

# Analyzing the Costs (and Benefits) of DNS, DoT, and DoH for the Modern Web

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## Abstract

Essentially all Internet communication relies on the Domain Name System (DNS), which first maps a human-readable Internet destination or service to an IP address before two endpoints establish a connection to exchange data. Today, most DNS queries and responses are transmitted in cleartext, making them vulnerable to eavesdroppers and traffic analysis. Past work has demonstrated that DNS queries can reveal everything from browsing activity to user activity in a smart home. To mitigate some of these privacy risks, two new protocols have been proposed: DNS-over-HTTPS (DoH) and DNS-over-TLS (DoT). Rather than sending queries and responses as cleartext, these protocols establish encrypted tunnels between clients and resolvers. This fundamental architectural change has implications for the performance of DNS, as well as for content delivery.

In this paper, we measure the effect of DoH and DoT on name resolution performance and content delivery. We find that although DoH and DoT response times can be higher than for conventional DNS (Do53), *DoT can perform better than both protocols in terms of page load times, and DoH can at best perform indistinguishably from Do53*. However, when network conditions degrade, webpages load quickest with Do53, with a median of almost 0.5 seconds faster compared to DoH. Furthermore, in a substantial amount of cases, a webpage may not load at all with DoH, while it loads successfully with DoT and Do53. Our in-depth analysis reveals various opportunities to readily improve DNS performance, for example through *opportunistic partial responses* and *wire format caching*.

## 1 Introduction

The Domain Name System (DNS) underpins nearly all Internet communication; DNS lookups map human-readable domain names to corresponding IP addresses of Internet endpoints. Because nearly every Internet communication is preceded by a DNS lookup, and because some applications may require tens to hundreds of DNS lookups for a single transaction, such as a web browser loading a page, the performance of DNS is paramount. Many historical DNS design decisions and implementations (e.g., caching, running DNS over UDP

instead of TCP) have thus focused on minimizing the latency of each DNS lookup.

In the past several years, however, DNS privacy has become a significant concern and design consideration. Past research has shown that DNS lookups can reveal various aspects of user activity including the web sites that a user is visiting, and even the devices that a user may have in their home (and how they are using them). As a result, various efforts have been developed to send DNS queries over encrypted transport protocols. Two prominent examples are DNS-over-TLS (DoT) and DNS-over-HTTPS (DoH). In both cases, a client sends DNS queries to the resolver over an encrypted transport (TLS), which relies on the Transmission Control Protocol (TCP).

The use of encrypted transports makes it impossible for passive eavesdroppers to observe DNS queries, like an attacker for devices on a shared network (e.g., a wireless network in a coffee shop). These transports also allow clients to send encrypted DNS queries to a third-party resolver (e.g., Google or Cloudflare), preventing a user’s ISP from seeing the DNS queries of its subscribers. As such, from a privacy perspective, DoT and DoH are attractive protocols, providing confidentiality guarantees that DNS previously lacked.

On the other hand, encrypted transports introduce new performance costs, including the overhead associated with TCP and TLS connection establishment, as well as additional application-layer overhead. The extent of these performance costs is not well-understood. An early preliminary study by Mozilla found that DoH lookups are only marginally slower than conventional, unencrypted DNS over port 53 (Do53) [23]. However, Mozilla only measured resolution timings, which does not accurately reflect the holistic end-user experience.

In this paper, we measure how encrypted transports for DNS affect end-user experience in web browsers. We find that DNS queries are typically slower with encrypted transports. Much to our surprise, however, we discovered that using DoT can result in *faster* page load times compared to using Do53 and DoH. When exploring the underlying reasons for this behavior, we discovered that encrypted transports have previously ignored quirks that significantly affect application performance. For example, when DNS requests are sent over a lossy network, DoH and DoT are able to recover faster than Do53 because TCP packets can be retransmitted within 2x the round-trip-time latency to a recursive resolver.

On networks with sub-optimal performance however, these protocols begin to suffer because of their connection and transport overhead. The relative costs and benefits of a particular DNS transport protocol and its corresponding implementation for DNS lookup performance and web page load time ultimately depend on the underlying network conditions. This variability suggests that in some cases, clients (i.e., operating systems or browsers) might consider using different transport protocols for DNS based on their varying cost, performance, and privacy trade-offs. Our findings also suggest uncontroversial and easy improvements to the conventional stub resolver and browser DNS implementations.

In this paper, we make the following contributions:

- *We provide the first extensive performance study of Do53, DoT, and DoH.* We measure DNS lookup and page load times across Do53, DoT, and DoH. We evaluate these DNS transports and implementations of them using popular open recursive resolvers operated by Cloudflare, Quad9, and Google, as well as a conventional DNS resolver operated by a university network.
- *We show that encrypted DNS transports can lead to improved user experience compared to unencrypted DNS.* We find that DNS lookup times for DoH and DoT are generally slower than Do53. However, page load times can be *faster* when using DoT, and DoH can perform at best indistinguishably from Do53. We offer several possible explanations, such as differences in UDP application timeouts and TCP retransmission times.
- *We give generally applicable insights to optimize DNS performance.* We identify underlying reasons for why DoT can outperform Do53 in page load times. Based on these insights, we then propose several optimizations to improve DNS lookup times, such as wire-format caching and support for partial responses.

## 2 Background

At a high level, the process for resolving domain names into IP addresses works in several steps. A client *queries* a recursive resolver (“recursor”), for example, “what is the IP address for `www.example.com`?”. The client has traditionally been a stub resolver, which is a lightweight process that manages DNS interactions with the global DNS infrastructure. If the recursor does not have an answer for the domain name cached, it will issue the query on the client’s behalf to upstream servers in the DNS hierarchy, including the root, TLD, and ultimately authoritative servers for a given domain. Once the answer is returned to the recursor, the recursor caches the response and sends it to the client.

Due to the historical origins of the DNS, there are several privacy problems that were not originally considered [3]. For example, DNS queries sent over port 53 (or “Do53”) are typically unencrypted. This means that any eavesdropper

listening to traffic between the client and a recursor can see what queries the client is making. Such information can be used to reveal personal information, such as browsing patterns and client device types, which can then be used to link user identity with user traffic. While recursors themselves could also observe every query a client makes, recent protocols have been introduced to (at least) improve privacy for DNS traffic in transit between clients and DNS servers.

Hu et al. proposed DNS-over-TLS (or “DoT”) in 2016 to prevent eavesdroppers from observing DNS traffic between a client and a recursor [16]. It works largely similar to Do53, but the DNS traffic is sent over an established TLS connection, which means that it relies on TCP by default rather than on UDP. Once the connection is established, all queries are encrypted by the transport sent over port 853. Although DoT is relatively new, it has seen a significant increase in popularity since its introduction as some operating systems, such as Android, have started to use DoT opportunistically [21].

In 2018, Hoffman et al. proposed DNS-over-HTTPS to prevent on-path manipulation of DNS responses [15]. DoH is similar to DoT, but uses HTTP as the transport protocol instead of TCP. Wire format DNS queries and responses are sent using HTTP, and client applications and servers are responsible for translating between the application-layer messages and traditional DNS infrastructure. An argument for DoH versus DoT has surrounded anti-censorship concerns, as DoH uses port 443 compared with port 853. Oppressive regimes sometimes censor the Internet by dropping DNS traffic, but DoH requires a malicious network operator to drop all HTTPS traffic (on port 443) to prevent name resolution.

In this paper, we do not investigate the privacy and anti-censorship properties offered by each protocol. Rather, we are focus on the effects that Do53, DoT, and DoH have on web performance and analyzing their respective costs and benefits. We believe such measurements are necessary for users to make informed decisions about protocol choice for this crucial function of the Internet.

## 3 Method

In this section, we first define the performance metrics that we study (DNS resolution time and web page load time), and explain how we measure them. Second, we describe our experiment setup.

### 3.1 Metrics

To understand how Do53, DoT, and DoH affect browser performance on the modern web, we measure page load time and DNS resolution time. DNS resolution timings are gathered using a custom client.

