Connection-Oriented DNS to Improve Privacy and Security (extended)

USC/ISI Technical Report ISI-TR-695, Feb 2015

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***Abstract*—The Domain Name System (DNS) seems ideal for connectionless UDP, yet this choice results in challenges of eavesdropping that compromises privacy, source-address spoofing that simplifies denial-of-service (DoS) attacks on the server and third parties, injection attacks that exploit fragmentation, and reply-size limits that constrain key sizes and policy choices. We propose *T-DNS* to address these problems. It uses TCP to smoothly support large payloads and to mitigate spoofing and amplification for DoS. T-DNS uses transport-layer security (TLS) to provide privacy from users to their DNS resolvers and optionally to authoritative servers. TCP and TLS are hardly novel, and expectations about DNS suggest connections will balloon client latency and overwhelm server with state. Our contribution is to show that T-DNS significantly improves security and privacy: TCP prevents denial-of-service (DoS) amplification against others, reduces the effects of DoS on the server, and simplifies policy choices about key size. TLS protects against eavesdroppers to the recursive resolver. Our second contribution is to show that with careful implementation choices, these benefits come at only modest cost: end-to-end latency from *TLS to the recursive resolver is only about 9% slower* when UDP is used to the authoritative server, and 22% slower with TCP to the authoritative. With diverse traces we show that connection reuse can be frequent (60–95% for stub and recursive resolvers, although half that for authoritative servers), and after connection establishment, experiments show that TCP and TLS latency is equivalent to UDP. With conservative timeouts (20 s at authoritative servers and 60 s elsewhere) and estimated per-connection memory, we show that *server memory requirements match current hardware*: a large recursive resolver may have 24k active connections requiring about 3.6 GB additional RAM. Good performance requires key design and implementation decisions we identify: query pipelining, out-of-order responses, TCP fast-open and TLS connection resumption, and plausible timeouts.**

I. Introduction

The Domain Name System (DNS) is the canonical example of a simple request-response protocol. DNS resolves domain names like www.iana.org into the IP addresses; rendering a single web page may require resolving several domain names, so it is desirable to minimize the latency of each query [14]. Requests and responses are typically small (originally required to be less than 512 B, and today under 1500 B as a practical matter), so a single-packet request is usually answered with a single-packet reply over UDP. Simplicity and efficiency has prompted DNS use in broader applications [88].

DNS standards have always required support for TCP, but it has been seen as a poor relative—necessary for large exchanges between servers, but otherwise discouraged. TCP is more expensive than UDP, since connection setup adds latency with additional packet exchanges, and tracking connections requires memory and computation at the server. Why create a connection if a two-packet exchange is sufficient?

This paper makes two contributions. First, we *demonstrate that DNS's connectionless protocol is the cause of a range of fundamental weaknesses in security and privacy that can be addressed by connection-oriented DNS*. Connections have a well understood role in longer-lived protocols such as ssh and HTTP, but DNS's simple, single-packet exchange has been seen as a virtue. We show that it results in weak privacy, denial-of-service (DoS) vulnerabilities, and policy constraints, and that these problems increase as DNS is used in new applications, and concerns about Internet safety and privacy grow. While prior problems have been discussed in isolation (for example, [11], [76]) and individual problems can often be worked around, taken together they prompt revisiting assumptions. We then propose T-DNS, where DNS requests should use TCP by default (not as last resort), and DNS requests from end-users should use Transport-Layer Security (TLS [24]). TCP prevents denial-of-service (DoS) amplification against others, reduces the effects of DoS on the server, and simplifies policy choices about DNSSEC key size, and that TLS protects queries from eavesdroppers to the recursive resolver.

Our second contribution is to show that *the benefits of connection-oriented DNS in T-DNS come at only modest cost*: For *clients*, end-to-end latency of T-DNS (time from a stub's request to an answer, considering all queries and caches) is only moderately more than connectionless DNS. Our models show latency increases by only 9% for TLS vs UDP-only where TLS is used just from stub to recursive-resolver, and it increases by 22% when we add TCP from recursive to authoritative. Connection reuse results in latencies almost the same as UDP once the connection is established. With moderate timeouts (20 s at authoritative servers and 60 s elsewhere), connection reuse is high for servers (85–98%), amortizing setup costs for client and server. Connection reuse for clients is lower (60–80% at the edge, but 20–40% at the root), but still results in amortized costs and lowered latencies. For *servers*, connection rates are viable for modest server-class hardware today. With conservative timeouts (20 s at authoritative servers and 60 s elsewhere) and overestimates of per-connection memory, a large recursive resolver may have 24k active connections using about 3.6 GB of RAM;

authoritative servers double those needs.

TCP and TLS are well established protocols, and many DNS variations have been proposed, with TCP in the original specification, and prior proposals to use TLS, DTLS, SCTP, and HTTP with XML or JSON. Our contribution is not protocol novelty, but *a careful evaluation of what is necessary to add established protocols to an existing ecosystem*: evaluation that shows the performance costs are modest and experiments that show the security and privacy benefits are real. With wide belief that connectionless DNS is mandatory for adequate performance, this study addresses a primary impediment to improving DNS privacy. While we evaluate our specific design, we suggest that our performance evaluation *generalizes* to most connection-like approaches to DNS, nearly all of which require some state at both ends. In addition, we identify the specific implementation choices needed to get good performance with TCP and TLS; alternative protocols for DNS encryption will require similar optimizations, and we suggest they will see similar performance.

Why: Connection-based communication is important to improve security in three ways. First, it *improves DNS privacy through the use of encryption*. We discuss alternatives in § VII-D: although some employ UDP, all effectively build connections at the application-layer to keep session keys and manage setup. DNS traffic is important to protect because hostnames are richer than already visible IP addresses and DNS queries expose application information (§ II-B3). DNS queries are increasingly vulnerable, with wireless networks, growth of third-party DNS (OpenDNS since 2006 [67] and Google Public DNS since 2009 [73]), meaning that end-user requests often cross several networks and are at risk of eavesdropping. Prior work has suggested from-scratch approaches [65], [23], [92]; we instead utilize existing standards to provide confidentiality for DNS, and demonstrate only moderate performance costs. As a side-effect, T-DNS also protects DNS queries from tampering over parts of their path.

Second, TCP *reduces the impact of denial-of-service (DoS) attacks* in several ways. Its connection establishment forces both sides of the conversation to prove their existence, and it has well-established methods to tolerate DoS attacks [30]. Lack of these methods has allowed UDP-based DNS to be exploited by attackers with amplification attacks; an anonymous attacker who spoofs addresses through a DNS server can achieve a 20× increase in traffic to its victim, a critical component of recent multi-Gb/s DoS attacks [3]. We examine performance under attack in § V.

Finally, *UDP limits on reply sizes constrains key sizes and DNS applications*. EDNS0 [21] often makes 4096 B replies possible, extending the original 512 B limit [61]. However, due to IP fragmentation [21], 1500 B is seen as an operational constraint and this limit has repeatedly affected policy choices in DNS security and applications. IP fragmentation presents several dangers: fragments require a resend-all loss recovery [49], about 8% of middleboxes (firewalls) block all fragments [91], and fragmentation is one component in a class of recently discovered attacks [38]. Of course current DNS replies strive to fit within current limits [87], but DNSSEC keys approaching 2048-bits lead to fragmentation, particularly during key rollover (§ II-B1). Finally, DNSSEC's guarantees make it attractive for new protocols with large replies, but new applications will be preempted if DNS remains limited to short replies.

How: On the surface, connection-oriented DNS seems untenable, since TCP setup requires an extra round-trip and state on servers. TCP is seen as bad for DNS, and so TLS' heavier weight handshake is impossible.

Fortunately, we show that *connection persistence*, reusing the same connection for multiple requests, amortizes connection setup. We identify the key design and implementation decisions needed to minimize overhead—query pipelining, out-of-order responses, TCP fast open and TLS connection resumption, shifting state to clients when possible. Combined with persistent connections with conservative timeouts, these optimizations balance end-to-end latency and server load.

Our key results are to show that T-DNS is feasible and that it provides a clean solution to a broad range of DNS problems across privacy, security, and operations. We support these claims with end-to-end models driven by analysis of day-long traces from three different types of servers and experimental evaluation of prototypes [1].

II. Problem Statement

We next briefly review today's DNS architecture, the specific problems we aim to solve, and our threat model.

II-A Background

DNS is a protocol for resolving *domain names* to different *resource records* in a globally distributed database. A *client* makes a *query* to a *server* that provides a *response* of a few dozen specific types. Domain names are hierarchical with multiple *components*. The database has a common root and millions of independent servers.

Originally DNS was designed to map domain names to IP addresses. Its success as a lightweight, well understood key-to-value mapping protocol caused its role to quickly grow to other Internet-related applications [88], including host integrity identification for anti-spam measures and replica selection in content-delivery networks [15]. Recently DNS's trust framework (DNSSEC) has been used to complement and extend traditional PKI/Certificate Authorities for e-mail [34] and TLS [39].

Protocols: DNS has always run over both connectionless UDP and connection-oriented TCP transport protocols. UDP has always been preferred, with TCP used primarily for zone transfers to replicate portions of the database, kilobytes or more in size, across different servers. Responses larger than

[1] This paper is a revision of the prior technical report ISI-TR-2014-693. We have added analysis of DNS's amplification attack and DNS server's performance under different attack scenarios with experiments (§ V). We believe these additions strengthen our claim that TCP reduces DoS attacks and it does not create new risks. This version also includes a number of editorial changes and clarifications throughout the body of the paper.

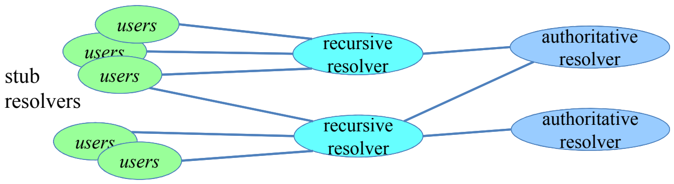


Fig. 1: *Stub*, *recursive*, and *authoritative* resolvers.

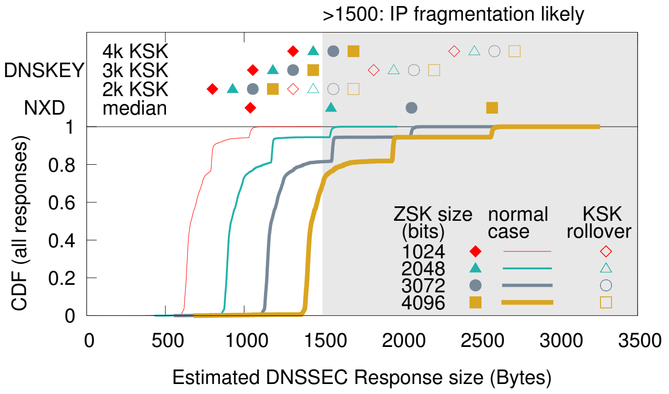


Fig. 2: Estimated response sizes with different length DNSSEC keys. Dots show sizes for DNSKEY and median for NXDomain replies. (Data: trace and modeling)

advertised limits are truncated, prompting clients to retry with TCP [86]. UDP can support large packets with IP fragmentation, at the cost of new problems discussed below.

The integrity of DNS data is protected by DNSSEC [4]. DNSSEC provides cryptographic integrity checking of positive and negative DNS replies, but not privacy. Since July 2010 the root zone has been signed, providing a root of trust through signed sub-domains.

As a Distributed System: DNS resolvers have both client and server components. Resolvers typically take three roles: stub, recursive, authoritative (Figure 1). *Stub resolvers* are clients that talk only to recursive resolvers, which handle name resolution. Stubs typically send to one or a few recursive resolvers, with configuration automated through DHCP [27] or by hand.

Recursive resolvers operate both as servers for stubs and clients to authoritative servers. Recursive resolvers work on behalf of stubs to iterate through each of the several components in a typical domain name, contacting one or more authoritative servers as necessary to provide a final answer to the stub. Much of the tree is stable and some is frequently used, so recursive resolvers *cache* results, reusing them over their *time-to-live*.

Authoritative servers provide answers for specific parts of the namespace (a *zone*). Replication between authoritative peers is supported through zone transfers with notifications and periodic serial number inquiries.

This three-level description of DNS is sufficient to discuss protocol performance for this paper. We omit both design and implementation details that are not relevant to our discussion. The complexity of implementations varies greatly [78]; we describe some aspects of one operator's implementation in § IV-A.

II-B The Limitations of Single-Packet Exchange

Our goal is to remove the limitations caused by optimizing DNS around a single-packet exchange as summarized in Table I. We consider transition in § III-D.

II-B1 Avoiding Arbitrary Limits to Response Size: Limitation in payload size is an increasing problem as DNS evolves to improve security. Without EDNS [21], UDP DNS messages are limited to 512 B. With EDNS, clients and servers may increase this limit (4096 B is typical), although this can lead to fragmentation which raises its own problems [49]. Due to problematic middleboxes, clients must be prepared to fall back to 512 B, or resend the query by TCP. Evidence suggests that 5% [91] or 2.6% [41] of users find TCP impeded. Such workarounds are often fragile and the complexities of incomplete replies can be a source of bugs and security problems [38].

Evolution of DNS and deployment of DNSSEC have pushed reply sizes larger. We studied Alexa top-1000 websites, finding that 75% have replies that are at least 738 B (see § A for details).

With increasingly larger DNS replies (for example, from longer DNSSEC keys), IP-level fragmentation becomes a risk in many or all replies. To quantify this problem, Figure 2 examines a 10-minute trace with 13.5M DNSSEC enabled responses of one server for .com. Over this real-world trace we model the effects of different key sizes by replacing current 1024-bit RSA signatures with longer ones. We model regular operation for several key sizes, showing CDFs for the size of all responses, and dots for negative responses (medians for NXD; quartiles are within 1% and so are omitted) using NSEC3 [52], and DNSKEY replies for several sizes of KSK (each row) and ZSK (different shapes, exact values).

Figure 2 shows that with a 2048-bit ZSK, 5% of DNSSEC responses and almost *all* NXDomain responses, and some DNSKEYs during rollover will suffer IP fragmentation (shown in the shaded region above 1500 B).

This evaluation supports our claim that connectionless transport *distorts current operational and security policies*. Worries about fragmentation have contributed to delay and concern about key rollover and use of 2048-bit keys. More importantly, other designs have been dismissed because of reply sizes, such as proposals to decentralize signing authority for the DNS root which might lead to requiring TCP for root resolution [82]. For some, this requirement for TCP is seen as a significant technical barrier forcing use of shorter keys or limitations of algorithms.

Finally, size can also *preempt future DNS applications*. Recent work has explored the use of DNS for managing trust relationships (for example [68]), so one might ask how DNS would be used if these constraints to response size

problem	**current DNS**	**with T-DNS** (why)
packet size limitations	guarantee: 512 B, typical: 1500 B	64 kB
source spoofing	spoof-detection depends on source ISP	most cost pushed back to spoofer (SYN cookies in TCP)
privacy (stub-to-recursive)	vulnerable to eavesdropping	privacy (from TLS encryption)
(recursive-to-authoritative)	aggregation at recursive	aggregation, or optional TLS

Table I: Benefits of T-DNS.

were removed. We examine the PGP web of trust [71] as a trust ecosystem that is unconstrained by packet sizes. Rather than a hierarchy, key authentication PGP builds a mesh of signatures, so 20% of keys show 10 or more signatures, and well connected keys are essential to connecting the graph. PGP public keys with 4 signatures exceeds 4kB, and about 40% of keys have 4 signatures or more [71]. If DNS either grows to consider non-hierarchical trust, or if it is simply used to store such information [94], larger replies will be important.

T-DNS's use of TCP replaces IP-level fragmentation with TCP's robust methods for retry and bytestream.

II-B2 Need for Sender Validation: Uncertainty about the source address of senders is a problem that affects both DNS servers and others on the Internet. Today source IP addresses are easy to spoof, allowing botnets to mount denial-of-service (DoS) attacks on DNS servers directly [42], [79], and to leverage DNS servers as part of an attack on a third party through a DNS Amplification attack [84], [55].

Work-arounds to DNS's role in DoS attacks exist. Many anti-spoofing mechanisms have been proposed, and DNS servers are able to rate-limit replies. T-DNS would greatly reduce the vulnerability of DNS to DoS and as DoS leverage against others. Well established techniques protect DNS servers from TCP-based DoS attacks [30], [81], and TCP's connection establishment precludes source address spoofing, eliminating amplification attacks.

We do not have data to quantify the number of DNS amplification attacks. However, measurements of source-IP spoofing shows that the number of networks that allow spoofing has been fairly steady for six years [9]. Recent measurement of distributed reflective denial-of-service (DRDoS) shows the majority of the attacks involve DNS amplification [76]. Recent reports of DoS show that DNS amplification is a serious problem, particularly in the largest attacks [3]. T-DNS suggests a long-term path to reduce this risk.

