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Securing Name Resolution in the IoT: DNS over CoAP

Paris, ACM CoNEXT'23, 2023-12-05

Contact: martine.lenders@tu-dresden.de

Outline

Motivation

A Brief Introduction into CoAP

Design Guidance from IoT DNS Traffic

DNS over CoAP

Evaluation

Further Improvements

Conclusion & Future Work

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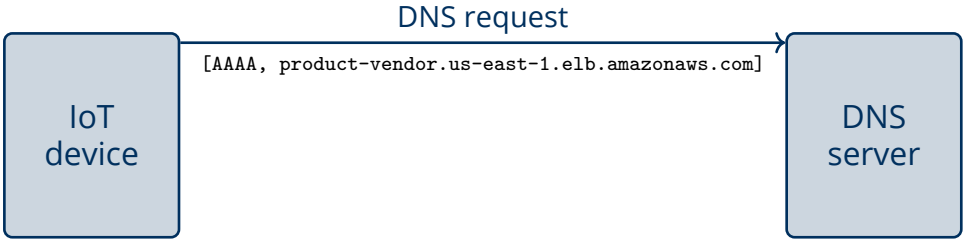

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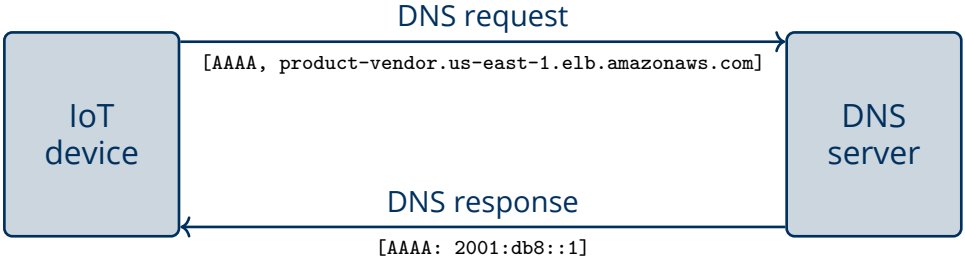

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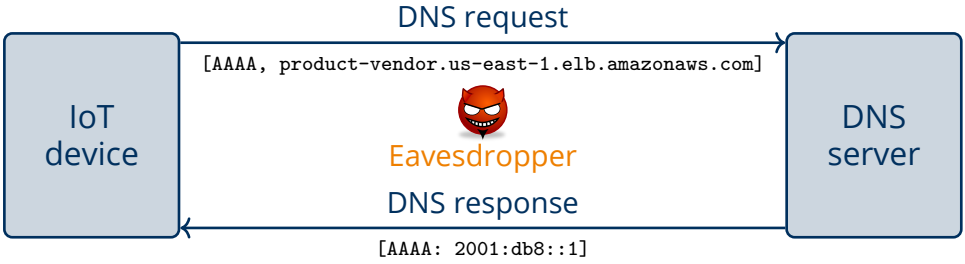

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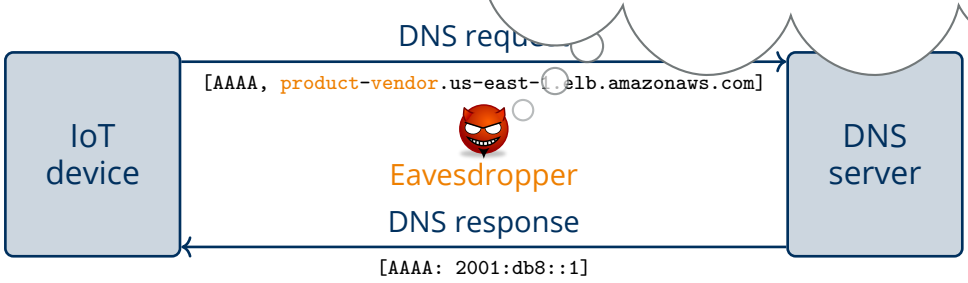

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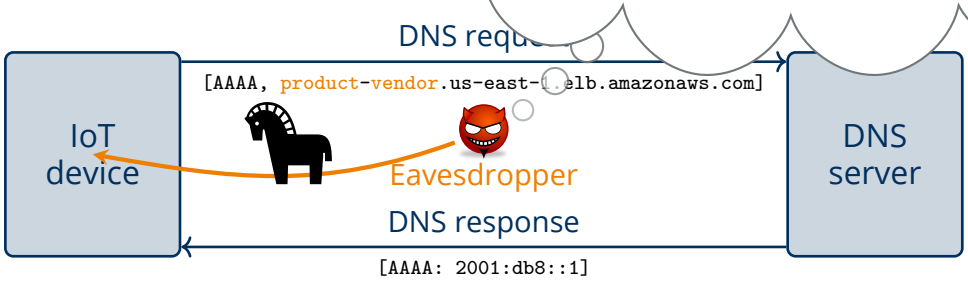

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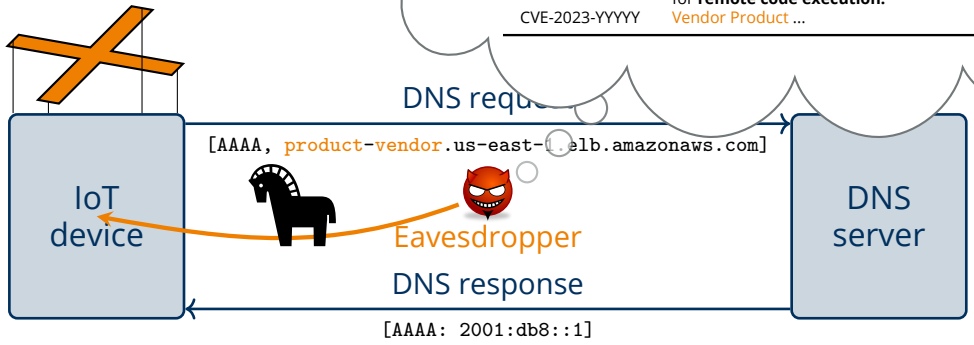

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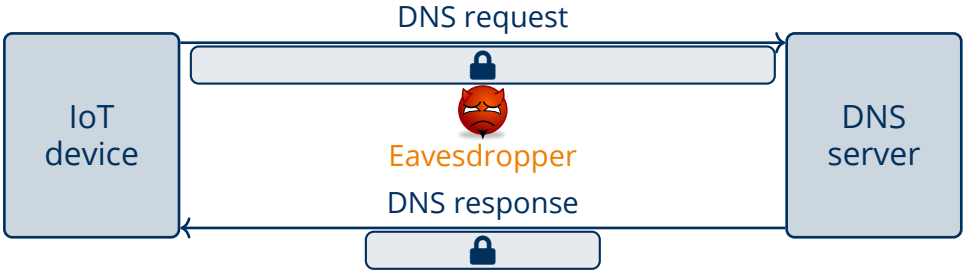
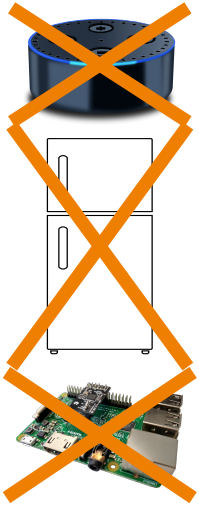


Countermeasure

Encrypt name resolution triggered by IoT devices against eavesdropping

Challenge: Constrained IoT



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Characteristic	Class 0	Class 1	Class 2
Data size [KiB]	$\ll 10$	≈ 10	≈ 50
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BLE

zigbee

LoRa

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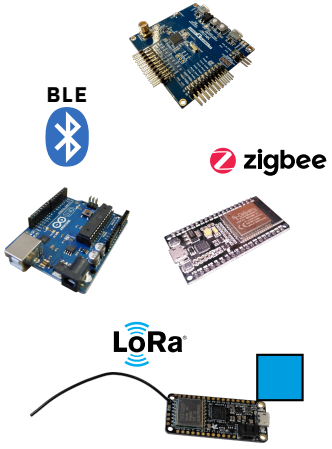

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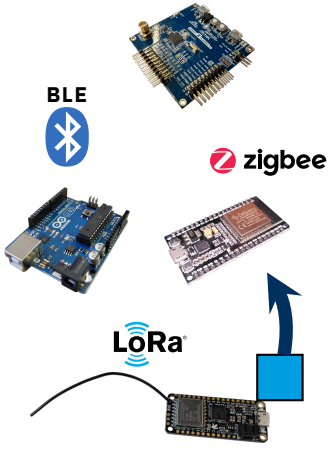

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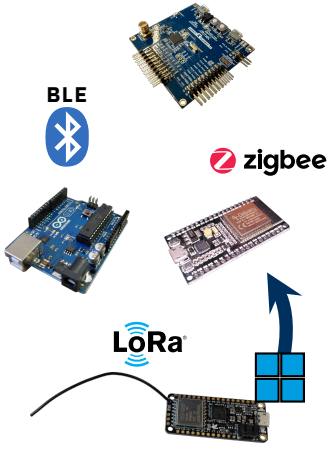

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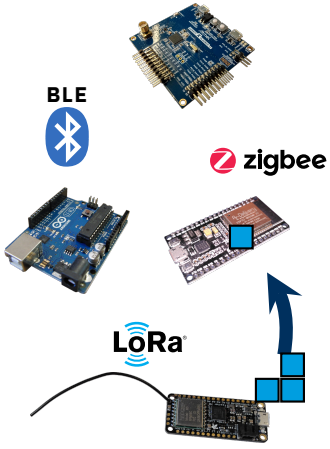

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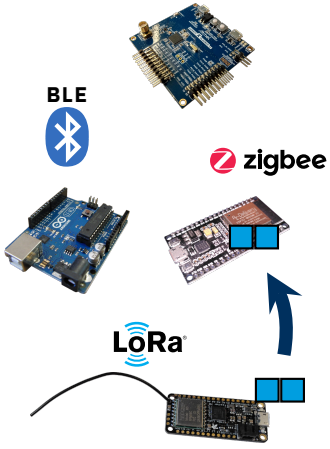

