# *Towards Digital Sovereignty in the Age of Hyper-giants*


Vaibhav Bajpai

CISPA HELMHOLTZ CENTER FOR INFORMATION SECURITY


**Team**

**Trinh Viet Doan**

**Mike Kosek**

**Justus Fries**

**Irina Tsareva**

**Malte Granderath**

**Thanks!**

RIPE NCC RIPE Atlas

Open INTEL

http archive

zmap

Computer Laboratory SRG Seminar
University of Cambridge, UK

March 10 / 2022


supported by

VolkswagenStiftung

# Outline | Towards Digital Sovereignty in the Age of Hyper-giants

1. Age of Hyper-giants
   → An Empirical View on Consolidation of the Web TOIT '22
   Evaluating Public DNS Services in the Wake of Increasing Centralization NETWORKING '21

2. Towards Digital Sovereignty: Improving Privacy in DNS
   Measuring DNS over TLS from the Edge PAM '21
   A First Look at DNS over QUIC PAM '22

# *Towards Digital Sovereignty* in the *Age of Hyper-giants*

The Internet is getting centralised

1. A long-term perspective on the growth and ubiquity of hyper-giants.

leading to security & privacy concerns

## An Empirical View on Consolidation of the Web TOIT '22

Trinh Viet Doan, Roland van Rijswijk-deij,
Oliver Hohlfeld, Vaibhav Bajpai

### Motivation and Problem Statement

- The Web was initially (30 years ago) designed to be a decentralised system.
- Lately, there are concerns of Web traffic increasingly getting brokered via hyper-giants.
- Such Web consolidation raises technical, societal (privacy) and economical (innovation) concerns.
- However, contemporary empirical studies on Web consolidation are still lacking.

To what extent does web content centralise at hyper-giants (Google *et al.*) for content delivery and hosting?

How lop-sided is the deployment of new innovations on the Internet (protocols) due to such large hyper-giants?

# Consolidation of the Web | Findings

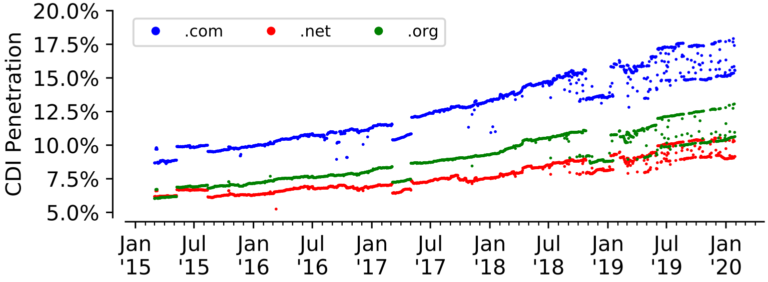
- Landing webpages
  - Consolidation (>160M websites) has increased by >80% from 8% (2015) to 15% (2020)
  - >24% of popular websites (top 1M) host their landing page on a hyper-giant.

- Web content
  - >56% of popular content (top 4.3M webpages) is hosted on a hyper-giant.
  - A landing page hosted on a hyper-giant, also has >80% of its content hosted on one of them.
  - Google and Amazon contribute to >52% of content hosted on hyper-giants.

A first study to provide a longitudinal empirical grounding of Web consolidation.

# Consolidation of the Web | Landing webpages

- .com | .net | .org (>160M domains) – 50% of global DNS namespace
- Hyper-giant penetration – 8.2% (2015) → 15% (2020), an increase by >83%
- Amazon accounts to >50% of hyper-giant growth alone in .com.




Hyper-giant penetration has nearly doubled from 2015–2020, and is higher among more popular domains.