Even if TCP reduces DoS attacks, we must ensure it does not create new risks, as we show experimentally in § V. Fortunately TCP security is well studied due to the web ecosystem. We describe our approaches to DoS above, and most other known attacks have defenses. A more detailed list of TCP-specific attacks that do not apply is in § H.

II-B3 Need for DNS Privacy: Lack of protection for query privacy is the final problem. Traditionally, privacy of Internet traffic has not been seen as critical. However, recent trends in DNS use, deployment and documentation of widespread eavesdropping increase the need for query privacy [11]. First, end-user queries are increasingly exposed to possible eavesdropping, through use of third-party DNS services such as OpenDNS and Google Public DNS, and through access on open networks such as WiFi hotspots. Second, presence of widespread eavesdropping and misdirection is now well documented, for government espionage [37], censorship [2], and criminal gain [58]. Finally, ISPs have recognized the opportunity to monetize DNS typos, redirecting non-existing domain responses (NXDOMAIN hijacking), a practice widespread since 2009 (for example [59]). For both corporate or national observation or interference, we suggest that one must follow the policies of one's provider and obey the laws of one's country, but we see value in making those policies explicit by requiring interaction with the operator of the configured recursive name server, rather than making passive observation easy.

DNS is also important to keep private because it is used for many services. While protecting queries for IP addresses may seem unnecessary if the IP addresses will then immediately appear in an open IP header, full domain-names provide information well beyond just the IP address. For web services provided by shared clouds, the domain name is critical since IP addresses are shared across many services. DNS is also used for many things other than translating names to IP addresses: one example is anti-spam services where DNS maps e-mail senders to reputation, exposing some e-mail sources via DNS [53].

Although DNS privacy issues are growing, most DNS security concerns have focused on the *integrity* of DNS replies, out of fear of reply modification. The integrity of DNS replies has been largely solved by DNSSEC which provides end-to-end integrity checks.

II-C Threat Model

To understand security aspects of these problems we next define our threat model.

For *DoS attacks* exploiting spoofed source addresses, our adversary can send to the 30M currently existing open, recursive resolvers that lack ingress filtering [57].

For *query eavesdropping* and attacks on privacy, we assume an adversary with network access on the network between the user and the recursive resolver. We assume aggregation and caching at the recursive resolver provide effective anonymization to authoritative servers; if not it could enable TLS.

We also assume the operator of the recursive resolver is trusted. Although outside the scope of this paper, this requirement can be relaxed by alternating requests across several DNS providers, implementing a mix network shuffling requests from multiple users, or padding the request stream with fake queries.

	system			
feature	**T-DNS**	**unbound**	**DNSCrypt**	**DNSCurve**
signaling	in-band	implicit	implicit	per-query
protocol/port	TCP/53	TCP/443	TCP/443	UDP/53
encryption	negotiable	from TLS	Curve25519	
stub/recursive	yes	yes	yes	no
recursive/authoritative	yes	no	no	yes
pipelining	yes	no*	from UDP	
out-of-order replies	yes	no*	from UDP	
TCP Fast Open	yes	no	n/a	n/a
TLS resumption	yes	no	n/a	n/a

Table II: Design choices in T-DNS as compared to alternatives.

Similarly, privacy attacks using cache timing are outside our scope, but solved by request padding [43].

For *fragmentation attacks* due to limited packet size, we assume an off-path adversary that can inject packets with spoofed source addresses, following Herzberg and Schulman [38].

Other attacks on query integrity are already largely prevented by DNSSEC and so they are outside the scope of this paper. (T-DNS augments DNSSEC, it is not intended to replace it.)

We depend on existing mechanisms to avoid person-in-the-middle attacks on T-DNS setup of TLS as discussed in § III-B. Concurrent with our work, Shulman identified information leakage in encrypted DNS [80]. This paper seeks to close the *primary* channel; we recognize side channels remain.

T-DNS clients may set their own policy for handling *downgrade attacks*, where a request for privacy is declined. An adversary in control of the network can interfere with TLS negotiation, preventing its use. A conservative client may retry other servers or refuse to provide non-private DNS, or it may alert the user.

III. Design and Implementation of T-DNS

Table II lists design choices for T-DNS; next we describe in-band TLS negotiation (our protocol addition), and implementation choices that improve performance (shown in § VI). These design choice are critical to amortize the cost of connections.

III-A DNS over TCP

Design of DNS support for TCP was in the original specification [61] with later clarifications [6]. However, *implementations* of DNS-over-TCP have been underdeveloped because it is not seen today as the common case. We consider three implementation decisions, two required to to make TCP performance approach UDP.

Pipelining is sending multiple queries before their responses arrive. It is essential to avoid round-trip delays that would occur with the stop-and-wait alternative. Batches of queries are common: recursive resolvers with many clients have many outstanding requests to popular servers, such as that for .com. End-users often have multiple names to resolve, since most web pages draw resources from multiple domain names. We examined 40M web pages (about 1.4% of CommonCrawl-002 [36]) to confirm that 62% of web pages have 4 or more unique domain names, and 32% have 10 or more.

Support for *receiving* pipelined requests over TCP exists in `bind` and `unbound`. However neither *sends* TCP unless forced to by indication of reply truncation in UDP; and although explicitly allowed, we know of *no* widely used client that sends multiple requests over TCP. Our custom stub resolver supports pipelining, and we are working to bring T-DNS to the `getdns` resolver.

Out-of-order processing (OOOP) at recursive resolvers is another important optimization to avoid head-of-line blocking. TCP imposes an order on incoming queries; OOOP means replies can be in a different order, as defined and explicitly allowed by RFC-5966 [6]. Without OOOP, queries to even a small percentage of distant servers will stall a strictly-ordered queue, unnecessarily delaying all subsequent queries. (For UDP, absence of connections means all prominent DNS servers naturally handle queries with OOOP.)

We know of no DNS server today that supports out-of-order processing of TCP queries. Both `bind` and `unbound` instead resolve each query for a TCP connection before considering the next. We have implemented out-of-order processing in our DNS proxy (converting incoming TLS queries back to UDP at the server), and have a prototype implementation in `unbound`.

Finally, when possible, we wish to **shift state from server to client**. Per-client state accumulates in servers with many connections, as observed in the TIME-WAIT state overheads due to closed TCP connections previously observed in web servers [32]. Shifting TCP state with DNS is currently being standardized [95].

These implementation details are important not only to DNS; their importance has been recognized before in HTTP [62], [32]. HTTP/1.1 supports only pipelining, but both are possible in DNS and proposed HTTP/2 [64].

III-B DNS over TLS

TLS for DNS builds on TCP, with new decisions about trust, negotiation, and implementation choices.

III-B1 Grounding Trust: TLS depends on public-key cryptography to establish session keys to secure each connection and prevent person-in-the middle attacks [24]. DNS servers must be given TLS certificates, available today from many sources at little or no cost.

Client trust follows one of several current practices. We prefer DANE/TLSA to leverage the DNSSEC chain of trust [39], but other alternatives are the current public-key infrastructures (PKI) or trusted Certificate Authorities (CAs) provided out-of-band (such as from one's OS vendor or company). To avoid circular dependencies between T-DNS and DANE, one may bootstrap T-DNS's initial TLS certificate through external means (mentioned above) or with DANE without privacy.

III-B2 Upwards TLS Negotiation: T-DNS must negotiate the use of TLS. Earlier protocols selected TLS with separate ports, but IETF now encourages in-protocol upgrade to TLS to reduce port usage; this approach is the current preference for many protocols (IMAP, POP3, SMTP, FTP, XMPP, LDAP, and NNTP, although most of these do have legacy, IANA-allocated, but not RFC-standardized, ports to indicate TLS, XMPP, the most recent, being an exception). to indicate TLS). We therefore propose a new EDNS0 extension [21] to negotiate the use of TLS. We summarize our proposal below and have provided a formal specification elsewhere [40].

Our negotiation mechanism uses a new "TLS OK" (TO) bit in the extended flags of the EDNS0 OPT record. A client requests TLS by setting this bit in a DNS query. A server that supports TLS responds with this bit set, then both client and server carry out a TLS handshake [24]. The TLS handshake generates a unique session key that protects subsequent, normal DNS queries from eavesdropping over the connection.

The DNS query made to start TLS negotiation obviously is sent without TLS encryption and so should not disclose information. We recommend a distinguished query with name "STARTTLS", type TXT, class CH, analogous to current support queries [93].

Once TLS is negotiated, the client and server should retain the TLS-enabled TCP connection for subsequent requests. Either can close connections after moderate idle periods (evaluated in § IV), or if resource-constrained.

III-B3 Implementation Optimizations: Two implementation choices improve performance. TLS **connection resumption** allows the server to give all state needed to securely re-create a TLS connection to the client [77]. This mechanism allows a busy server to discard state, yet an intermittently active client can regenerate that state more quickly than a full, fresh TLS negotiation. A full TLS handshake requires three round-trip exchanges (one for TCP and two for TLS); TLS resumption reduces this cost to two RTTs, and reduces server computation by reusing the master secret and ciphersuite. Experimentally we see that resumption is $10\times$ faster than a new connection (§ VI-A).

TLS close notify allows one party to request the other to close the connection. We use this mechanism to shift TCP TIME-WAIT management to the client.

III-C Implementation Status

We have several implementations of these protocols. Our primary client implementation is a custom client resolver that we use for performance testing. This client implements all protocol options discussed here and uses either the OpenSSL or GnuTLS libraries. We also have some functionality in a version of `dig`.

We have three server implementations. Our primary implementation is in a new DNS proxy server. It provides a minimally invasive approach that allows us to test any recursive resolver. It receives queries with all of the options described here, then sends them to the real recursive resolver via UDP. When the proxy and real resolver are on the same machine or same LAN we can employ unfragmented 9 kB UDP packets, avoid size limitations and exploiting existing OOOP for UDP. It uses either the OpenSSL or GnuTLS libraries.

In the long run we expect to integrate our methods into existing resolvers. We have implemented subsets of our approach in BIND-9.9.3 and unbound-1.4.21.

III-D Gradual Deployment

Given the huge deployed base of DNS clients and servers and the complexity of some implementations [91], any modifications to DNS will take effect gradually and those who incur cost must also enjoy benefits. We discuss deployment in detail elsewhere § G since the length of full discussion forces it outside the scope of the body of this report, but we summarize here.

T-DNS deployment is *technically feasible* because our changes are backwards compatible with current DNS deployments. TLS negotiation is designed to disable itself when either the client or server is unaware, or if a middlebox prevents communication. Approaches analogous to DNSSEC-trigger [63] may be used to bootstrap through temporarily interfering middleboxes, and can report long-term interference, prompting middlebox replacement or perhaps circumvention using a different port. In the meantime, individuals may select between immediately correcting the problem or operating with DNS privacy. DNS already supports TCP, so clients and servers can upgrade independently and will get better performance with our implementation guidelines. T-DNS benefits from TCP extensions like fast-open that are only very recently standardized [18], so T-DNS performance depends their deployment (Fast Open is in Linux-3.7 since December 2012). Gradual deployment does no harm; as clients and servers upgrade, privacy becomes an option and performance for large responses improves.

Motivation for deployment stems from T-DNS's privacy and DoS-mitigation. Some users today want greater privacy, making it a feature ISPs or public DNS-operators can promote. The DoS-mitigation effects of TCP allows DNS operators to reduce their amount of capacity overprovisioning to handle DoS. T-DNS's policy benefits from size require widespread adoption of TCP, but the penalty of slow adoption is primarily lower performance, so complete deployment is not necessary.

T-DNS deployment is feasible and motivations exist for deployment, but the need for changes to hardware and software suggests that much deployment will likely follow the natural hardware refresh cycle.

IV. Connection Reuse and Resources

Connection reuse is important for T-DNS performance to amortize setup over multiple queries (§ VI). Reuse poses a fundamental trade-off: with plentiful resources and strict latency needs, clients prefer long-lived connections. But servers share resources over many clients and prefer short-lived connections.

We next examine this trade-off, varying connection timeout to measure the *connection hit fraction*, how often an existing connection can be reused without setup, and *concurrent connections*, how many connections are active on a server at any time. We relate active connections to server resource use.

dataset	date	client IPs	records
DNSChanger	2011-11-15		
all-to-one		15k	19M
all-to-all		692k	964M
DITL/Level 3	2012-04-18		
cns4.lax1		282k	781M
cns[1-4].lax1		655k	2412M
DITL/B-root	2013-05-29	3118k	1182M

Table III: Datasets used to evaluate connection reuse and concurrent connections. Each is 24 hours long.

IV-A Datasets

We use three different datasets (Table III) to stand in for stub clients, recursive resolvers, and authoritative servers in our analysis. These datasets are derived from server logging (Level3) or packet capture (the others). While more data is always better, we believe our data captures very diverse conditions and more data is very unlikely to change the conclusions.

DNSChanger: DNSChanger is a malware that redirects end-users' DNS resolvers to a third party so they could inject advertising. This dataset was collected by the working group that, under government authority, operated replacement recursive resolvers while owners of infected computers were informed [58]. It includes timing of all queries from end-user IP addresses with this malware as observed at the working group's recursive resolvers. We use this dataset to represent stub-to-recursive traffic, and select traffic to the busiest server (all-to-one) in § IV-C and the traffic from all sources to all servers (all-to-all) in § VI-D. (We know of no public sources of stub-to-recursive data due to privacy concerns.)

DITL/Level 3: Level 3 operates DNS service for their customers, and also as an open public resolver [74]. Their infrastructure supports 9 sites, each with around 4 front-end recursive resolvers, each load-balanced across around 8 back-end resolvers, as verified by the operators. We use their 48-hour trace hosted by DNS-OARC [26].

We examine two subsets of this data. We first select a random site (lax1, although we confirmed other sites give similar results). Most client IP addresses (89%) access only one site, so we expect to see all traffic for each client in the dataset (`cns[1-4].lax1`). Many clients (75%) only access one front-end at a site, so we select the busiest front-end at this site (`cns4.lax1`) to provide a representative smaller (but still large) subset. We use these Level 3 traces to represent a recursive resolver.

DITL/B-Root: This dataset was collected at the B-Root nameserver as part of DITL-2013 and is also provided through DNS-OARC. We selected B-Root because at the time of this collection it did not use anycast, so this dataset captures all traffic into one root DNS instance. (Although as one of 13 instances it is only a fraction of total root traffic.) We use this traffic to represent an authoritative server, since commercial authoritative server data is not generally accessible.

Generality: These datasets cover each class of DNS resolver (Figure 1) and so span the range of behavior in different parts of the DNS system and evaluate our design. However, each dataset is unique. We do not claim that any represents *all* servers of that class, and we are aware of quirks in each dataset. In addition, we treat each source IP address as a computer; NAT may make our analysis optimistic, although this choice is correct for home routers with DNS proxies.

IV-B Trace Replay and Parameterization

To evaluate connection hits for different timeout windows we replay these datasets through a simple simulator. We simulate an adjustable timeout window from 10 to 480 s, and track active connections to determine the number of concurrent connections and the fraction of connection hits. We ignore the first 10 minutes of trace replay to avoid transient effects due to a cold cache.

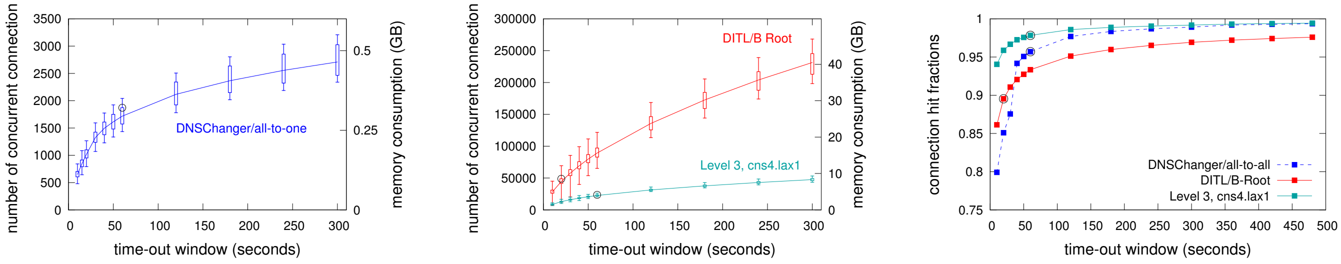
We convert the number of concurrent connections to hardware memory requirements using two estimates. First, we measure memory experimentally idle TCP connections by opening 10k simultaneous connections to `unbound` and measuring peak heap size with `valgrind`. On a 64-bit x86 computer running Fedora 18, we estimate TCP connection at 260 kB, and each TLS connection at 264 kB; to this we estimate about 100 kB kernel memory, yielding 360 kB as a very loose upper bound. Second, Google transitioned gmail to TLS with no additional hardware through careful optimizations, reporting 10 kB memory per connection with minimal CPU cost due to TLS [51]. Based on their publicly available optimizations, we use a conservative 150 kB as the per connection memory cost.

