ATHENE
National Research Center
for Applied Cybersecurity

Attacking with Something That Does Not Exist: ‘Proof of Non-Existence’ Can Exhaust DNS Resolver CPU

Authors

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Contents

Outline

Analysis of the NSEC3-Encloser attack (CVE-2023-50868), which leads to CPU load and DoS on DNS resolvers.

Key Contributions:

- A tool for automated evaluation of the attack
- Investigate the attack beyond proof-of-concept in the CVE.
- First evaluation of an attack that exploits NSEC3 records for creating a load on DNS resolvers.

Background: DNS

Domain **N**ame **S**ystem RFC1034:
Hierarchical, distributed database to map human-readable domain names (e.g., www.example.com) to arbitrary resource records, foremost IP-addresses and server addresses.

Core infrastructure of the internet on which other services rely on.

```
                            |
                            |
          +-----------------+------------------------+
          |                 |                        |
         COM               DE                      ARPA
          |                 |                        |
          |                 |                        |
     +----+---+      +------+--------+     +------+------+-----+
     |        |      |               |     |      |            |
  EXAMPLE  USENIX  ATHENE-CENTER  UNI-FRANKFURT  IN-ADDR  SRI-NIC  ACC
```

Background: DNS

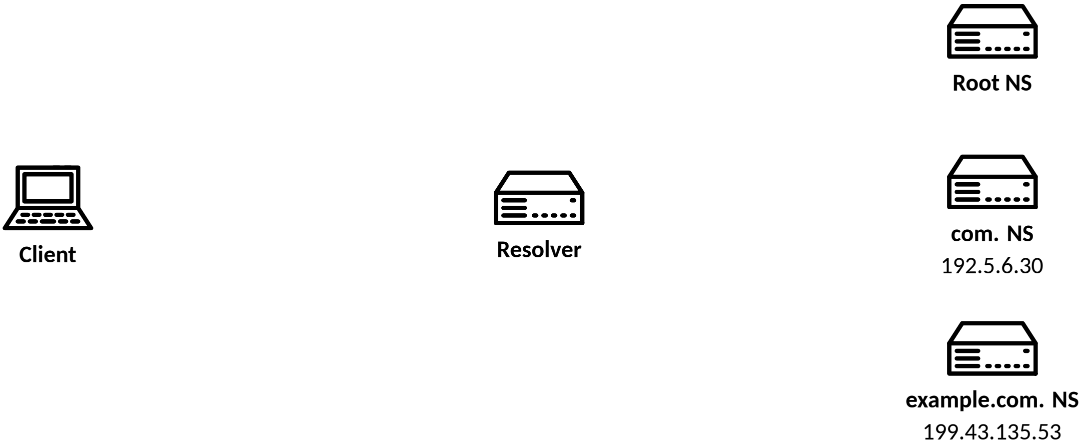

Figure: DNS Recursive Request Example.

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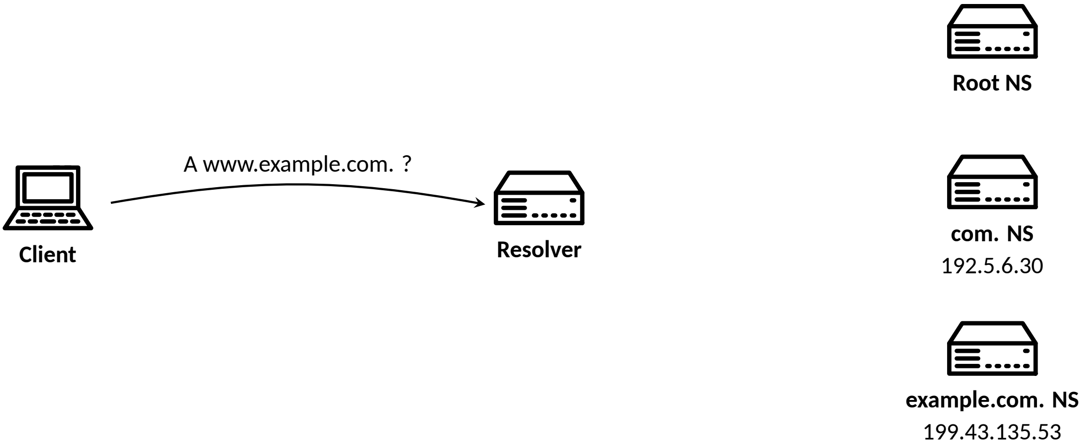