# Consolidation of the Web | Content and Assets

- A handful of hyper-giants deliver majority of the Web content.
- Google and Amazon contribute to >52% of content hosted on hyper-giants.

| | Provider | # Assets (↓) | Sum of Sizes [GB] | Share of CDI Assets by Num. | Share of CDI Assets by Size | Share of All Assets by Num. | Share of All Assets by Size |
|---|---|---|---|---|---|---|---|
| 1) | Google | 76.6M | 1,494.9 | 34.5% | 24.0% | 19.5% | 11.1% |
| 2) | Amazon | 38.9M | 1,277.2 | 17.5% | 20.5% | 9.9% | 9.5% |
| 3) | Cloudflare | 27.5M | 956.4 | 12.4% | 15.3% | 7.0% | 7.1% |
| 4) | Facebook | 17.7M | 423.4 | 8.0% | 6.8% | 4.5% | 3.1% |
| 5) | Akamai | 15.7M | 496.7 | 7.1% | 8.0% | 4.0% | 3.7% |
| 6) | Fastly | 10.8M | 411.3 | 4.9% | 6.6% | 2.7% | 3.0% |
| 7) | WordPress | 4.1M | 109.3 | 1.9% | 1.8% | 1.1% | 0.8% |
| 8) | Twitter | 4.0M | 65.8 | 1.8% | 1.1% | 1.0% | 0.5% |
| 9) | Microsoft | 3.8M | 181.0 | 1.7% | 2.9% | 1.0% | 1.3% |
| 10) | NetDNA | 3.6M | 148.5 | 1.6% | 2.4% | 0.9% | 1.1% |

| Asset Type | # CDI Assets | CDI Pen. of Type | # All Assets of Type | Share (All) (↓) |
|---|---|---|---|---|
| image | 82,613,713 | 46.8% | 176,660,130 | 45.0% |
| javascript | 64,223,345 | 64.1% | 100,195,949 | 25.5% |
| text | 21,676,628 | 50.4% | 43,017,071 | 11.0% |
| html | 19,590,470 | 69.6% | 28,148,091 | 7.2% |
| other | 11,864,834 | 70.4% | 16,847,204 | 4.3% |
| font | 14,245,056 | 86.0% | 16,569,827 | 4.2% |
| application | 6,303,607 | 68.4% | 9,220,762 | 2.4% |
| video | 1,135,211 | 91.8% | 1,236,756 | 0.3% |
| audio | 265,302 | 62.2% | 426,583 | 0.1% |
| **Total** | 221,918,166 | 56.6% | 392,322,373 | 100.0% |

- >56% of the content of 4.3M webpages is hosted on a hyper-giant.
- Hyper-giant penetration is especially high for JavaScript and fonts.

# Consolidation of the Web | Ads and Trackers

- Identification based on *EasyList* and *EasyPrivacy* blocklists.
- Google delivers >66% (ads) and >55% (tracker) services.
- Facebook is under-sampled in the dataset due to missing out on logged in pages (Deep Web).
- >22% of ads delivered by Amazon are via the online store, remaining are delivered by users renting AWS.

| | Provider | # Ads (↓) | Share (all Ads) | Provider | # Trackers (↓) | Share (all Trackers) |
|---|---|---|---|---|---|---|
| (1) | Google | 8,776,465 | 66.6% | Google | 15,995,822 | 55.3% |
| (2) | — | 2,715,437 | 20.6% | — | 5,073,329 | 17.5% |
| (3) | Amazon | 401,946 | 3.1% | Amazon | 2,466,341 | 8.5% |
| (4) | Akamai | 362,619 | 2.8% | Akamai | 1,170,836 | 4.0% |
| (5) | Yahoo | 291,181 | 2.2% | Facebook | 914,088 | 3.2% |
| (6) | Cloudflare | 220,693 | 1.7% | Fastly | 680,578 | 2.4% |
| (7) | Edgecast | 123,498 | 0.9% | WordPress | 598,954 | 2.1% |
| (8) | Fastly | 116,593 | 0.9% | Twitter | 513,694 | 1.8% |
| (9) | Highwinds | 32,702 | 0.2% | Cloudflare | 423,429 | 1.5% |
| (10) | Internap | 21,971 | 0.2% | Microsoft | 323,466 | 1.1% |

Google is the largest player (with more than half share) in ad and tracking delivery.

