Solving Interoperability and Performance Challenges over heterogeneous IoT Networks – DNS-based solutions

Antoine BERNARD

November 26th, 2021

Thesis available at https://thesis.a-bernard.eu/

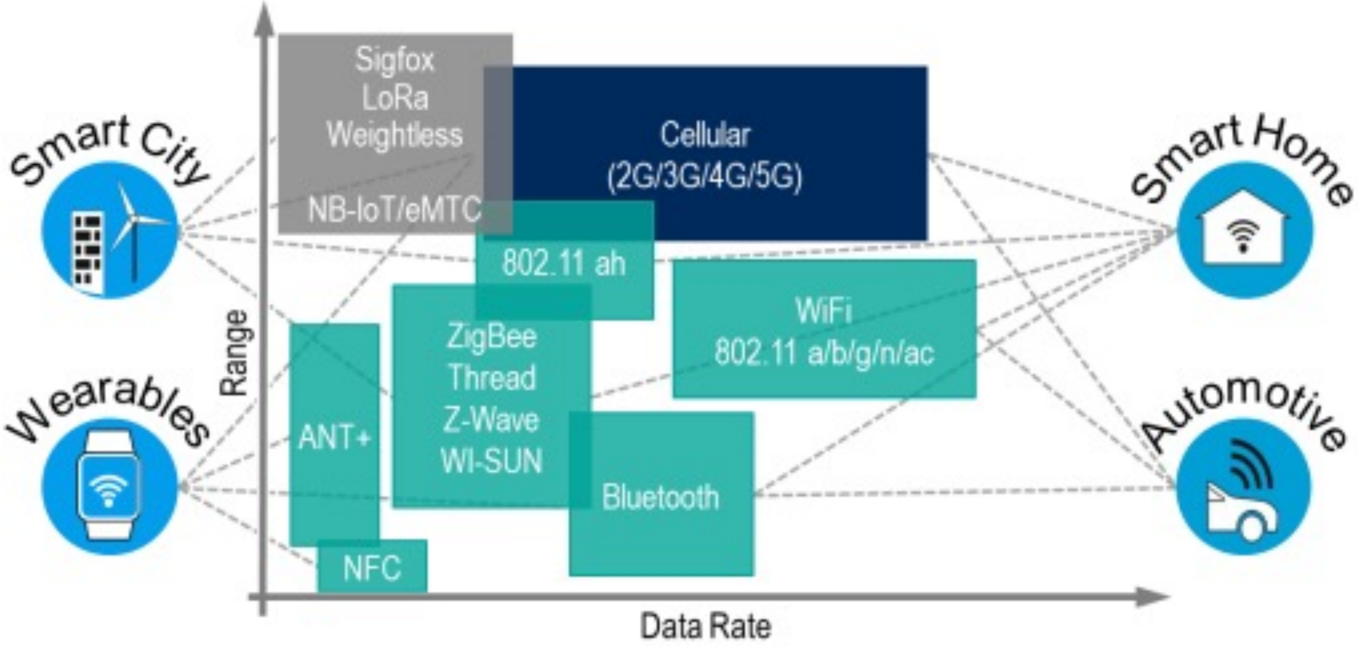
This work was partly financed by the French National Research Agency through the CIFRE program [2018/0668]. Part of this work contributed to the Energy4Climate Interdisciplinary Center (E4C) of IP Paris and Ecole des Ponts ParisTech. It was supported by 3rd Programme d'Investissements d'Avenir [ANR-18-EUR-0006-02].