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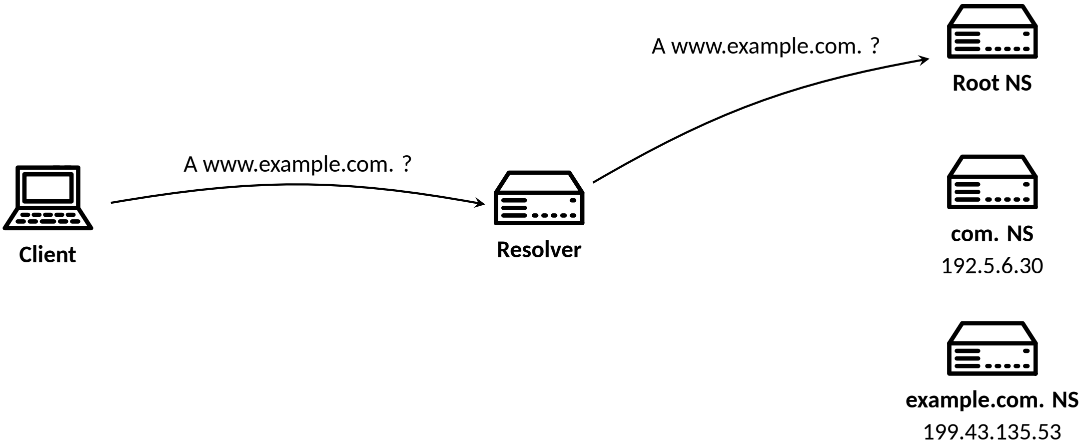

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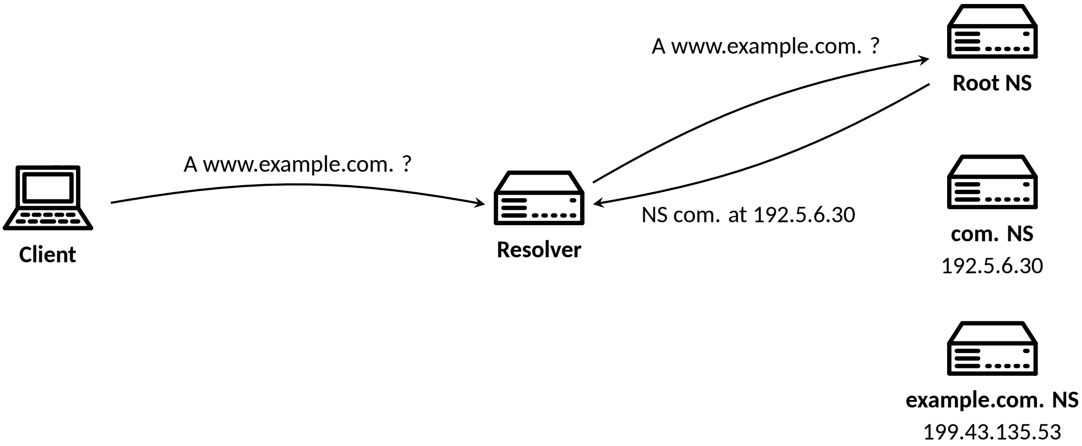

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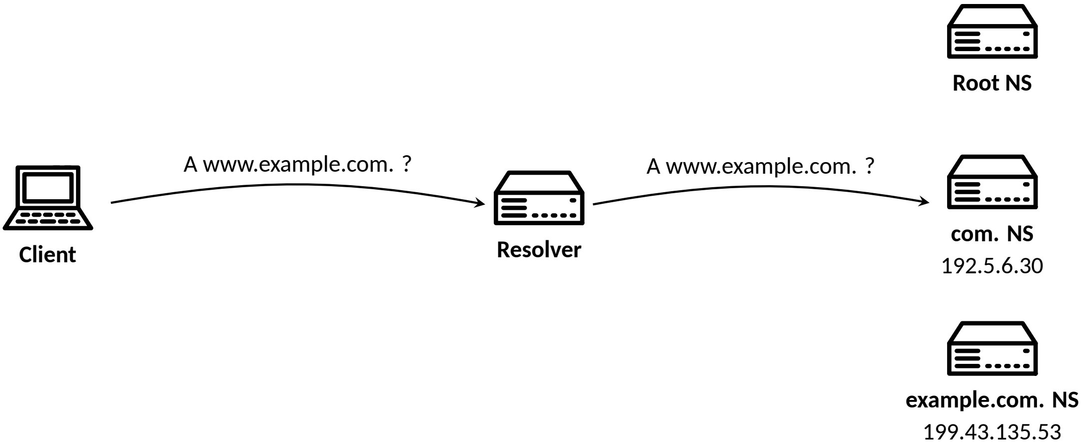