# Consolidation of the Web | TLS 1.3

- Only 12% (>50M resources) reveal TLS information in the dataset.
- Half of the resources over TLS are delivered over TLS 1.3 (while other half over TLS 1.2)
- Google (>59%), Facebook, and Cloudflare contribute to the majority of TLS 1.3.

| | Provider | TLS 1.0 | | TLS 1.1 | | TLS 1.2 | | TLS 1.3 (↓ %) | | Identified Resources |
|---|---|---|---|---|---|---|---|---|---|---|
| (1) | WordPress | 0 | (0.0%) | 0 | (0.0%) | 0 | (0.0%) | 692,339 | (100.0%) | 692,339 |
| (2) | Facebook | 0 | (0.0%) | 0 | (0.0%) | 8 | (0.0%) | 3,053,978 | (100.0%) | 3,053,986 |
| (3) | Google | 152 | (0.0%) | 16 | (0.0%) | 783,129 | (5.0%) | 14,914,626 | (95.0%) | 15,697,923 |
| (4) | Cloudflare | 7 | (0.0%) | 0 | (0.0%) | 444,503 | (17.6%) | 2,083,359 | (82.4%) | 2,527,869 |
| (5) | Highwinds | 0 | (0.0%) | 0 | (0.0%) | 302,426 | (29.8%) | 711,909 | (70.2%) | 1,014,335 |
| (6) | Akamai | 6 | (0.0%) | 0 | (0.0%) | 1,672,169 | (58.3%) | 1,194,278 | (41.7%) | 2,866,453 |
| (7) | Fastly | 1 | (0.0%) | 0 | (0.0%) | 1,335,349 | (92.1%) | 114,748 | (7.9%) | 1,450,098 |
| (8) | — | 291,196 | (2.2%) | 3,329 | (0.0%) | 11,711,507 | (90.3%) | 959,160 | (7.4%) | 12,965,192 |
| (9) | Amazon | 35,941 | (0.6%) | 85 | (0.0%) | 6,125,713 | (97.3%) | 130,728 | (2.1%) | 6,292,467 |
| (10) | NetDNA | 0 | (0.0%) | 0 | (0.0%) | 677748 | (100.0%) | 3 | (0.0%) | 677,751 |
| | **All** | **332,835** | **(0.7%)** | **3,609** | **(0.0%)** | **25,225,360** | **(50.0%)** | **24,885,884** | **(49.3%)** | **50,447,688** |

Google , Facebook and Wordpress leverage TLS 1.3 almost exclusively (>95%) for content delivery

Hypergiants play a key role in deployment of new Internet technologies

# *Towards Digital Sovereignty* in the *Age of Hyper-giants*

The Internet is getting centralised

2. Evaluating this recent trend where hyper-giants push to offer new services traditionally delivered by ISPs.

leading to security & privacy concerns

# Outline | Towards Digital Sovereignty in the Age of Hyper-giants

1. Age of Hyper-giants
   - An Empirical View on Consolidation of the Web TOIT '22
   - → Evaluating Public DNS Services in the Wake of Increasing Centralization NETWORKING '21
2. Towards Digital Sovereignty: Improving Privacy in DNS
   - Measuring DNS over TLS from the Edge PAM '21
   - A First Look at DNS over QUIC PAM '22

## Evaluating Public DNS Services in the Wake of Increasing Centralization of DNS NETWORKING'21

Trinh Viet Doan, Justus Fries, Vaibhav Bajpai

| Launch | | IPv4 Address | IPv6 Address |
|---|---|---|---|
| 2020-05 | NextDNS | 45.90.28.0 | 2a07:a8c0:: |
| 2018-04 | Cloudflare DNS | 1.1.1.1 | 2606:4700:4700::1111 |
| 2017-11 | Quad9 | 9.9.9.9 | 2620:fe::9 |
| 2017-02 | CleanBrowsing | 185.228.168.168 | 2a0d:2a00:1::1 |
| 2017-02 | Neustar UltraRecursive | 156.154.70.1 | 2610:a1:1018::1 |
| 2015-09 | VeriSign Public DNS | 64.6.64.6 | 2620:74:1b::1:1 |
| 2013-11 | Yandex DNS | 77.88.8.8 | 2a02:6b8::feed:ff |
| 2009-12 | Google Public DNS | 8.8.8.8 | 2001:4860:4860::8888 |
| 2006-07 | OpenDNS | 208.67.222.123 | 2620:0:ccc::2 |
| 2000-06 | OpenNIC | 185.121.177.177 | 2a05:dfc7:5::5353 |