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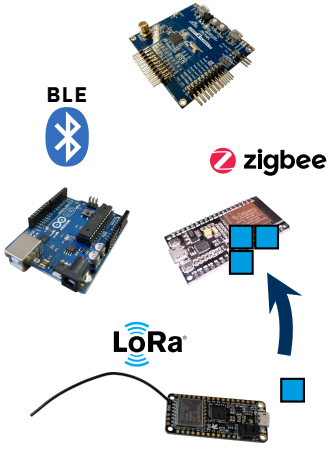

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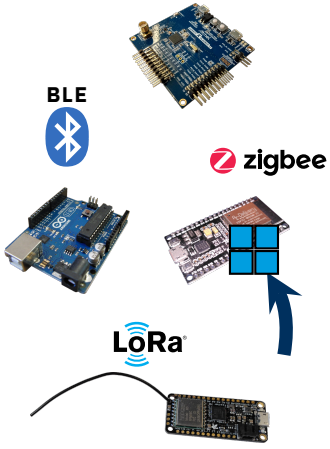

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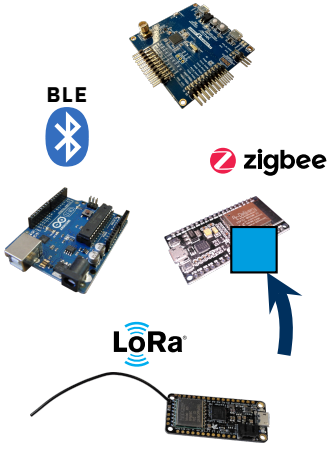

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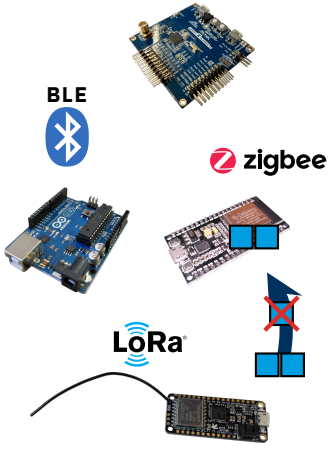

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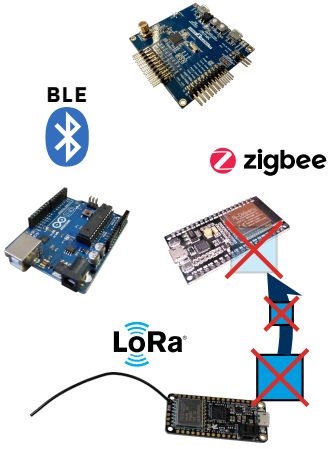

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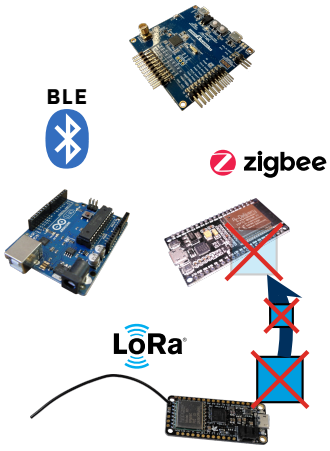

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Data rate [kBit/s]	124–162	125–2000	0.3–5
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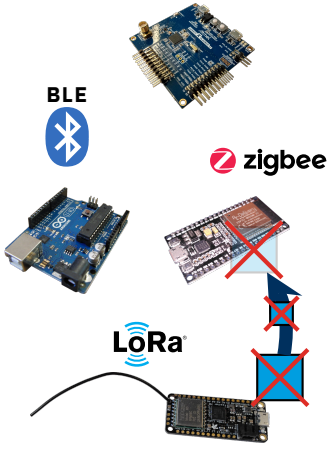

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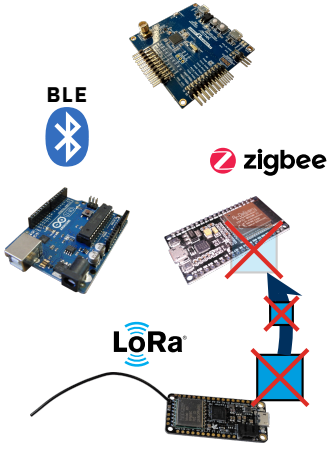

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Constrained

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- High penalties on large packets (link la… …fragmentation)

0.000003% – 0.0009%
slower than WiFi 6

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Possible Solutions for Encrypted DNS

DNS over HTTPS (RFC 8484)

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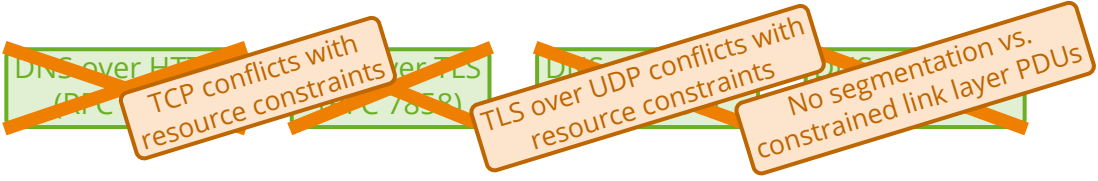

Possible Solutions for Encrypted DNS

Our proposal: DNS over CoAP

(`https://datatracker.ietf.org/doc/draft-ietf-core-dns-over-coap/`)

- **Encrypted communication** based on DTLS or OSCORE
- **Block-wise message transfer** provides message segmentation
- **En-route caching** mitigates high link layer packet loss
- **Share system resources** with CoAP applications
  - Same socket and buffers can be used
  - Re-use of the CoAP retransmission mechanism

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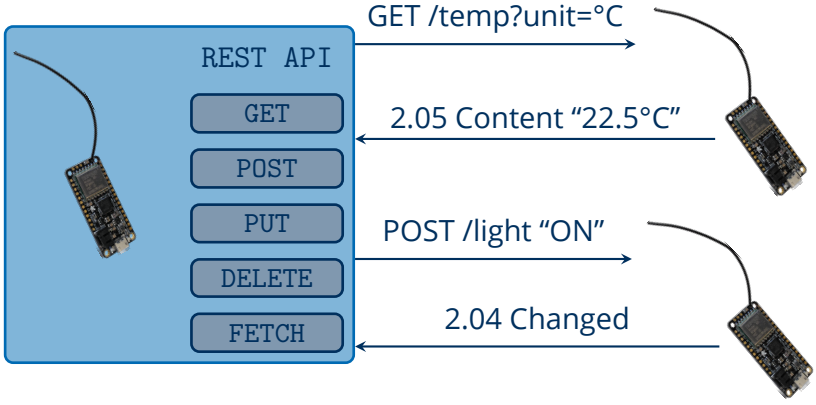
CoAP: The Constrained Application Protocol

“REST over UDP” ∼ The HTTP for IoT



CoAP Security Modes

DTLS Datagram Transport Layer Security (≈ TLS over UDP)

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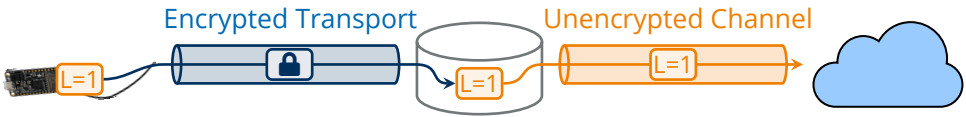

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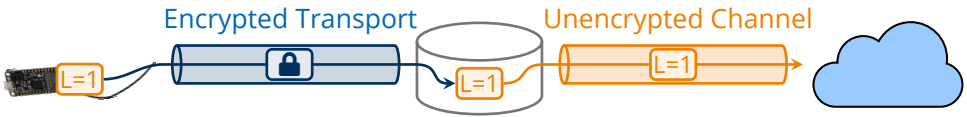

OSCORE Object Security for Constrained RESTful Environment

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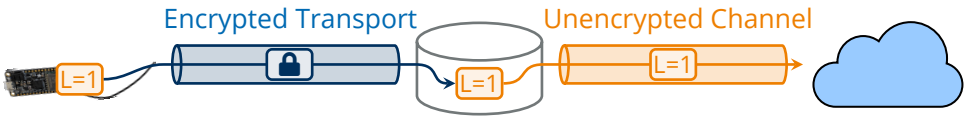

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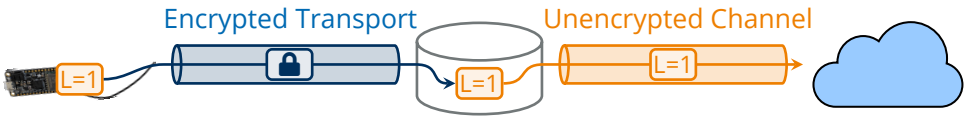