Summary

- **Introduction**
- **Interoperability and device mobility**
  - Building a Roaming Federation
  - Prefetching DNS information
- **Performance challenges**
  - Compressing Headers
  - Minimize network traffic
- **Conclusion**

Introduction

IoT diversity

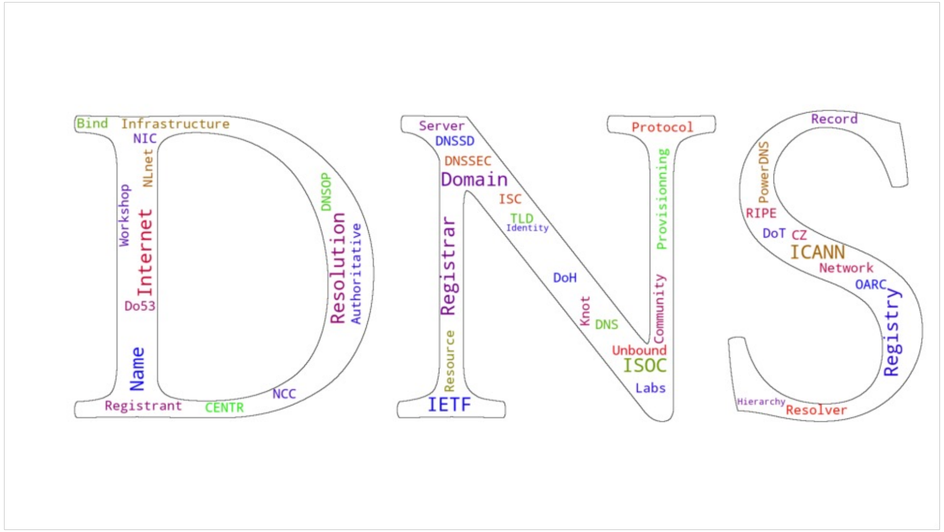


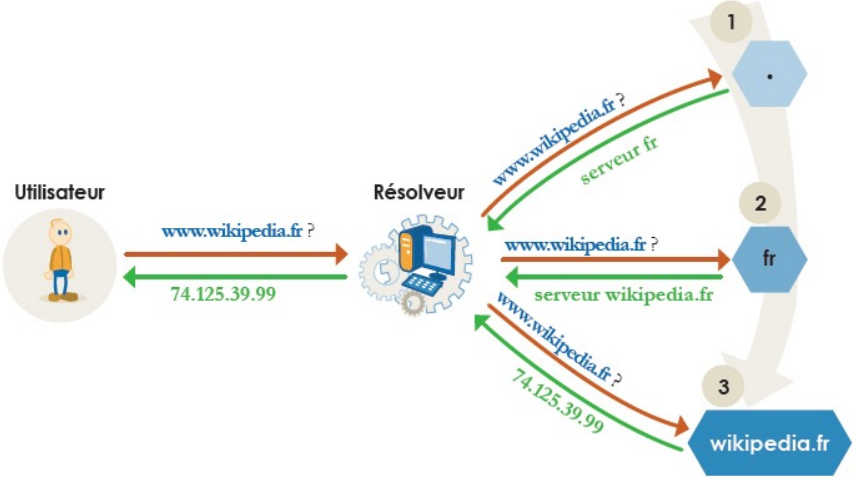
Source : Whitepaper Rhode & Schwarz

LoRaWAN, a Low-Power Wide-Area Network

- **Constraint network**
  - Low data rate
  - High latency
  - Small packet size
  - Duty cycle limitations
- **Long range**
- **Star topology**

DNS


Bind
Infrastructure
NIC
NLnet
Workshop
Internet
Do53
Name
Registrant
CENTR
NCC
DNSOP
Resolution
Authoritative
Server
DNSSD
DNSSEC
Domain
ISC
TLD
Identity
Registrar
Resource
IETF
DoH
Knot
DNS
Unbound
ISOC
Labs
Community
Provisionning
Protocol
Record
PowerDNS
RIPE
DoT
CZ
ICANN
Network
OARC
Registry
Hierarchy
Resolver


Utilisateur
www.wikipedia.fr ?
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Résolveur
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Recent evolutions

- **IoT**
  - Standardization and interoperability are key concerns [1]
  - Connect IoT to the Internet [2]
  - Adding intelligence to the network [3]