### Motivation and Problem Statement

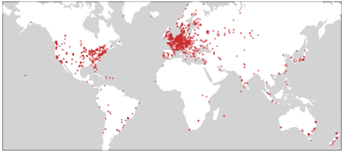
- Many new public DNS services have lately emerged.
- They promise reliability, lower latency and security.
- Previous studies (>5 years old) showed ISP resolvers are commonly used and provide better performance.
- However, there exists a large gap in the evaluation of new public DNS services.

What is the popularity, closeness (path lengths), and latency of these new public DNS services?

In which scenarios would switching to these public DNS services offer benefit?

# DNS Centralisation | Findings

### Methodology



∗ 2.5K RIPE Atlas home probes (>1K IPv6 capable)
∗ covering 720 ASes in > 85 countries.
∗ 10 public resolvers + ISP local resolvers.
∗ 30K ICMP traceroutes to DNS + ISP local resolvers.
∗ 12M DNS over UDP/53 requests/responses.

- **Popularity**

  $>$28% of all probes use $\geq$1 public DNS service.

  Google public DNS used by $>$75% of these probes.

- **Closeness**

  Google Public DNS is one AS hop away from the ISP.

  Cloudflare/Quad9 Public DNS have a transit AS in between.

- **Response Times**

  Public DNS service is slower than ISP resolvers in regions beyond EU and NA.

  Latencies over IPv6 to public DNS services are inflated in SA and AF.

# DNS Centralisation | Popularity

- >7.5k probes use local ISP resolvers. (>71%)
- 3k probes use at least one public DNS service.

  1.4k probes use only public DNS services.

  1.6k probes use a mix of local ISP + public DNS service.

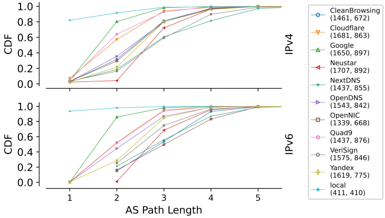
  Google is the most popular DNS service.
- 1k probes use one and only one public DNS service.

| | # Probes | # Probes with $n$ Publ. Services | # Employing Probes |
|---|---|---|---|
| Public only | 1,371 (12.9%) | 978, $n = 1$ (71.3%)<br>355, $n = 2$ (25.9%)<br>38, $n = 3$ (2.8%) | Google: 1,001 (55.5%)<br>Cloudflare: 527 (29.2%)<br>Quad9: 126 (7.0%)<br>OpenDNS: 122 (6.8%)<br>Yandex: 12 (0.7%)<br>NextDNS: 8 (0.4%)<br>VeriSign: 3 (0.2%)<br>Neustar: 2 (0.1%)<br>CleanBrowsing: 1 (<0.1%) |
| Public + local | 1,636 (15.4%) | 825, $n = 1$ (50.4%)<br>811, $n = 2$ (49.6%) | Google: 1,357 (56.7%)<br>VeriSign: 656 (27.4%)<br>Cloudflare: 263 (11.0%)<br>OpenDNS: 54 (2.3%)<br>Quad9: 47 (2.0%)<br>Yandex: 13 (0.5%)<br>Neustar: 2 (0.1%)<br>NextDNS: 2 (0.1%)<br>OpenNIC: 1 (<0.1%) |

>28% of 10.6k RIPE atlas probes (and their host network) use at least one public DNS service

>9% use one and only one public DNS service

Probes that use public DNS service by default will conduct measurements with unintended side-effects




- >18% AS paths to ISP resolvers have lengths > 1.
- >80% AS paths to Google have lengths 2.
- >90% AS paths to Cloudflare/Quad9 have lengths 3.

