PRIVACY OF DNS-OVER-HTTPS: REQUIEM FOR A DREAM?

Levente Csikor*
Trustwave

Himanshu Singh*
IIIT Naya Raipur

Min Suk Kang
KAIST

Dinil Mon Divakaran
Trustwave, NUS

NUS National University of Singapore

Trustwave®

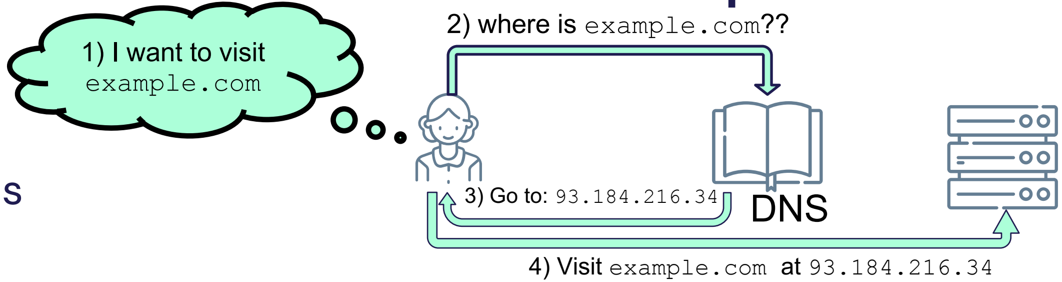
*Authors were with NUS during this work.

PRIVACY OF THE DOMAIN NAME SYSTEM

Isn't HTTP**S** enough?

- Since Snowden: privacy is of utmost importance
  - >90% of Web traffic is **HTTPS**
- **Every (website) visit is preceded with a bunch of DNS queries**
- DNS in a nutshell
  - Phonebook of the Internet
  - Translate hostnames to IP address
  - (Used to be) plain-text
    - *"I might not see the content you consume, but I CAN see where it comes from"*
- Main three reasons of being plain-text

1. Historically, less focus on privacy and security
2. DNS is an overhead → simplest → fastest
3. Services heavily rely on DNS data



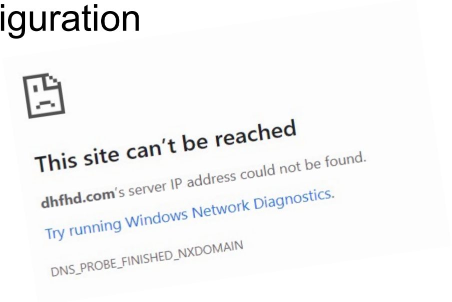
1) I want to visit example.com
2) where is example.com??
3) Go to: 93.184.216.34
DNS
4) Visit example.com at 93.184.216.34

DNS IS A DOUBLE-EDGE SWORD

Services based on plain-text DNS

Your **Internet Service Provider (ISP)**

- Firewall
- Parental-control
- Pay-as-you-go-models (e.g., at hotels)
- Content caching / Proxy
- Broadband router configuration
- Blocking Ads
- Law-enforcements



This site can't be reached

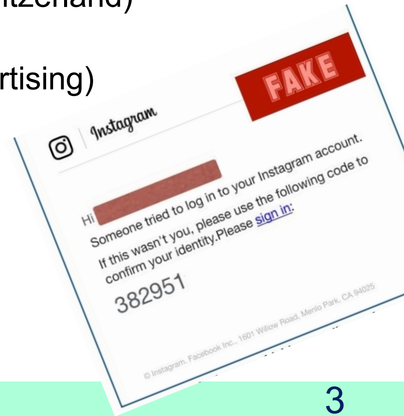
dhfhd.com's server IP address could not be found.

Try running Windows Network Diagnostics.

DNS_PROBE_FINISHED_NXDOMAIN

Malicious actors and authoritarian regimes

- Blocking websites and contents
  - Political speech (e.g., in China)
  - Foreign gambling (e.g., in Switzerland)
- Spy on the users
  - Monetize DNS data (for advertising)
- Tampering and redirection
  - Malicious (phishing) websites



Instagram

Hi [redacted]

Someone tried to log in to your Instagram account.