Source :
[1] Debasis Bandyopadhyay and Jaydip Sen. “Internet of Things: Applications and Challenges in Technology and Standardization”. (May 2011)
[2] Michele Zorzi et al. “From today’s INTRAnet of things to a future INTERnet of things: a wireless- and mobility-related view” (Dec, 2010)
[3] Benjamin Sliwa, Nico Piatkowski, and Christian Wietfeld. “LIMITS: Lightweight Machine Learning for IoT Systems with Resource Limitations” (June 2020)

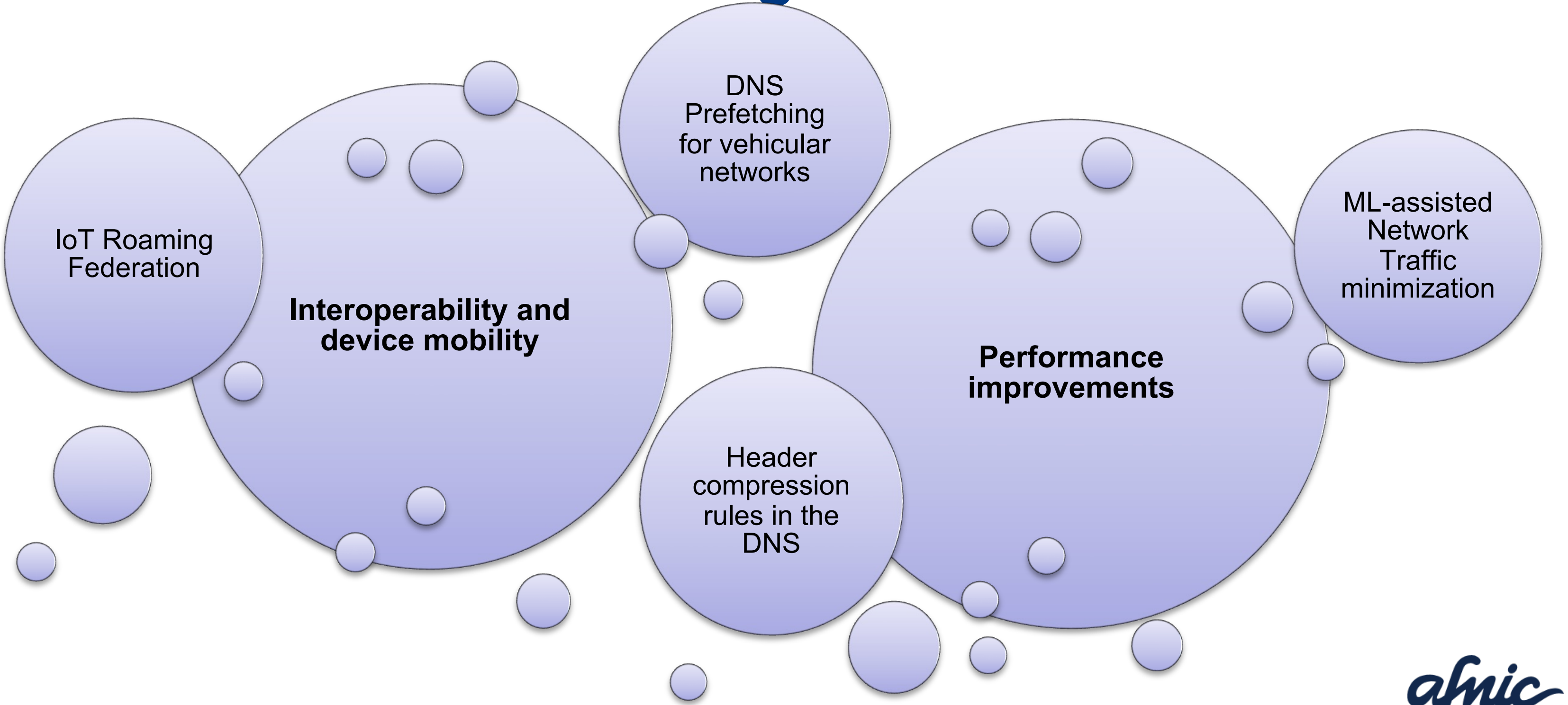
- **DNS [4] :**
  - Over 300 Related RFCs
  - 50+ within the last 10 years
- **Key concern :**
  - Security
    - DoT, DoH
    - DNSSEC
    - DANE
  - DNS-SD

[4] https://powerdns.org/dns-camel/

Problem Statement

How can the DNS infrastructure improve IoT architectures and services?