IV-C Concurrent Connections and Hit Fraction

Trace replay of the three datasets provides several observations. First we consider how usage changes over the course of the day, and we find that variation in the number of active connections is surprisingly small. When we measure counts over one-second intervals, connections vary by ±10% for Level 3, with slightly more variation for DNSChanger and less for B-Root (graphs omitted due to space). Connection hit fractions are even more stable, varying by only a few percent. Given this stability, Figure 3 summarizes usage with medians and quartiles. (§ C shows raw data.)

The three servers have very different absolute numbers of active connections, consistent with their client populations. (Figure 3a DNSChanger: for this dataset, a few thousand uncorrected users; Figure 3b: Level 3: many thousand customers per site and B-Root: potentially any global recursive resolver).) All servers show asymptotic hit fractions with diminishing benefits beyond timeouts of around 100 s (Figure 3c). The asymptote varies by server: with a 120 s window, DNSChanger is at 97-98%, Level 3 at 98-99%, and B-Root at 94-96%. These fractions show that *connection caching will be very successful*. Since much network traffic is bursty, it is not surprising that caching is effective.

Finally, comparing the authoritative server (B-Root) with recursive resolvers, we see the ultimate hit fraction is consid-



(a) Median and quartiles of numbers concurrent connections. Dataset: DNSChanger

(b) Median and quartiles of numbers concurrent connections. Datasets: Level 3/cns4.lax1 and B-Root

(c) Median connection hit fractions, taken server-side. (Quartiles omitted since always less than 1%.)

Fig. 3: Evaluation of concurrent connections and connection hit fractions. Black circles show design point.

erably smaller (consistently several percent lower for a given timeout). We believe the lower hit fraction at B-Root is due to its diverse client population and is relatively small zone. We expect this result will hold for servers that provide static DNS zones. (DNS servers providing dynamic content, such as blackhole lists, are likely to show different trends.)

Recommendations: We propose timeouts of 60 s for recursive resolvers and 20 s for authoritative servers, informed by Figure 3, with a conservative approach to server load. We recommend that clients and servers not preemptively close connections, but instead maintain them for as long as they have resources. Of course, timeouts are ultimately at the discretion of the DNS operator who can experiment independently.

These recommendations imply server memory requirements. With 60 s and 20 s timeouts for recursive and authoritative, each DNSChanger needs 0.3 GB RAM (2k connections), Level 3 3.6 GB (24k connections), and B-Root 7.4 GB (49k connections), based on the 75%iles in Figure 3, for both user and kernel memory with some optimization, in addition to memory for actual DNS data. These values are well within current, commodity server hardware. With Moore's law, memory is growing faster than root DNS traffic (as seen in DITL [17]), so future deployment will be even easier. Older servers with limited memory may instead set a small timeout and depend on clients to use TCP Fast Open and TLS Resume to quickly restart terminated connections.

V. Performance Under Attack

We next consider the role of DNS in denial-of-service attacks: first DNS's role in attacking others through amplification attacks, then the performance of a DNS server itself under attack. In both cases we show that TCP mitigates the problem, and that TLS does not make things worse.

V-A DNS: Amplifying Attacks on Others

Recently, amplification attacks use DNS servers to magnify attack effects against others [84], [55]. An attacker's botnet spoofs traffic with a source address of the victim, and the DNS server amplifies a short query into a large reply.

Table IV shows our measurements of amplification factors of three classes of attacks: DNS over UDP, and DNS over TCP without and with SYN cookies. DNS allows an attacker to turn a short UDP request into a large UDP reply, amplifying the attack by a factor of up to 40. TCP can amplify an attack as well, since a single SYN can solicit multiple SYN-ACKs attempts [50], but only by a factor of 6. With SYN cookies, TCP does not retransmit SYN-ACKs, so there is no amplification for the attacker.

	DNS	TCP-SYNs	
action	(UDP)	no cookies	w/cookies
query	82 B	76 B	76 B
reply	200–4096 B	66–360 B	66 B
amplification	3–40×	1–6×	1×

Table IV: Amplification factors of DNS/UDP and TCP with and without SYN cookies.

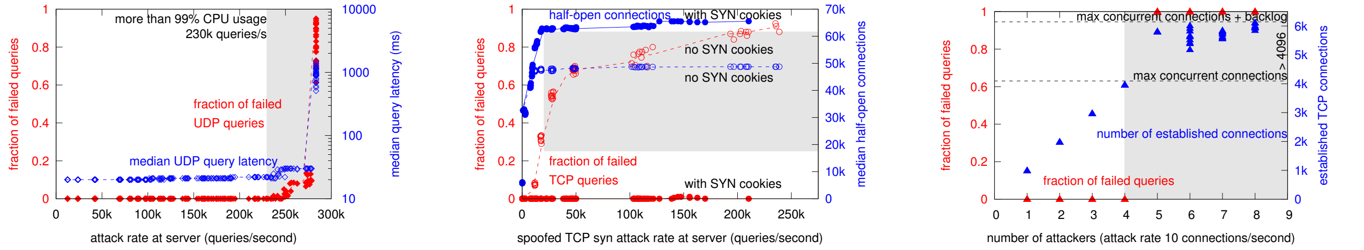
DoS-prevention also requires rate limiting, which can help defuse UDP-based amplification. Such rate limiting will be important during a potential transition from UDP to TCP for DNS: wide use of TCP can allow more aggressive rate limits for TCP, as we show in § V-B, and partial use of TCP can allow more aggressive rate limiting, as we discuss next.

We conclude that, although TCP does not eliminate DoS attacks, full use of TCP eliminates amplification of those attacks, and partial use of TCP allows more aggressive rate limiting during transition.

V-B Direct Denial-of-Service on the DNS Server

We next consider UDP and TCP attacks designed to overwhelm the DNS server itself. While some DoS attacks overwhelm link bandwidth, UDP attacks on DNS often target server CPU usage, and TCP attacks overwhelm OS-limits on active connections. Current DNS operators greatly overprovision to absorb attacks, with best-practices recommending a factor of three [13]. We next aim to show that UDP attacks are a threat, and attacks on a naive TCP service are deadly, but a TCP service using TCP SYN cookies forces attackers to use far more resources than today.

To evaluate a DoS attack, we deploy the network shown in Figure 4 in the DETER testbed. We send foreground traffic



(a) UDP-based DNS performance under DoS attack.

(b) TCP-based DNS performance under spoofed DoS attack, with (filled circles) and without (empty circles) SYN cookies.

(c) TCP-based DNS performance with non-spoofed DoS attack.

Fig. 5: Evaluation of denial-of-service attacks on DNS servers. Dataset: testbed experiment

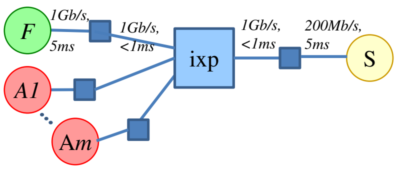


Fig. 4: Network topology for DoS attack evaluation: legitimate (F), attackers (A), and server (S).

	attacker		**foreground**	
protocol	**src IP**	**cookies**	**protocol**	**resource limit**
UDP	spoofed	n/a	UDP	CPU
TCP	spoofed	no	TCP	TCP control buffers
TCP	spoofed	yes	TCP	TCP control buffers
TCP	real	yes	TCP	TCP control buffers

Table V: Limited resource for each protocol combination in tested DoS attacks.

from *F* to a DNS server *S*, then evaluate the effects of attack traffic (*A1* to *Am*) sent to the server. The traffic merges at a router (IXP, an Internet Exchange Point) and is sent to the server behind a bottleneck link. The server hosts a DNS domain with 6.5M names in `example.com`, and the attacker queries random names that exist in this domain. The server is a single-core 2.4 GHz Intel Xeon running Linux Ubuntu-14.04 (64-bit). This scenario (hardware and network speeds) represents a scaled down version of a typical deployment.

We compare several combinations of protocols for attacker and legitimate, foreground traffic (Table V). We focus on all-UDP traffic and three cases of all-TCP use to compare current DNS with proposed TCP deployments. While the future will include both TCP and UDP usage, these two “pure” cases show the limits. We use NSD-4.1.0 as our DNS server, with the OS and application configured to support either 65k or 4k TCP sessions. Since we are only testing connection initiation, we do not use persistent connections or TCP fast-open. Foreground traffic is sent with the `dig` program. Attack traffic uses a custom-written UDP/TCP flooder or `hping3`; we vary the number of attackers and measure the observed attack rate. For each kind of attack scenario, we repeat the experiment for 10 times.

UDP-based DNS under attack: First we consider a current DNS where all traffic is UDP. A UDP receiver cannot verify source addresses, so an attacker will spoof query source addresses to defeat source-based rate-limiting or filtering. Servers must reply to both foreground and attack queries; the attacker exploits this to exhaust either host processing power or network capacity in the reverse path. In the experiment, two attackers can easily DoS the server if not network-limited (we pace the attackers to study a range of rates). In Figure 5a we see that our server handles about 230k queries/s at full capacity (CPU limited in the gray region). Both reply latency for completed queries (dashed blue line and right axis) and the number of unanswered queries (solid red line and left axis) rise dramatically under overload. These results are typical of DNS servers under DoS attacks that are not limited by network speed; they show why robust DNS operations are heavily overprovisioned.

DNS-over-TCP under attack: Next we consider three variations of a TCP SYN-flood attack in Figure 5b. Here, the attacker’s goal is to exhaust the number of available TCP connections on the server (right axis), resulting in unanswered queries (left axis).

First, we allow the attacker to spoof source addresses and operate the server without SYN cookies. By default, half-open connections persist for tens of seconds, and legitimate queries must compete with attack traffic for connection slots. In Figure 5b, without SYN cookies on the server (lines with empty circles), a single attacker can easily send 60k SYN/s and consume all possible TCP connections on the server, resulting in 70% of foreground queries being dropped. With SYN cookies (lines with filled circles), all state is pushed back on the sender, so *attack traffic consumes no memory at the server* and *no* foreground replies are lost.

Finally we consider a TCP SYN-flood attack without spoofed addresses. A wise server will use SYN cookies to prevent spoofed attacks, and will rate-limit new connections to bound non-spoofed attacks. If we rate-limit to 10 new connections/s per IP address (for DNS with p-TCP, there should never be more than 1 active connection per IP), and the server has 60k TCP connection slots, then it requires 6k attackers to fully consume the server's connections. In experiment we test a scaled-down version of this scenario: attackers are limited to 10 connection/s and the server supports 4096 active connections. Figure 5c shows the outcome: 5 attackers are required to consume most connection slots, at which point *all* legitimate traffic is dropped. Although this experiment is scaled down to fit our testbed, full-scale server would support 60k connections or more. With SYN cookies against spoofers and rate limiting to 1 TCP connection per source-IP when under attack, a single server can tolerate thousands of attackers, many times what are required for a UDP attack. Large DNS providers often serve from clusters of machines, requiring even more attackers.

A final threat is attacks on TLS, with the goal of consuming server CPU [7]. Since TLS handshakes are expensive, we expect servers to adopt strict rate limits per source address, perhaps 4 TLS connections/s per IP address. A 2006 study shows that a server with a PIII-933 MHz, dual CPU can handle more than 1000 TLS connections/s with optimizations [20] (we expect this number to be much larger on current hardware), requiring an attacker with 250 machines. Since we require non-spoofed addresses, active filtering to these attacks become possible. *A DoS attacker requires more resources against an all-TLS DNS server* when compared to an all-UDP DNS server. We know that TLS-based websites survive DoS attacks, suggesting TLS-based DNS can as well.

To summarize, we show that TCP with SYN cookies and TLS greatly increase the work factor for an attacker to overwhelm the DNS server itself, compared with UDP. Our experiments use a moderate-size DNS server, but this work-factor increase means it is even harder for attacker to defeat large DNS deployments such as authoritative servers for large zones. With the overhead and performance optimizations we describe, large-size servers should find TCP and TLS both feasible and highly beneficial to the mitigation of DoS attacks.

VI. Client-side Latency

For clients, the primary cost of T-DNS is the additional latency due to connection setup. Using experiments, we next examine stub-to-recursive and recursive-to-authoritative query latency with TCP and TLS, highlighting the effects of pipelining and out-of-order processing. Three parameters affect these results: the *computation time* needed to execute a query, the *client-server RTT*, and the *workload*. We show that RTTs dominate performance, not computation. We study RTTs for both stub-to-recursive and recursive-to-authoritative queries, since the RTT is much larger and more variable in the second case. We consider two workloads: *stop-and-wait*, where each query is sent after the reply for the last is received, and *pipelining*, where the client sends queries as fast as possible. These experiments support modeling of end-to-end latency.

step	**OpenSSL**	**GnuTLS**	**DNSCrypt/ DNSCurve**
TCP handshake	0.15 ms		none
packet handling	0.12 ms		none
crypto handshake	25.8 ms	8.0 ms	23.2 ms
key exchange	13.0 ms	6.5 ms	—
CA validation	12.8 ms	1.5 ms	—
crypto resumption	1.2 ms	1.4 ms	no support
DNS resolution	0.1–0.5 ms	same	same
crypto	∼1 ms		0.7–1.8 ms

Table VI: Computational costs of connection setup and packet processing.

VI-A Computation Costs

We next evaluate CPU consumption of TLS. Our experiments' client and server are 4-core x86-64 CPUs, running Fedora 19 with Linux-3.12.8 over a 1Gb/s Ethernet. We test our own client and the Apache-2.4.6 web-server with GnuTLS and OpenSSL. We also measure the DNSCurve client [56], and the DNSCrypt proxy [66].

We report the median of 10 experimental trials, where each trial is the mean of many repetitions because each event is brief. We measure 10k TCP handshakes, each by setting up and closing a connection. We estimate TCP packet processing by sending 10k full-size packets over an existing connection. We measure TLS connection establishment from 1000 connections, and isolate key exchange from certificate validation by repeating the experiment with CA validation disabled. We measure TLS connection resumption with 1000 trials.

Table VI compares TLS costs: TCP setup and DNS resolution are fast (less than 1 ms). TLS setup is more expensive (8 or 26 ms), although costs of key exchange and validation vary by implementation. We see that TLS resumption is ten times faster than full TLS setup for both OpenSSL and GnuTLS.

We also examine DNSCurve and DNSCrypt cost in Table VI and find similar computation is required for their session key establishment. Their client and server can cache session keys to avoid this computation, but at the expense of keeping server state, just as T-DNS keeps TCP and TLS state. If elliptic curve cryptography has performance or other advantages, we expect it to be added to future TLS protocol suites.

Finally, prior work has reported server rates of 754 uncached SSL connections per second [10]. These connection rates sustain steady state for recursive DNS, and two servers will support steady state for our root server traces. Provisioning for peaks would require additional capacity.

Although TLS is computationally expensive, *TLS computation will not generally limit DNS*. For clients, we show (§ VI-E) that RTT dominates performance, not computation. Most DNS servers today are bandwidth limited and run with very light CPU loads. We expect server memory will be a larger limit than CPU. While our cost estimation is very promising, we are still in the progress of carrying out full-scale experimental evaluation of T-DNS under high load.

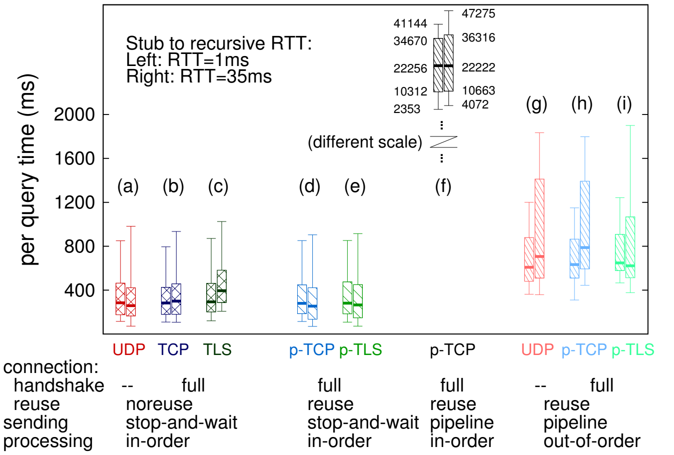


Fig. 6: Per-query response times with a cold cache for 140 unique names with different protocol configurations and two stub-to-recursive RTTs (1 ms and 35 ms). Boxes show median and quartiles. Case (f) uses a different scale.

VI-B Latency: Stub-to-Recursive Resolver

We next carry out experiments to evaluate the effects of T-DNS on DNS use between stub and both local and public recursive resolvers.