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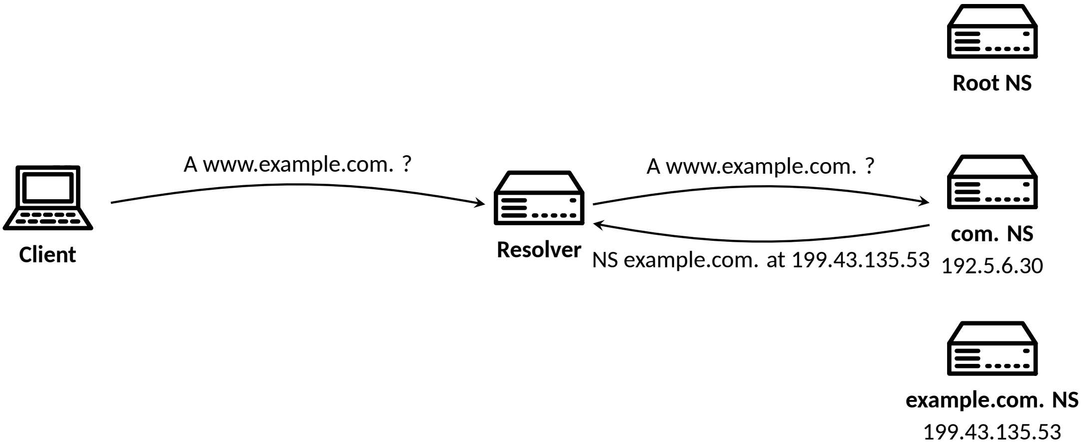

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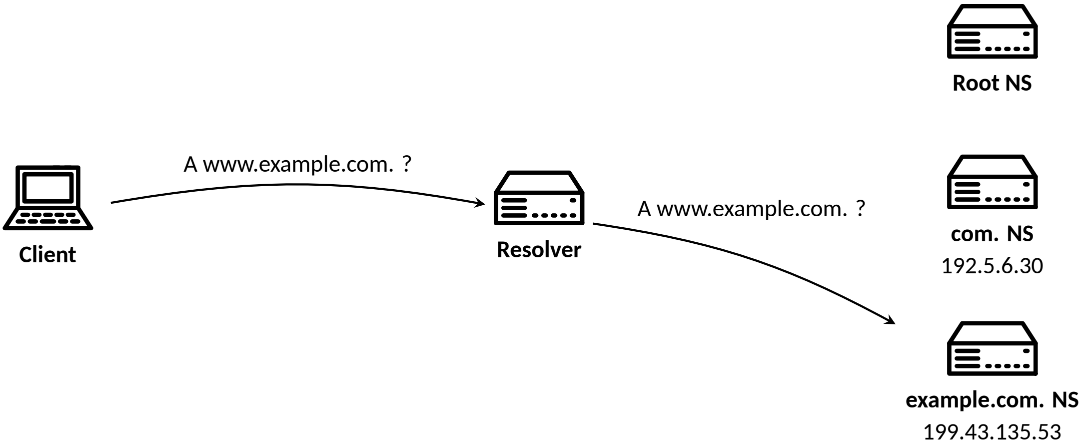