Two main challenges



IoT Roaming Federation

Interoperability and device mobility

DNS Prefetching for vehicular networks

Header compression rules in the DNS

Performance improvements

ML-assisted Network Traffic minimization

Improving device mobility

Building an IoT Roaming federation

IoTRoam

Improving mobility ?

- **Siloed structures [1]**

- **Improving mobility**
  - Coverage
  - Roaming

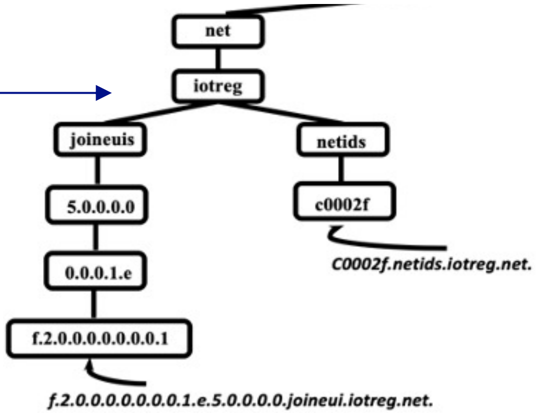
- **Building Roaming facilitators**
  - Peer-to-peer
  - Hub [2]
  - Federation [3]

Reference :

[1] Michele Zorzi et al. “From today’s INTRAnet of things to a future INTERnet of things: a wireless- and mobility-related view” (Dec, 2010)
[2] https://www.thethingsindustries.com/peering/
[3] https://eduroam.org/

Substituting prior configuration

Peer Net-ID
Roaming Policy
Peer’s channel plan
Peer’s fNS URL
Peer’s sNS URL
Peer’s NS IP address
Peer JS URL
Peer JS IP Address
Peer JS Http Credentials