OSCORE Object Security for Constrained RESTful Environment

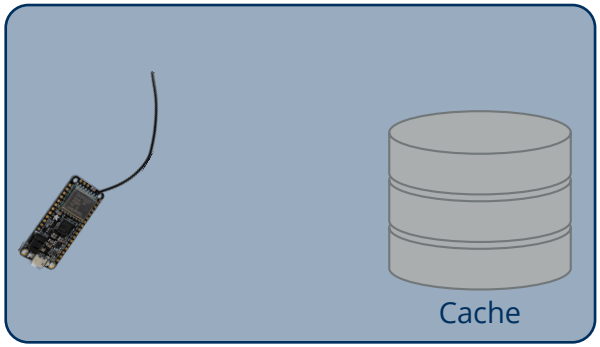
CoAP Caching

Client

Cache

Server

CoAP Caching

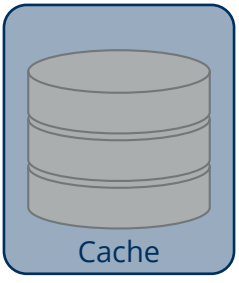


On client node

Server

CoAP Caching

Client



On proxy node

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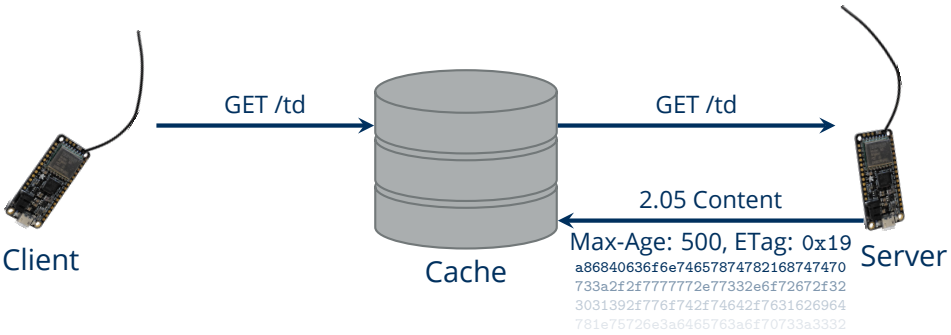
CoAP Caching

Caching provides **decoupling from packet loss**



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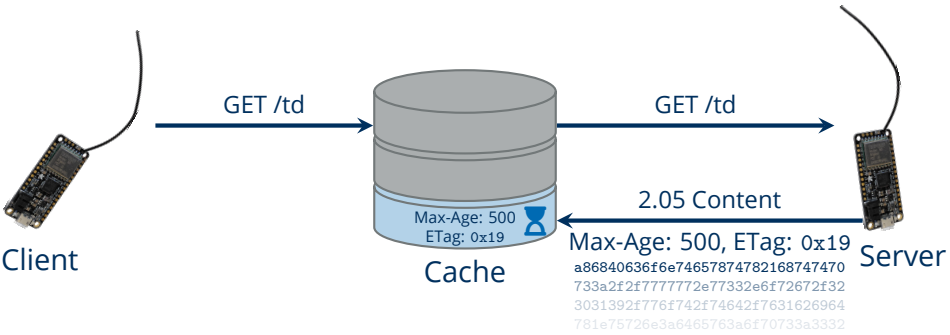

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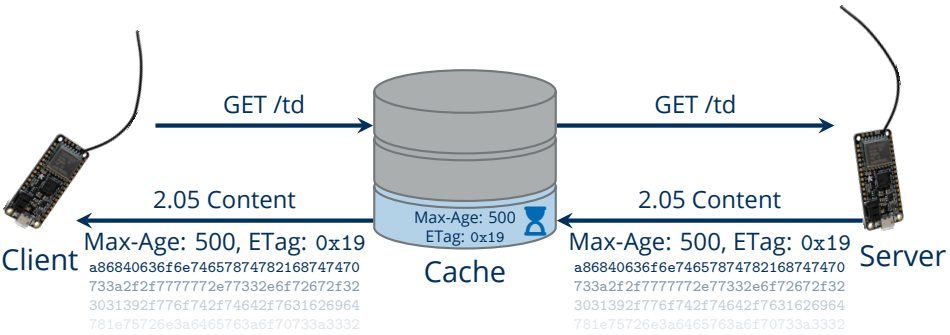

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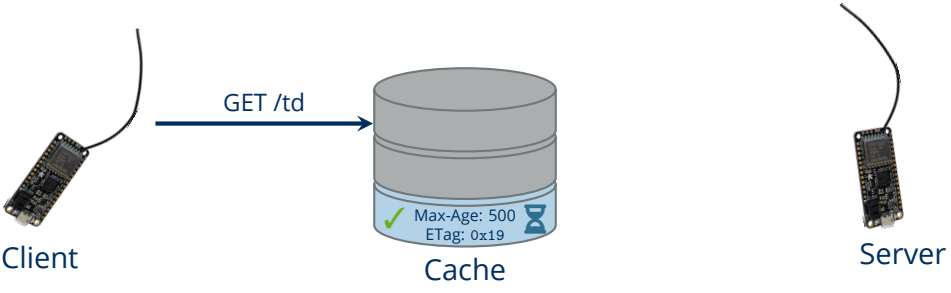

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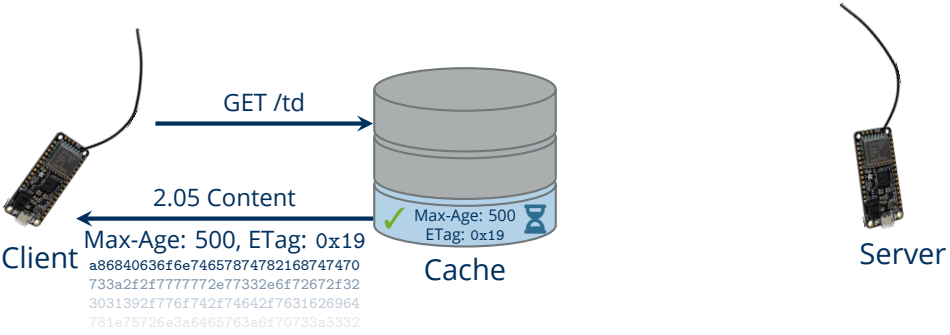

CoAP Caching

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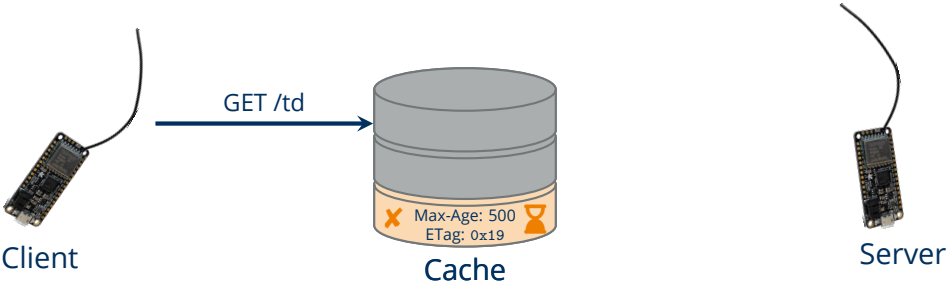

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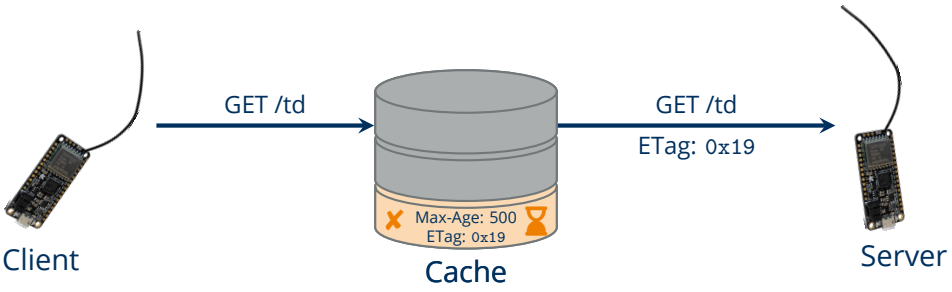
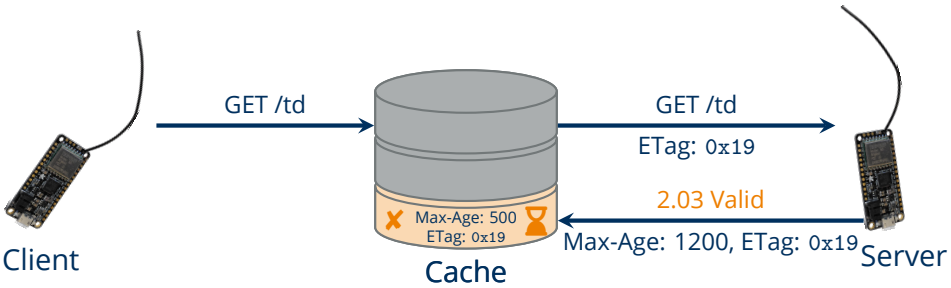


CoAP Caching

Cache validation **reduces data overhead**



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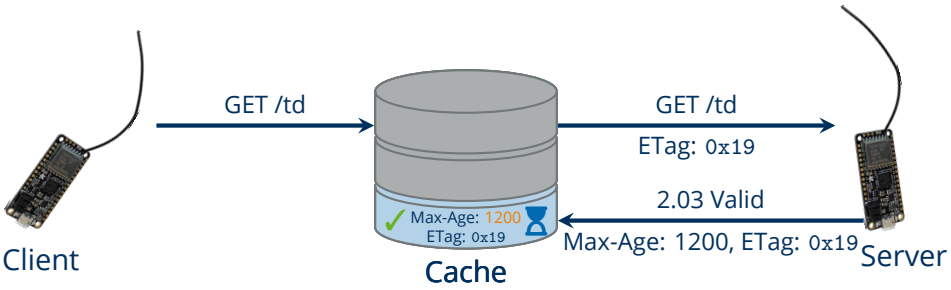

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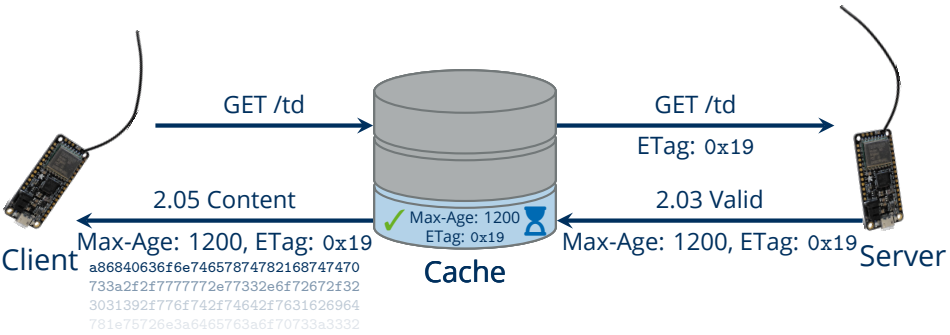