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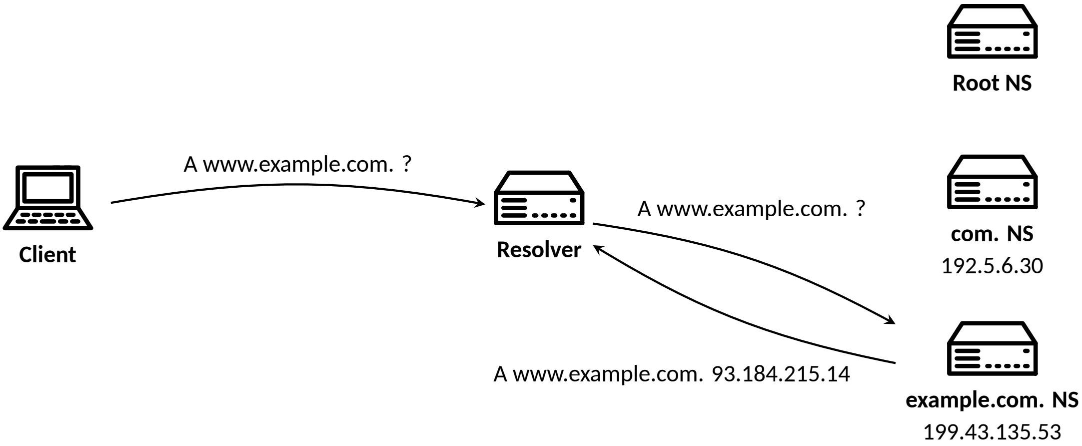

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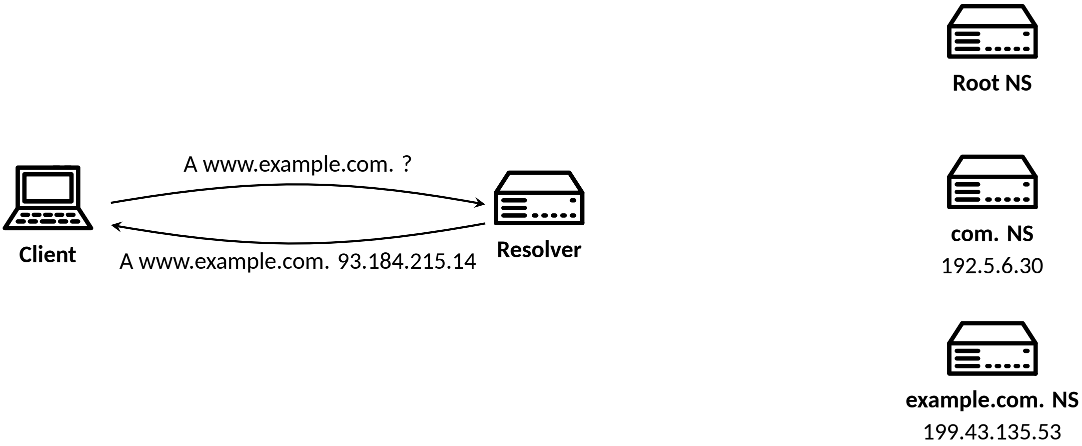


Figure: DNS Recursive Request Example.

Background: Proving Non-Existence in DNS

NSEC

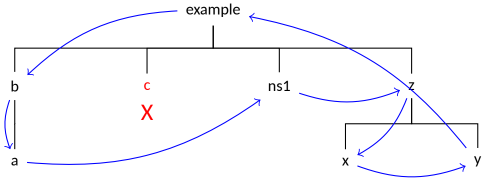
NSEC record links domain names in zone to its canonical successor.

Proves non-existence of domain names that fall inbetween.

e.g., `a.b.example. NSEC ns1.example.`

Problem:

Reveals zone tree via zone walking.



NSEC3

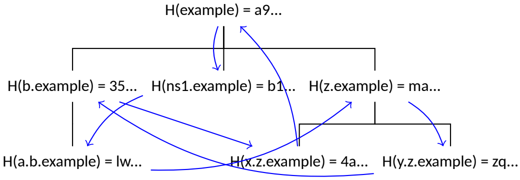
NSEC3 record links the hash of a domain name to the alphanumeric next hash in the zone.

Poves non-existence of any preimages to hashes in this range.

e.g., `lw...g4.example. NSEC3 ma...6e`

Advantage: Obfuscates zone tree.

Disadvantage: Requires more elaborate validation.



Background: NSEC3

Closest Encloser Proof

Proving non-existence resolver-side based on NSEC3 RRs: **Closest Encloser Proof**

E.g., proving `v.w.x.y.z.example.` $\notin$ `example.` zone requires finding a pair of encloser/next closer:

`v.w.x.y.z.example.`

- `z.example.` — existing encloser
- `y.z.example.` — non-existing next closer

Proof algorithm sequentially strips away labels until closest encloser is found:

1. Hash the name
2. Return NXDOMAIN if closest encloser identified
3. Remove fist label, goto 1.

Background: NSEC3

Parameters

NSEC3 allows zone operators to choose NSEC3 parameters in the NSEC3PARAM RR to harden against dictionary attacks.