Typical RTTs: We estimate typical stub-to-recursive resolver RTTs in two ways. First, we measure RTTs to the local DNS server and to three third-party DNS services (Google, OpenDNS, and Level3) from 400 PlanetLab nodes. These experiments show ISP-provided resolvers have very low RTT, with 80% less than 3 ms and only 5% more than 20 ms. Third-party resolvers vary more, but anycast keeps RTT moderate: median RTT for Google Public DNS is 23 ms, but 50 ms or higher for the "tail" of 10–25% of stubs; other services are somewhat more distant. Second, studies of home routers show typical RTTs of 5-15 ms [83].

Methodology: To estimate T-DNS performance we experiment with a stub resolver with a nearby (1 ms) and more distant (35 ms) recursive resolver (values chose to represent typical extremes observed in practice). We use our custom DNS stub and the BIND-9.9.3 combined with our proxy as the recursive. For each protocol (UDP, TCP, TLS), the stub makes 140 unique queries, randomly drawn from the Alexa top-1000 sites [1] with DNS over that protocol. We restart the recursive resolver before changing protocols, so each protocol test starts with a known, cold cache. We then vary each combination of protocol (UDP, TCP, and TLS), use of pipelining or stop-and-wait, and in-order and out-of-order processing. Connections are either *reused*, with multiple queries per TCP/TLS connection (p-TCP/p-TLS), or *no reuse*, where the connection is reopened for each query. We repeat the experiment 10 times and report combined results.

Cold-Cache Performance: Figure 6 shows the results of these experiments. We see that UDP, TCP, and TLS performance is generally similar when other parameters are held consistent (compare (a), (b), and (c), or (g), (h), and (i)). Even when the RTT is 35 ms, the recursive query process still dominates protocol choice and setup costs are moderate. The data shows that out-of-order processing is essential when pipelining is used; case (f) shows head-of-line blocking compared to (h). This case shows that while current servers support TCP, our optimizations are necessary for high performance. Pipelining shows higher latency than stop-and-wait regardless of protocol (compare (g) with (a) or (i) with (c)). This difference occurs when 140 simultaneous queries necessarily queue at the server when the batch begins; UDP is nearly equally affected as TCP and TLS (compare (i) and (h) with (g)). Finally, we see that the costs of TLS are minimal here: comparing (c) with (b) and (a) or (i) with (g) and (h), natural variation dominates performance differences.

Warm-Cache Performance: Cold-cache performance is dominated by communication time to authoritative name servers. For queries where replies are already cached this communication is omitted and connection setup times become noticeable. For connection handling, performance of cache hits are equivalent to authoritative replies, so our recursive-to-authoritative experiments in § VI-C represent warm-cache performance with 100% cache hits. (We verified this claim by repeating our stub-to-recursive experiment, but making each query twice and reporting performance only for the second query that will always be answered from the cache.) While cache hits are expensive when they must start new connections, persistent connections *completely* eliminate this overhead (Figure 7, cases (e) and (f) compared to (a)). In addition, median TCP out-of-order pipelined connections (cases (h) and (i)) are slightly faster than UDP (case (g)) because TCP groups multiple queries into a single packet.

We conclude that *protocol choice makes little performance difference between stub and recursive* provided RTT is small and connections is not huge and connection reuse is possible. This result is always true with cold caches, where connection setup is dwarfed by communication time to authoritative name servers. This result applies to warm caches provided connections can be often reused or restarted quickly. We know that connections can be reused most of the time (§ IV-C), and TCP fast open and TLS resumption can reduce costs when they are not reused. A more detailed discussion of these experiments can be found in § D-A.

VI-C Latency: Recursive to Authoritative

We next consider performance between recursive resolvers and authoritative name servers. While recursives are usually near stubs, authoritative servers are globally distributed with larger and more diverse RTTs.

Typical RTTs: To measure typical recursive-to-authoritative RTTs, we use both the Alexa top-1000 sites, and for diversity, a random sample of 1000 sites from Alexa top-1M sites. We query each from four locations: our institution in Los Angeles (isi.edu), and PlanetLab sites in China (www.pku.edu.cn), UK (www.cam.ac.uk), and Australia (www.monash.edu.au). We query each domain name

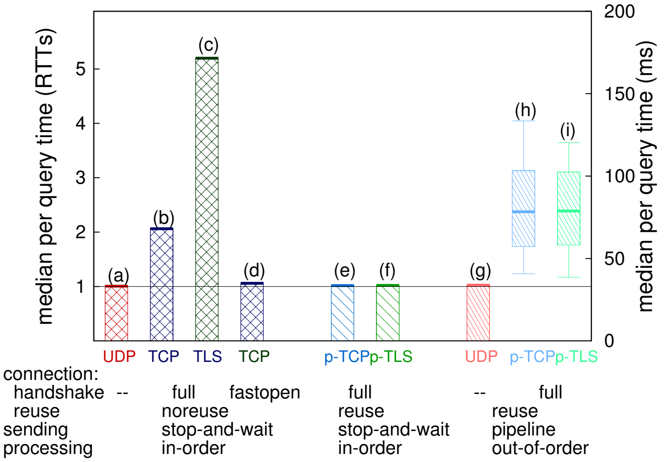


Fig. 7: Per-query response times for 140 repeated queries with different protocols, measured in RTTs (left axis) and ms (right). (Medians; boxes add quartiles.)

iteratively and report the time fetching the last component, taking the median of 10 trials to be robust to competing traffic and name server replication. We measure query time for the last component to represent caching of higher layers.

The U.S. and U.K. sites are close to many authoritative servers, with median RTT of 45 ms, but a fairly long tail with 35% of RTTs exceeding 100 ms. Asian and Australian sites have generally longer RTTs, with only 30% closer than 100 ms (China), and 20% closer than 30 ms (Australia), while the rest are 150 ms or more. This jump is due to the long propagation latency for services without sites physically in these countries. (See Figure 17 for data.)

Methodology: To evaluate query latencies with larger RTTs between client and server, we set up a DNS authoritative server (BIND-9.9.3) for an experimental domain (example.com) and query it from a client 35 ms (8 router hops on a symmetric path) away. Since performance is dominated by round trips and not computation we measure latency in units of RTT and these results generalize to other RTTs. For each protocol, we query this name server directly, 140 times, varying the protocol in use. As before, we repeat this experiment 10 times and report medians of all combined experiments (Figure 7). Variation is usually tiny, so standard deviations are omitted except for cases (h) and (i).

Performance: Figure 7 shows the results of this experiment. We first confirm that performance is dominated by protocol exchanges: cases (a), (b) and (c) correspond exactly to 1, 2, and 5 RTTs as predicted. Second, we see the importance of connection reuse or caching: cases (e) and (f) with reuse have *identical* performance to UDP, as does TCP fast open (case (d)).

As before, pipelining for TCP shows a higher cost because the 140 queries queue behind each other. Examination of packet traces for cases (h) and (i) shows that about 10% of queries complete in about 1 RTT, while additional responses arrive in batches of around 12, showing stair-stepped latency.

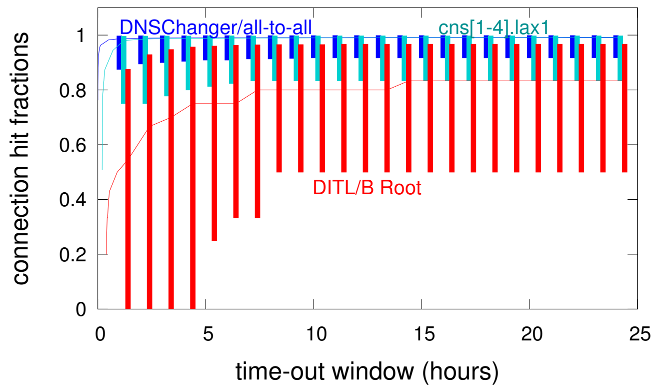


Fig. 8: Median client-side connection hit fractions with quartiles with larger time-out windows

For this special case of more than 100 queries arriving simultaneously, a single connection adds some latency.

We next consider the cost of adding TLS for privacy. The community generally considers aggregation at the recursive resolver sufficient for anonymity, but TLS may be desired there for additional privacy or as a policy [31] so we consider it as an option. Without connection reuse, a full TLS query always requires 5 RTTs (case (c), 175 ms): the TCP handshake, the DNS-over-TLS negotiation (§ III-B2), two for the TLS handshake, and the private query and response.

However, once established TLS performance is *identical* to UDP: cases (f) and (a) both take 1 RTT. Encryption's cost is tiny compared to moderate round-trip delays when we have an established connection. We expect similar results with TLS resumption.

Finally, when we add pipelining and out-of-order processing, we see similar behavior as with TCP, again due to how the large, batched queries become synchronized over a single connection.

We conclude that RTTs completely dominate recursive-to-authoritative query latency. We show that connection reuse can eliminate connection setup RTT, and we expect TLS resumption will be as effective as TCP fast-open. We show that TCP is viable from recursive-to-authoritative, and TLS is also possible. A more detailed discussion of these experiments can be found in § D-B.

VI-D Client connection-hit fractions

Connection reuse is important and § IV-C found very high reuse from the server's perspective. We next show that *client* connection-hit fractions are lower because many clients query infrequently.

To evaluate client connection hit fractions, we replay our three DNS traces through the simulator from § IV-C, but we evaluate connection hit fractions per client. Figure 9 shows these results, with medians (lines) and quartiles (bars, with slight offset to avoid overlap).

Among the three traces, the DNSChanger hit fraction exceeds Level 3, which exceeds B-Root, because servers further

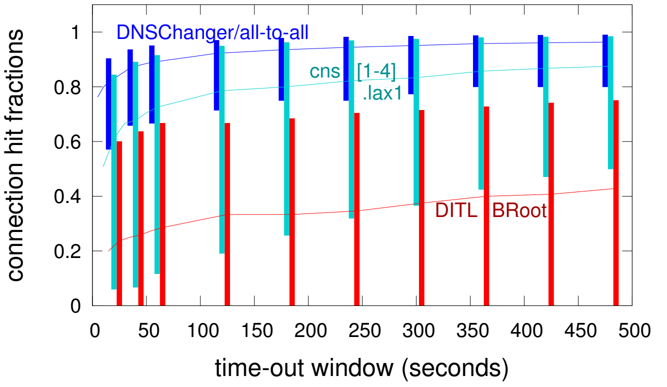


Fig. 9: Median client-side connection hit fractions with quartiles.

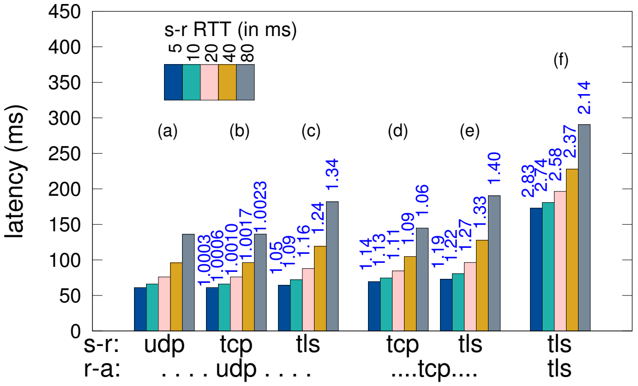


Fig. 10: End-to-end-performance as a function of protocol choice and stub-to-resolver RTT

up the hierarchy see less traffic from any given client. We see that the top quartile of clients have high connection hit fractions for all traces (at 60 s: 95% for DNSChanger, 91% for Level 3, and 67% for B-Root). The connection hit rate for the median client is still fairly high for DNSChanger and Level 3 (89% and 72%), but quite low for B-Root (28%). Since most B-Root content can be cached, many clients only contact it infrequently and so fail to find an open connection.

These results suggest that clients making few requests will need to restart connections frequently. Fortunately TCP Fast Open and TLS Resumption allow these clients to carry the state needed to accelerate this process.

VI-E Modeling End-to-End Latency for Clients

With this data we can now model the expected *end-to-end* latency for DNS users and explore how stub, recursive and authoritative resolvers interact with different protocols and caching. Our experiments and measurements provide parameters and focus modeling on connection setup (both latency and CPU costs). Our model captures clients restarting connections, servers timing out state, and the complex interaction of stub, recursive, and authoritative resolvers. Our modeling has two limitations. First, we focus on typical latency for *users, per-query*; the modeling reflects query frequency, emphasizing DNS provisioning for common queries and reflecting queries to rare sites only in proportion to their appearance in our traces. We do not evaluate mean latency per-site, since that would be skewed by rarely used and poorly provisioned sites. Second, our models provide mean performance; they cannot directly provide a full distribution of response times and "tail" performance [22]. We are interested in using trace replay to determine a full distribution with production-quality servers, but as significant future work.

Modeling: We model latency from client to server, $L_{c\sigma}$, as the probability of connection reuse ($P^C_{c\sigma}$) and the cost of setting up a new connection ($S^C_{c\sigma}$) added to the the cost of the actual query ($Q_{c\sigma}$):

$$L_{c\sigma} = (1 - P^C_{c\sigma})S^C_{c\sigma} + Q_{c\sigma} \tag{1}$$

From Figure 7, $Q_{c\sigma}$ is the same for all methods with an open connection: about one client-server RTT, or $R_{c\sigma}$. Setup cost for UDP ($S^{C,udp}_{c\sigma}$) is 0. With the probability for TCP fast-open (TFO), $P^{TFO}_{c\sigma}$, TCP setup costs:

$$S^{C,tcp}_{c\sigma} = (1 - P^{TFO}_{c\sigma})R_{c\sigma} \tag{2}$$

We model TLS setup ($S^{C,tls}_{c\sigma}$) as the probability of TLS resumption ($P^{RE}_{c\sigma}$) and its cost $S^{C,tls_r}_{c\sigma}$, or the cost of setting up a completely new TLS connection $S^{C,tls_n}_{c\sigma}$:

$$S^{C,tls}_{c\sigma} = P^{RE}_{c\sigma}S^{C,tls_r}_{c\sigma} + (1 - P^{RE}_{c\sigma})S^{C,tls_n}_{c\sigma} \tag{3}$$

For simplicity, we assume TCP fast open and TLS resumption have the same timeout, so $P^{RE}_{c\sigma} = P^{TFO}_{c\sigma}$. Thus, $S^{C,tls_r}_{c\sigma}$ is $2R_{c\sigma} + S^{cpu_r}_{\sigma}$ (1 each for TLS negotiation and handshake) and $S^{C,tls_n}_{c\sigma}$ is $4R_{c\sigma} + S^{cpu_n}_{\sigma}$ (1 for TCP, 1 for TLS negotiation, and 2 for TLS handshake). We set $S^{cpu_n}_{\sigma}$ at 25.8 ms and $S^{cpu_r}_{\sigma}$ is at 1.2 ms(Table VI, with and without CA validation). We estimate $P^C_{c\sigma}$, $P^{RE}_{c\sigma}$ and $P^{TFO}_{c\sigma}$ from our timeout window and trace analysis (Figures 8 and 9).

To compute end-to-end latency (stub-to-authoritative, L_{sa}), we combine stub-to-recursive latency (L_{sr}) with behavior at the recursive resolver. For a cache hit (probability P^N_r) the recursive resolver can reply immediately. Otherwise it will make several (N^Q_r) queries to authoritative resolvers (each taking L_{ra}) to fill its cache:

$$L_{sa} = L_{sr} + (1 - P^N_r)N^Q_r L_{ra} \tag{4}$$

Where L_{sr} and L_{ra} follow from Equation 1. We model recursive with the Level 3 data and authoritative as B-Root. With our recommended timeouts (60 s and 20 s), we get $P^C_{sr} = 0.72$ and $P^C_{ra} = 0.24$. We assume TCP fast open and TLS resumption last 2 hours at recursive ($P^{RE}_{sr} = P^{TFO}_{sr} = 0.9858$) and 7 h at authoritative ($P^{RE}_{ra} = P^{TFO}_{ra} = 0.8$). Prior studies of recursive resolvers suggest P^N_r ranges from 71% to 89% [43].

We determine N^Q_r by observing how many queries BIND-9.9.3 requires to process the Alexa top-1000 sites. We repeat this experiment 10 times, starting each run with a cold cache, which leads to $N^Q_r = 7.24$ (standard deviation 0.036, includes

0.09 due to query retries). We round N_r^Q to 7 in our analysis of estimated latency. Although this value seems high, the data shows many incoming queries require multiple outgoing queries to support DNSSEC, and due to the use of content-delivery networks that perform DNS-based redirection.

Scenarios: With this model we can quickly compare long-term average performance for different scenarios. Figure 10 compares six protocol combinations (each group of bars) We consider $R_{sr} = 5\,\text{ms}$ and $R_{sr} = 20\,\text{ms}$ suitable for a good U.S. or European ISP, but we report stub-to-recursive RTTs from 5 to 80 ms.