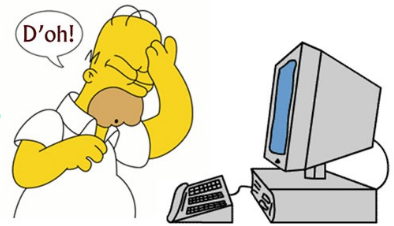
If this wasn't you, please use the following code to confirm your identity.Please sign in:

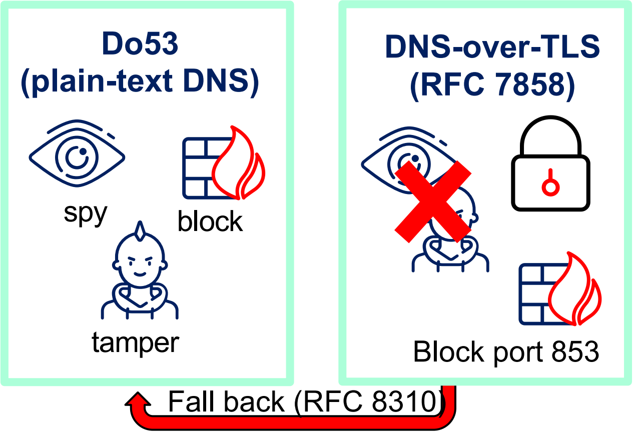
382951

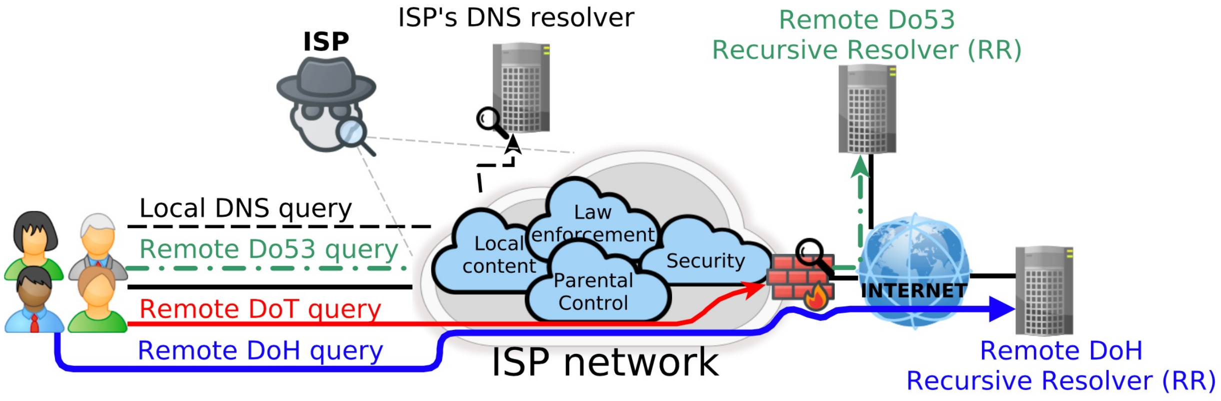
© Instagram. Facebook Inc., 1601 Willow Road, Menlo Park, CA 94025

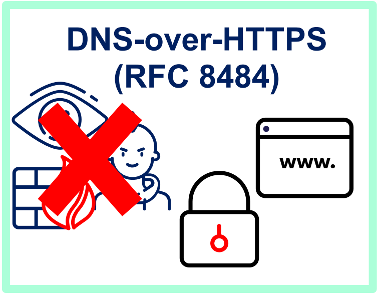
DoH! Headache for ISPs…

…privacy heaven for users and malicious actors?









DNS-over-HTTPS: circumventing all ISP measures

- Inherently blends into regular encrypted HTTPS traffic
  - Cannot be filtered, cannot be differentiated, cannot be blocked
- All ISP services break
  - No firewall, no parental control, no cache, no malware detection, etc.
- **Enhanced Privacy vs. Weakened Protection**

IN THIS PAPER

Is DoH indeed indistinguishable from Web traffic?

NO

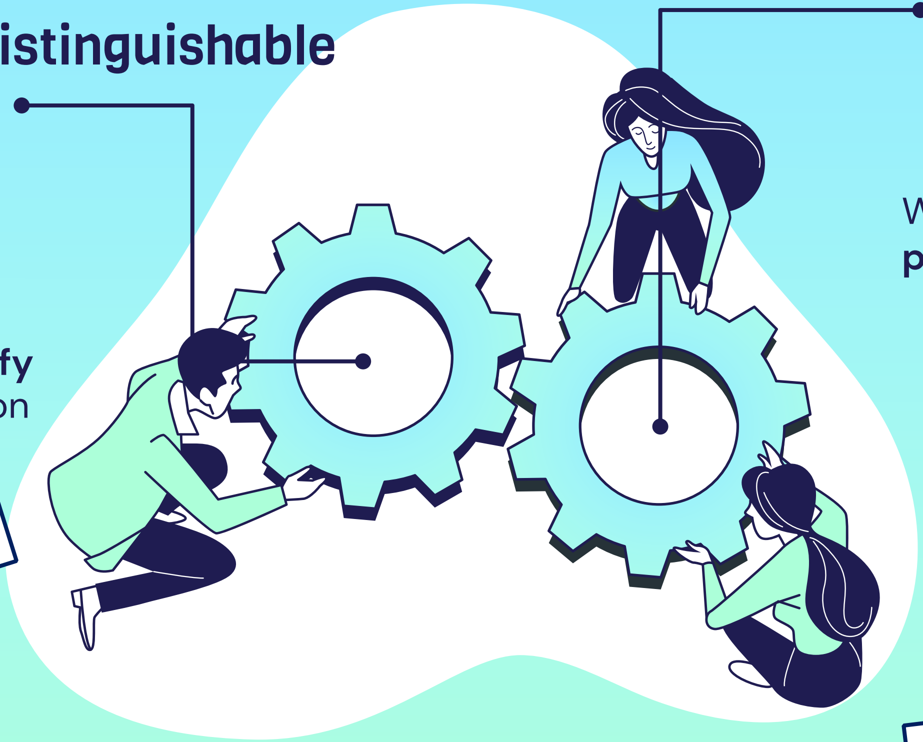
We build a **Machine Learning model to identify** each encrypted packet (on port 443) as **Doh** or **Web**