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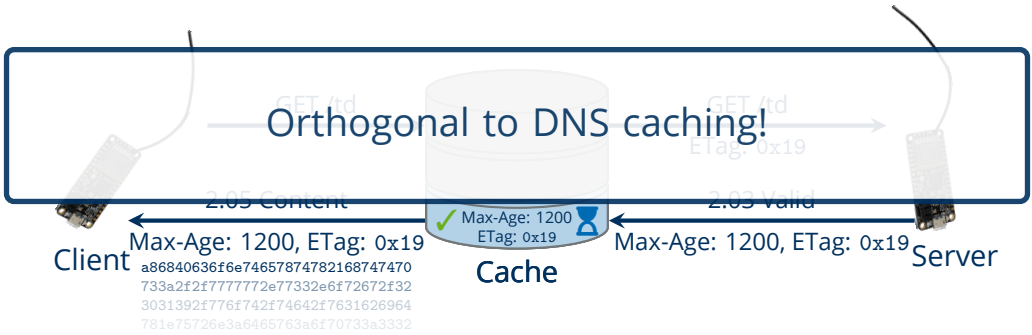

Outline

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Design Guidance from IoT DNS Traffic

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Evaluation

Further Improvements

Conclusion & Future Work

Data Corpus for IoT DNS Traffic Analysis

IoT data sets

YourThings[1] | IoTFinder[2] | MonIoTr[3]

- Collected throughout 2019
- DNS & mDNS (DNS-SD) traffic
- 90 consumer devices from 50 vendors
- 0.2 million queries
- 1.3 million responses
- 2336 unique queried names

IXP data set

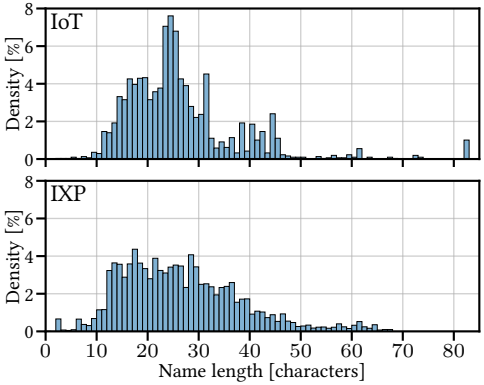
- Large Central European IXP
- Collected January 2022
- DNS only
- Sampling rate: 1/16000 pkts.
- 1.6 million queries
- 2.4 million responses
- Names anonymized to lengths

[1] O. Alrawi, C. Lever, M. Antonakakis, and F. Monrose. 2019. **SoK: Security Evaluation of Home-Based IoT Deployments**. In *IEEE S&P 2019*. 1362–1380.

[2] R. Perdisci, T. Papastergiou, O. Alrawi, and M. Antonakakis. 2020. **IoTFinder: Efficient Large-Scale Identification of IoT Devices via Passive DNS Traffic Analysis**. In *IEEE EuroS&P 2020*. 474–489.

[3] J. Ren, D.J. Dubois, D. Choffnes, A.M. Mandalari, R. Kolcun, and H. Haddadi. 2019. **Information Exposure for Consumer IoT Devices: A Multidimensional, Network-Informed Measurement Approach**. In *Proc. of the Internet Measurement Conference (IMC)*. ACM.

DNS IoT Traffic: Name Lengths



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Data set	Min	Max	Mean	Std. Dev.	Median
YourThings	2	83	24.5	9.7	24
IoTFinder	7	82	26.8	10.5	24
MonIoTr	9	83	27.1	14.7	23
IoT total	2	83	25.9	1.3	24
IXP	0	68	26.1	1.7	25

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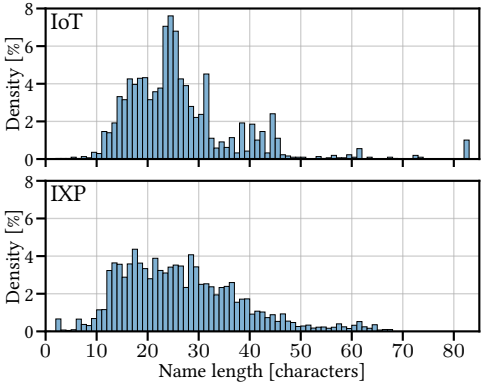

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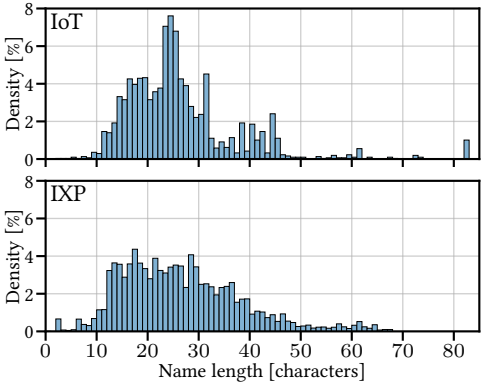

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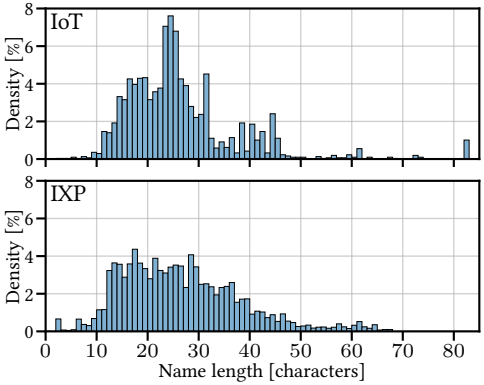

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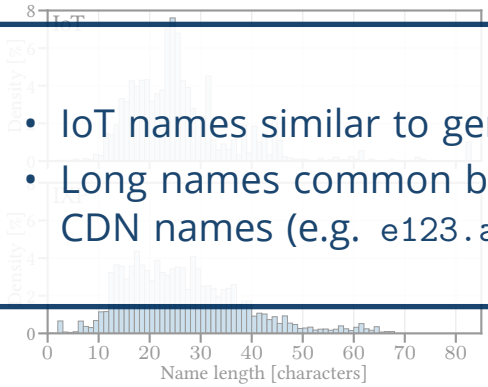

- IoT names similar to general Internet names
- Long names common because of cloud services and CDN names (e.g. `e123.abcd.akamaiedge.net`)

DNS IoT Traffic: Queried Record Type

Queried Record Type	IoT Devices w/ mDNS	IoT Devices w/o mDNS	IXP
A	53.6%	75.8%	64.5%
AAAA	16.4%	23.5%	17.6%
ANY	8.2%	—	1.7%
HTTPS	—	—	9.1%
NS	—	—	0.7%
PTR	19.6%	0.3%	1.8%
SRV	1.0%	—	0.4%
TXT	1.2%	0.1%	0.7%
Other	< 0.1%	0.3%	3.5%

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Mainly address resolution

Also service discovery & information

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- A/AAAA resolution is prevalent also in the IoT
- Group OSCORE may offer solution for encrypted DNS-SD
- Unsolicited `NS` records increase response sizes
  $\Rightarrow$ Should be avoided with DoC

Also service discovery & information

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DNS over CoAP (DoC)

- Just map the DoH methods **GET** and **POST**?

DNS over CoAP (DoC)

- Just map the DoH methods **GET** and **POST**?

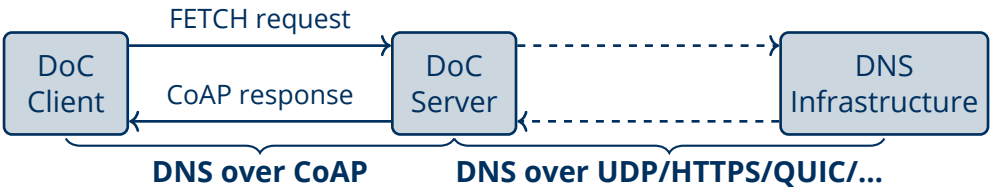
	HTTP	
	GET	POST
Responses cacheable	✓	✗
Application data carried in body	✗	✓
Block-wise transferable query	✗	✓

DNS over CoAP (DoC)

- Just map the DoH methods **GET** and **POST**?
- **FETCH** method in CoAP: best of both worlds (RFC 8132)

	CoAP		
	HTTP		
	GET	POST	FETCH
Responses cacheable	✓	✘	✓
Application data carried in body	✘	✓	✓
Block-wise transferable query	✘	✓	✓

DNS over CoAP (DoC): Example Query



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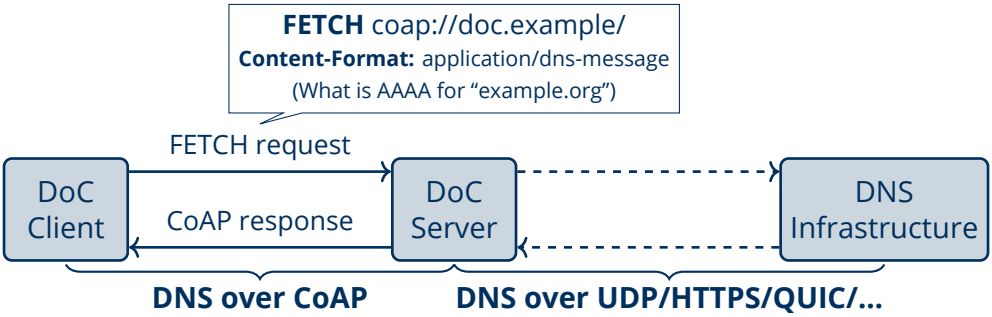