Iterations

A number of how many times the hash needs to be re-hashed.

Salt

An up to 255-byte value that must be appended to the hashed value for each hash iteration.

Key Size	Iterations
1024	150
2048	1500
4096	2500

Table: Iterations Parameter Limits Are Based on Key Size

Background: NSEC3

Parameters

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An up to 255-byte value that must be appended to the hashed value for each hash iteration.

Expected closest encloser proof complexity:
$\mathcal{O}(\text{nr of labels} \cdot \text{iterations} \cdot \text{salt length})$

Key Size	Iterations
1024	150
2048	1500
4096	2500

Table: Iterations Parameter Limits Are Based on Key Size

NSEC3-Encloser Attack

CVE-2023-50868

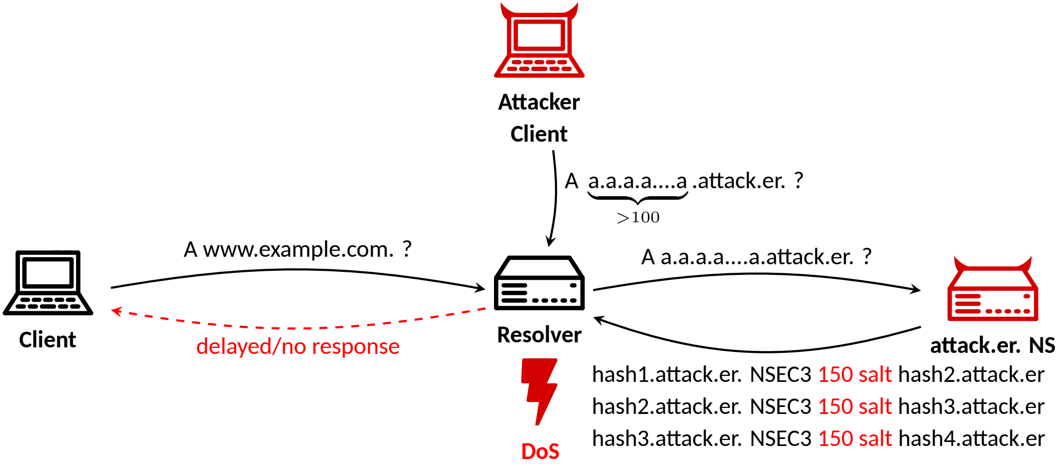

Figure: DNS NSEC3-Encloser Attack.

The issue is not new…

RFC9276: Guidance for NSEC3 Parameter Settings (Aug 2022)

Acknowledges for iterations:

- Attackers “likely [are] able to find most of the ”guessable” names despite any level of additional hashing iterations.”
- “Most names published in the DNS are rarely secret or unpredictable.”

Acknowledges for salt:

- “[N]o single pre-computed table works to speed up dictionary attacks against multiple target zones.”
- “This makes very frequent re-salting impractical and renders the additional salt field functionally useless.”

Recommends for validating resolvers:

- Resolvers are “encouraged to lower their default limit for returning SERVFAIL when processing NSEC3 parameters containing large iteration count values.”
- No concrete advice for handling salt.

Attack Evaluation

Zonfile Generator

- Generates keys and static zonefiles for reproducing the attack
- Allows generation of many different iterations and salt values for testing

https://github.com/Goethe-Universitat-Cybersecurity/NSEC3-Encloser-Attack

Setup

- Containerized resolvers running with one CPU and DNSSEC enabled
- NSD nameserver serving the attacker zones
- Self-developed attacker client

```
;; ZONE 'ATTACK.ER'

ATTACK.ER. 0 IN SOA NS1.ATTACK.ER. NS1.ATTACK.ER. 0 0 0 10 0

ATTACK.ER. 0 IN NS NS1.ATTACK.ER.

ATTACK.ER. 0 IN DS 35650 7 1 e8316...

ATTACK.ER. 0 IN DNSKEY 257 3 7 AwEA...
ATTACK.ER. 0 IN DNSKEY 256 3 7 AwEA...

ATTACK.ER. 0 IN NSEC3PARAM 1 0 150 -

HKHV...38AU.ATTACK.ER. 0 IN NSEC3 1 1 150 - HKHV...38B0

HKHV...38B0.ATTACK.ER. 0 IN NSEC3 1 1 150 - QCQC...7U45

NS1.ATTACK.ER 0 IN A 6.6.6.6

QCQC...7U45.ATTACK.ER. 0 IN NSEC3 1 1 150 - SN5U...89IT A RRSIG

SN5U...89IT.ATTACK.ER. 0 IN NSEC3 1 1 150 - SN5U...89IU NS SOA
    DS RRSIG DNSKEY NSEC3PARAM

SN5U...89IU.ATTACK.ER. 0 IN NSEC3 1 1 150 - HKHV...38AU

[...] ;; RRSIG records
```