### 3.1.1 DNS Resolution Time

To obtain precise, accurate DNS lookup timings, we use the getdns and libcurl C libraries to measure Do53, DoT, and DoH performance.<sup>1</sup>

Getdns is a library that provides a modern API for making Do53 and DoT queries in various programming languages [14]. We use the C bindings to make Do53 and DoT queries for each unique domain in the HARs that we collect. To simulate Firefox page loads, we ensure that DoT queries use the same TLS connection for up to 10 seconds. We also ensure that all Do53 queries are made over UDP.

Libcurl is a library that allows developers to use cURL features in their applications [35]. It supports POST requests over HTTPS, which can be used to make DoH queries after adding the “application/dns-message” MIME type. As of April 2019, libcurl supports HTTP/2, which we use because HTTP/2 being the recommended minimum HTTP version for DoH due to HTTP/2 multiplexing [15].

### 3.1.2 Page Load Time

We use Mozilla Firefox controlled by Selenium to visit a list of websites in our dataset and record timings. We measure page load times are gathered by inspecting HTTP Archive objects (HARs), which can be collected from any webpage in Firefox [39]. We collect HARs for each website, which include timings for the onLoad event, as well as for individual components for each request that the browser made, including all resources of a page.

Although HARs also provide DNS lookup timings, we discovered during the course of our experiments that the timings for individual components, including DNS lookup times, are inaccurate. For example, we discovered that the first request that a HAR contains can show DNS timings of 0 ms, even in cases where it is impossible because we begin every browsing session with an empty cache and the latency to the recursor is larger than 10 ms. This is the case because, depending on how a website issues HTTP redirects, the first request occurring in the HAR is not actually the first request that the browser performed. Instead, the browser might have performed a variety of other HTTP requests and DNS queries before, which may still be in-progress or already cached.

Interestingly, this peculiarity not only results in timings of 0 ms, but other values as well. Other values are possible because the browser may issue multiple requests to the same domain at different times through its thread pool, with the first one being redirected (thus, itself not being in the HAR, and the redirection target having a timing of 0 ms), and other requests made in between resolving the name of the domain for the domain’s first request.

In turn, the subsequent requests’ domain lookups can be answered from the cache that the domain’s first request populated. However, the request itself does not appear in the HAR. Depending on when the requests are made, which depends on

factors such as rendering time, the timings can take any value and shift the timings to the left. This would even be the case if we would use the maximum of all values, because the first request that triggers resolving the domain may not be present in the HAR. Therefore, we only rely on the onLoad event timings for page loads from the HAR; onLoad event timings should be more accurate because onLoad is an event widely used by JavaScript code running on millions of webpages. It is also implemented by all major browser vendors.

## 3.2 Experiment Setup

To ensure that our results are generalizable and are representative of diverse network conditions and configurations, we perform measurements across multiple resolvers, networks, and website lists. Doing so allows us not only to measure browser experience for different users, but also to understand how Do53, DoH, and DoT perform under different network conditions. We describe our hardware configuration, our choices of website lists, resolvers, and networks below.

### 3.2.1 Hardware

Our experiment setup includes three desktop-class PCs running Debian testing (buster). Each machine includes 32 GB of RAM and an 8th generation Intel Core i7 CPU. The machines are connected to the differing provider networks over Ethernet, and run a measurement suite designed to collect browser-based statistics as well as raw DNS performance statistics. We create a Docker image<sup>2</sup> to deploy the measurement suite across all of the machines.

### 3.2.2 DNS Recursors and Transport Protocols

We measure how selection of the recursive resolver and DNS transport affect browser performance. Accordingly, we chose three popular publicly-available recursive resolvers: Google, Quad9, and Cloudflare. Each resolvers offers public resolution for Do53, DoT, and DoH.

Do53 and DoH are natively supported in Firefox, the browser we use to drive our measurements. However, as of April 2019, DoT must be configured by using a stub resolver on a user’s machine outside of Firefox. For our measurements, we use Stubby for DoT resolution, a stub resolver based on the getdns library [10]. Stubby listens on a loopback address and responds to Do53 queries. All DNS requests received by Stubby are then sent out to a configured recursive resolver over DoT. We modify /etc/resolv.conf on our measurement systems to point to the loopback address served by Stubby. This forces all DNS requests initiated by Firefox to be sent over DoT.

We also use a local university resolver to measure page load times and DNS performance. However, this resolver only supports Do53, and not DoT or DoH. Thus, this resolver serves as a baseline for browser performance over DNS on a university network.

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<sup>1</sup>The tool will be publicly released at the time of publication.

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<sup>2</sup>The Docker image will be publicly released at publication.

| Connectivity      | Recurser   | Minimum Latency | Average Latency | Maximum Latency | Standard Deviation $\sigma$ | Observations |
|-------------------|------------|-----------------|-----------------|-----------------|-----------------------------|--------------|
| Wired University  | Default    | 0.28ms          | 0.44ms          | 11.42ms         | 0.11ms                      | 49,999       |
|                   | Quad9      | 2.20ms          | 3.00ms          | 55.29ms         | 0.34ms                      | 149,993      |
|                   | Google     | 2.54ms          | 2.94ms          | 53.18ms         | 0.34ms                      | 149,987      |
|                   | Cloudflare | 2.36ms          | 2.85ms          | 166.06ms        | 0.62ms                      | 149,964      |
| Cellular 4G       | Default    | 52.67ms         | 53.91ms         | 90.93ms         | 0.71ms                      | 49,744       |
|                   | Quad9      | 54.68ms         | 56.46ms         | 291.57ms        | 1.26ms                      | 149,240      |
|                   | Google     | 54.91ms         | 56.39ms         | 215.91ms        | 1.07ms                      | 149,172      |
|                   | Cloudflare | 54.77ms         | 56.29ms         | 263.51ms        | 1.10ms                      | 149,204      |
| Cellular 4G Lossy | Default    | 52.67ms         | 53.93ms         | 92.11ms         | 0.68ms                      | 49,244       |
|                   | Quad9      | 54.68ms         | 56.85ms         | 336.34ms        | 9.73ms                      | 147,489      |
|                   | Google     | 54.95ms         | 56.57ms         | 333.59ms        | 6.48ms                      | 147,659      |
|                   | Cloudflare | 54.72ms         | 56.55ms         | 335.53ms        | 8.55ms                      | 147,565      |
| Cellular 3G       | Default    | 142.44ms        | 150.75ms        | 449.63ms        | 5.14ms                      | 48,937       |
|                   | Quad9      | 144.54ms        | 153.64ms        | 622.37ms        | 10.80ms                     | 146,466      |
|                   | Google     | 144.78ms        | 153.38ms        | 456.77ms        | 8.00ms                      | 146,652      |
|                   | Cloudflare | 144.57ms        | 153.41ms        | 454.11ms        | 10.30ms                     | 146,660      |

Table 1: Recursor latency characteristics for different network conditions.

### 3.2.3 Provider Networks

Our goal is to understand relationships between end-user (*i.e.*, browser) performance, DNS, and network performance. DNS performance is greatly effected by a client’s Internet service provider, as the ISP’s network configuration determines the paths the DNS traffic will use to reach a resolver (should the client opt to use a resolver that is hosted outside of the ISP network). We are particularly interested in web performance over networks that exhibit packet loss or high latency. We believe it is important to simulate cellular performance as an increasing number of users are browsing the web on their phones. Furthermore, organizations like Cloudflare have released mobile applications to force the operating system to use encrypted DNS transports. We perform our measurements using different ISP network scenarios, including conditions that emulate mobile network characteristics.

First, we connect one machine to the Internet via a university campus network. The university has a 20 Gb/s connection to the Internet. It is a well-connected network to Cloudflare, Quad9, and Google, respectively (Table 1). We also gather measurements using the default resolver that is managed by the university and hosted locally. We chose this network to measure the best-case effect of different DNS transports on web performance.