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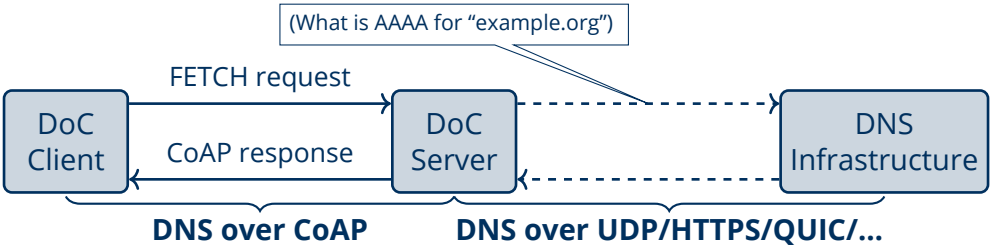
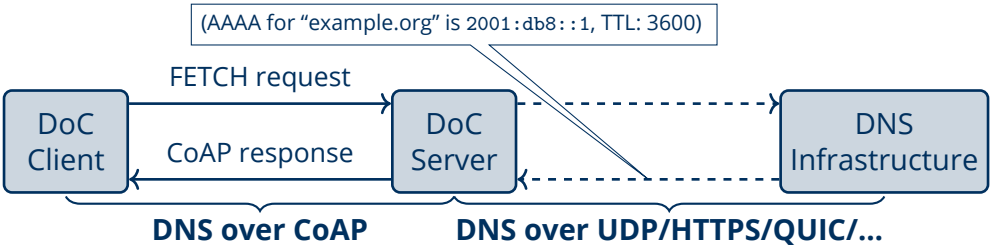


DNS over CoAP (DoC): Example Query



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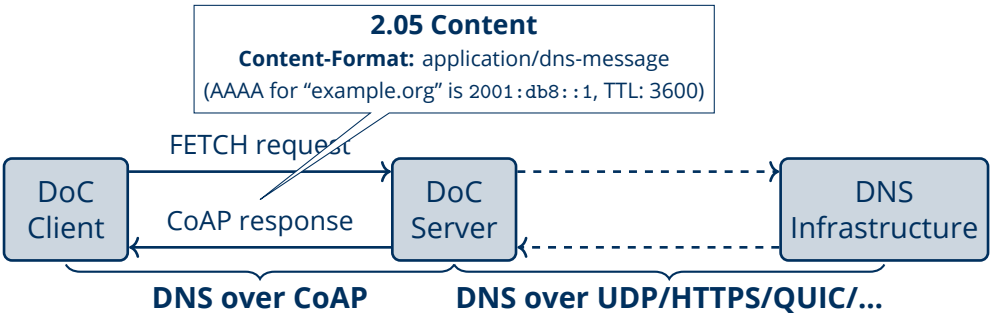

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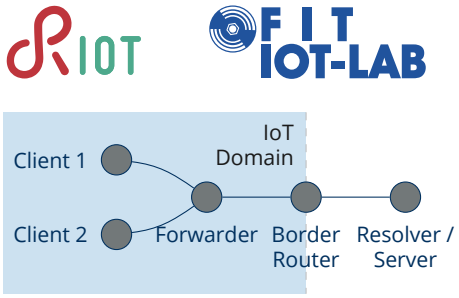
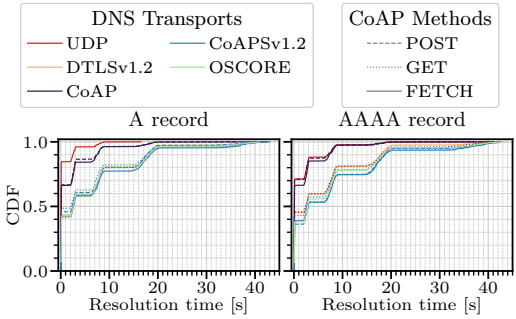
Evaluation Setup: DNS Transfer Protocol Comparison



- Client 1 and 2 query records for names of length 24 chars (median of IoT data) via
  - UDP
  - DTLSv1.2
  - CoAP (unencrypted)
  - CoAPSv1.2 (CoAP over DTLSv1.2)
  - OSCORE
- 50 A and AAAA records each (most in IoT data)
- Poisson distribution: $\lambda = 5$ queries / sec
- 10 runs on IoT-nodes (incl. border router): Cortex-M3 with IEEE 802.15.4 radio

Experiment: Resolution Time



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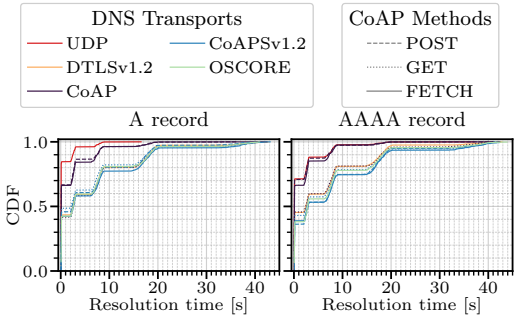
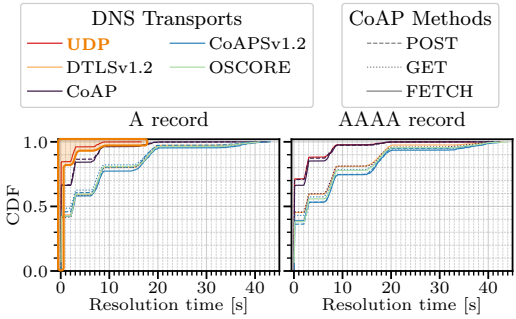


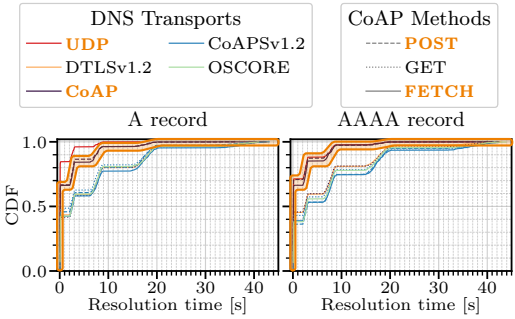
Clear performance groups visible

Experiment: Resolution Time



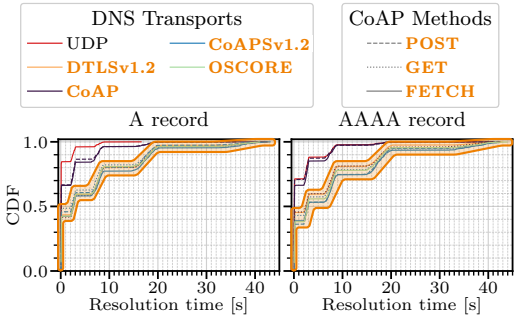
Group 1

Experiment: Resolution Time



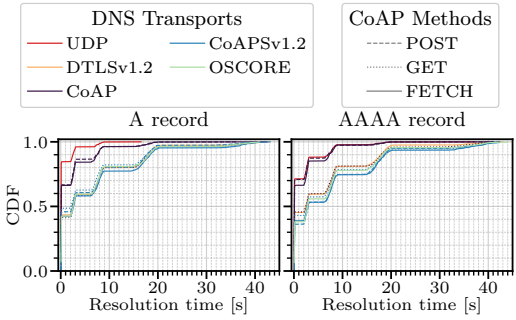
Group 2

Experiment: Resolution Time



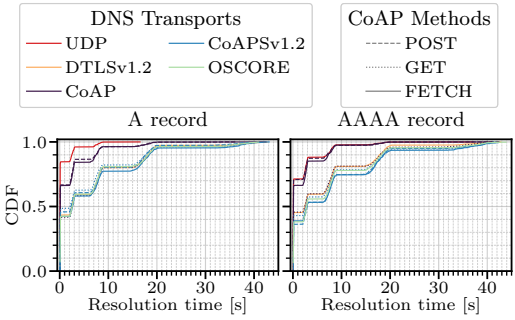
Group 3

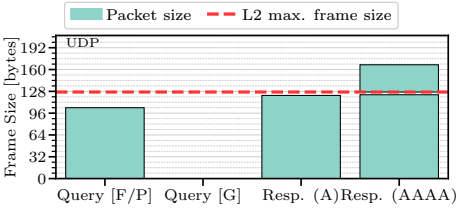
Experiment: Resolution Time



Where do performance groups come from?

Experiment: Resolution Time & Packet Sizes





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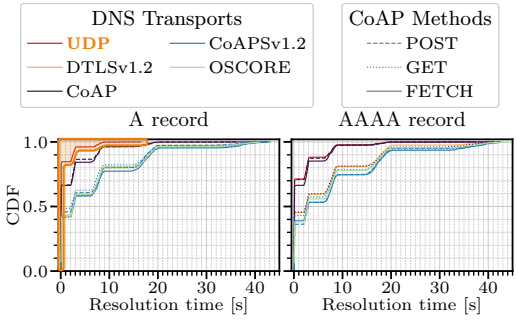
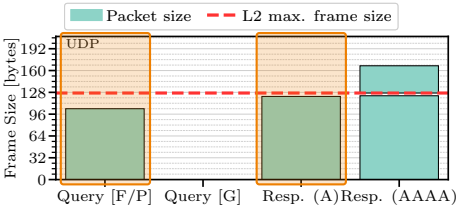
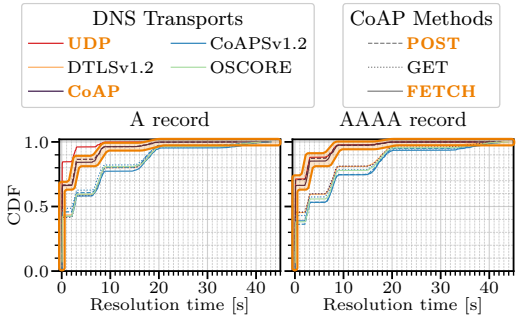
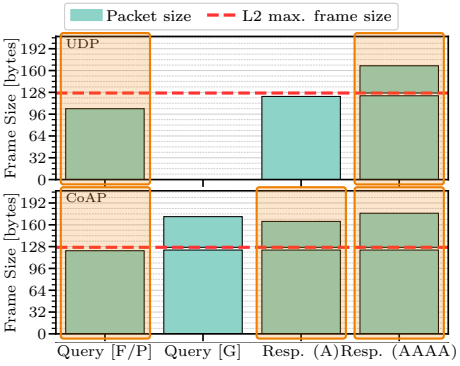