Google often directly peers with the ISP.

Google edge caches deployed inside the ISP do not (yet) offer public DNS services.

Paths in South America to all public DNS services are more inflated than at other regions

# DNS Centralisation | Latency

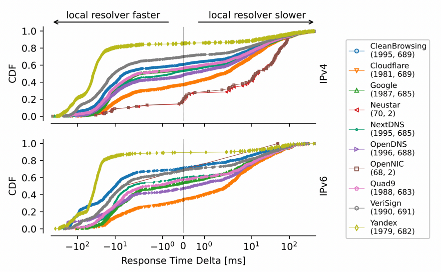
IPv4

| | AF | AS | EU | NA | OC | SA |
|---|---|---|---|---|---|---|
| CleanBrowsing | 71.8 | 33.6 | 24.3 | 21.3 | 25.1 | 111.1 |
| Cloudflare | 8.6 | 10.2 | 12.7 | 15.7 | 9.5 | 23.8 |
| Google | 177.0 | 23.8 | 19.1 | 21.1 | 23.6 | 28.2 |
| Neustar | | 30.7 | 1.8 | 1.3 | 0.9 | 1.9 |
| NextDNS | 48.6 | 30.1 | 18.6 | 20.4 | 10.8 | 23.4 |
| OpenDNS | 62.1 | 26.0 | 17.0 | 17.0 | 19.2 | 39.6 |
| OpenNIC | | 30.8 | 1.7 | 1.3 | 1.0 | 4.1 |
| Quad9 | 23.2 | 57.8 | 19.6 | 22.5 | 25.6 | 131.2 |
| VeriSign | 174.9 | 86.9 | 26.8 | 31.0 | 140.0 | 161.4 |
| Yandex | 204.1 | 202.7 | 46.9 | 150.1 | 315.7 | 261.2 |
| local | 46.6 | 24.1 | 13.9 | 23.2 | 29.2 | 17.9 |

IPv6

| | AF | AS | EU | NA | OC | SA |
|---|---|---|---|---|---|---|
| CleanBrowsing | 281.9 | 79.4 | 25.2 | 24.3 | 36.2 | 146.2 |
| Cloudflare | 2.7 | 9.8 | 12.3 | 15.7 | 7.5 | 18.8 |
| Google | 185.4 | 11.6 | 18.2 | 21.4 | 25.5 | 26.4 |
| Neustar | | 23.5 | 2.5 | | | |
| NextDNS | 19.8 | 173.4 | 19.2 | 22.3 | 20.7 | 35.2 |
| OpenDNS | | 15.0 | 16.8 | 17.7 | 24.7 | 35.8 |
| OpenNIC | | 22.6 | 2.5 | | | |
| Quad9 | | 71.5 | 18.0 | 21.6 | 22.7 | 138.6 |
| VeriSign | 154.8 | 48.8 | 22.5 | 30.2 | 140.7 | 137.9 |
| Yandex | 189.8 | 259.6 | 46.9 | 154.7 | 298.9 | 254.2 |
| local | 2.9 | 14.0 | 15.4 | 22.7 | 11.5 | 17.0 |

Response Time [ms] (colour scale 0–300)




- 75% of all samples within 40ms latency.
- Cloudflare and OpenDNS faster than ISP resolvers in 50% of the probes.
- Google public DNS latencies inflated in AF.
- Public DNS resolvers slower than ISP resolvers in regions beyond EU and NA.

Users in EU and NA do not substantially benefit in latency when switching to a public DNS service.

Latencies offered by public DNS services over IPv6 remain inflated in AF and SA.

# *Towards Digital Sovereignty* in the *Age of Hyper-giants*

On combating this centralisation trend?

Encrypted DNS

QUIC

Could new secure (QUIC) and privacy-enhancing protocols (encrypted DNS) be used to give users back *some* control of their data?