Second, we place a measurement node on the university network, but with traffic shaping applied to emulate 4G mobile network performance. We shape outgoing traffic with an additional latency of 53.3 ms and jitter set to 1 ms. We also dropped 0.5% of packets to mimic the loss that cellular data networks can exhibit. Finally, we shape our uplink rate to 7.44 Mb/s and our downlink rate to 22.1 Mb/s. These settings are based on an OpenSignal report of mobile network experience across providers [38].

Third, we apply traffic shaping to emulate a 4G network with additional loss (4G Lossy in Table 1). We use the same latency and jitter settings as 4G, but we increase the loss rate to 1.5% of packets.

Finally, we emulate 3G network performance by adding 150 ms of latency and 8 ms of jitter, along with 2.1% packet loss and uplink and downlink rates of 1 Mb/s each. While users in well-connected areas are increasingly less likely to experience 3G performance, it remains prevalent globally, particularly in less developed areas. Table 1 shows the measured latencies to different DNS providers from our varying network conditions.

To avoid biasing results due to network quiet and busy times, as well as the potential effect of a query warming the recursive cache for subsequent queries from the other protocols tested, we randomize several aspects of the measurement suite. First, for each run through the list of websites, we shuffle the order of websites prior to browsing. Next, for each individual website, we randomize the order of DNS protocol as well as the DNS provider.

### 3.2.4 Websites

We collect HARs (and resulting DNS lookups) for the top 1,000 websites on the Tranco top-list to understand browser performance for the average user [22] visiting popular sites. Furthermore, we measure the bottom 1,000 of the top 100,000 websites (ranked 99,000 to 100,000) to understand browser performance for websites that are less popular. We chose to measure the tail of the top 100,000 instead of the tail of the top 1 million because we found through experimentation that many of the websites in the tail of the top 1 million were offline at the time of our measurements. Furthermore, there is significant churn in the tail of top 1 million, which means that we would not be accurately measuring browser performance for the tail across the duration of our experiment.

### 3.3 Limitations

Our research has some limitations that may affect the generalization of our results. Nonetheless, we argue that our work will further the research community’s understanding of how DNS affects user experience, and how various DNS stakeholders can improve it.

First, we performed our measurements exclusively on the Debian operating system, which means that its networking stack and parameters for networking algorithms will affect our measurements. However, networking stacks are often heavily optimized, so we expect our results to generalize across operating systems.

Second, we rely on Mozilla Firefox to measure page load times, which means that its DNS implementations will influence our results. Considering that web browsers are among the most used software today and also highly optimized for performance, we also expect our results to generalize across browsers.

Finally, we conducted our experiments from a single network at a major university on the east coast of the United States. On one hand, this means that we are not able to generalize our results across other networks. On the other hand, this network is equally well-connected to all three external recursors (Cloudflare, Google, and Quad9), with an average of 2.85ms to 3.0ms and a standard deviation between 0.34ms and 0.62ms (Table 1). This allows us to contrast recursors and protocols directly, without being negatively effected by additional delay to certain recursors due to peering.

## 4 Measurement Results

In this section, we describe our measurement results for DNS resolution times and page load times, and analyze the underlying protocols to understand the performance we see. Our measurement was performed continuously over the course of seven days using the setup described in Section 3. These results provide some insight into how a user’s choice of networks, resolvers, and protocols affect end-user experience.

### 4.1 DNS Resolution Time

Intuitively, DNS resolution time is the most critical metric when characterizing DNS performance, as web pages typically include many objects (e.g., images, javascript, frames, etc.), which all must have their underlying server names resolved to IP addresses. Indeed, previous work has shown that DNS lookups can cause performance bottlenecks on website page loads [40]. Accordingly, we begin our study with the resolution times for our network environments.

We note that Mozilla conducted a measurement study of DoH lookup times in 2018 with Firefox Nightly users. In their measurement study, they found that most requests were 6 ms slower than Do53 requests, and that DoH actually has faster lookup times than Do53 for the slowest requests [23]. However, Mozilla’s experiment was limited to Cloudflare’s DoH resolver, and they report no data for other recursive

resolvers, like Quad9 and Google. Furthermore, they only measure DoH, ignoring DoT entirely.

To fill these gaps and independently validate Mozilla’s results, we designed our own experiment to measure lookup times for DoH, DoT, and Do53 across different networks and resolvers. For each HAR file that we collected with our automated browser, we extracted all unique domain names. We then time the resolution time for each domain name through our own tool, which uses getdns and libcurl.

For DoT requests, we enabled connection reuse with an idle timeout of 10 seconds in order to amortize the TCP handshake and TLS connection setup. Although Firefox does not currently support DoT within the browser, we believe this is a realistic setting, and is the default timeout used by DoT stub resolvers such as Stubby. For DoH requests, we also enabled connection reuse, and we sent requests over HTTP/2, which is the recommended minimum HTTP version for DoH and which Firefox uses for DoH (we independently verified that Firefox uses HTTP/2 through a packet capture with mitmproxy and Wireshark [5, 7]).

Figure 1 shows CDFs for DNS resolution times on the university network for the top 1,000 websites and the top 99k-100k websites combined. As expected, we find that Do53 performs better than DoT and DoH on for most lookups across all resolvers. The additional overhead introduced by encrypted transports for DoT and DoH leads to an increase in resolution time. Interestingly, however, we find that DoH is slightly faster than Do53 for the slowest queries on Cloudflare and Quad9. We believe this can be attributed to HTTP caching, which we discuss in further detail in Section 5.2.2.

Comparing DoT with DoH, we see some differences between providers. Cloudflare DoT and DoH appear to perform equally for the majority of requests, though DoH begins to outperform DoT for requests that take longer than  $\approx 50$ ms. Google, on the other hand, shows that DoT generally outperforms DoH for requests that take less than  $\approx 100$ ms, above which DoH performs better. We posit that this could be due to the experimental nature of Google’s DoH service, as it may have a different caching backend than the DoT or Do53 Google recursors. Quad9 shows the largest range in terms of performance, with DoT requests experiencing long latencies compared to all other recursors and protocols. Quad9’s DoH recursor tends to perform better in comparison, but still lags behind their Do53 service.

### 4.2 Page Load Time

Based on our resolution results, we expect page load times to follow a similar pattern, with Do53 outperforming both DoT and DoH. Figure 2 shows CDFs for differences in page load times between each configuration when running our measurements on the university network. The vertical line on each subplot indicates the median for the CDF. A median that is less than 0s on the x-axis means that the configuration (recursor, protocol) specified by the row title is faster than the configuration specified by the column title (indicated in blue

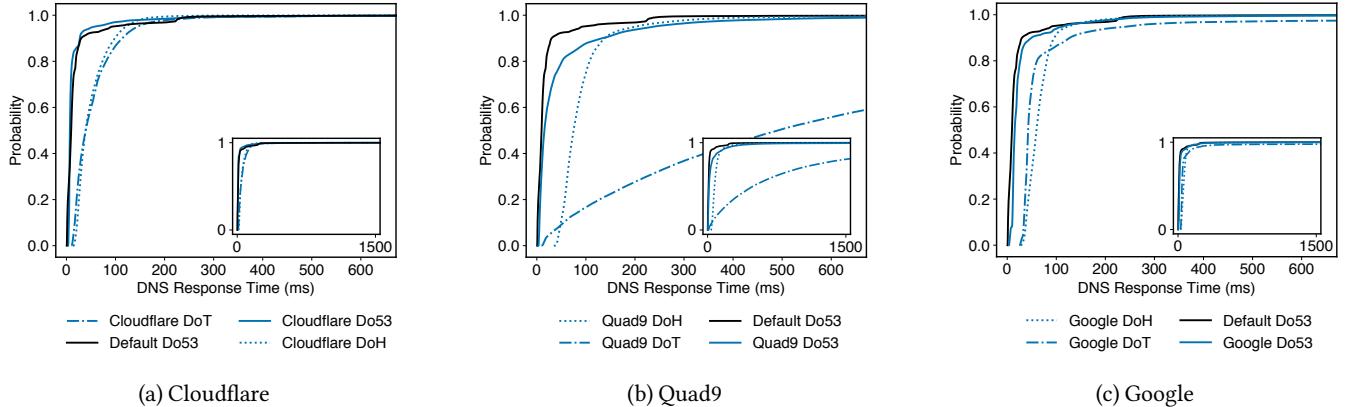


Figure 1: Resolution times for each provider on a university network.

hues). Correspondingly, a median that is greater than 0s on the x-axis means that the configuration specified by the row title is slower than the configuration specified by the column title (indicated in red hues). Finally, a median that is close to 0s (between -0.03s and 0.03s) indicates that row configuration and column configuration perform indistinguishably from each other (0.03s correspond to 1 frame at 30Hz).