For the *local resolver*, the analysis shows that *use of TCP and TLS to the local resolver adds moderate latency*: current DNS has mean of 61 ms, and TCP is the same, and TLS is only 5.4% slower with UDP upstream. Second, we see that use of connections between recursive and authoritative is more expensive: with TLS stub-to-recursive, adding TCP to the authoritative is 19% slower and adding TLS to the authoritative more than 180% slower. This cost follows because a single stub-to-recursive query can lead to multiple recursive-to-authoritative queries, at large RTTs with a lower connection-hit fraction. However this analysis is pessimistic; the expected values underestimate possible locality in those queries.

For a *third-party resolver* ($R_{sr} = 20\,\text{ms}$), the trends are similar but the larger latency to the recursive resolver raises costs: TLS to recursive (with UDP to authoritative), is 15.5% slower than UDP.

VII. Related work

Our work draws on prior work in transport protocols and more recent work in DNS security and privacy.

VII-A Siblings: DNSSEC and DANE/TLSA

DNS Security Extensions (DNSSEC) uses public-key cryptography to ensure the integrity and origin of DNS replies [4]. Since the 2010 signature of the root zone, it has provided a root of trust for DNS. DNS-based Authentication of Named Entities for TLS (DANE/TLSA) allows DNS to serve as a root of trust for TLS certificates [39]. Our work complements these protocols, addressing the related area of privacy.

Although DNSSEC protects the integrity and origin of requests, it does not address query privacy. We propose TLS to support this privacy, complementing DNSSEC. Although not our primary goal, TLS also protects against some attacks such as those that exploit fragmentation; we discuss these below.

DANE/TLSA's trust model is unrelated to T-DNS's goal of privacy. See § III-B1 for how they interact.

VII-B DNSCrypt and DNSCurve

OpenDNS has offered elliptic-curve cryptography to encrypt and authenticate DNS packets between stub and recursive resolvers (DNSCrypt [65]) and recursive resolvers and authoritative servers (DNSCurve [23]). We first observe that these protocols address only privacy, not denial-of-service nor limits to reply size.

These protocols address the same privacy goal as our use of TLS. While ECC is established cryptography, above this they use a new approach to securing the channel and a new DNS message format. We instead reuse existing DNS message format and standard TLS and TCP. Although DNSCrypt and DNSCurve are attractive choices, we believe TLS' run-time negotiation of cryptographic protocol is important for long-term deployment. We also see significant advantage in adopting existing standards with robust libraries and optimizations (such as TLS resumption) rather than designing bespoke protocols for our new application. In addition, while TLS implementations have reported recent flaws, our view is that common libraries benefit from much greater scrutiny than new protocols. Finally, DNSCurve's mandate that the server's key be its hostname cleverly avoids one RTT in setup, but it shifts that burden into the DNS, potentially adding millions of nameserver records should each zone require a unique key.

DNSCrypt suggests deployment with a proxy resolver on the end-user's computer. We also use proxies for testing, but we have prototyped integration with existing servers, a necessity for broad deployment.

We compare DNSCrypt and DNSCurve performance in § VI-A, and features in Table II.

VII-C Unbound and TLS

We are not the first to suggest combining DNS and TLS. A recent review of DNS privacy proposed TLS [11], and NLnet Lab's `Unbound` DNS server has supported TLS since December 2011. Unbound currently supports DNS-over-TLS only on a separate port, and doesn't support out-of-order processing § III-A, and there is no performance analysis. Our work adds in-band negotiation and out-of-order processing (see Table II), and we are the first to study performance of DNS with TCP and TLS. Since the only difference is signaling TLS upgrade, our performance evaluation applies to other TLS approaches, although unbound's use of a new port avoids 1 RTT latency.

VII-D Reusing Other Standards: DTLS, TLS over SCTP, HTTPS, and Tcpcrypt

Although UDP, TCP and TLS are widely used, additional transport protocols exist to provide different semantics. Datagram Transport Layer Security (DTLS) provides TLS over UDP [75], meeting our privacy requirement. While DTLS strives to be lighter weight than TCP, it must re-create parts of TCP: the TLS handshake requires reliability and ordering, DoS-prevention requires cookies analogous to SYN cookies in TCP's handshake, and it caches these, analogous to TCP fast-open. Thus with DoS-protection, DTLS provides *no* performance advantage, other than eliminating TCP's data ordering. (We provide a more detailed evaluation of these in § I.) Applications using DTLS suffer the same payload limits as UDP (actually slightly worse because of its additional header), so it does not address the policy constraints we observe. Since DTLS libraries are less mature than TLS and DTLS offers few unique benefits, we recommend T-DNS .

TLS over SCTP has been standardized [44]. SCTP is an attractive alternative to TCP because TCP's ordering guarantees are not desired for DNS, but we believe performance is otherwise similar, as with DTLS.

Several groups have proposed some version of DNS over HTTP. Kaminsky proposed DNS over HTTP [46] with some performance evaluation [47]; Unbound runs the DNS protocol over TLS on port 443 (a non-standard encoding on the HTTPS port); others have proposed making DNS queries over XML [69] or JSON [12] and full HTTP or HTTPS. Use of port 443 saves one RTT for TLS negotiation, but using DNS encoding is non-standard, and HTTP encoding is significantly more bulky. Most of these proposals lack a complete specification (except XML [69]) or detailed performance analysis (Kaminsky provides some [47]). At a protocol level, DNS over HTTP must be strictly slower than DNS over TCP, since HTTP requires its own headers, and XML or JSON encodings are bulkier. One semi-tuned proxy shows 60 ms per query overhead [85], but careful studies quantifying overhead is future work.

Tcpcrypt provides encryption without authentication at the transport layer. This subset is faster than TLS and shifts computation to the client [10]. T-DNS's uses TLS for privacy (and DNSSEC for authentication), so tcpcrypt may be an attractive alternative to TLS. Tcpcrypt is relatively new and not yet standardized. Our analysis suggests that, since RTTs dominate performance, tcpcrypt will improve but not qualitatively change performance; experimental evaluation is future work.

The very wide use of TCP and TLS-over-TCP provides a wealth of time-tested implementations and libraries, while DTLS and SCTP implementations have seen less exercise. We show that TCP and TLS-over-TCP can provide near-UDP performance with connection caching. Because DTLS carries out the same protocol exchange as TLS (when spoof prevention is enabled), it will have the same latency. Our analysis applies directly to HTTP-based approaches, although its more verbose framing may have slightly higher overhead.

VII-E Other Approaches to DNS Privacy

Zhao et al. [97] proposed adding cover traffic (additional queries) to DNS to conceal actual queries from an eavesdropper, Castillo-Perez and Garcia-Alfaro extend this work [16]. These approaches may help protect against an adversary that controls the recursive resolver; we instead provide only communications privacy, without range queries.

Lu and Tsudick [54] identify a number of privacy threats to DNS and propose replacing it with a DHT-based system, and Zhao et al. [96] later propose DNS modifications to support their range queries [97]. Such approaches can provide very strong privacy guarantees, but such large protocol modifications pose significant deployment challenges.

VII-F Specific Attacks on DNS

As a critical protocol, DNS has been subject to targeted attacks. These attacks often exploit currently open DNS recursive name servers, and so they would be prevented with use of TLS' secure client-to-server channel. Injection attacks include the Kaminsky vulnerability [45], mitigated by changes to DNS implementations; sending of duplicate replies ahead of the legitimate reply [2], mitigated by Hold-On at the client [28]; and injection of IP fragments to circumvent DNSSEC [38], mitigated by implementation and operations changes.

Although specific countermeasures exist for each of these attacks, responding to new attacks is costly and slow. Connection-level encryption like TLS may prevent a broad class of attacks that manipulate replies (for example, [38]). Although TLS is not foolproof (for example, it can be vulnerable to person-in-the-middle attacks), and we do not resolve all injection attacks (such as injection of TCP RST or TLS-close notify), we believe TLS significantly raises the bar for these attacks.

Similarly, recent proposals add cookies to UDP-based DNS to reduce the impact of DoS attacks [29]. While we support cookies, a shift to TCP addresses policy constraints as well as DNS, and enables use of TLS.

VIII. Conclusion

Connectionless DNS is overdue for reassessment due to privacy limitations, security concerns, and sizes that constrain policy and evolution. Our analysis and experiments show that *connection-oriented DNS addresses these problems*, and that latency and resource needs of T-DNS are manageable.

Acknowledgments

We would like to thank several that contributed data to this effort: DNS-OARC DITL program, operators of A, J, B Root name servers, Level3 and Common Crawl. Calvin Ardi extracted domain names from web pages from the Common Crawl dataset. Xun Fan helped collect data from PlanetLab. Christos Papadopoulos provided servers at CSU for our high-latency experiments. John Wroclawski, Bill Manning, and prior anonymous reviewers provided comments on the paper, many helpful. We also thank colleagues at Verisign and participants at the 2014 DNS-OARC workshop for comments and many though-provoking questions, particularly about deployment. We thank Ted Faber and Joe Touch for their discussions about TCP.

Research by Liang Zhu, Zi Hu, and John Heidemann in this paper is partially sponsored by the Department of Homeland Security (DHS) Science and Technology Directorate, HSARPA, Cyber Security Division, BAA 11-01-RIKA and Air Force Research Laboratory, Information Directorate under agreement number FA8750-12-2-0344, and contract number D08PC75599. The U.S. Government is authorized to make reprints for Governmental purposes notwithstanding any copyright. The views contained herein are those of the authors and do not necessarily represent those of DHS or the U.S. Government.

References

[1] Alexa, http://www.alexa.com/.

[2] Anonymous, "The collateral damage of internet censorship by DNS injection," *SIGCOMM Comput. Commun. Rev.*, Jun. 2012.

[3] Arbor Networks, “Worldwide infrastructure security report,” Arbor Networks, Tech. Rep., Sep. 2012.

[4] R. Arends, R. Austein, M. Larson, D. Massey, and S. Rose, “DNS Security Introduction and Requirements,” RFC 4033, Mar. 2005.

[5] H. Ballani, P. Francis, and S. Ratnasamy, “A measurement-based deployment proposal for IP anycast,” in *Proc. of ACM IMC*. Rio de Janeiro, Brazil: ACM, Oct. 2006, pp. 231–244.

[6] R. Bellis, “DNS Transport over TCP - Implementation Requirements,” RFC 5966, Internet Engineering Task Force, Aug. 2010.

[7] V. Bernat, “SSL computational DoS mitigation,” blog http://vincent.bernat.im/en/blog/2011-ssl-dos-mitigation.html, Nov. 2011.

[8] R. Beverly, A. Berger, Y. Hyun, and k claffy, “Understanding the efficacy of deployed internet source address validation filtering,” in *Proc. of ACM IMC*. Chicago, Illinois, USA: ACM, Nov. 2009, pp. 356–369.

[9] R. Beverly, R. Koga, and kc claffy, “Initial longitudinal analysis of IP source spoofing capability on the Internet,” *Internet Society*, Jul. 2013.

[10] A. Bittau, M. Hamburg, M. Handley, D. Mazières, and D. Boneh, “The case for ubiquitous transport-level encryption,” in *Proceedings of the 19th USENIX Conference on Security*, ser. USENIX Security’10. Berkeley, CA, USA: USENIX Association, 2010, pp. 26–26.

[11] S. Bortzmeyer, “DNS privacy problem statement,” Dec. 2013, Internet draft.

[12] ——, “JSON format to represent DNS data,” Feb. 2013, work in progress (Internet draft draft-bortzmeyer-dns-json-01).

[13] R. Bush, D. Karrenberg, M. Kosters, and R. Plzak, “Root name server operational requirements,” Internet Request For Comments, RFC 2870, Jun. 2000, (also Internet BCP-40).

[14] M. Butkiewicz, H. V. Madhyastha, and V. Sekar, “Understanding website complexity: Measurements, metrics, and implications,” in *IMC*, Nov. 2011, pp. 313–328.

[15] M. Calder, X. Fan, Z. Hu, E. Katz-Bassett, J. Heidemann, and R. Govindan, “Mapping the expansion of Google’s serving infrastructure,” in *Proc. of ACM IMC*. Barcelona, Spain: ACM, Oct. 2013, p. to appear.

[16] S. Castillo-Perez and J. Garcia-Alfaro, “Evaluation of two privacy-preserving protocols for the DNS,” in *Proc. of 6thIEEE International Conference on Information Technology: New Generations*. IEEE, Apr. 2009, pp. 411–416.

[17] S. Castro, D. Wessels, M. Fomenkov, and K. Claffy, “A day at the root of the Internet,” *ACM Computer Communication Review*, vol. 38, no. 5, pp. 41–46, Oct. 2008.

[18] Y. Cheng, J. Chu, S. Radhakrishnan, and A. Jain, “TCP Fast Open,” RFC 7413, Internet Engineering Task Force, Dec. 2014.

[19] A. Cheung, “CDN demonstration: EdgeCast application delivery network,” web page http://demo.cheungwaikin.com/adn/adn-a.html, Apr. 2013.

[20] C. Coarfa, P. Druschel, and D. S. Wallach, “Performance analysis of TLS web servers,” vol. 24, no. 1, pp. 39–69, Feb. 2006.

[21] J. Damas, M. Graff, and P. Vixie, “Extension mechanisms for DNS (EDNS(0)),” RFC 6891, Internet Engineering Task Force, Apr. 2013.

[22] J. Dean and L. A. Barroso, “The tail at scale,” *Communications of the ACM*, vol. 56, no. 2, pp. 74–80, Feb. 2013.

[23] M. Dempsky, “DNSCurve: Link-level security for the Domain Name System,” Feb. 2010, internet draft.

[24] T. Dierks and E. Rescorla, “The Transport Layer Security TLS Protocol Version 1.2,” RFC 5246, Internet Engineering Task Force, Aug. 2008.

[25] T. Dietrich, “DNSSEC support by home routers in Germany,” Presention at RIPE-60, May 2010.

[26] DNS-OARC, https://www.dns-oarc.net/.

[27] R. Droms, “Dynamic host configuration protocol,” Internet Request For Comments, RFC 2131, Mar. 1997.

[28] H. Duan, N. Weaver, Z. Zhao, M. Hu, J. Liang, J. Jiang, K. Li, and V. Paxson, “Hold-on: Protecting against on-path DNS poisoning,” in *SATIN*, 2012.

[29] D. E. Eastlake, “Domain Name System (DNS) cookies,” Jan. 2014, work in progress (Internet draft draft-eastlake-dnsext-cookies-04.txt).

[30] W. Eddy, “TCP SYN flooding attacks and common mitigations,” Internet Request For Comments, RFC 4987, Aug. 2007.

[31] Electronic Frontier Foundation, “Encrypt the web with HTTPS everywhere,” Web page https://www.eff.org/https-everywhere, Aug. 2011.

[32] T. Faber, J. Touch, and W. Yue, “The TIME-WAIT state in TCP and its effect on busy servers,” INFOCOMM, 1998.

[33] P. Ferguson and D. Senie, “Network ingress filtering: Defeating denial of service attacks which employ IP source address spoofing,” Internet Request For Comments, RFC 2267, May 2000, also BCP-38.

[34] T. Finch, “Secure SMTP using DNS-based authentication of named entities (DANE) TLSA records.” Feb. 2014, internet draft.

[35] F. Gont and S. Bellovin, “Defending against sequence number attacks,” Internet Request For Comments, RFC 6528, Feb. 2012.

[36] L. Green, “Common crawl enters a new phase,” Common Crawl blog http://www.commoncrawl.org/common-crawl-enters-a-new-phase/, Nov. 2011.

[37] G. Greenwald, “NSA collecting phone records of millions of Verizon customers daily,” *The Guardian*, June 2013.

[38] A. Herzberg and H. Shulmanz, “Fragmentation considered poisonous,” in *Proc. of IEEE Conference on Communications and Network Security (CNS)*, Oct. 2013.

[39] P. Hoffman and J. Schlyter, “The DNS-based authentication of named entities (DANE) transport layer security (TLS) protocol: TLSA,” Internet Request For Comments, RFC 6698, Aug. 2012.

[40] Z. Hu, L. Zhu, J. Heidemann, A. Mankin, and D. Wessels, “Starting TLS over DNS,” Jan. 2014, work in progress (Internet draft draft-start-tls-over-dns-00).

[41] G. Huston, “A question of protocol,” Talk at RIPE ’67, 2013.

[42] ICANN, “Root server attack on 6 February 2007,” ICANN, Tech. Rep., Mar. 2007.

[43] J. Jung, E. Sit, H. Balakrishnan, and R. Morris, “DNS performance and the effectiveness of caching,” *ACM/IEEE ToN*, vol. 10, Oct. 2002.

[44] A. Jungmaier, E. Rescorla, and M. Tuexen, “Transport Layer Security over Stream Control Transmission Protocol,” RFC 3436, Internet Engineering Task Force, Dec. 2002.

[45] D. Kaminsky, “It’s the end of the cache as we know it,” Presentation, Black Hat Asia, Oct. 2008.