Group 1
No message fragmentation

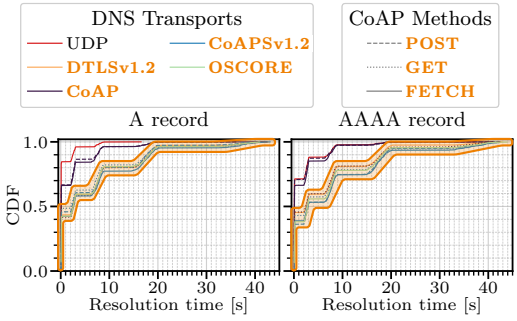
Experiment: Resolution Time & Packet Sizes

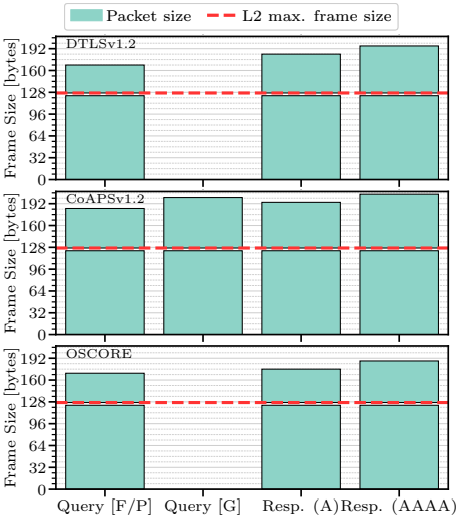




Group 2
Query unfragmented
Response fragmented

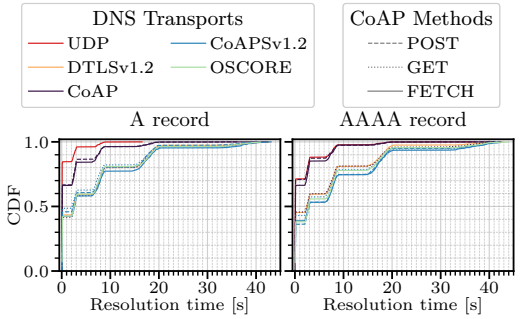
Experiment: Resolution Time & Packet Sizes

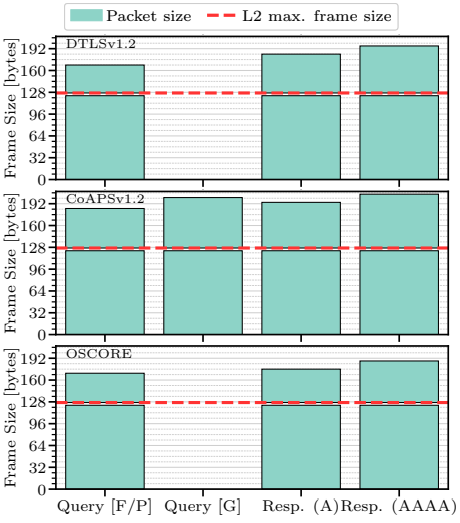




Group 3
Both messages fragmented

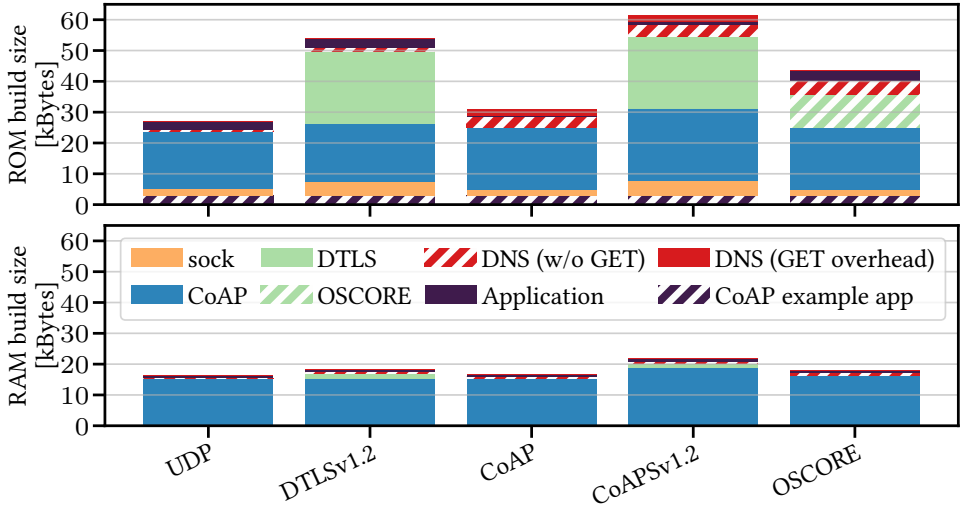
Experiment: Resolution Time & Packet Sizes





⇒ **Fragmentation has larger impact on performance** compared to transfer protocol or CoAP method

Memory Consumption



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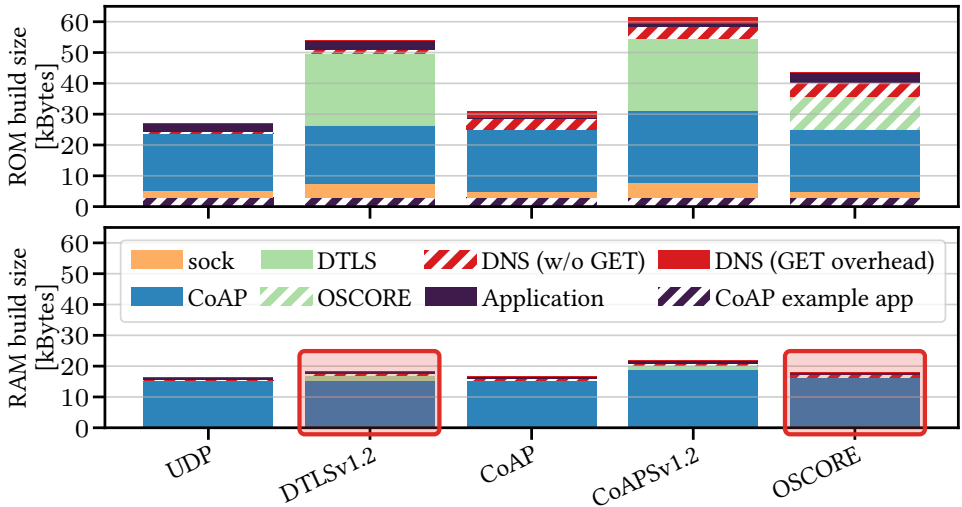

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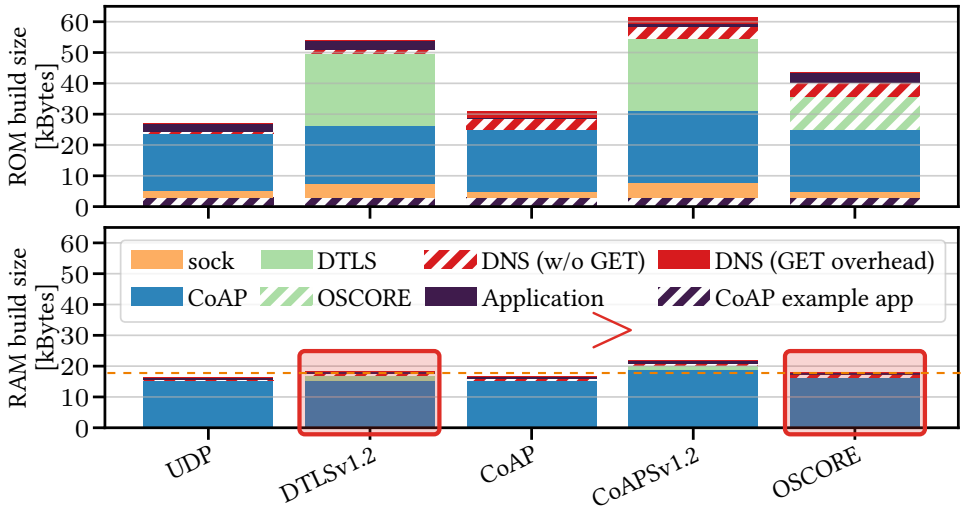

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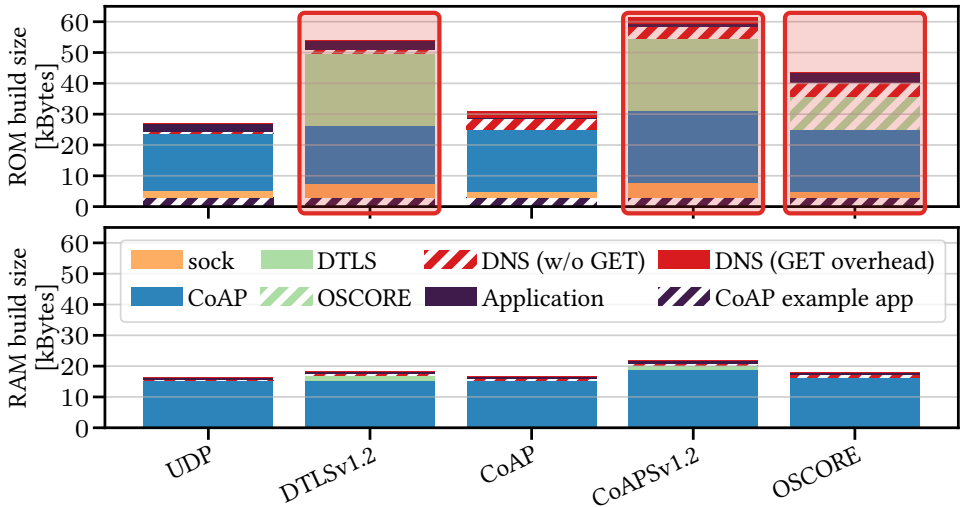