Interestingly, Cloudflare DoT outperforms all other non-Cloudflare configurations, including the default Do53 recursor. Similarly, Cloudflare Do53 and DoH outperform most non-Cloudflare configurations. Lastly, Cloudflare DoH, DoT, and Do53 perform indistinguishably from each other. These results stand in contrast to our naïve expectation that page load times for DoT and DoH would be slower than Do53 due to additional latency for individual requests, as our results in Section 4.1 show that DoT and DoH requests are on average slower than Do53 requests.

We believe the reason why Cloudflare DoT, DoH, and Do53 perform so similarly on a university network in page load times is because the additional latency introduced by DoT and DoH is minimal compared to the overall page load time. As Figure 1a shows, 70% of DoH and DoT queries complete in less than  $\approx 50$ ms. On the other hand, 70% of Do53 queries complete in less than  $\approx 10$ ms. However, the difference in page load times between these protocols is indistinguishable on a well-connected network.

Importantly, the client implementations of Do53, DoT, and DoH differ substantially. As we discuss in Section 4.5, DoH has a higher overhead per query than Do53 and DoT. However, for Do53 and DoT, Firefox resolves names synchronously with a thread pool (via the operating system through `getaddrinfo()`) [25]. On the other hand, the DoH implementation is asynchronous using Firefox’s optimized HTTP/2 implementation [26, 28]. This may mean that DoH may be able to make up for its larger overhead than Do53 and DoT because page loads won’t be blocked by synchronous queries if the thread pool is exhausted.

We note that pages that were loaded with DoT and DoH were slightly slower with Quad9. Similarly, pages that were

loaded with DoH were significantly slower with Google. There are multiple reasons why this might be the case, such as caching performance and recursor implementations. We discuss these reasons in depth in Section 4.4.

### 4.3 Effect of Network Conditions

We also study how network conditions affect lookup times and page load times for Do53, DoT, and DoH. Our results in Section 4.1 and Section 4.2 are based on measurements conducted from a well-connected university network. However, cellular network users and users in developing regions often access the Internet through networks with high latency and significant loss. We expect such less-than-ideal conditions of these networks may significantly affect how Do53, DoT, and DoH perform.

Figure 3a and Figure 3b show CDFs for resolution times with Cloudflare’s recursor on an emulated cellular 4G network and an emulated lossy cellular 4G network. We focus on Cloudflare’s recursor because it performs better than Quad9 and Google (Figure 1 and Figure 2). On cellular networks, Do53 significantly outperforms DoT and DoH in terms of resolution time. Interestingly, it appears that DNS timings on a cellular 4G and lossy cellular 4G network are similar, independent of the additional 1% loss.

Figure 3c shows CDFs for resolution times for cellular 3G network characteristics, which have higher loss, higher latency, and less bandwidth than 4G networks, and, in turn, we expect it affects DNS performance dramatically. We find that DoT and DoH resolution times are substantially longer than Do53 resolution times. The fastest DoH and DoT lookups take  $\approx 470$ ms, whereas the fastest Do53 lookups take  $\approx 150$ ms. In fact, even the slowest DoH and DoT lookups never close the latency gap to the slowest Do53 lookups. Based on this significant difference, we expect page load performance on 3G to be better with Do53 than with DoT or DoH.

To test our hypothesis, we also measure page load times on the emulated networks. Figure 4 compares page load times across all of our tested networks and protocols for Cloudflare’s recursors. On the cellular 4G network, DoT performs indis-

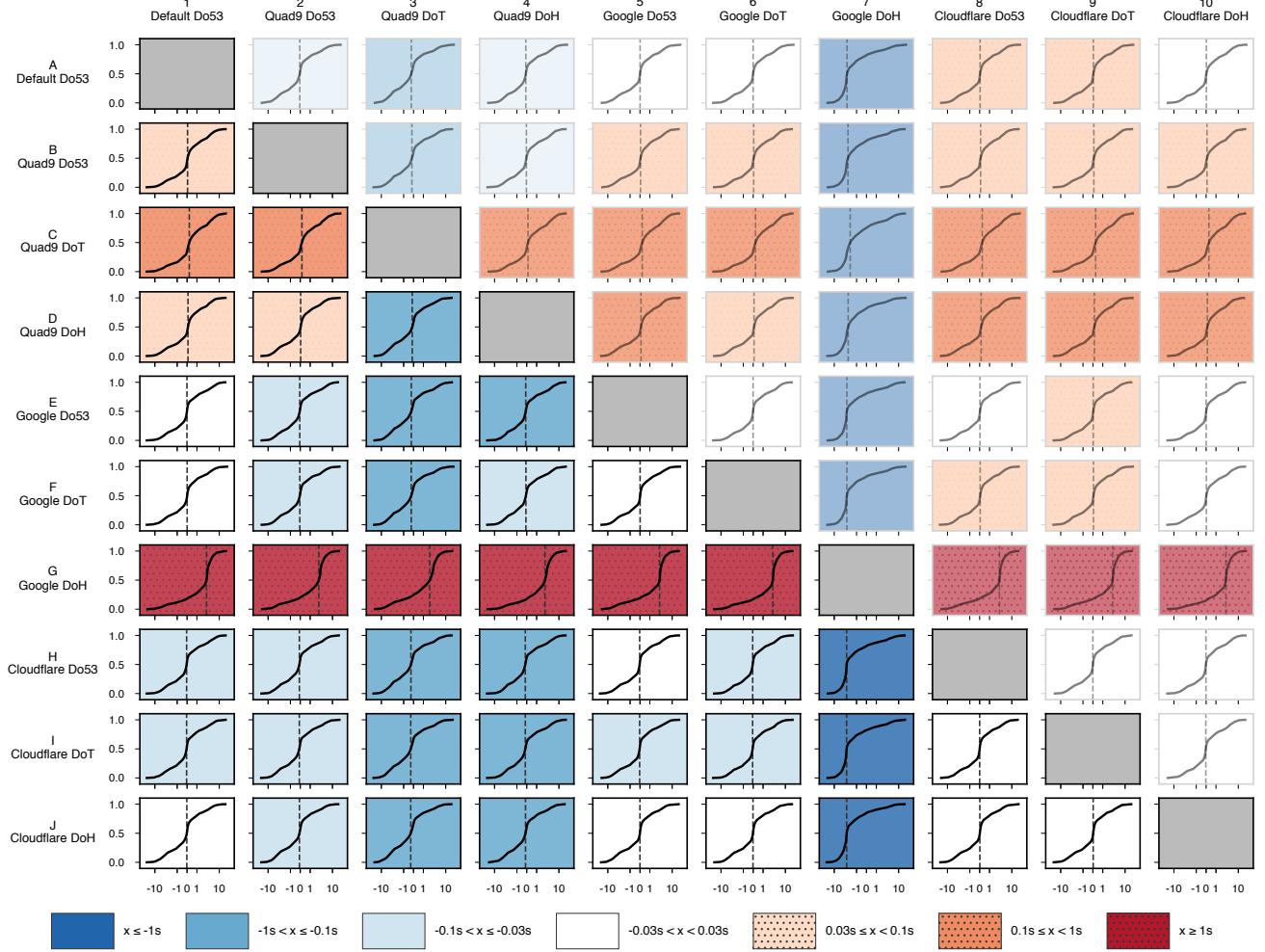


Figure 2: CDFs for differences in page load times between each configuration.