Figure: Generated attack zonefile example.

Attack Evaluation

Resolver Implementations

Resolver	Version	Iteration Limit
Bind9	9.16.1	RFC5155
Bind9	9.18.12	150
Unbound	1.17.1	150
PowerDNS	4.8.2	150
Knot	5.6.0	150

Table: Resolver versions and iterations limits in the test setup.

Attack Evaluation
Parameter Iterations

Analysis of NSEC3 iterations on the CPU load.

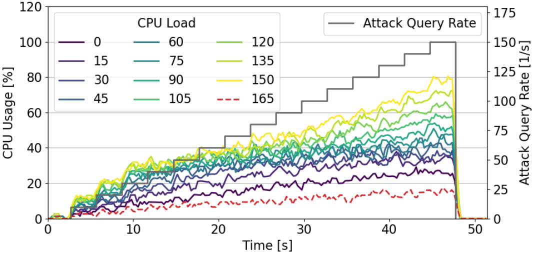

Figure: Unbound

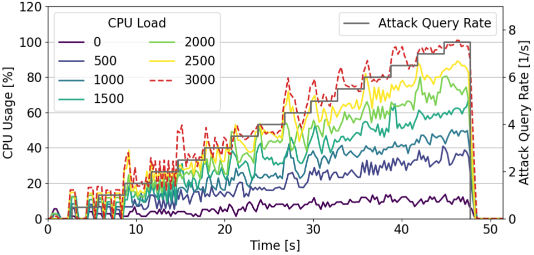

Figure: Bind9.16.1

Attack Evaluation

Parameter Iterations

Analysis of NSEC3 iterations on the CPU load using maximum (150/2500) iterations.

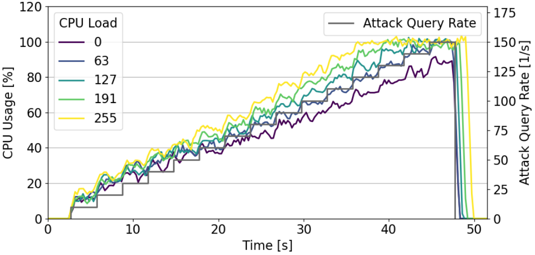

Figure: Unbound

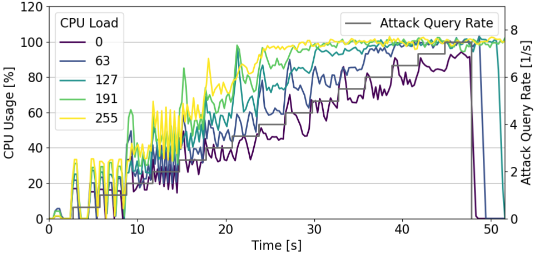

Figure: Bind9.16.1

Attack Evaluation

Comparative Analysis

Comparison of CPU workload between resolvers.

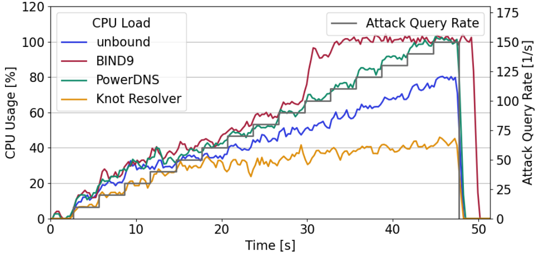

Figure: 150 iterations, 0 byte salt

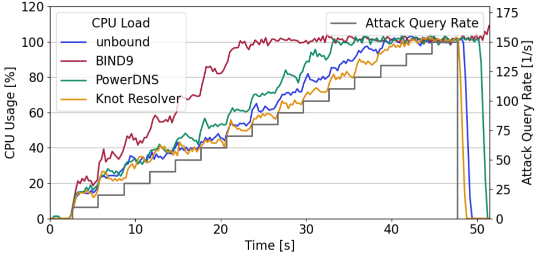

Figure: 150 iterations, 255 byte salt

Attack Evaluation
Benign Analysis

Evaluation of peak benign traffic drop rates under stress conditions.