97.4 %
Closed-world

90 %
Open-world

At extremely low false-positive rate (FPR=10^{-4})

ISPs can identify and block it → transparently fall back to Do53



Countermeasures?

YES

We study a wide set of **padding techniques**

To disguise the DoH identification model trained on the padded data

The anti-identification model **significantly reduces** the classification accuracy

53 %
Closed-world

0 %
Open-world

DATASET COLLECTION

Multiple cities across multiple continents to capture diverse network statistics

- Easy to deploy Docker containers
- Alexa top-1M domains
  - Visit the first 20K one-by-one (to flush DNS cache)
- Using 25 DoH resolvers[1]
  - Well-known: Google, Cloudflare, Quad9, CleanBrowsing
- Containers deployed "world-wide"
  - *LocA* – South America: University of Campinas, Brazil (x86)
  - *LocB* – North America: Multiple Cloudlab sites (x86, arm64)
  - *LocC* – Asia: National University of Singapore (x86)

[1] https://github.com/curl/curl/wiki/DNS-over-HTTPS

TRAIN A SUPERVISED MACHINE LEARNING MODEL 01

- Chosen ML model: Random forest
  - out of six models evaluated
- Train-test ratio: 90-10%
  - Found similar results with 80-20%, 70-30%

FEATURES 02

- IP length of current packet
- IP length of the previous packet
- Inter-packet arrival, i.e., time lag, of current packet
- Time lag of previous packet

03 IMPORTANT METRICS

- Precision, Recall and F_1-score
- False-positive rate (FPR)
- Recall at low FPR
  - Not deployable if Web packets are blocked due to misclassification

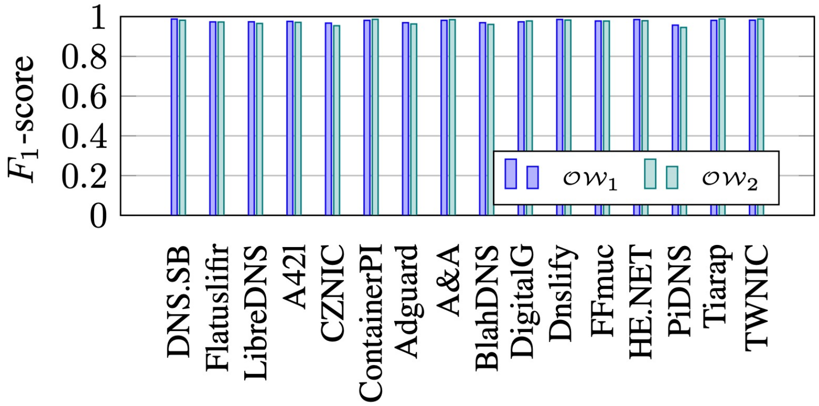
04 SETTINGS FOR EVALUATION

- Closed-world
  - Same resolvers, same domains visited
- Open-world 1
  - Different resolvers, same domains visited
- Open-world 2
  - Different resolvers, different domains visited

RESULTS

Closed- and Open-world results for the data gathered in `LocC` (Asia)

- Best-case:
  - Resolvers used for training
    - Prominent: `Google, Cloudflare, Quad9, CleanBrowsing`
    - + worst-performing: `Comcast, OpenDNS, Doh.li`
  - Closed-world: F_1-score **>0.99** (FPR=**0.009**)
  - Open-world: F_1-score = **~0.975** (FPR=**0.0055**)
- Best-case at **low FPR < 0.0001**:
  - Closed-world Recall = **0.974**
  - Open-world: Recall = **0.9**