[46] ——, “The DNSSEC diaries, ch. 6: Just how much should we put in DNS?” blog post http://dankaminsky.com/2010/12/27/dnssec-ch6/, Dec. 2010.

[47] ——, “DNSSEC interlude 1: Curiosities of benchmarking DNS over alternate transports,” blog post http://dankaminsky.com/2011/01/04/dnssec-interlude-1/, Jan. 2011.

[48] J. Kelsey, “Compression and information leakage of plaintext,” in *NinthIACR International Workshop on Fast Software Encrytpion*. Leuven, Belgium: Springer, Feb. 2002, pp. 263–276.

[49] C. A. Kent and J. C. Mogul, “Fragmentation considered harmful,” in *SIGCOMM*, Aug. 1987, pp. 390–401.

[50] M. Kührer, T. Hupperich, C. Rossow, and T. Holz, “Hell of a handshake: Abusing TCP for reflective amplification DDoS attacks,” in *Proc. of USENIX Workshop on Offensive Technologies*. San Diego, CA, USA: USENIX, Aug. 2014.

[51] A. Langley, “Overclockign SSL,” blog post https://www.imperialviolet.org/2010/06/25/overclocking-ssl.html, Jun. 2010.

[52] B. Laurie, G. Sisson, R. Arends, and D. Blacka, “DNS security (DNSSEC) hashed authenticated denial of existence,” Internet Request For Comments, RFC 5155, Mar. 2008.

[53] C. Lewis and M. Sergeant, “Overview of best email DNS-based list (DNSBL) operational practices,” Internet Request For Comments, RFC 6471, Jan. 2012.

[54] Y. Lu and G. Tsudik, “Towards plugging privacy leaks in domain name system,” in *Proc. of IEEE International Conference on Peer-to-Peer Computing*. Delft, Netherlands: IEEE, Aug. 2010.

[55] J. Markoff and N. Perlroth, “Attacks used the Internet against itself to clog traffic,” *New York Times*, March 2013.

[56] Matthew Dempsky, “Dnscurve client tool,” https://github.com/mdempsky/dnscurve/.

[57] J. Mauch, “Open resolver project,” Presentation, DNS-OARC Spring 2013 Workshop (Dublin), May 2013, https://indico.dns-oarc.net//contributionDisplay.py?contribId=24&sessionId=0&confId=0.

[58] W. Meng, R. Duan, and W. Lee, “DNS Changer remediation study,” Talk at M3AAWG 27th, Feb. 2013.

[59] C. Metz, “Comcast trials (domain helper service) DNS hijacker,” The Register, Jul. 2009.

[60] B. P. Miller, L. Fredriksen, and B. So, “An empirical study of the reliability of UNIX utilities,” *Communications of the ACM*, vol. 33, no. 12, pp. 32–44, Dec. 1990.

[61] P. Mockapetris, “Domain names—implementation and specification,” RFC 1035, Internet Engineering Task Force, Nov. 1987.

[62] H. F. Nielsen, J. Gettys, A. Baird-Smith, E. Prud'hommeaux, H. Lie, and C. Lilley, "Network performance effects of http/1.1, css1, and png," in *SIGCOMM*, Sep. 1997.

[63] NLnetLabs, "Dnssec-trigger," web page http://www.nlnetlabs.nl/projects/dnssec-trigger/, May 2014.

[64] M. Nottingham, "HTTP/2 frequently asked questions," web page http://http2.github.io/faq/#why-is-http2-multiplexed, 2014.

[65] OpenDNS, "Dnscrypt," http://www.opendns.com/technology/dnscrypt.

[66] ——, "Dnscrypt proxy tool," https://github.com/opendns/dnscrypt-proxy.

[67] ——, "Opendns website," www.opendns.com, 2006.

[68] E. Osterweil, B. Kaliski, M. Larson, and D. McPherson, "Reducing the X.509 attack surface with DNSSEC's DANE," in *Proc. of Workshop on Securing and Trusting Internet Names (SATIN)*, Teddington, UK, Mar. 2012.

[69] M. Parthasarathy and P. Vixie, "draft-mohan-dns-query-xml-00," Sep. 2011, work in progress (Internet draft draft-mohan-dns-query-xml-00).

[70] V. Paxson, M. Allman, J. Chu, and M. Sargent, "Computing TCP's retransmission timer," Internet Request For Comments, RFC 6298, Jun. 2011.

[71] H. P. Penning, "Analysis of the strong set in the PGP web of trust," web page http://pgp.cs.uu.nl/plot/, Jan. 2014.

[72] R. Potharaju and N. Jain, "Demystifying the dark side of the middle: A field study of middlebox failures in datacenters," in *Proc. of ACM IMC*. Barcelona, Spain: ACM, Oct. 2013, p. to appear.

[73] P. Ramaswami, "Introducing Google Public DNS," Google Official Blog http://googleblog.blogspot.com/2009/12/introducing-google-public-dns.html, Dec. 2009.

[74] S. Reifschneider, "4.2.2.2: The story behind a DNS legend," http://www.tummy.com/articles/famous-dns-server/.

[75] E. Rescorla and N. Modadugu, "Datagram Transport Layer Security Version 1.2," RFC 6347, Internet Engineering Task Force, Jan. 2012.

[76] C. Rossow, "Amplification hell: Revisiting network protocols for DDoS abuse," in *Proc. of ISOC Network and Distributed System Security Symposium*. San Diego, California, USA: The Internet Society, Feb. 2014.

[77] J. Salowey, H. Zhou, P. Eronen, and H. Tschofenig, "Transport Layer Security (TLS) Session Resumption without Server-Side State," RFC 5077, Internet Engineering Task Force, Jan. 2008.

[78] K. Schomp, T. Callahan, M. Rabinovich, and M. Allman, "On measuring the client-side DNS infrastructure," in *IMC*, Oct. 2013.

[79] S. Sengupta, "Warned of an attack on the Internet, and getting ready," *New York Times*, p. B1, Mar. 31 2012.

[80] H. Shulman, "Pretty bad privacy: Pitfalls of DNS encryption," in *Proc. of 13th ACM Workshop on Privacy in the Electronic Society*. Scottsdale, Arizona: ACM, Nov. 2014, pp. 191–200.

[81] W. Simpson, "TCP cookie transactions (TCPCT)," Jan. 2011.

[82] A. Sullivan, "More keys in the DNSKEY RRset at ".", and draft-ietf-dnsop-respsize-nn," DNSOP mailing list, Jan. 2014, https://www.mail-archive.com/dnsop@ietf.org/msg05565.html.

[83] S. Sundaresan, N. Feamster, R. Teixeira, and N. Magharei, "Measuring and mitigating web performance bottlenecks in broadband access networks," in *Proc. of ACM IMC*. Barcelona, Spain: ACM, Oct. 2013, p. to appear.

[84] R. Vaughn and G. Evron, "DNS amplification attacks," http://isotf.org/news/DNS-Amplification-Attacks.pdf, Mar. 2006.

[85] Verisign Labs, "DNS over JSON prototype," 2014.

[86] P. Vixie, "Extension mechanisms for DNS (EDNS0)," Internet Request For Comments, RFC 1999, Aug. 1999.

[87] P. Vixie and A. Kato, "DNS referral response size issues," May 2012, internet draft.

[88] P. Vixie, "What DNS is not," *ACM Queue*, Nov. 2009.

[89] ——, "Response Rate Limiting in the Domain Name System (DNS RRL)," blog post http://www.redbarn.org/dns/ratelimits, Jun. 2012.

[90] P. T. Watson, "Slipping in the window: TCP reset attacks," presentation at CanSecWest, 2004.

[91] N. Weaver, C. Kreibich, B. Nechaev, and V. Paxson, "Implications of Netalyzr's DNS measurements," in *Proc. of Workshop on Securing and Trusting Internet Names (SATIN)*, Apr. 2011.

[92] W. Wijngaards and G. Wiley, "Confidential dns," Mar. 2014, internet draft.

[93] S. Woolf and D. Conrad, "Requirements for a Mechanism Identifying a Name Server Instance," RFC 4892, Internet Engineering Task Force, Jun. 2007.

[94] P. Wouters, "Using DANE to associate OpenPGP public keys with email addresses," Feb. 2014, internet draft.

[95] P. Wouters and J. Abley, "The edns-tcp-keepalive EDNS0 option," Oct. 2013, work in progress (Internet draft draft-wouters-edns-tcp-keepalive-00).

[96] F. Zhao, Fukuoka, Y. Hori, and K. Sakurai, "Analysis of existing privacy-preserving protocols in domain name system," in *IEICE TRANSACTIONS on Information and Systems*, May 2010.

[97] F. Zhao, Y. Hori, and K. Sakurai, "Analysis of privacy disclosure in DNS query," in *5th Intl. Conf. on Multimedia and Ubiquitous Engineering*. Loutraki, Greece: FTRI, Apr. 2007.

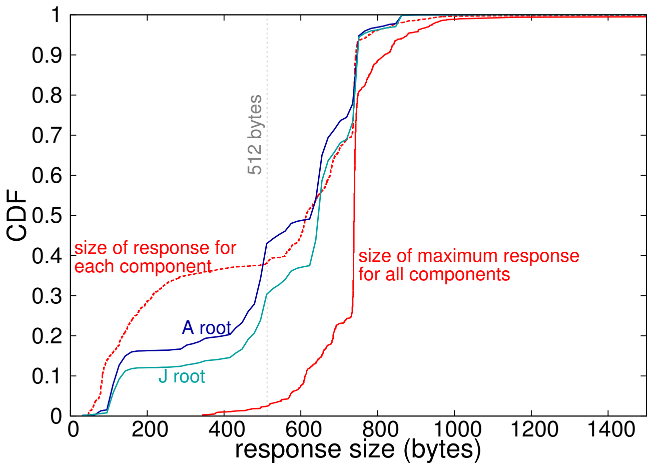


Fig. 11: Response sizes from name servers of the Alexa top-1000 websites (as of 2014-01-24), and UDP response sizes out of two root servers. (Data: 2013-10-01)

Appendix A Current Query Response Sizes

Figure 11 shows the size of responses from popular authoritative name servers and from two root DNS servers. This table shows resolution of full domain names for the Alexa top-1000 websites. We show the distribution of responses for *each* component as well as the maximum seen over all components of each domain name. From this graph we see that responses today are fairly large: nearly 75% of top 1000 result in a response that is at least 738 bytes (the DNSSEC-signed reply for .com). Resolvers today require EDNS support for large replies.

Resolution of these domain names typically requires 600–800 B replies. Many Internet paths support 1500 B packets without fragmentation, making these sizes a good match for today's network. This result is not surprising: of course DNS use is tailored to match current constraints. However, *transient conditions stress these limits*. Examples are the two methods of DNSSEC key rollover: with pre-published keys, DNSKEY responses grow, and with double-signatures all signed responses are temporarily inflated. Both stretch reply sizes for the transition period of hours or days, during which IP fragmentation reduces performance of affected domains (like .com) for everyone.

Appendix B Domain Names per Web Page

To demonstrate the need for pipelining DNS queries for end-users (§ III-A), we examined about 40M web pages (about 1.4%) from a sample of CommonCrawl-002 [36]. The sample is selected arbitrarily, so we do not expect any bias. We count the number of unique domain names per page.

Figure 12 shows the results: to confirm that 62% of web pages have 4 or more unique domain names, and 32% have 10 or more.

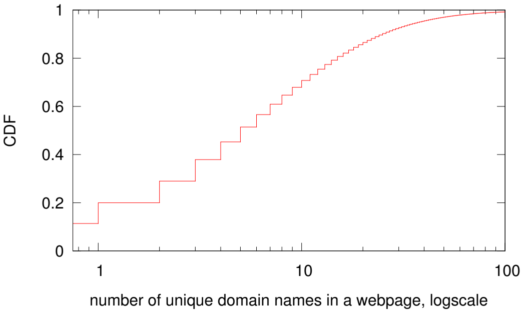


Fig. 12: CDF of number of unique hostnames per web page. (Dataset: 40584944 page sample from CommonCrawl-002 [36]).

Appendix C Additional Data for Server-Side Latency

Figure 13 and shows the number of connections over the day for all three datasets, Figure 14 shows the hit fraction over the day for all three datasets, expanding on the data in Figure 3.

Figure 15 summarizes the data in Figure 14 by quartiles.

Appendix D Detailed Discussion of Latency

This appendix provides a detailed, case-by-case discussion of latency for our experiments, expanding on the discussion in § VI-B and § VI-C.

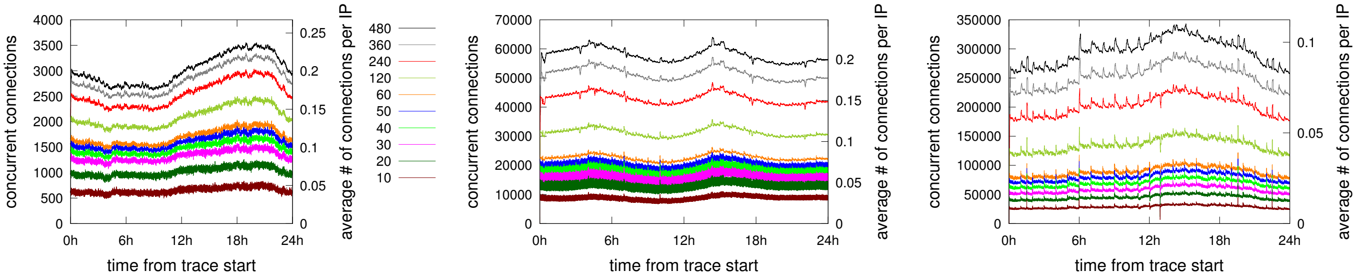
D-A Detailed Discussion of Latency: Stub-to-Recursive Resolver

We first estimate what RTTs to expect for stub-to-recursive, then compare protocol alternatives.

D-A1 Typical Stub-to-Recursive RTTs: Stubs typically talk to a few (one to three) recursive resolvers. Recursive resolvers are usually provided as a service by ones ISP, and so they are typically nearby in the network. Alternatively, some users use third-party resolvers. These may have a higher round-trip-time (RTT) from the stub, but provide a very large cache and user population.

We measure the RTT between stub and recursive resolvers across 400 PlanetLab nodes to their local (ISP-provided) resolver, and also to three third-party DNS services (Google, OpenDNS, and Level 3). For each case, we issue the same query 7 times, each after the previous reply, and report the median. We expect the first query to place the result in the cache, so the following query latency approximates RTT. We report the median to suppress noise from interfering traffic.

The result confirms that the ISP-provided recursive resolver almost always has very low latency (80% less than 3 ms). Only a few stragglers have moderate latency (5% above 20 ms). For third-party resolvers, we see more variation, but most have fairly low latency due to distributed infrastructure. Google Public DNS provides median latency of 23 ms and the others only somewhat more distant. The tail of higher latency here

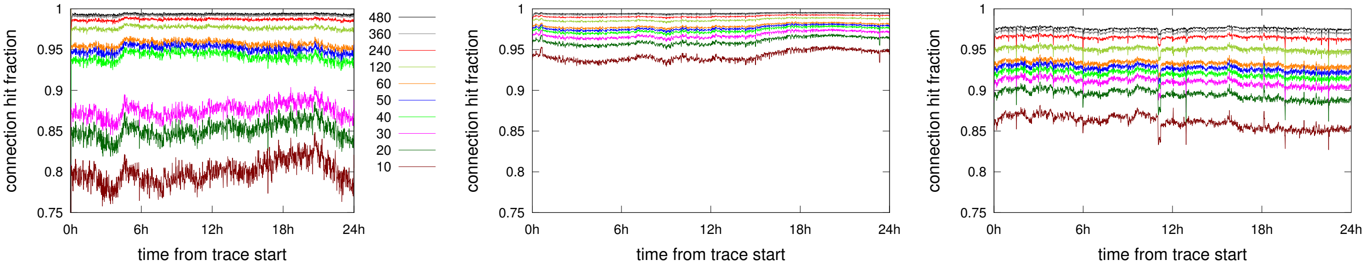


(a) Dataset: DNSChanger

(b) Dataset: Level 3, cns4.lax1.

(c) Dataset: B Root

Fig. 13: The number of concurrent connections given by different time-out window sizes.