# Outline | Towards Digital Sovereignty in the Age of Hyper-giants

1. Age of Hyper-giants

   An Empirical View on Consolidation of the Web TOIT '22

   Evaluating Public DNS Services in the Wake of Increasing Centralization NETWORKING '21

2. Towards Digital Sovereignty: Improving Privacy in DNS

   → Measuring DNS over TLS from the Edge PAM '21

   A First Look at DNS over QUIC PAM '22

## Measuring DNS over TLS from the Edge: Adoption, Reliability, and Response Times PAM'21

Trinh Viet Doan, Irina Tsareva, Vaibhav Bajpai

### Motivation and Problem Statement

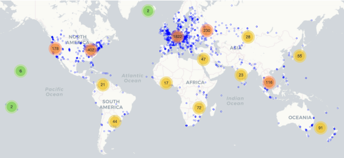
- The Domain Name System (DNS) is a cornerstone of communication on the Internet.
- However, DNS over UDP/53 is vulnerable to eavesdropping and information exposure.
- DNS over TLS/853 (DoT) standardized in 2016 (RFC 7858) to encrypt DNS messages.
- DoT is supported since Android 9 (2018) and iOS/MacOS (2020).
- However, previous work on DoT largely considers university – proxy – data-center networks.

What is the state of adoption and traffic share of DoT at the edge?

Do home users experience benefit (or suffer) from accessing the Internet using DoT (in terms of reliability and latency) when compared to traditional DNS/53?

# DNS over TLS | Findings

## Methodology




>3.2K RIPE Atlas home probes
>15 public resolvers (5 with DoT) + local resolvers.
>200 domains queried for A records over IPv4.
>90M DNS requests/responses overall.

- **Adoption**
  - <1% amongst 1.2M open DNS resolvers.
  - Albeit, adoption has increased by >23% (2020).
  - TLS 1.3 support (in DoT) has increased to 20%.
- **Reliability**
  - DoT failures can be inflated by up to 30% compared to Do53.
  - Possibly due to ossification caused by middle-boxes.
- **Response Times**
  - Higher by >100 ms for DoT compared to Do53.
  - Comparable across local / public resolvers.

A first study to provide empirical grounding of using DNS over TLS from the edge of the network.

# DNS over TLS | Adoption

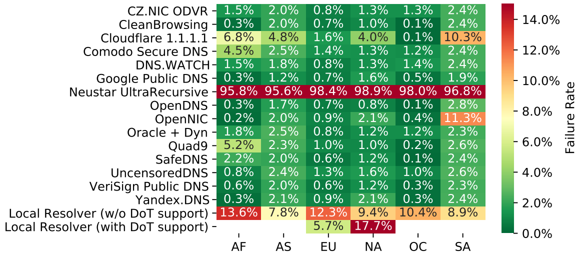
- Step 1: Scan the IPv4 address space for Open DNS resolvers (UDP/53)
- Step 2: Check DoT support for 1.2M IP endpoints (2019).

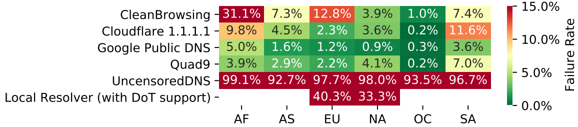
| | April 2019 | January 2020 | |
|---|---|---|---|
| DoT Open Resolvers | 1,747 | 2,151 | + 23.1% |
| Support TLS 1.3 | 79 (4.5%) | 433 (20%) | + 448% |
| Support TLS 1.2 | 1,701 (97%) | 2,149 (99.9%) | + 26.3% |
| No Support for TLS 1 or 1.1 | 80 (4.6%) | 508 (24%) | + 535% |
| Use self-signed cert | 11 (0.63%) | 355 (17%) | |
| Use GoDaddy as CA | 1,572 (90%) | 1,534 (71%) | |
| Use Let's Encrypt as CA | 90 (5.2%) | 118 (5%) | |

DoT (and subsequently TLS 1.3) adoption has increased by >23% (>20%)

Albeit, overall adoption is still low (<1%)