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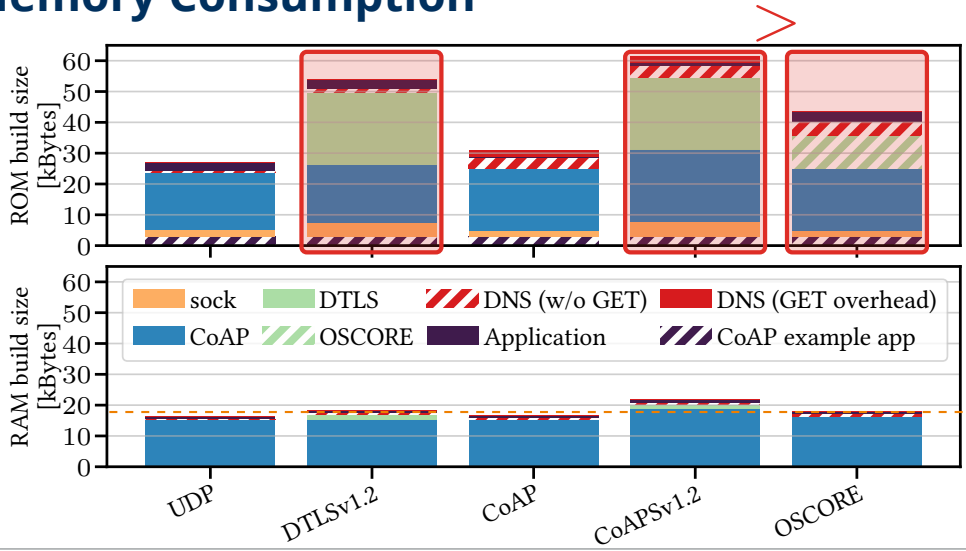

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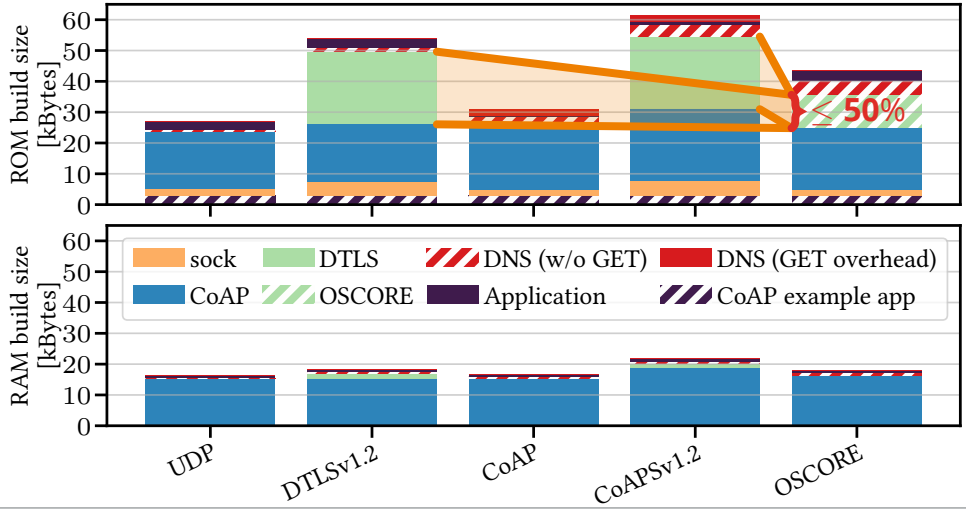

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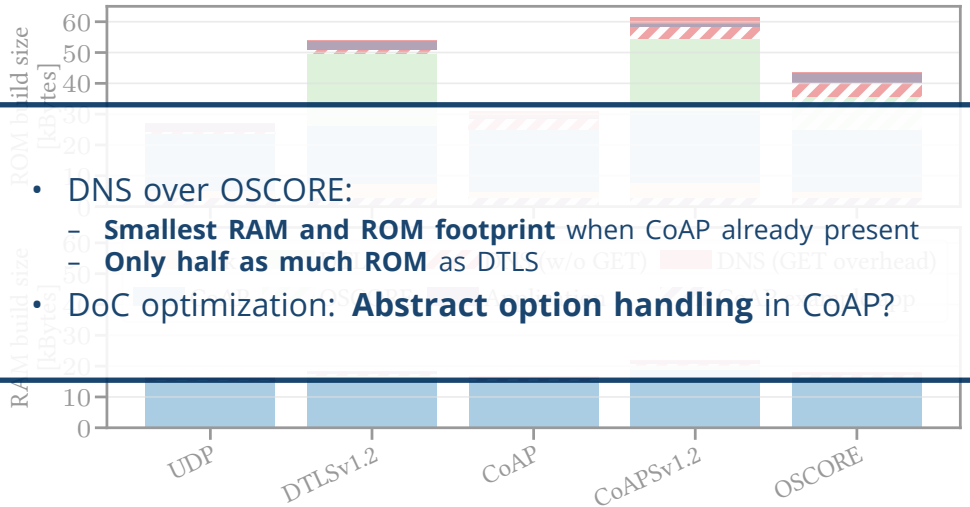

- DNS over OSCORE:
  - **Smallest RAM and ROM footprint** when CoAP already present
  - **Only half as much ROM** as DTLS
- DoC optimization: **Abstract option handling** in CoAP?

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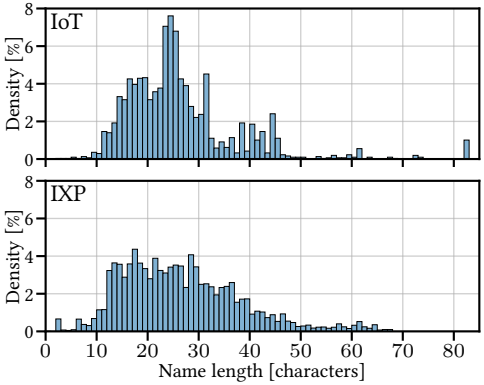

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Further Improvements

Concise DNS Message Representation

Constrained Networks, e.g., IEEE 802.15.4 with PDU of 127 bytes

Name Length

2 chars (minimum)

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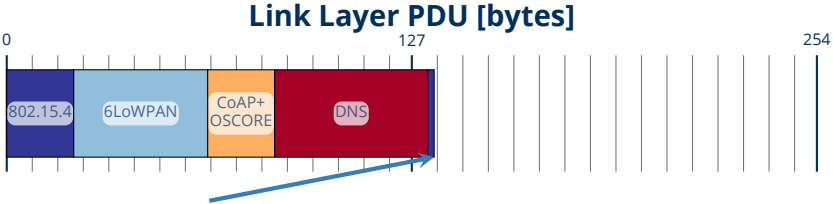
Concise DNS Message Representation

Constrained Networks, e.g., IEEE 802.15.4 with PDU of 127 bytes

Name Length	Message Type
2 chars	AAAA Response

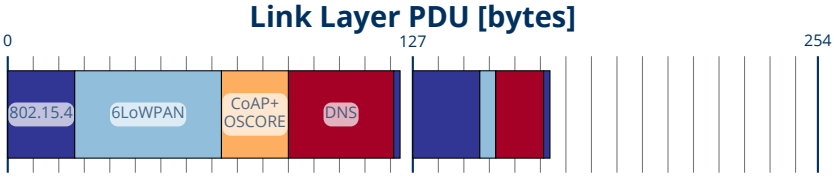


Further Improvements

Concise DNS Message Representation

Constrained Networks, e.g., IEEE 802.15.4 with PDU of 127 bytes

Name Length	Message Type
2 chars	AAAA Response



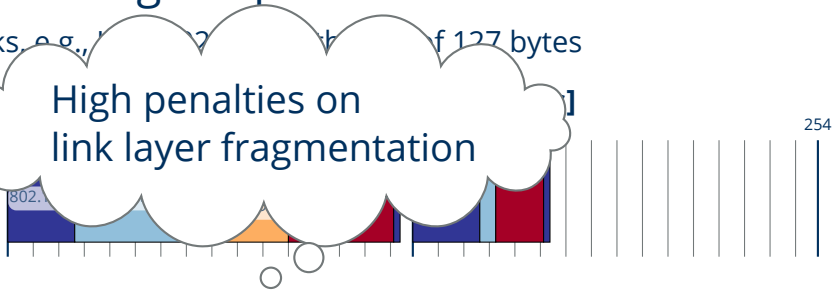
⇒ Fragmentation

Further Improvements

Concise DNS Message Representation

Constrained Networks, e.g., [illegible] of 127 bytes

Name Length	Messa[illegible] Type	]
2 chars	AAAA Response	



⇒ Fragmentation

Further Improvements

C

Co

Concise DNS messages are needed

`application/dns+cbor`

Media Type and Content-Format

(*i.e.*, usable with both DoC and DoH)

`https://datatracker.ietf.org/doc/draft-lenders-dns-cbor/`

Objectives:

- Concise encoding of DNS messages using existing implementation (CBOR)
- Omits (redundant) DNS fields in DNS queries and responses
- Provides (optional) address and name compression using CBOR-packed

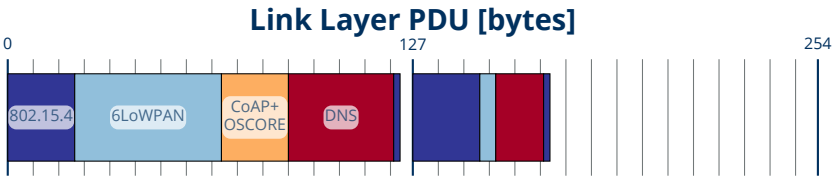
Further Improvements

Concise DNS Message Representation

Constrained Networks, e.g., IEEE 802.15.4 with PDU of 127 bytes

Name Length | **Message Type**

2 chars | AAAA Response




```
11 ac 80 00 00 01 00 01 00 00 00 00 02 67 77 00
00 1c 00 01 c0 0c 00 1c 00 01 00 00 0e 10 00 10
20 01 0d b8 00 00 00 00 00 00 00 00 00 00 00 01
```