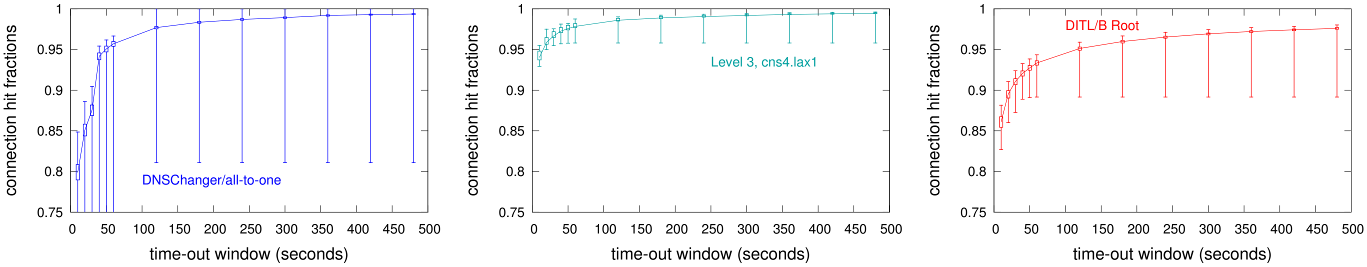


(a) Dataset: DNSChanger

(b) Dataset: Level 3, cns4.lax1.

(c) Dataset: B Root

Fig. 14: Server-side hit ratio (connection reuse) of queries given by different time-out window sizes



(a) Dataset: DNSChanger, all-to-one

(b) Dataset: Level 3, cns4.lax1.

(c) Dataset: B Root

Fig. 15: Quartile plot of server-side connection hit fraction.

affects more stubs, with 10–25% showing 50 ms or higher. (See Figure 16 for data.)

PlanetLab nodes are primarily hosted at academic sites and so likely have better-than-typical network connectivity. These observed third-party DNS latency may be lower than typical. However, with this sample of more than 300 organizations, this data provide some diversity in geography and configuration of local DNS.

D-A2 TCP connection setup: stub-to-recursive: We next evaluate the costs of TCP connection setup for stub-to-recursive queries.

We emulate both a close (RTT=1 ms) and a far (RTT=35 ms) stub to recursive resolver configurations. We use our custom DNS stub and the BIND-9.9.3 server with our DNS proxy. For each protocol (UDP, TCP, TLS), the stub makes 140 unique queries, randomly drawn from the Alexa top-1000 sites [1] with DNS over that protocol. We restart the recursive resolver before changing protocols, so each protocol test starts with a cold cache.

For each protocol we also vary several policies. On the client side we consider *pipeline*: send several queries before the responses arrive and *stop-and-wait*: wait for response before sending the next query. Processing on the server, we compare *in-order*, where queries are processed sequentially and *out-of-order processing* (OOOP), where queries are processed concurrently. Connections are either *reused*, with multiple queries per TCP/TLS connection (p-TCP/p-TLS), or *no reuse*, where the connection is reopened for each query.

We repeat the whole experiment 10 times and report results combining all experiments.

Figure 6 shows the results of these experiments. We first consider *UDP compared to TCP*: when queries are sent in stop-and-wait mode, and server processes them in-order, TCP can always achieve almost the same latency as UDP (a: left) with (d: left) or without (b: left) connection reuse, when RTT is small. When RTT becomes larger, TCP without (b: right) connection reuse incurs slightly higher latency due to the handshake cost than UDP (a: right). However, TCP with (d: right) connection reuse still can achieve similar latency as UDP. This experiment demonstrates that *with small client-server RTTs, TCP setup time is irrelevant*; it is dwarfed by overall cost of resolving a new name. Even with large RTT, TCP could still get the same latency as UDP by reusing connections.

To consider pipelining, sending multiple queries before the replies return. In Figure 6 the four rightmost whiskerbars (f, g, h, i) indicate pipelining. First, we see that per-query resolution times are actually higher with pipelining than when done sequentially (stop-and-wait). This delay occurs because all 140 queries arrive at the server at nearly the same time, so they queue behind each other as they are processed by our 4-core computer. Second, with pipeline but in-order processing, TCP (f) has horrible latency. The reason for this high latency is that while both BIND-9 and Unbound can process multiple queries from UDP concurrently(out-of-order), they process queries from the same TCP connection sequentially(in-order), which causes head of line blocking: later queries get blocked by previous ones. While correct, current resolvers *are not optimized for high-performance TCP* query handling.

DNS specifications require support for out-of-order queries and responses, even though current implementations do not process queries this way (see prior discussion in § III-A). Here we approximate native resolvers support for out-of-order TCP queries by placing a proxy resolver on the same computer as the real resolver. The proxy receives queries from the stub over TCP, then forwards them to recursive resolver over UDP. This approach leverages current native out-of-order UDP processing and incurs no fragmentation since UDP is sent inside the same machine (over the loopback interface). The proxy then returns replies over TCP to the stub, but in whatever order the recursive resolver generates results. The light blue whiskerbar (h) in the right side of Figure 6 shows the effects of this improvement: TCP (h) and UDP (g) performance are again equivalent.

Finally, pipelining and OOOP improve aggregate throughput, and they are essential to make batch query performance approach that of UDP. While batch performance appears slower than individual (compare (g) to (a)), this difference is because we estimate times from batch start and is independent of protocol (the cost in (i) to (c) is similar to that of (g) to (a)).

D-A3 TLS privacy: stub-to-recursive: Connection establishment for TLS is much more expensive than TCP, requiring additional round trips and computation to establish a session key. We repeat our experiments from the prior section, this time comparing UDP with TLS. For consistency with our out-of-order experiments, we place our proxy resolver on the same machine as the recursive resolver.

Figure 6 show TLS performance as cases (c), (e) and (i), all green bars. With sequential queries: when RTT is small, TLS (c: left) performance is almost the same as UDP (a: left) and TCP (b:left), because TLS handshake cost (3 RTTs) is negligible relative to the cost of the recursive-to-authoritative query (ten vs. hundreds of ms). When RTT becomes larger, TLS without (c: right) connection reuse incurs somewhat higher latency than UDP (a: right), but their performance is equivalent with connection reuse (e: right). With both pipelining and out-of-order processing: TLS performance (i) is comparable with UDP (g), no matter the RTT is large or not. In all cases, variation in timing, as shown by the quartile boxes, is far larger than differences in medians, although variation rises with larger RTTs.

D-A4 Overall Stub-to-Recursive: In summary, this section shows that when the stub and recursive resolvers are close to each other the extra packet exchanges add very small latency to the query, and even the TLS connection setup cost is dwarfed by the costs involved in making distributed DNS queries to authoritative name servers. Second, minimizing connection setup requires reusing connections, and we showed that head-of-line blocking in the TCP processing of current resolver implementations adds significant latency. Current resolvers have most of the machinery to fix this problem, and our experiments show out-of-order processing allows DNS performance with both TCP and TLS to be very close to that of simple UDP.

D-B Detailed Discussion of Latency: Recursive Resolver to Authoritative Server

We next turn to latency we expect between the recursive resolvers and authoritative name servers. While stubs query only a few, usually nearby recursive resolvers, authoritative servers are distributed around the globe and so the recursive/authoritative round-trip times are both larger and more diverse.

D-B1 Typical Recursive-to-Authoritative RTTs: To estimate typical recursive-to-authoritative RTTs, we again turn to the Alexa top-1000 sites. We query each from four locations: our institution in Los Angeles (isi.edu), and PlanetLab sites in China (www.pku.edu.cn), UK (www.cam.ac.uk), and Australia (www.monash.edu.au).

For each site we query each domain name. We use `dig +trace` to resolve each domain component from the root to the edge, including DNSSEC where possible. We report the median of 10 repetitions of the query time of the last step to estimate of best-case recursive-to-authoritative RTTs. This method represents performance as if higher layers were already cached by the recursive resolver, and median provides some robustness to competing traffic and random selection from multiple name servers.

We observe that the U.S. and UK sites are close to many authoritative servers, with median RTT of 45 ms, but it also has a fairly long tail, with 35% more than 100 ms. The Chinese site has generally longer RTTs, with only 30% responding in 100 ms. While many large sites operate Asian mirrors, many don't. The Australian site shows a sharp shift with about 20%

of sites less than 30 ms, while the remaining 150 ms or longer. This jump is due to the long propagation latency for services without sites physically in Australia. (See Figure 17 for data.)

We see a similar shift when we look at less popular services. Examination of 1000 domains randomly chosen from the Alexa top-1M sites shows that median RTT is 20–40 ms larger than for the top-1000 sites, with the largest shifts in China and Australia. (See Figure 18 for data.)

Overall, the important difference compared to stub-to-recursive RTTs is that while a few authoritative servers are close (RTT $<$ 30 ms), many will be much further.

D-B2 TCP connection setup: recursive-to-authoritative: With noticeably larger RTTs to authoritative servers compared to the stub/recursive RTTs, we expect to see a much higher overhead for connection negotiation with TCP and TLS.

To evaluate query latencies with larger RTTs between client and server, we set up a DNS authoritative server for an experimental domain and queried it from a client 35 ms (8 router hops on a symmetric path) away. Since performance is dominated by round trips instead of computation, we measure latency in units of RTT and these results generalize to other RTTs.

We operate a BIND-9.9.3 server as the authoritative name server for an experimental domain (example.com) at one site. For each protocol, we query this name server directly, 140 times (query example.com), then vary the protocol in use. As before, we repeat this experiment 10 times and report results combining all experiments.

We first compare UDP with TCP without connection reuse , the two leftmost bars (a, b) in Figure 7. We see that all queries made by TCP (b) take about 70 ms, exactly two RTTs, due to TCP's handshake followed by the request and response. This overhead goes away with TCP fast-open (d), even without connection reuse.

With connection reuse, TCP (e) also takes only 35 ms, one RTT per query. This difference shows the *importance in reusing TCP connections for multiple queries* to avoid connection setup latency, highlighting the need for good connection hit ratios (§ IV).

We next consider pipelining multiple queries over a single TCP connection and supporting out-of-order processing. Basic UDP already supports both of these. To match our prior experiment we implement these options for TCP with a proxy server running on the same computer as the authoritative server, and we plot these results as (h, light blue) in Figure 7. In this case, median TCP latency is about 2.5 RTTs. Examination of the raw data shows that 10% of the queries complete with performance similar to UDP, while the other queries take slightly longer, in steps. We examined packet traces and verified each step is a single TCP packet with 12 or 13 responses. Thus the delay is due to synchronization overhead as all 140 responses, processed in parallel, are merged into a single TCP connection in our proxy. For this special case of more than 100 queries arriving simultaneously, a single connection can add some latency.

D-B3 TLS privacy: recursive-to-authoritative: Next we consider the addition of TLS. Use of TLS from recursive-to-authoritative is a policy decision; one might consider aggregation at the recursive resolver to provide sufficient anonymity, or one might employ TLS on both hops as a policy matter (for example, as with HTTPS Everywhere [31]). Here we consider the effects on latency of full use of TLS.

In Figure 7, green cases (c), (f), and (i) show TLS usage. Without connection reuse (c), TLS always takes 5 RTTs (175 ms). This corresponds to one RTT to setup TCP, one to negotiate DNS-over-TLS (§ III-B2), two for the TLS handshake, and then the final private query and response.

However, once established, the TLS connection can easily be reused. If we reuse the existing TLS connection and send queries in stop-and-wait mode (f), TLS performance is *identical* to UDP with a mean latency of one RTT, except for the first TLS query. This result shows that the expense of encryption is tiny compared to moderate round-trip delays, when we have an established connection.

Finally, when we add pipelining and out-of-order processing , we see similar stair-stepped behavior as with TCP, again due to synchronization over a single connection and our unoptimized proxy. The rightmost case (i, light-green) shows connection reuse, pipelining, and out-of-order processing; with this combination TLS performance is roughly equivalent to TCP, within measurement noise.

D-B4 Overall Recursive-to-Authoritative: This section showed that *round-trip latency* dominates performance for queries from recursive resolvers to authoritative name servers. Latency is incurred in connection setup, with TCP adding one additional RTT and TLS three more. This latency is very expensive, but it can be largely eliminated by connection reuse.

Appendix E
Data To Estimate Stub-to-Recursive and Recursive-to-Authoritative RTTs

We need to know the typical stub-to-recursive and recursive-to-authoritative RTTs in order to accurately estimate the end-to-end query latency with our model in § VI-E. We use different ways to measure stub-to-recursive (§ D-A1) and recursive-to-authoritative (§ D-B1) RTTs.

Stub-to-Recursive RTT: Figure 16 shows the CDF of Stub-to-Recursive RTT from 400 Planetlab nodes to the ISP-provided and three third-party recursive resolvers. ISP-provided recursive resolvers are almost always close. Third-party resolvers show more variation, but most have fairly low latency due to distributed infrastructure.

Recursive-to-Authoritative RTT: Figure 17 shows the CDF of Recursive-to-Authoritative RTT from recursive resolvers at four locations to authoritative servers of Alexa top-1000 domains. Different locations give different results: U.S. and UK sites are close to many authoritative servers while China and Australia shows longer RTTs.

To understand if top-1000 sites use better quality DNS providers than top-1M sites, Figure 18 shows the recursive-to-authoritative RTTs: from recursive resolvers at four locations:

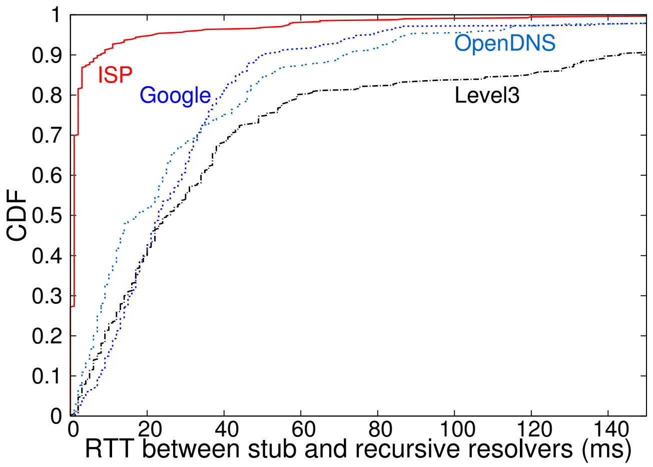


Fig. 16: Measured RTTs from stub and recursive resolver from 400 PlanetLab nodes, for the ISP-provided and three third-party recursive resolvers.

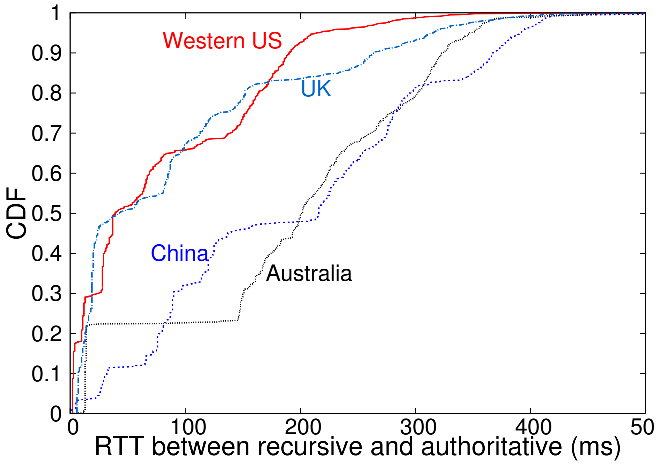


Fig. 17: RTTs from recursive resolvers at four locations to authoritative servers of Alexa top-1000 domains

Los Angeles, China, UK and Australia to authoritative servers of 1000 domains chosen randomly from Alexa top-1M. The data shows that top-1000 sites use better DNS providers, with lower global latency. The results are most strong when viewed from China or Australia—about 20% of the top-1000 have DNS service local to Australia, but that drops to about 8% of the top-1M.

Implications for modeling: This evaluation implies that estimates of median latency based on the top-1000 sites are better than estimates based on the top-1M sites. However, the top-1000 sites get many queries. Analysis of a sample (1M queries) of Level3/cns4.lax1 shows that top-1000 sites get 20% of queries, while 80% are sent to the non-top-1000 sites.

Our modeling is based on $R_{ra} = 40\,\text{ms}$, drawn from Figure 17. Since the top-1000 represent typical common queries, this modeling is representative for what end-users will experience for typical queries. Latency will be larger for

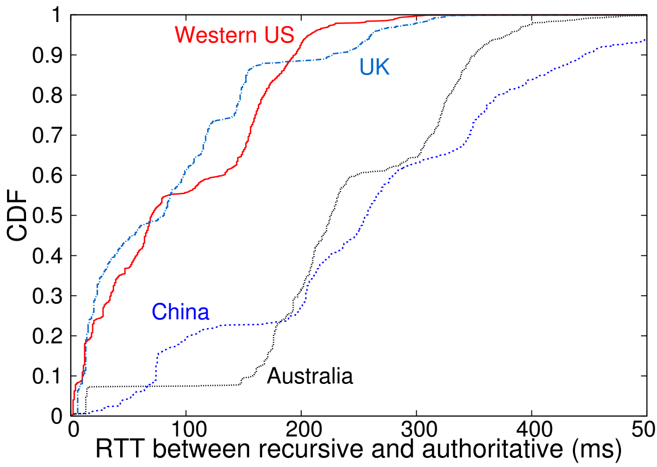


Fig. 18: RTTs from recursive resolvers at four locations to authoritative servers of 1000 domains chosen randomly from Alexa top-1M

rarely used sites with poorer DNS infrastructure; our modeling underestimates the cost measured across all sites because rarely used sites are more greatly affected. We suggest that this focus is appropriate, since the Internet should be designed to support users, not site operators. It also suggests the need for anycast support for DNS hosting to lower latency for global users.