# DNS over TLS | Reliability

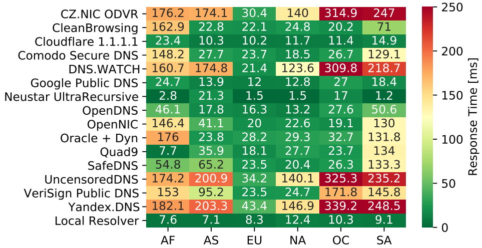


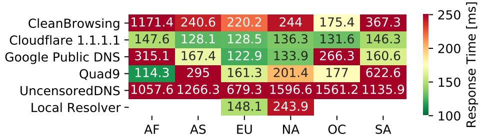



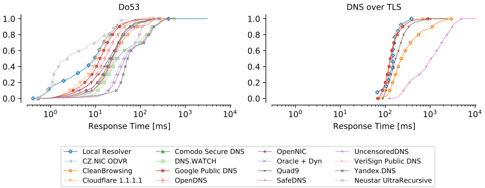

- Failures due to timeouts, socket and TCP/TLS errors.
- DoT failures can be up to >30%
- Possibly caused by blackholing of DoT packets by middle-boxes.
- Higher failures in AF and SA.
- DoT failures higher over local than public resolvers.

DoT exhibits higher failures than Do53. Failures are more pronounced over local resolvers.

# DNS over TLS | Response Times




- Do53: <30 ms for most resolvers (median)
  DoT: <150 ms for faster resolvers (median)
- Higher response times in AF and SA.

DoT response times inflated by >100 ms compared to Do53.

DoT response times for local resolvers comparable to that of public resolvers.

# Outline | Towards Digital Sovereignty in the Age of Hyper-giants

1. Age of Hyper-giants
   An Empirical View on Consolidation of the Web TOIT '22
   Evaluating Public DNS Services in the Wake of Increasing Centralization NETWORKING '21

2. Towards Digital Sovereignty: Improving Privacy in DNS
   Measuring DNS over TLS from the Edge PAM '21
   → A First Look at DNS over QUIC PAM '22

## A First Look at DNS over QUIC PAM'22

Mike Kosek, Trinh Viet Doan,
Malte Granderath, Vaibhav Bajpai

### Motivation and Problem Statement

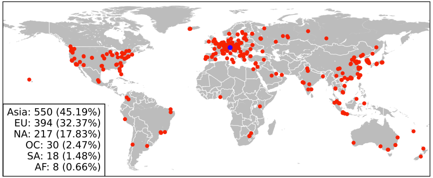
- DNS over TLS (standardized in 2016) and DNS over HTTPs (in 2018) leverage TLS/TCP for transport.
- However, both are constrained by limitations of TCP.
- QUIC solves head of line blocking, supports multiplexing, and lowers handshake times.
- DNS over QUIC (under standardisation) is the natural evolution to improve DNS performance and privacy.
- However, there exists no previous work on DoQ yet.

What is the state of adoption of DoQ?

Do DoQ servers and clients leverage the full potential of QUIC to improve privacy and lower response times?

# DNS over QUIC | Findings

## Methodology




Measurements from the TUM research network (blue dot)

>25 weeks of ZMAP scans towards DoQ/DoUDP ports.

* A three step validation phase using:
  - QUIC version negotiation
  - ALPN identifiers and
  - QUIC connection establishment
* developed `dnsperf` to measure DoQ, DoTCP, DoUDP, DoT, DoH response times by querying an `A` record.

- Adoption

  >1.2k resolvers offer DoQ support.
  >1.8k unique X.509 certs observed.

- Response Times

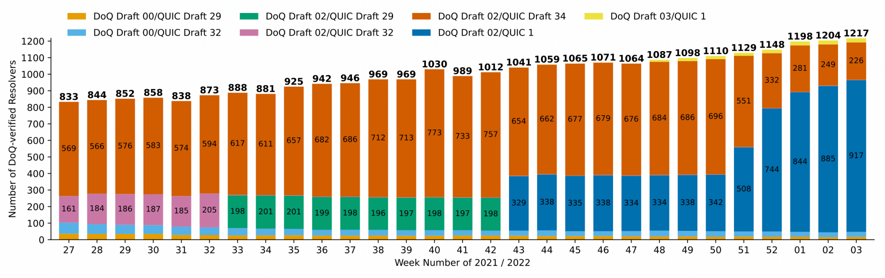
  Only 20% of the samples show DoQ interactions utilising full DoQ.