LoRaWAN Backend Interfaces specification

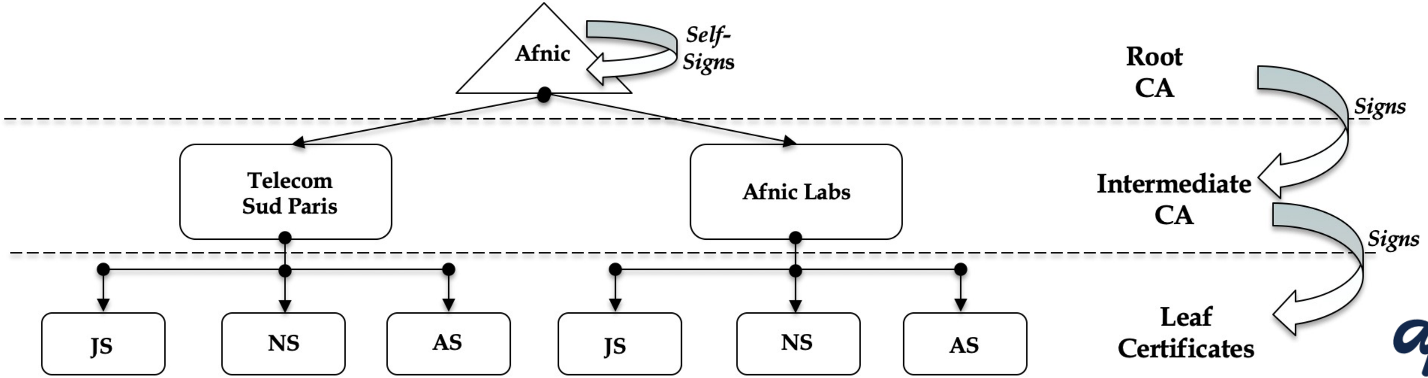
Security concerns

Securing the channel

Building trust between network

Handling global authentication

Conform with LoRaWAN specification



Configuration

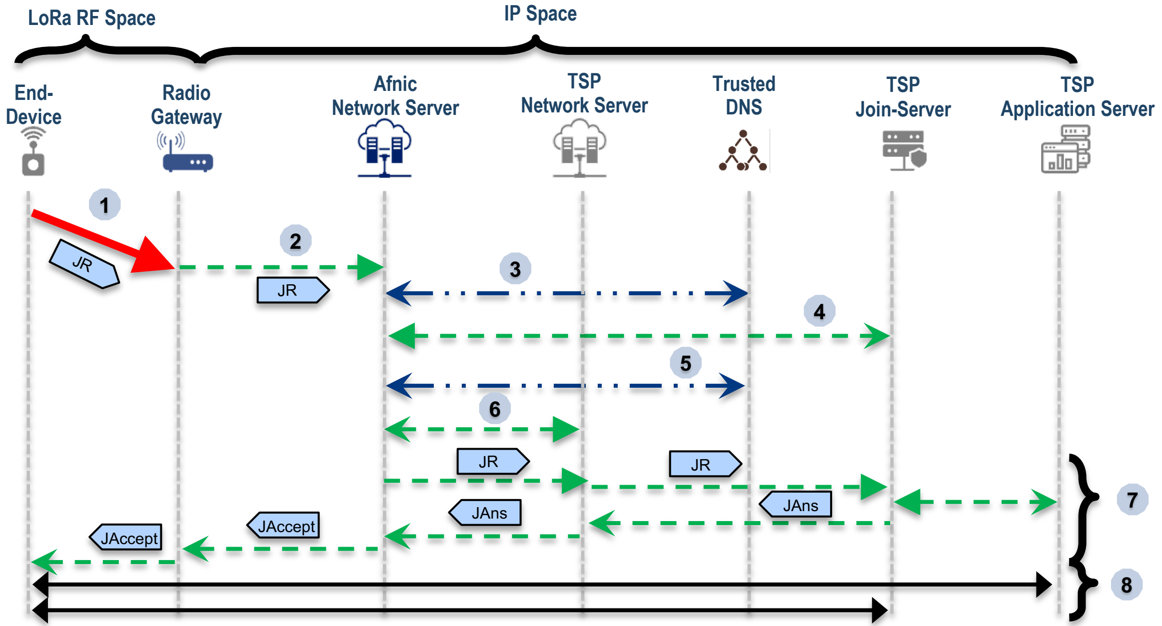
- **DNS (provisionning and autoconfiguration)**

- **Two central ecosystem**
  - DNS Registries
  - Certificate Authorities

- **Use DNS as PKI**
  - Let’s encrypt impossible to use
  - Paid certificate make the solution less open
  - DNSSEC and DANE