Appendix F
Additional Data for Client-Side Latency

Figure 19 shows the data that underlies Figure 9.

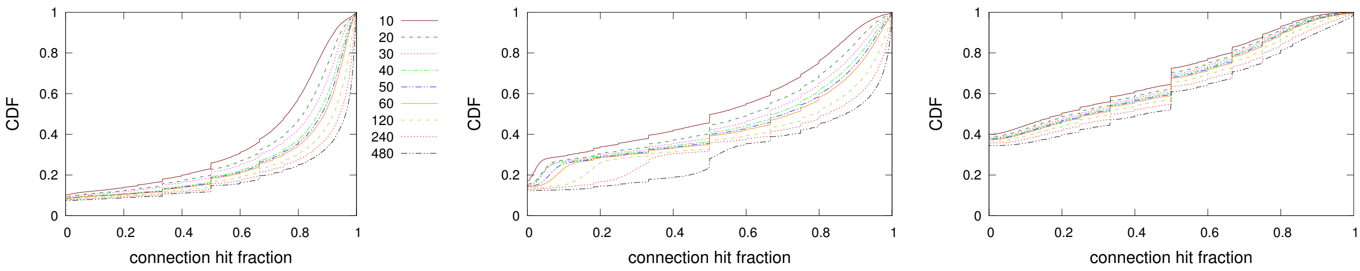
Appendix G
Detailed Evaluation of Deployment

Full exploration of deployment of T-DNS is complicated by the large and varied installed base of DNS resolvers and servers, the necessity of incremental deployment, and the challenge of non-compliant implementations and possibly interfering middleboxes. We discuss these issues next in the context of our three goals: improving privacy, preventing DoS, and relaxing policy constraints.

G-A *Overall goals and constraints*

Overall, our view is that T-DNS can be deployed gradually and incrementally. Its benefits accrue to those who deploy it at both client and server, and until both sides upgrade it either disabled on trial or passive and unexercised. Since T-DNS is "hop-by-hop," some interfering middleboxes can essentially result in a downgrade attack, causing clients to fall back to standard DNS. Middleboxes might affect TCP and TLS differently. Policy benefits of T-DNS require widespread deployment; we discuss how partial deployment affects them below.

Effective gradual deployment requires that costs and benefits be aligned, and that costs be minimal. We show that costs and



(a) Dataset: DNSChanger

(b) Dataset: Level 3, cns[1-4].lax1.

(c) Dataset: B Root

Fig. 19: CDF of client-side connection hit fraction

benefits are most strongly aligned for privacy and DoS, where users or operators are directly affected.

We assume clients and servers use current commodity hardware and operating systems, and DNS client and server software with the changes we suggest. An implicit cost of our work is therefore the requirement to upgrade legacy hardware, and to deploy software with our extensions. This requirement implies full deployment concurrent with the natural business hardware upgrade cycle, perhaps 3 to 7 years. The client and server software changes we describe are generally small, and our prototypes are freely available.

Some clients today struggle or even fail to receive large responses. We believe these problems are due to overly restrictive firewalls, or incorrect implementations. Netalyzr results suggest about 5% cannot do TCP [91], but this error rate is much lower than the 8% and 9% that cannot send or receive fragmented UDP. More recent data suggests only 2.6% of web users are behind resolvers that fail to retry queries over TCP [41]. A 2010 study of DNSSEC through home routers showed mixed results, although full success when DNSSEC clients bypass DNS proxies in home routers [25]. This data suggests that TCP is the *best current* choice to handle large responses and T-DNS is more deployable than the alternatives (such as fragmented UDP messages), but it will be unsuitable for a small fraction of clients (5% or less) until home equipment is reconfigured or upgraded.

We recognize that some clients and servers are more challenging. For clients, it may not be economical to field-upgrade embedded clients such as home routers. We suggest that such systems still often have an upgrade cycle, although perhaps a longer one that is driven by improvements to the wireless or wireline access networks.

Some ISPs have developed extensive and custom server infrastructure. For example, Schomp et al. identifies the mesh of recursive and caching servers used by Google and similar large providers [78]. This infrastructure is proprietary and so it is difficult to speculate on the difficulty of their ability to supporting large responses internally. Since the IETF standards require support for large replies, they may already include such support, and if it employs TCP or a similar program their cost of upgrade may be similar to T-DNS . Upgrade is more challenging if they make assumptions that assume a subset the specifications, such as assuming UDP is always sufficient. However, a single provider with internal infrastructure may have upgrade paths unavailable to the decentralized Internet, such as mandating use of 9 kB UDP jumbograms.

A final complexity in resolvers are use of load balancers and anycast. We observe that the web server community manages both of these challenges, with large-scale load balancers in cloud providers, although at some cost (for example, see [72]). DNS traffic, even over TCP, is much easier to handle than web queries, since query response traffic is much smaller than most web traffic and queries are stateless. A load balancer that tracks all TCP connections will face the same state requirements as end servers, with 50–75k active connections in a large authoritative server. As with servers, we allow load balancers to shed load should they exceed capacity; DNS's anycast and replication can assist distributing hot spots.

Anycast for DNS implies that routing changes may redirect TCP connections to servers at other sites. Since a new site lacks state about connections targeted elsewhere, a routing change causes open connections to reset and clients must then restart. Fortunately, routing changes are relatively rare for 99% of clients [5] and even the most frequent changes occur many times less often than our TCP timeout interval and so will affect relatively few connections. We also observe that some commercial CDNs (such as Edgecast [19]) provide web traffic with anycast successfully, strongly suggesting few problems are likely for T-DNS .

G-B *Improving privacy*

Use of T-DNS to improve privacy requires updates to both the stub and recursive resolvers, and their ability to operate without interference. Usually the stub resolver is determined by the host operating system, but applications can use custom stub resolvers if they choose to. Recursive resolvers are usually controlled by ones ISP, but millions of users opt in to third-party, public DNS infrastructure. We anticipate deployment for most users will occur automatically through the process of upgrades to end-host OSes and ISP resolvers. Upgrades to both ends do not need to be synchronized: T-DNS will be enabled as soon as both sides are upgraded.

Because privacy is an issue between users and their ISPs (or their providers of public DNS service), costs and benefits are well aligned: users interested in private DNS can seek it out and providers may use privacy as a differentiator. Just as HTTPS is now widely deployed for webmail, privacy can become a feature that operators of public DNS services promote (for example [31]), justifying the higher computational cost they incur.

Interference from middleboxes is the primary threat to T-DNS privacy. We consider adversarial and accidental middleboxes. We offer no alternatives against an on-path, adversarial middlebox that intentionally disables TLS negotiation, other than to allow the client to refuse to operate if TLS is disabled. We know of no security protocol that can recover from an adversary that can drop or alter arbitrary packets.

There are several flavors of accidental middleboxes that may affect T-DNS . We expect a T-DNS-aware middlebox to receive T-DNS queries, and make outgoing TCP or TLS queries, or perhaps transparently forward T-DNS that use TLS. Our T-DNS upgrade is designed to be discarded by conforming middleboxes unaware of it, since both EDNS0 extensions and CHAOS queries are defined to be hop-by-hop and so should not be forwarded. Thus an EDNS0-conforming transparent DNS accelerator will drop the TO-bit in T-DNS negotiation, disabling T-DNS but not preventing regular DNS. A non-conforming middlebox that passes the TO-bit but does not understand TLS will attempt to interpret TLS negotiation as DNS-encoded queries. A likely outcome is that the DNS client and server will fail TLS negotiation; clients should be prepared to fall back without T-DNS in this case. The middlebox will interpret the TLS negotiation as malformed DNS packets; should discard them if it is robust to fuzz testing [60], as all protocols that interpret packets from the public network. A less robust middlebox may crash, indicating it is likely vulnerability to buffer overruns.

Although we cannot study all possible middleboxes, we tested an unmodified version of dnsmasq, a DNS forwarder that is widely used on home routers. We confirmed that it correctly doesn't forward our request to upgrade to TLS, and that it does not crash but suppresses a "forced" TLS attempt. A T-DNS-aware implementation of dnsmasq is future work.

A special case of an interfering middlebox is "hotspot signon" interception. Public networks such as wifi hotspots often require end-user identification via a web form before opening access to the public Internet. They redirect all DNS and web traffic to a proxy where the user self-identifies, allowing an opportunity for billing or access control. Applications today must cope with this transient state where network access is limited and all traffic is redirected. DNSSEC-trigger shows a possible work-around: on network activation, it identifies DNSSEC failure, alerts the user, and retries frequently waiting for full network access [63].

We do not focus on use of TLS between recursive and authoritative servers. Recursive resolvers that choose to use TLS will face similar challenges as above, and deployment of TLS across millions of authoritative resolvers will be a long-term proposition. Fortunately, aggregation at the recursive resolver provides some degree of privacy to stubs, so slow deployment here has relatively little privacy penalty.

G-C Preventing DoS

Traditional anti-DoS methods have been challenged by needing near-full deployment to be effective, and a misalignment of costs with benefits. As a result, deployment of practices like ingress filtering [33] has been slow [8].

Two effects help align T-DNS deployments costs with benefits of reducing DoS attacks. First, DNS operators suffer along with victims in DNS amplification attacks—DNS operators must support the traffic of the requests and the amplified responses. Desire to constrain these costs motivates deployment of solutions at the DNS server.

Second, large DNS operators today typically deploy a great deal of overcapacity to absorb incoming UDP-based DoS attacks. We suggest that shifting some of that capacity from UDP to TCP can provide robustness to absorbing DoS attacks.

The main challenge in use of T-DNS to reduce DoS is the necessity of backwards compatibility with a UDP-based client population. Authoritative resolvers must accept queries from the entire world, and UDP-based queries must be accepted indefinitely. To manage this transition, we support the idea of rate-limiting UDP responses, which is already available in major implementations and in use by some DNS operators [89]. A shift to TCP would allow these rates to be greatly tightened, encouraging large queriers to shift to TCP.

A secondary challenge is optimizing TCP and TLS use servers so that they do not create new DoS opportunities. Techniques to manage TCP SYN floods are well understood [30], and large web providers have demonstrated infrastructure that serves TCP and TLS in the face of large DoS attacks. We are certain that additional work is needed to transition these practices to TCP-based DNS operations.

G-D Removing Policy Constraints

Global changes to address policy constraints are very challenging—costs affect everyone and benefits accrue only with near-full adoption. However, EDNS0 shows migration is possible (although perhaps slow), from standardization in 1999 [86] to widespread use today.

EDNS0 deployment was motivated by the need of DNSSEC to send responses larger than 512 B, and the implications of not supporting EDNS0 is reduced performance. We suggest that T-DNS presents a similar use-case. Because *all* DNS implementations *require* TCP today when UDP results in a truncated reply, defaulting to TCP for DNS instead of trying UDP and failing over to TCP is largely about improving performance (avoiding a UDP attempt and the TCP retry), not about correctness. EDNS0 suggests we might expect a transition time of at least ten years.

G-E Comparison to deployment of alternatives

Finally, it is useful to consider the deployment costs of T-DNS relative to alternatives.

DNS-over-HTTPS (perhaps using XML or JSON encodings) has been proposed as a method that gets through middleboxes. We believe DNS-over-HTTPS has greater protocol overheads than T-DNS: both use TCP, but use of HTTP adds a layer of HTTP headers. It also requires deployment of an completely new DNS resolution infrastructure in parallel with the current infrastructure. Its main advantage is avoiding concerns about transparent DNS middleboxes that would be confused by TLS. We suggest that the degree to which this problem actually occurs should be studied before "giving up" and just doing HTTP. The performance analysis of T-DNS largely applies to DNS-over-HTTPS, offering guidance about what performance should be expected.

Use of a new port for T-DNS would avoid problems where middleboxes misinterpret TLS-encoded communication on the DNS port. It also allows skipping TLS negotiation, saving one RTT in setup. Other protocols have employed STARTTLS to upgrade existing protocols with TLS, but an experimental study of interference on the DNS reserved port is future work. The DNS ports are often permitted through firewalls today, so use of a new port may avoid problems with DNS-inspecting middleboxes only to create problems with firewalls requiring an additional open port.

Appendix H
Potential Vulnerabilities Raised by TCP

Wide use of TCP risks raising new vulnerabilities in DNS. We address several here.

There are a set of attacks on TLS that exploit compression to leak information about compressed-then-encrypted text [48]. Versions of these attacks against HTTPS are known as CRIME and BREACH. For HTTPS, these attacks depend on the attacker being able to inject input that precedes the target text in the reply. For DNS queries this condition is not met and so CRIME does not pay.

One may be concerned that long-lived DNS TCP connections can lead to exhaustion of TCP ports. This concern is incorrect for several reasons. The main reason is that the number of TCP ports is defined by the 4-tuple of (source IP, source port, destination IP, destination port). It is not defined only by destination port, which for DNS will always be fixed at 53. The (source IP, source port) portion provides an effectively unlimited resource because interactions with many different servers will get many source IPs, and we expect individual servers to keep TCP connections open and reuse them. The worst scenario is that an attacker can spoof 65k source ports for a single victim, but even then the DNS server will return SYN-ACKs with SYN cookies to the victim; if such an attack becomes common victims could deploy countermeasures such as discarding unsolicited SYN-ACKs. This analysis applies to DNS servers, clients, and load balancers. Additional safety comes from our approach to deal with all resource exhaustion: a server can always close connections to shed resources if it detects resource contention, such as running low on free memory. Finally, the existence of large-scale web servers demonstrates that it is clearly possible to scale to support many concurrent TCP connections, well within the tens of thousands of active connections we project as being required.

Attacks on the TCP sequence number space are another potential risk, with concerns that connections could be reset [90] or even data injected. T-DNS provides strong protection against traffic injection when TLS is used. For TCP-only queries, risk of these attacks is minimized with strong initial sequence numbers [35]. T-DNS clients must be prepared to resume interrupted connections, so a successful connection reset (an expensive proposition to guess the sequence number) will cause only a slight delay.

Appendix I
Relationship of T-DNS and TLS to DTLS

We have asserted that our modeling of T-DNS also applies to DNS-over-DTLS, if one removes the RTT for the TCP three-way-handshake, because both implement the same fundamental cryptographic protocol. In short, our argument is that There Is No Free Lunch—DTLS must pay nearly the same costs as TLS over TCP, because both require ordering and sequencing in the TLS handshake. We next review that argument in more detail.

TLS Handshake: The DTLS handshake reproduces the TLS handshake, including the assumption that messages are delivered reliably and in-order.

DTLS lacks the TCP three-way handshake, saving one RTT. However to avoid DoS attacks, it adds a cookie analogous to TCP SYN cookies. DTLS makes cookie exchange optional as a separate step. If done separately it becomes equivalent to the TCP handshake. If done with the first step of the TLS handshake, it avoids an extra RTT but allows an amplification attack. Cookies can be cached and replayed, analogous to TCP fast-open.

To provide reliability and ordering of an arbitrary-sized TLS handshake process DTLS adds a message sequence number and fragmentation handling to message exchanges, recreating a subset of TCP. DTLS's uses timeouts based on TCP's [70], but the implementation is intentionally simpler (for example, omitting fast retransmit). It seems unlikely that DTLS retransmission will perform better than TCP under loss, and likely that it may perform somewhat worse.

Operation: The primary operational difference, post handshake, is that DTLS forces use of block ciphers, not stream ciphers, and that DTLS does not force packet ordering. Block ciphers expose some information hidden in stream ciphers, where prior traffic affects subsequent encryption.

DTLS requires each DTLS record fit in a single datagram and it strives to avoid IP fragmentation. Thus DTLS *exacerbates* the existing problems with large DNS replies, adding at least 12 bytes to each packet.

TCP bytestreams allow aggregation of concurrent requests into a single packet. Aggregation reduces per-packet overhead by sending more information in each packet. We disable Nagle's algorithm in our work to avoid adding latency; in experiments we still see aggregation when multiple requests occur in bursts. This kind of aggregation is not possible with DNS-over-DTLS (over UDP).

DTLS and TLS trade-offs: Because the cryptographic protocols of TLS over TCP and DTLS over UDP are so similar we see little performance difference between them. There are two semantic differences: DTLS is advantageous because it imposes no ordering on individual requests. Thus it gets pipelining and out-of-order processing automatically, just as basic UDP does; we describe how to provide those in the application for TCP, but we still suffer from head-of-line blocking from lost packets. TCP is advantageous because it imposes no per-packet size limits. We identify policy constraints brought on by per-packet size limits as a problem, so for this reason we prefer DNS-over-TLS and TCP over DNS-over-DTLS and UDP.