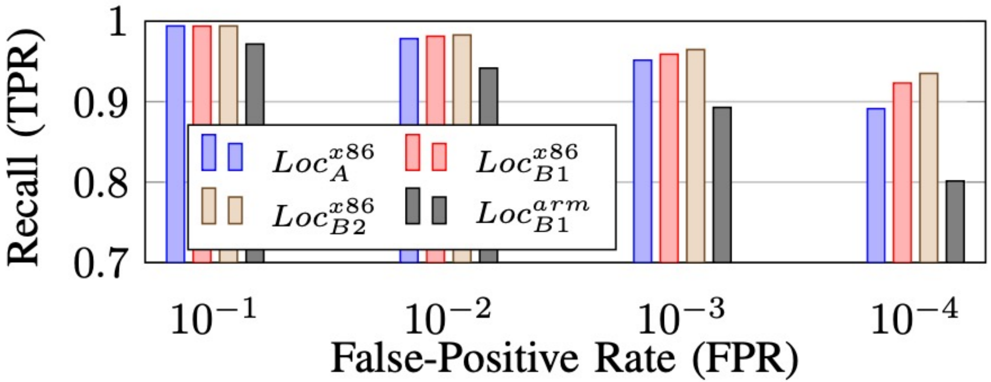


FPR=10^{-4} → 1 out of 10,000 Web packet is misclassified as DoH

RESULTS

Robustness of the DoH identification model

- Worst-case:
  - Model trained in one location and tested at other locations
    - Trained at `LocC` (`x86`), tested at `LocA` and `LocB` (`arm` and `x86`)
  - Closed-world:
    - `x86`: Recall = **~0.90** (FPR=**0.0001**)
    - `arm`: Recall = **~0.80** (FPR=**0.0001**)



FPR=10^{-4} → 1 out of 10,000 Web packet is misclassified as DoH

COUNTERMEASURES?

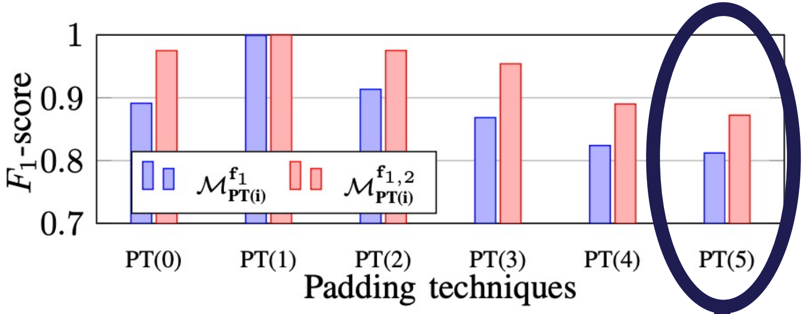
ISPs deploying the DoH identification model can filter out DoH packets with high accuracy and low FPR

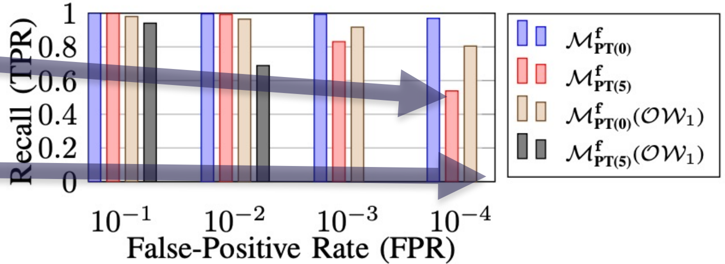
- **Two fundamental packet characteristics** to manipulate:
  - Packet length and time lag
- **Idea**: Pad the DNS packets to look more like Web packets
  1) Fix padding (RFC8467) – closest multiple of 128B
  2) Random padding
  3) Pad to the average of the Web packets
  4) Pad to a random recent Web packet
  5) Pad a sequence of DoH packets to a recent sequence of Web packets

EVALUATION OF PADDING TECHNIQUES

Proposal for a DoH anti-identification model

- Preliminary analysis
  - Padding **packet lengths only**
  - **Closed-world** setting
    - Feature f_1 = packet length
    - Feature f_2= previous packet length
    - PT(*i*) = different padding techniques
    - PT(0) = original non-padded data
- Apply PT(5) on all features as well
  - at low FPR=**0.0001**





53 %
Closed-world

0 %
Open-world

SUMMARY

- Privacy of the DNS is important
- DoH is designed to blend DNS traffic into HTTPS Web traffic
  - Cannot be monitored, cannot be filtered, cannot be blocked
- Our main contributions
  - DoH identification model to distinguish DoH and Web packets with high accuracy
    - **97.4%** and **90%** in the **closed-** and **open-world** setting, respectively
    - With a **false-positive rate of 0.0001**
  - Develop DoH anti-identification model as a counter-measure
    - **53%** and **0%** in the **closed-** and **open-world** setting, respectively
    - With a **false-positive rate of 0.0001**

Q&A

Levente Csikor

Trustwave

levente.csikor@gmail.com

Container for data collection:

- https://github.com/cslev/doh_docker
- https://hub.docker.com/r/cslev/doh_docker

Machine Learning algorithm:

- https://github.com/cslev/doh_ml

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