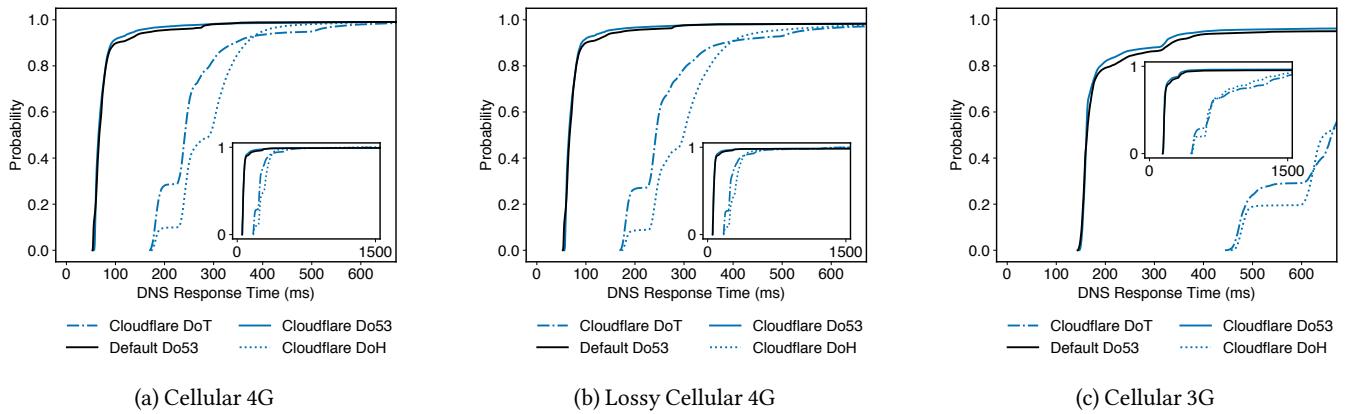


Figure 3: DNS timings for Cloudflare across each protocol on three emulated lossy networks

tinguishably from Do53. However, DoT performs slightly *better* than Do53 on the lossy 4G network, with page load times that are slightly faster (between 100ms and 1s faster).

Interestingly, DoH performs indistinguishably from Do53 on the lossy 4G network, but it performs worse on the standard 4G network.

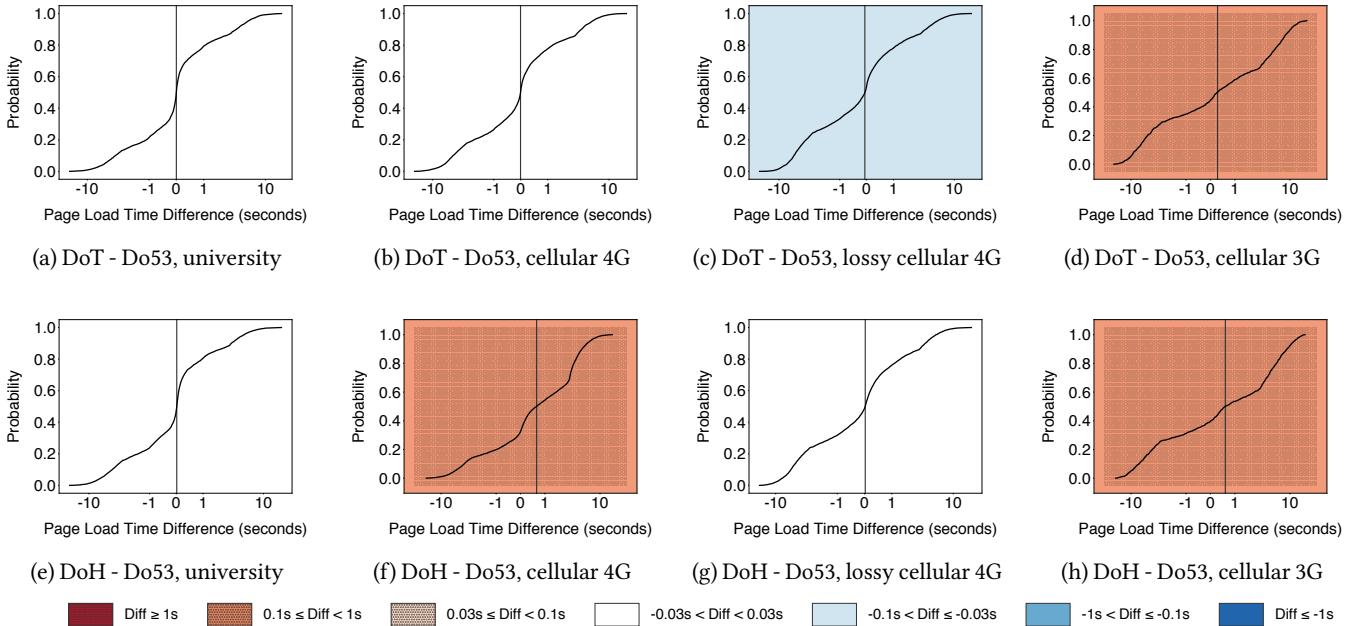


Figure 4: Comparison of page load times between protocols and networks using Cloudflare’s resolver

It may seem counter-intuitive that page loads using DoT and DoH perform indistinguishably or better than Do53 on the 4G and lossy 4G networks due to substantially longer lookups (Figure 3). However, the differences in how DNS timeouts are handled between TCP and UDP offer a possible explanation. For example, the default timeout for Do53 requests in Linux is set to 5 seconds by `resolvconf` [20]. For DoT and DoH on the other hand, DNS packets may be retransmitted within 2x the round-trip-time latency to a recursive resolver because of TCP. If the round-trip time to a recursive resolver is on the order of hundreds of milliseconds, then DoT and DoH will more quickly re-transmit dropped packets than Do53.

However, as throughput decreases and loss increases on a 3G network, DoT and DoH are no longer able to perform as well as Do53 concerning website page loads. We believe this can be attributed to their higher overhead compared to Do53, which contributes to link saturation for most websites. Correspondingly, DoH’s has a higher overhead than DoT, which leads to significantly slower page loads (Figure 4d and Figure 4h). Furthermore, if name resolutions fail entirely, then objects on the web page cannot load, and the web page fails to load completely.

Table 2 shows the prevalence and types of errors we encountered during our page load measurements. Overall, we see that in lossier conditions, DoH experiences higher failure rates compared with Do53. For instance, using the 3G settings, Cloudflare Do53 has 4.84 percentage points (27.4%) more successful page loads compared with Cloudflare DoH. We also see that DNS errors spike for DoH in poor network conditions. Conversely, DoT tends to maintain higher rates of success compared with DoH.

#### 4.4 Recursor Behavior

Cloudflare’s recursors result in consistently lower page load times than any other recursor we measured, including the default Do53 recursor provided by the university network (Figure 2, H1 through J10). We believe that Cloudflare’s caching strategy is a core reason for their better performance. Specifically, their recursors can cache responses more easily because they do not support the EDNS Client Subnet extension (ECS) [4, 6], which Google generally supports [12], and Quad9 may support for some upstream authoritative name-servers [31, 37].

The purpose of ECS is to forward the client’s address or network to the authoritative server via the recursor, which allows the authoritative server to provide a response to the recursor that takes the client’s address into account, for example to direct it to a server that is located nearby. By not supporting ECS, Cloudflare’s recursors can have higher cache hit rates, in particular for a client’s first requests. Specifically, Cloudflare does not need to limit cached responses to the client’s IP address or network indicated through ECS in the original query, that is, their cache is client agnostic. On the contrary, the caches for Google and partially Quad9 must be client specific because of ECS.

Website and CDN operators should therefore consider abandoning DNS-based localization and stop relying on ECS, and instead adopt anycast. Interestingly, the cost that recursor cache misses incur because of ECS could actually negate the benefits of directing a user to a local server via ECS in a variety of cases, and even directing him to a single central data center (without anycast) could lead to a better user experience than ECS. Overall, *disabling ECS not only improves client*

privacy, but our results show that it can also decrease client page load times, leading to an immediate improvement in a user’s browsing experience.

