid.co
Query Type	AAAA	AAAA	AAAA	AAAA	AAAA
Date	20190227	20190227	20190228	20190228	20190228
Client Side					
Probes	9095	9109	9105	9117	8869
Probes (val.)	8991	9009	8950	8981	8572
Probes (disc.)	104	100	155	136	117
VPs	15996	16025	15834	15910	15274
Queries	96438	96585	103666	107912	90553
Responses	96492	96645	103666	107912	90553
Responses (val.)	96469	96603	103640	107861	90553
Responses (disc.)	23	42	26	51	0
Authoritative Server					
Querying IPs	12967	10334	11166	7882	13773
Queries	126763	43220	92547	20325	60813(only AAAA)
Responses	126763	43220	92547	20325	60813(only AAAA)

Table 10: TTL experiments: clients and authoritative view [43].



(a) RTT CDF for unique QNAMES

(b) RTT CDF for shared QNAMES

(c) RTT distribution for unique QNAMES

(d) RTT distribution for shared QNAMES

Figure 11: Distribution of client latency from Atlas VPs to controlled DNS with different TTLs.

VPs. This controlled experiment confirms improved latency seen for Uruguay (Figure 10a), since TTL86400 (the leftmost, green line) has much lower median latency than TTL60 (the right, daker, blue line).

Longer TTL reduces latency, even more than anycast: In addition, this controlled experiment lets us compare to an anycast service (Figure 11b). We see that *caching is far better than anycast at reducing latency*, comparing TTL86400 (the left, ligher red line) against anycast (the center orange line, median RTT =29.95 ms). While anycast helps a great deal in the tail of the distribution, caching greatly helps the median. (At 75%ile, 60 s TTLs have 106 ms latency, with anycast that drops to 67 ms, but 86,400 s TTLs reduce it to 24 ms.) This result is consistent with prior work that showed diminishing returns from very large anycast networks [47]. The cache in a recursive close to the client is often *far* faster even than an anycast site 100 km away.

6.3 Recommendations

While our analysis does not suggest *one* "best" TTL value, we carefully describe the trade-offs, resulting in the following recommendations for different situations:

TTL Duration: Choice of TTL depends in part on external factors (§6.1) so no *single* recommendation is appropriate for all networks or network types.

For *general zone owners, we recommend longer TTLs*: at least one hour, and ideally 4, 8, or 24 hours. Assuming planned maintenance can be scheduled in advance, long TTLs have little cost.

For *TLD and other registry operators*: DNS operators that allow public registration of domains (such as most ccTLDs, `.com`, `.net`, `.org` and many SLDs) allow clients to duplicate the TTLs in their zone files for client NS records (and glues if in-bailiwick). While §3.3 shows that most resolvers use TTL values from the child delegation, *some* use the parent's TTL. We therefore recommend longer TTLs for NS records of both parent and child records (at least one hour, preferably more).

Users of DNS-based load balancing or DDoS-prevention may require short TTLs: TTLs may be as short as 5 minutes, although 15 minutes may provide sufficient agility for many operators. Shorter TTLs here help agility; they are an exception to our first recommendation for longer TTLs.

Use A/AAAA and NS records: TTLs of A/AAAA records should be equal (or optionally shorter) to the TTL for NS records for *in-bailiwick* DNS servers (§4.2). Our reasoning is they will be treated that way by many resolvers, so the configuration should reflect what will happen in practice.

For *out-of-bailiwick* servers, A and NS records are usually cached independently, so different TTLs, if desired, will be effective.

In either case, short A and AAAA records may be desired if DDoS-mitigation services are an option.

Who is in control: Given that most resolvers are child-centric, one can directly control used TTLs within the zone itself (§3). However, one should recognize that a fraction of resolvers will use TTLs from glue records stored served by a zone's parents, so operators should either configure both in-zone and glue TTLs identically, or recognize some users will use one or the other. (Unfortunately EPP [23, 24], the standard protocol for domain registration, does not support setting TTLs.)