  40% samples show higher handshake times due to additional round-trips.

A first study to evaluate support of DNS over QUIC in the real world.

# DNS over QUIC | Adoption

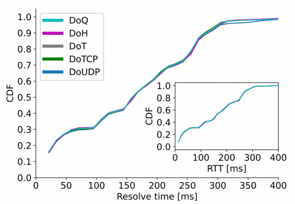
- Number of DoQ verified resolvers (>1.2k) steadily rose by >46% in 29 weeks.
- Multiple resolvers use Adguard Home DoQ server implementation (using QUIC v1).

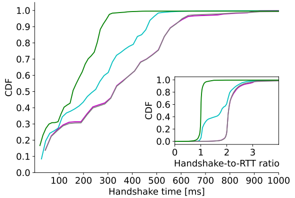



Large fraction of DoQ resolvers observed in Asia (>45%) and Europe (>32%)

AdGuard and nextDNS use DoQ as part of the DNS-based ad and tracker blocking services

# DNS over QUIC | Response Times




- We observed no support for TCP keepalives, TFO or 0−RTT.
- DNS request-response time is comparable across all DoX protocols and resembles the RTT of the end-to-end connection.

- DoTCP has the fastest handshake. DoT and DoH handshake times are slower and comparable (TCP + TLS 1.3)
- Only 20% DoQ samples match DoTCP handshake times.
- 40% DoQ samples exhibit additional 1 RTT due to some servers enforcing traffic amplification limits on already validated clients.

DoQ offers the best choice for DNS privacy. It outperforms both DoT and DoH in latency.

1. Age of Hyper-giants

- An Empirical View on Consolidation of the Web TOIT '22
  Hyper-giant penetration has nearly doubled from 2015–2020.
  and is higher among more popular domains.

- Evaluating Public DNS Services in the Wake of Increasing Centralization NETWORKING '21
  Google edge caches deployed inside the ISP do not (yet) offer DNS services.
  Users in EU/NA do not substantially benefit in latency with a public DNS service.
  Latencies offered by public DNS services over IPv6 remain inflated in AF and SA.

2. Towards Digital Sovereignty: Improving Privacy in DNS

- Measuring DNS over TLS from the Edge PAM '21
  DoT adoption has increased year over year, although overall adoption is still low (<1%)
  DoT exhibits higher failures than Do53, and are more pronounced over local resolvers.
  DoT response times are inflated by >100 ms compared to Do53.
  DoT response times are comparable for local and public resolvers.

- A First Look at DNS over QUIC PAM '22
  First usage of DoQ seen as part of DNS-based ad and tracker blocking services
  DoQ offers the best choice for DNS privacy, outperforms both DoT and DoH in latency.

# References | Publications Covered in the Talk


TOIT'22 **An Empirical View on Consolidation of the Web**
T.V.Doan, R.Rijswijk-Deij, O.Hohlfeld, V.Bajpai
https://doi.org/10.1145/3503158

NETWORKING'21 **Evaluating Public DNS Services in the Wake of Increasing Centralization of DNS**
T.V.Doan, J.Fries, V.Bajpai
https://doi.org/10.23919/IFIPNetworking52078.2021.9472831

PAM'21 **Measuring DNS over TLS from the Edge: Adoption, Reliability, and Response Times**
T.V.Doan, I.Tsareva, V.Bajpai
https://doi.org/10.1007/978-3-030-72582-2_12

PAM'22 **One to Rule them All? A First Look at DNS over QUIC**
M.Kosek, T.V.Doan, M.Granderath, V.Bajpai
https://arxiv.org/abs/2202.02987 (to appear)