We also observe that Google DoH performs significantly worse than all other DNS recursors or protocols on the university network (Figure 2, G1 through G10). For example, when using Google DoH instead of Cloudflare DoT—the fastest configuration we measured—*the same website loads 2.02s slower in the median case* (G9 and I7). This may be the case because Google’s DoH recursor is still experimental and the deployment is not optimized for production use. Google’s DoH production deployment may perform better, but it only speaks a proprietary JSON format that is incompatible with Mozilla Firefox and other RFC8484-compliant DoH clients [11].

Quad9 DoT performs worse in page load times than all recursors besides Google DoH, and a website loads 0.26s faster using Cloudflare DoT over Quad9 DoT. Similarly, Cloudflare DoT is faster than Quad9 Do53, which is the quickest protocol for Quad9. This is the case even though our latency to Quad9 is lower than to Cloudflare and has smaller variance (Table 1), indicating that *recursor performance and characteristics are more important for page load times than network connectivity to the recursor*. Considering DNS resolution times (Figure 1), we believe that Quad9 DoT does not correctly cache responses, which leads to stacked normal distributions for the connection to the recursor and the recursor’s connections to authoritative nameservers. Another possible explanation for Quad9 DoT’s odd behavior is that the recursor is trying to connect to authoritative nameservers via DoT, which fails and then triggers a retry via Do53. We disclosed our findings to Quad9, but we did not receive an explanation.

## 4.5 Query Cost Amortization

We also investigate when the overhead cost of sending DoH and DoT requests is amortized. At first glance, it seems that DoT and DoH requests are strictly more expensive than Do53 requests. The client must establish a TLS connection with the recursor before it can send any DoT or DoH requests, which requires hundreds of bytes to be sent on its own. Subsequent requests would then be accompanied by an IP header, TCP header, TLS header, and a DNS header. In the case of DoH, an HTTP/2 header must also be sent. On the other hand, Do53 does not require a TLS connection, and requests just have an IP header, a UDP header, and a DNS header.

Fortunately, much of the TLS connection setup overhead for DoT and DoH can be amortized if requests are sent over a single, or relatively few, TLS connection(s). Furthermore, multiple DoT/DoH requests that quickly follow one another can share a TCP packet (Nagle’s algorithm [29]), whereas each Do53 request must be its own UDP packet. Therefore, we want to approximate how many requests must be sent before the setup costs of DoT and DoH can be amortized.

For simplicity, we assume that a fully qualified domain name is 10 bytes long. We also assume that a Do53 query

| Connectivity      | Status            | Cloudflare |        |        |
|-------------------|-------------------|------------|--------|--------|
|                   |                   | Do53       | DoT    | DoH    |
| Wired University  | Successful        | 76.39%     | 76.24% | 75.13% |
|                   | Page-load Timeout | 9.71%      | 9.70%  | 9.47%  |
|                   | DNS Error         | 9.32%      | 9.27%  | 9.42%  |
|                   | Selenium Error    | 1.86%      | 1.86%  | 1.79%  |
|                   | Other Error       | 4.58%      | 4.79%  | 5.98%  |
| Cellular 4G       | Successful        | 77.18%     | 77.58% | 77.48% |
|                   | Page-load Timeout | 10.59%     | 10.33% | 10.23% |
|                   | DNS Error         | 9.30%      | 9.29%  | 9.51%  |
|                   | Selenium Error    | 1.74%      | 1.86%  | 1.84%  |
|                   | Other Error       | 2.93%      | 2.80%  | 2.78%  |
| Cellular 4G Lossy | Successful        | 76.97%     | 77.92% | 77.89% |
|                   | Page-load Timeout | 10.52%     | 10.23% | 9.98%  |
|                   | DNS Error         | 9.29%      | 9.25%  | 9.50%  |
|                   | Selenium Error    | 1.71%      | 1.72%  | 1.69%  |
|                   | Other Error       | 3.22%      | 2.60%  | 2.63%  |
| Cellular 3G       | Successful        | 22.46%     | 22.42% | 17.62% |
|                   | Page-load Timeout | 66.40%     | 66.51% | 51.40% |
|                   | DNS Error         | 9.25%      | 9.25%  | 29.48% |
|                   | Selenium Error    | 1.59%      | 1.51%  | 1.22%  |
|                   | Other Error       | 1.89%      | 1.82%  | 1.50%  |

Table 2: Successful website page-loads and error percentages for different network conditions when using Cloudflare’s recursor. Please see Appendix A.1 for success and error rates for all providers.

consists of 56 bytes, i.e. the UDP header (8 bytes), the IP header (20 bytes), the DNS header (18 bytes), and the domain name (10 bytes). Similarly, a DoT query consists of 33 bytes, i.e. the TLS header (5 bytes), the DNS header (18 bytes), and the domain name (10 bytes). Lastly, a DoH query consists of 55 bytes because it contains the same headers and data as a DoT query (33 bytes) and the minimal HTTP/2 headers (22 bytes). We do not include the TCP/IP headers (40 bytes) for each DoH/DoT query because multiple requests will be made in one TCP packet.

We also estimate the static overhead associated with establishing a DoH or DoT connection on the client-side. For DoT, the static overhead to the recursive resolver is 506 bytes, comprised of the bytes needed to complete a TCP handshake (80 bytes), send the TLS CLIENT HELLO (260 bytes), and send the TLS CLIENT DONE (166 bytes). Similarly, for DoH, the static overhead is 872 bytes, comprised of the bytes needed to complete a TCP handshake (80 bytes), send the TLS CLIENT HELLO (260 bytes), send the TLS CLIENT DONE (166 bytes), and send HTTP/2 settings (366 bytes).

Finally, the minimum size of the headers in a TCP packet is 40 bytes, comprised of the IPv4 header (20 bytes) and the TCP header (20 bytes), which means that there are at most 1460 bytes available in a TCP packet for DoT/DoH requests sent over Ethernet (MTU = 1500). Based on our estimates, we

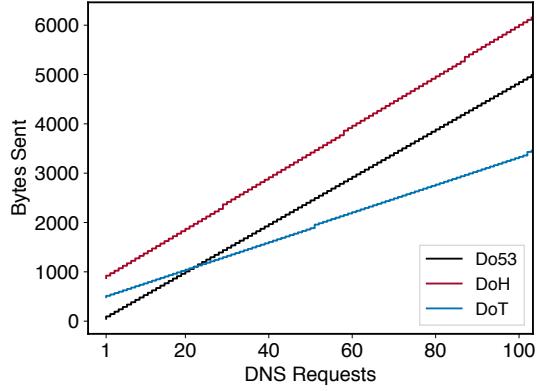


Figure 5: Approximate cost in bytes of sending Do53, DoT, and DoH requests

can define the bytes that the client needs to send to resolve  $r$  domain names:

$$Bytes_{Do53} = 56 \times r$$

$$Bytes_{DoT} = 40 \times \lceil \frac{r}{\lfloor \frac{1460}{33} \rfloor} \rceil + (33 \times r) + 285$$

$$Bytes_{DoH} = 40 \times \lceil \frac{r}{\lfloor \frac{1460}{55} \rfloor} \rceil + (55 \times r) + 872$$

Figure 5 shows the corresponding number of bytes sent by the client over Do53, DoT, and DoH as more requests are issued. The cost of DoT requests are amortized over a single TLS connection if more than 24 requests are made. This is because a new UDP packet must be created for each Do53 query, whereas multiple DoT requests are able to share a single TCP packet. Interestingly, DoH requests can *never* be amortized for different values of  $r$ . The costs of HTTP/2 headers and sending HTTP/2 settings prevent DoH from being less costly than DoT and Do53.

In the HARs we collect on a university network, the top 1,000 websites contain resources from a mean 16.25 domains, a median of 10 domains, and a maximum of 216 domains. Using the equations we defined in Section 4.5, we estimate that for 10 requests ( $r = 10$ ), 876 bytes are sent with DoT, and 560 bytes are sent with Do53. Thus, for the median website in the top 1,000 list, 316 more bytes over DoT than Do53. These results suggest that although DoT requests are not typically amortized over a single TLS connection in a web browser, the additional overhead of DoT is not prohibitively costly. On the other hand, if a single TLS connection to a recursor was shared by a web browser with multiple processes on a given system, then the cost of DoT queries would be quickly amortized. Such behavior would provide a clear performance advantage to DoT over Do53.