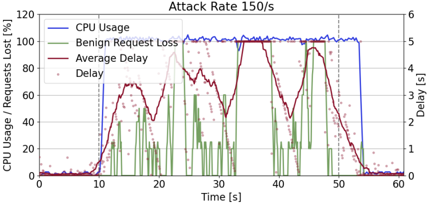

Figure: Unbound attacked with rate 150/s

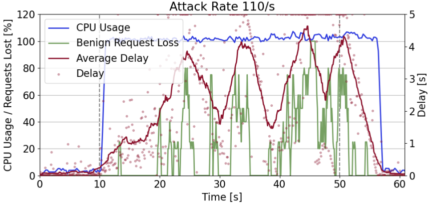

Figure: Bind9.18.12 attacked with rate 110/s

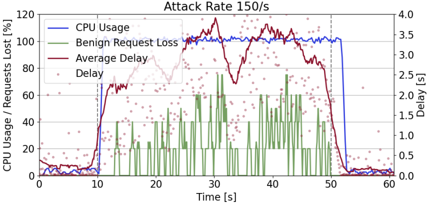

Figure: Knot attacked with rate 150/s

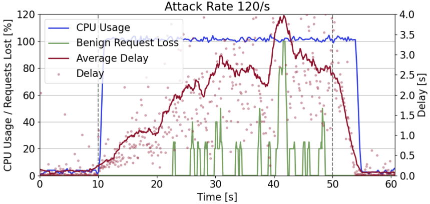

Figure: PowerDNS attacked with rate 120/s

Attack Evaluation

Measured Drop Rates

Resolver	Attack Rate	Total Loss Rate	Adjusted Loss Rate*
Bind9.18.12	150/s	5.10%	7.01%
Bind9.18.12	110/s	16.42%	22.99%
Unbound	150/s	**24.75**%	**34.66**%
PowerDNS	150/s	1.97%	2.76%
PowerDNS	120/s	5.62%	7.87%
Knot	150/s	12.87%	18.01%

(*Total loss rate relative to the attack duration)

Table: Measured peak client request loss rate with an attack over 40s, 150 iterations, and 255 byte salt.

Measurements of Signed Domains

Goal: Find out how NSEC3 is used in the internet and how the RFC9276 guidelines are applied.
Methodology: Query DNSSEC information of nameservers of the Tranco Top-1M domains (in the week following 2024-03-10).

Key insights:

- 66 339 (6.63%) of the Tranco Top-1M domains are signed.
- Of these, 27 761 (41.85%) use NSEC3 while 37 354 (56.31%) use NSEC.
- 21 522 (77.53%) of the domains using NSEC3 send records with iterations > 0 (median 5, maximum 500 iterations), 21 248 (76.54%) of the domains utilizing NSEC3 employ a salt (median 8, maximum 64 bytes).

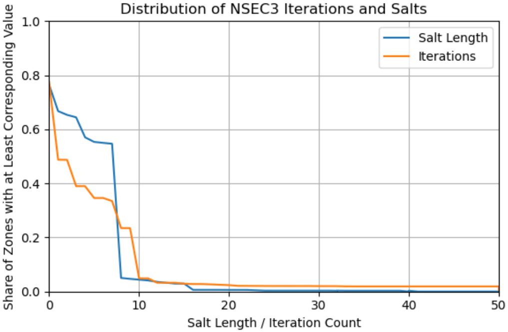

Figure: Share of zones which meet or exceed the configured Salt Length / Iteration Count in signed DNS zones.

Conclusion

- We performed the first evaluation of the attack and measured the impact on resolvers
- We developed a test setup to evaluate the impact of DNS DoS attacks on clients
- NSEC3-Encloser can exhaust resolver CPU with attack rate in the low hundreds
- There is impact on benign drop rates, causing up to 34.66% loss
- Overall, the impact is limited, since it requires high attack volumes for relatively limited impact. The attack is inferior to other attacks, such as KeyTrap.