Classic DNS

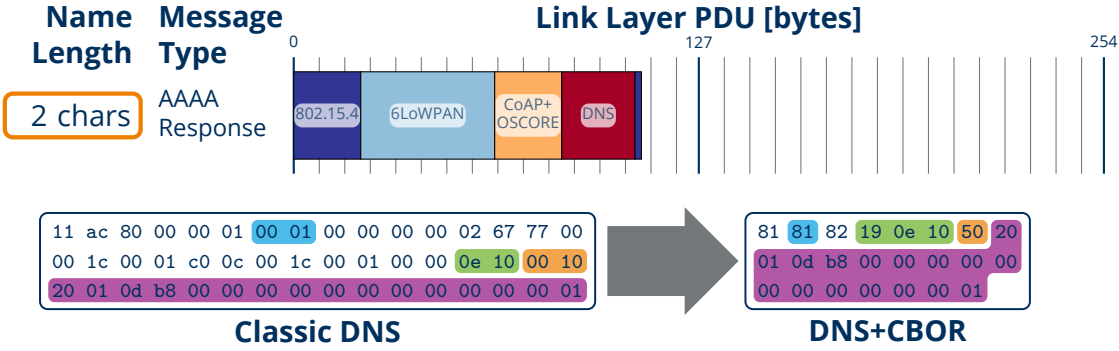
```
81 81 82 19 0e 10 50 20
01 0d b8 00 00 00 00 00
00 00 00 00 00 00 01
```

DNS+CBOR

Further Improvements

Concise DNS Message Representation

Constrained Networks, e.g., IEEE 802.15.4 with PDU of 127 bytes



Outline

Motivation

A Brief Introduction into CoAP

Design Guidance from IoT DNS Traffic

DNS over CoAP

Evaluation

Further Improvements

Conclusion & Future Work

Conclusion & Future Work

Secure & privacy-friendly DNS is ready for the constrained IoT:

- DoC with FETCH provides encrypted, cachable, and segmentable DNS
- En par in resolution time with existing UDP-based transfer protocols
- OSCORE outperforms DTLS and CoAPS both in packet and memory size

Future Work:

- Specify and evaluate concise DNS message format (`draft-lenders-dns-cbor`)
- Potential mDNS protection with Group OSCORE?

Reproducible Research: Our Artifacts

- https://zenodo.org/record/8193681
- https://github.com/anr-bmbf-pivot/Artifacts-CoNEXT23-DoC

Standardization in IETF:

https://datatracker.ietf.org/doc/draft-ietf-core-dns-over-coap/

Backup slides

Outline

IoT DNS Traffic

Comparison with QUIC

Evaluation: Caching Approaches

Name Length: More Statistical Properties

	Length of domain names [chars]							
Data set	min	max	mode	μ	σ	Q_1	Q_2	Q_3
YourThings	2	83	31	24.5	9.7	18	24	30
IoTFinder	7	82	24	26.8	10.5	20	24	30
MonIoTr	9	83	18	27.1	14.7	18	23	30
IoT total	2	83	24	25.9	1.3	19	24	30
IXP	0	68	17	26.1	1.7	17	25	33

Outline

IoT DNS Traffic

Comparison with QUIC

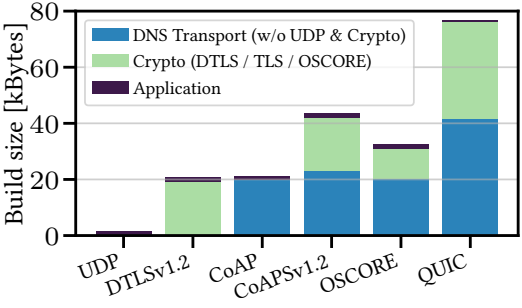
Evaluation: Caching Approaches

Comparison with QUIC: Method

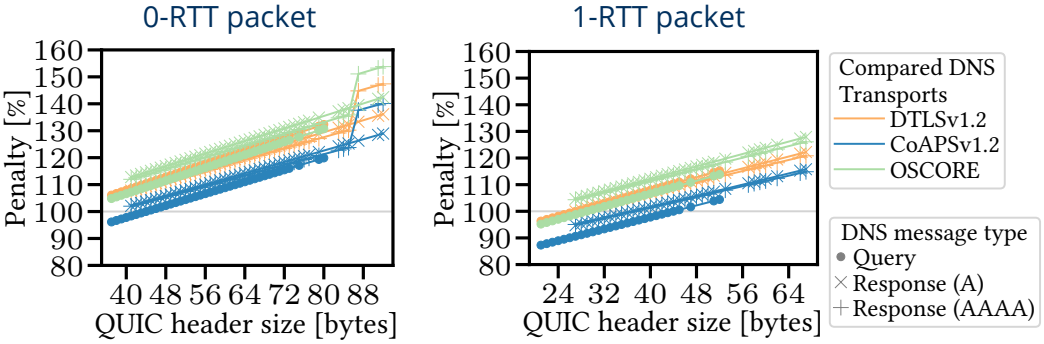
- Point of Reference: Quant[1]
- Memory Size: Quant & our requester application build for ESP32
- Packet Size: Numerical evaluation based on RFC9000

[1] Lars Eggert. 2020. Towards Securing the Internet of Things with QUIC. In *Proc. of 3rd NDSS Workshop on Decentralized IoT Systems and Security (DISS)* (San Diego, CA, USA). Internet Society (ISOC).

Comparison with QUIC: Code Sizes



Comparison with QUIC: Additional Link Layer Data



Outline

IoT DNS Traffic

Comparison with QUIC

Evaluation: Caching Approaches

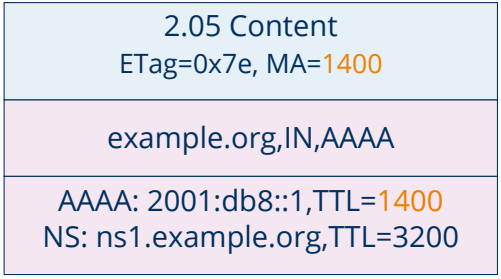
Caching Approaches

DoH-like

example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=1800 NS: ns1.example.org,TTL=3600

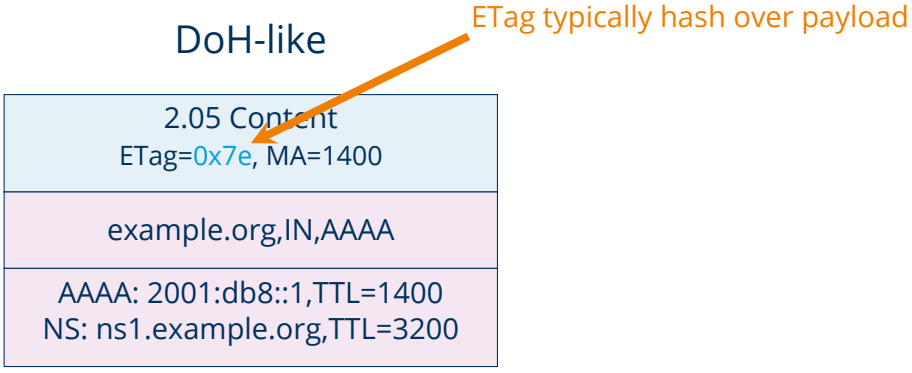
Caching Approaches

DoH-like



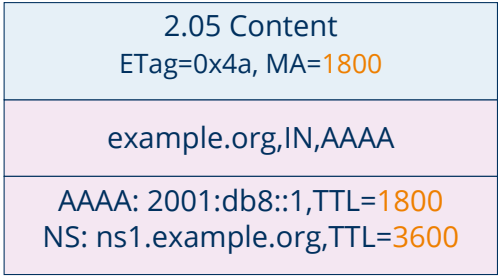
Caching Approaches

DoH-like



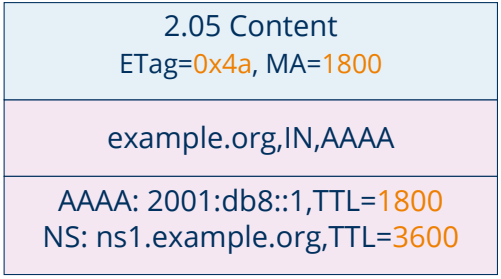
Caching Approaches

DoH-like



Caching Approaches

DoH-like



Caching Approaches

DoH-like

2.05 Content ETag=0x4a, MA=1800
example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=1800 NS: ns1.example.org,TTL=3600

⇒ Cache validation fails on TTL changes

Caching Approaches

DoH-like

2.05 Content ETag=0x4a, MA=1800
example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=1800 NS: ns1.example.org,TTL=3600

EOL-TTLs

example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=1400 NS: ns1.example.org,TTL=3200

⇒ Cache validation fails on TTL changes

Caching Approaches

DoH-like

2.05 Content ETag=0x4a, MA=1800
example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=1800 NS: ns1.example.org,TTL=3600

EOL-TTLs

2.05 Content ETag=0x95, MA=1400
example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=0 NS: ns1.example.org,TTL=0

⇒ Cache validation fails on TTL changes

Caching Approaches

DoH-like

2.05 Content ETag=0x4a, MA=1800
example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=1800 NS: ns1.example.org,TTL=3600

EOL-TTLs

2.05 Content ETag=0x95, MA=1800
example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=0 NS: ns1.example.org,TTL=0

⇒ Cache validation fails on TTL changes

Caching Approaches

DoH-like

2.05 Content ETag=0x4a, MA=1800
example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=1800 NS: ns1.example.org,TTL=3600

⇒ Cache validation fails on TTL changes

EOL-TTLs

2.05 Content ETag=0x95, MA=1800
example.org,IN,AAAA
AAAA: 2001:db8::1,TTL=0 NS: ns1.example.org,TTL=0

⇒ Decoupling of cache validation from TTL changes

Evaluation: Caching Approaches