## 5 Discussion

Based on our results, we offer several insights to improve Do53, DoT, and DoH resolution times, which can reduce page load times and improve user experience. We first discuss our DoH-specific insights, followed by our transport-independent insights.

### 5.1 DoH Improvements

Our results indicate that DoH is almost always worse than DoT in all network conditions despite its implementation being asynchronous. It is worse in the percentage of pages that load successfully (Table 3), and in page load times (Figure 2). Notwithstanding, we recognize that DoH over HTTP/2 *could* improve resolution time and page load performance in specific circumstances, and it may have a future among DNS transports for (at least) two reasons: *HTTP/2 server push* and *compression*.

#### 5.1.1 HTTP/2 Server Push

HTTP/2 server push enables web servers to push content to a client that the client has not yet requested [1], but which it is expected to request. It is based on the assumption that when a client requests a web page, it will also request the embedded objects shortly after receiving the initial page. Instead of requiring manual inlining of the page’s resources, the web server can respond with multiple HTTP objects and preempt and prevent additional requests by the client. When preparing the request for a resource, the client realizes the domain name points to the same address and can use the response it already received through server push, without the request ever being sent to the server. The scope of when server push is permissible, however, is limited for security reasons: Pushing resources for a different domain that may be hosted on the same server or CDN still requires looking up the domain through DNS.

HTTP/2 server push for DoH aims to eliminate this domain lookup by also including the DNS response. It has received some basic attention in DoH’s RFC [15], but various operational questions remain unanswered and require further exploration before it could be adopted. For example, it is unclear how web servers and DoH servers would collaborate, which they would have to, to allow the web server to push a DNS response that the client can verify as valid and also accept (as DoH and web server may be different, and, thus, their scope for permissible pushes is different). Effectively, only large content-delivery networks like Cloudflare and Google would be able to deploy such systems, which has raised concerns over centralized DoH or “DNS over Cloud” (DoC) among DNS stakeholders [17]. Similarly, HTTP/2 server push would require the application to resolve DNS itself, at least partially, which would transgress current norms, and has sparked a heated debate on the IETF DoH mailing list [18].

### 5.1.2 Compression

Another potential advantage is compression of HTTP responses and, in turn, DNS responses. It could provide a non-negligible improvement to DNS response sizes, if they are sufficiently large and repetitive that the compression overhead can be amortized. Intuitively, this may be true for additional and authoritative sections of a DNS response, however, public recursors often remove these sections from their responses to prevent denial-of-service amplification, and, thus, DNS responses are relatively small. Taking into account that HTTP/2 response compression occurs per HTTP/2 frame, responses must be compressed individually and compression cannot exploit repetition across responses.

Therefore, HTTP compression does not benefit the majority of DNS responses today. TLS compression may appear to be a solution, but it is not supported by TLS 1.3 anymore [32] and best current practices recommend to disable TLS 1.2 compression to prevent compression-related attacks [34]. For queries with more than one question  $QDCOUNT > 1$  (see also Section 5.2.1), compression could reduce DoH’s overhead to be less than DoT’s or Do53’s, but it is currently unclear if HTTP/2 compression could improve on existing DNS compression [24, Section 4.1.4].

More research is necessary to investigate the yet-unexplored potential advantages of HTTP/2 as a transport for DNS more closely, and measure their potential benefit for the DNS ecosystem. *Today, however, DoH results in a worse user experience than DoT for comparable and well-managed recursors.*

## 5.2 Overall DNS Improvements

Based on our measurements and observations, we believe that two improvements can be readily made to improve performance of Do53, DoT, and DoH: *opportunistic partial responses* and *wire format caching*.

### 5.2.1 Opportunistic Partial Responses

We discovered that current DNS clients do not utilize part of the DNS Internet Standard that could improve client performance and user experience. Unfortunately, DNS servers *violate* this part of the DNS Internet Standard [24] by *not supporting* queries with more than one question ( $QDCOUNT > 1$ ). The three public recursors we studied either do not respond (Quad9 and Cloudflare), or incorrectly only respond to the first question (Google).

Without compatible recursors, clients cannot utilize this part of the standard to send fewer larger queries, and, thus, less bytes due to reduced overhead. We were unable to discover any reason in RFCs and on the IETF dnsop and dnsext mailing lists why servers may misbehave. We speculate that it could be because the DNS Internet Standard sets the expectation that  $QDCOUNT$  is “usually 1” [24].

Naïvely, it also appears that there is no good reason to support more than one question because it would delay the

response to a large query until all authoritative answers have been received, which may take multiple seconds and, in turn, severely degrade user experience. Furthermore, it would effectively eliminate the benefit of out of order responses that single question queries enable. Out of order responses are currently implemented in Do53 through UDP, in DoT through response reordering [9], and in DoH through HTTP/2’s stream multiplexing [1].

We believe that *opportunistic partial responses* could be a solution: A client indicates that it wants to use partial responses on the first single question query through a EDNS partial response option, which the server confirms if it supports it. Thereafter, the client can send multiple questions in the same query when including the same EDNS partial response option, and the server can respond with individual answers or multiple answers in a single DNS response as authoritative answers arrive. We are currently exploring authoring a corresponding Internet-Draft.

### 5.2.2 Wire Format Caching

In our DNS timing measurements, we confirmed Mozilla’s findings that the mean DoH response time is higher than for DoT or Do53, but that its variance is lower, which results in a reduced response time in the distribution’s tail. This appears to be the case because Firefox uses a hard-coded DNS transaction ID of 0 [27], which allows DoH recursors, including Cloudflare, to leverage HTTP response caching of the DNS response’s wire format more aggressively and at the edge. Correspondingly, this side-steps the issue of having to always construct the DNS response and reduces the response time, even if it can be constructed from a local cache database.

The security effect of a fixed transaction ID is limited for DoH because it relies on TLS, which makes it difficult to inject a spoofed response that could be used to poison the client’s cache. For DoT, the same argument can be made and it is similarly amenable to wire format caching. For Do53, a fixed transaction ID would allow cache poisoning, and, hence, it is not a viable solution.

Generally, to improve tail response times, we suggest to cache the DNS response wire format regardless of transaction ID, and to simply replace the two byte transaction ID before responding (e.g., via XOR), which also has the benefit of being compatible with DoT clients that send random transaction IDs. It is important to note that the DNS TTL values of a response also need to be updated (decremented) regularly, and this invalidates the HTTP response or wire format cache, but by decreasing the TTL by more than the required amount, the wire format cache can be kept valid longer.

## 6 Related Work

In this section, we compare to related work on encrypted DNS transport, measurements on how DNS impacts page load times, and we touch on DNS privacy concerns.

Zhu et al. [41] introduced DNS over TLS, that is DNS over TLS over TCP, to provide confidentiality guarantees that DNS lacked. They measured the performance costs and benefits of sending DNS queries over a TLS connection, and find that DoT response times are only up 22% slower than Do53. We measure higher DoT response times when measuring response times naively due to fewer queries being sent and less connection reuse. Different from Zhu et al., our study focuses on how different DNS transports affect user experience, through page load times, and how it differs in the face of different network conditions. We find that DoT improves web page load times even if only few DNS queries are necessary because of faster retransmits and Nagle’s algorithm.

To our knowledge, no comparable prior work exists for DNS over HTTPS, and we believe that we provide the first in-depth study that investigates costs and benefits for users of Do53, DoT, and DoH for the modern web.