Revoir

LoRaWAN roaming exchange



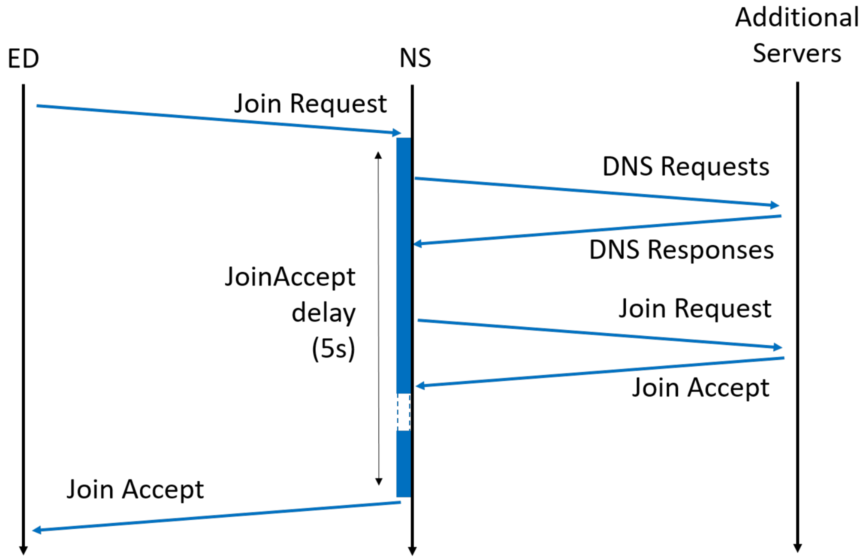
🟥→ Unencrypted

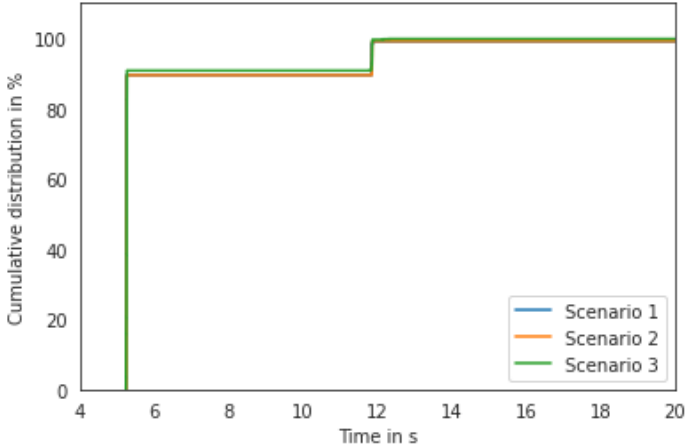
↔ Encrypted communication based on generated session keys

— · → Unencrypted communication. Origin and integrity of the received data can be verified thanks to DNSSEC

- - → Encrypted communication thanks to PKI based on self-signed certificates

Introduced latency ?





- **1. No Roaming**
- **2. Passive Roaming**
- **3. Passive Roaming with additionnal encryption**

Contributions

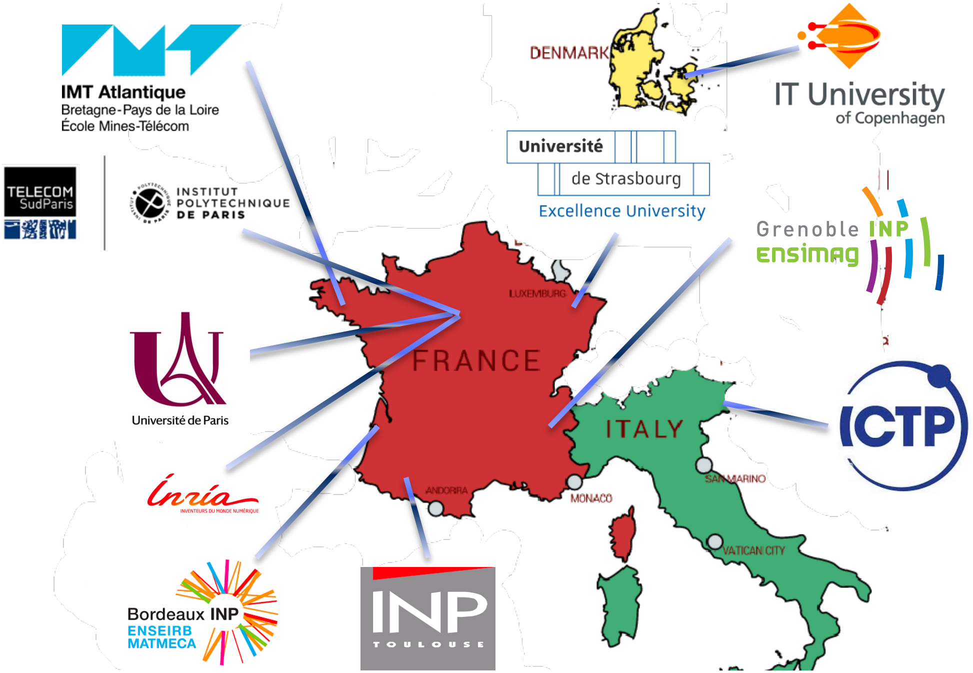
- **Test infrastructure of LoRaWAN using DNS**
- **Build and validate the IoTRoam infrastructure**
- **LoRaWAN specification contribution**
- **Contribute to the opensource LoRaWAN stack**
- **Operational, running and open infrastructure**