We recommend that *developers of resolver software move to child-centric resolution*, even if it means additional queries. DNSSEC verification requires evaluation of queries from the child zone, and it seems preferable to favor the actual domain owner's choice of TTL over the parent zone operator. In the meantime, we recommend that resolver developers document their resolver behavior as parent- or child-centric, and if they trust or discard the additional section of DNS responses (§4).

7 RELATED WORK

DNS performance and caching efficiency: Prior work has studied client-side caching through recursive resolvers from several perspectives. First, Jung *et al.* [27], in 2002, carried out simulations based on university traces to estimate the DNS cache hit rate given TTL. They showed that longer TTLs improves caching, but TTLS shorter than 1000 s were sufficient to reap most of the benefits. In their subsequent study [26], they modeled DNS caches as a function of TTL to explain their earlier results. Ager *et al.* [2] compare local DNS resolvers against Google and OpenDNS public ones. While they cover query response time, they do not cover its relation to DNS records TTLs as we do.

Second, researchers at CWRU have explored client-side DNS [11, 48], showing how TTLs are used by clients in the wild, and that short TTLs are generally honored. Other researchers examined mobile clients, showing most TTLs are short [4]. Our work instead focuses on provider-side configuration, to make sure providers get the times they desire, and how those times influence response times and query volume.

Third, several groups evaluated DNS performance at the root. Danzig *et al.* showed that there was a significant number of misbehaving resolvers [14]. Fomenkov *et al.* examined Root DNS latency before anycast was widespread [16], and then Liu *et al.* reexamined performance with anycast [31]. Thomas and Wessels showed how complicated caching is as seen from the Roots DNS servers [51].

Finally, recently Moura *et al.* [36] evaluated caching hit rates with datasets from production networks and experiments with RIPE Atlas, finding cache hit rates of around 70% for TTLs ranging from 1800–86400 s. While this prior work measured caching and its effects, our work instead focuses on how TTLs set in different places interact to *create* an effective TTL.

Resolver Centricity and Stickiness: Guðmunsson [18] previously studied router stickiness, and both he and Qiao [42] studied resolver centricity. We extend their prior studies to examine how centricity and stickiness affects caching, and how they behave today.

TTL and DNS resilience: Pappas *et al.* proposed changes two strategies to improve DNS resilience to DDoS with NS-record caching [40]. They proposed refreshing TTLs in some circumstances, and renewing (pre-fetching before expiration) NS records for popular domains.

In addition to considering caching efficiency, Moura *et al.* also examined the relationship between TTLs in DNS and resilience to DDoS attacks [36]. They simulated a series of scenarios with various degrees and packet loss and showed that, together with retries, caching is a key component of DNS resilience. They showed that, to be most effective, TTLs must be longer than the DDoS attack. They recommend long TTLs where possible, but refrain from suggesting specific values.

Unlike these two papers, we focus on DNS under normal operation. We examine how different records create ambiguity in the effective TTL, and make recommendations for TTL values and where they must be set.

Ripe Atlas: It is well known that the global distribution of RIPE Atlas probes is uneven, skewed towards Europe [8, 9, 47]. Although quantitative data analysis might be generally affected by this distribution bias, our qualitative analysis, contributions and conclusions do not depend on the geographical location of probes.

8 CONCLUSION

This paper examined DNS TTLs, showing that the effective DNS TTL is often different from what is configured because TTLs appear in multiple locations and resolvers make different choices in which TTL they prefer. We use controlled experiments to demonstrate how these factors interact, and that one must control TTL in both parent and child zones. We showed that longer TTLs have important performance benefits, since caching greatly reduces latency, even more than anycast, as well as reducing traffic. Our scans of deployed DNS show that operators today have little consensus on typical TTLs. Initial discussions with selected operators suggest interest in

longer TTLs, and changes at Uruguay's .uy, after our discussions, result in much lower median latency to users, as did two other ccTLDs. We list the issues operators should consider when selecting TTLs, and suggest while those using DNS-based load-balancing or DDoS-mitigation may require short TTLs (5 or 15 minutes), others may benefit from longer TTLs (of a few hours).

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