In addition to DoT and DoH, other protocols have been proposed to ensure privacy of the communication between a client and a recursive resolver. DNSCrypt [8] utilizes cryptographic signatures to authenticate a recursive resolver to a client, which prevents DNS responses from being spoofed or tampered with. Similarly, DNSCurve [2] utilizes elliptic-curve cryptography to provide confidentiality, authenticity, and integrity of DNS responses. However, for DNSCrypt and DNSCurve, the recursive resolver remains aware of what names a client queries for, which has privacy implications as it allows the recursor to learn about the websites that the client visits and when it visits them. Schmitt et al. [33] proposed oblivious DNS, which prevents a resolver from associating queries to the clients that sent them, and, thus, prevents a recursor from learning a client’s browsing behavior.

Sundaresan et al. [36] measured and identified performance bottlenecks for web page load time in broadband access networks and found that page load times are influenced by slow DNS response times and can be improved by prefetching. An important distinction is that they define the DNS response time only as the lookup time for the first domain, while we consider the set of unique fully qualified domain names of all resources contained in a page. They investigate only nine high-profile websites, which stands in contrast to the 2,000 popular and normal websites that we analyze, and they estimate page load times through Mirage and validate their findings through a headless browser PhantomJS, while we utilize Mozilla Firefox, which is a full browser.

Wang et al. [40] introduced WProf, which is a profiling system to analyze page load performance. They identified that DNS lookups, in particular uncached, cold lookups can significantly affect web performance, accounting for up to 13% of the critical path delay for page loads.

In 2012, Otto et al. [30] found that CDN performance was negatively affected when clients choose recursive resolvers that were geographically separated from CDN caches. We conjecture that this was the case because recursors did not support ECS at the time (ECS was only introduced in January

2011, and standardized in May 2016) and CDNs only slowly started adopting anycast. Therefore, clients were likely redirected to sub-optimal data center based on the recursor’s address or network, instead of the client’s address. We suspect that with the wide-spread adoption of ECS and anycast since 2012, CDN performance may not be considerably negatively affected anymore when choosing a recursor that is geographically far away from a CDN.

We note that there are also privacy concerns related to DNS that are above the recursive resolver in the DNS hierarchy. For example, Imana et al. [19] posit that clients could be tracked above the recursor through personally identifiable queries, such as for “clintonemail.com.” Similarly, Hardaker [13] analyzed data sent by recursors in residential networks to root servers over two months, and he discovered query names that allow to identify specific smart home devices, such as cameras. We focus on the costs and benefits of DNS protocols that mitigate privacy risks directly impacted by a user’s choice of configuration. Because the user cannot influence the recursor’s protocol to the authoritative, we consider above the recursive resolver as out of scope.

## 7 Conclusion

In this paper, we investigated DNS timings and page load times using different DNS transport protocols in multiple network conditions. We find that although privacy-focused DNS protocols result in higher resolution times for individual queries, page load times improve due to inherent benefits of the underlying transport protocols.

Based on our findings, DNS stakeholders can take several concrete steps to improve DNS performance. For example, browser currently use synchronous calls for DNS resolution, and asynchronous calls could greatly benefit Do53 and DoT performance. We find that client localization using anycast is better than ECS, and, in fact, clients have an incentive to *not* use ECS. Similarly, clients and recursors supporting QDCOUNT > 1 along with partial responses could reduce the question overhead for Do53, DoT, and Do53. This could be accomplished in a backward compatible way through a new EDNS option if the recursor will be extended to allow for opportunistic partial responses. Another opportunity to improve DoT and Do53 response times that we discovered is wire format caching.

Our findings also indicate that a user’s recursor choice can have a significant impact on the number of pages that load successfully, and reduce the time they need to load. Therefore, users should choose their DNS protocol based on network conditions and their recursor based on intuitive metrics like successful page loads and page load time, instead of pure DNS response time, as the specific recursor choice can lead to direct quality of life improvements.

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## A Appendix

### A.1 Error Table for All Providers

Please see Table 3.

| Connectivity      | Status            | Default |        | Quad9  |        | Google |        | Cloudflare |        |        |        |
|-------------------|-------------------|---------|--------|--------|--------|--------|--------|------------|--------|--------|--------|
|                   |                   | Do53    | Do53   | DoT    | DoH    | Do53   | DoT    | DoH        | Do53   | DoT    | DoH    |
| Wired University  | Successful        | 76.11%  | 76.29% | 75.53% | 73.65% | 76.08% | 75.51% | 74.63%     | 76.39% | 76.24% | 75.13% |
|                   | Page-load Timeout | 9.77%   | 9.61%  | 10.05% | 9.18%  | 9.95%  | 9.83%  | 9.63%      | 9.71%  | 9.70%  | 9.47%  |
|                   | DNS Error         | 9.44%   | 9.46%  | 9.43%  | 10.57% | 9.29%  | 9.28%  | 9.72%      | 9.32%  | 9.27%  | 9.42%  |
|                   | Selenium Error    | 1.84%   | 1.83%  | 1.89%  | 1.74%  | 1.86%  | 1.89%  | 1.86%      | 1.86%  | 1.86%  | 1.79%  |
|                   | Other Error       | 4.68%   | 4.64%  | 4.99%  | 6.60%  | 4.68%  | 5.38%  | 6.02%      | 4.58%  | 4.79%  | 5.98%  |
| Cellular 4G       | Successful        | 76.59%  | 76.92% | 76.32% | 75.08% | 76.91% | 77.43% | 76.55%     | 77.18% | 77.58% | 77.48% |
|                   | Page-load Timeout | 10.49%  | 10.53% | 11.23% | 10.14% | 10.47% | 10.55% | 10.44%     | 10.59% | 10.33% | 10.23% |
|                   | DNS Error         | 9.37%   | 9.46%  | 9.47%  | 11.63% | 9.27%  | 9.28%  | 10.09%     | 9.30%  | 9.29%  | 9.51%  |
|                   | Selenium Error    | 1.86%   | 1.88%  | 1.85%  | 1.79%  | 1.80%  | 1.72%  | 1.82%      | 1.74%  | 1.86%  | 1.84%  |
|                   | Other Error       | 3.55%   | 3.09%  | 2.98%  | 3.15%  | 3.35%  | 2.74%  | 2.92%      | 2.93%  | 2.80%  | 2.78%  |
| Cellular 4G Lossy | Successful        | 77.42%  | 77.10% | 76.65% | 75.18% | 77.18% | 77.59% | 76.24%     | 76.97% | 77.92% | 77.89% |
|                   | Page-load Timeout | 10.42%  | 10.74% | 11.19% | 9.46%  | 10.65% | 10.48% | 10.40%     | 10.52% | 10.23% | 9.98%  |
|                   | DNS Error         | 9.36%   | 9.39%  | 9.42%  | 12.16% | 9.23%  | 9.23%  | 10.47%     | 9.29%  | 9.25%  | 9.50%  |
|                   | Selenium Error    | 1.81%   | 1.60%  | 1.71%  | 1.89%  | 1.71%  | 1.76%  | 1.87%      | 1.71%  | 1.72%  | 1.69%  |
|                   | Other Error       | 2.80%   | 2.77%  | 2.74%  | 3.20%  | 2.94%  | 2.70%  | 2.89%      | 3.22%  | 2.60%  | 2.63%  |
| Cellular 3G       | Successful        | 22.65%  | 22.29% | 22.13% | 9.86%  | 22.45% | 22.67% | 13.66%     | 22.46% | 22.42% | 17.62% |
|                   | Page-load Timeout | 66.21%  | 66.50% | 66.54% | 29.02% | 66.46% | 66.02% | 40.63%     | 66.40% | 66.51% | 51.40% |
|                   | DNS Error         | 9.32%   | 9.39%  | 9.50%  | 60.11% | 9.23%  | 9.32%  | 44.39%     | 9.25%  | 9.25%  | 29.48% |
|                   | Selenium Error    | 1.48%   | 1.53%  | 1.56%  | 0.65%  | 1.55%  | 1.70%  | 0.95%      | 1.59%  | 1.51%  | 1.22%  |
|                   | Other Error       | 1.82%   | 1.82%  | 1.83%  | 1.01%  | 1.86%  | 1.99%  | 1.32%      | 1.89%  | 1.82%  | 1.50%  |

Table 3: Successful website page-loads and error percentages for different network conditions.