References :
https://lora-alliance.org/resource_hub/lorawan-back-end-interfaces-v1-0/
https://github.com/brocaar/chirpstack-network-server/releases/tag/v3.11.0
https://github.com/AFNIC/IoTRoam-Tutorial/

Further work

- **Explore dual connectivity**
- **Enhance with new DNS standards:**
    - DNSSEC
    - DANE
- **Develop the IoTRoam network**

Building a roaming federation



Improving device mobility

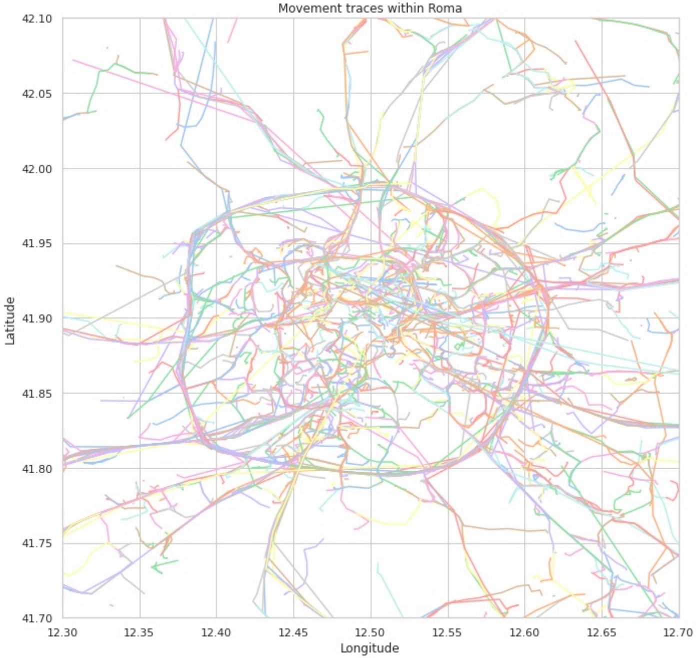
Prefetching IoT information onto antennas using DNS

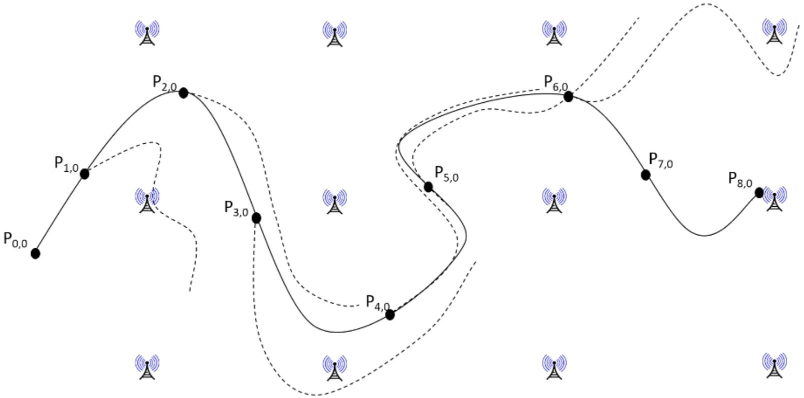
Proposal

- **Extend uses from the web**
- **Exploit vehicle traffic prediction to realize the prefetching operation**
- **Prefetch using DNS for its high availability**

References :
Driving path stability in VANETs, Laroui et al., 2018
https://www.chromium.org/developers/design-documents/dns-prefetching

Methodology - Traces

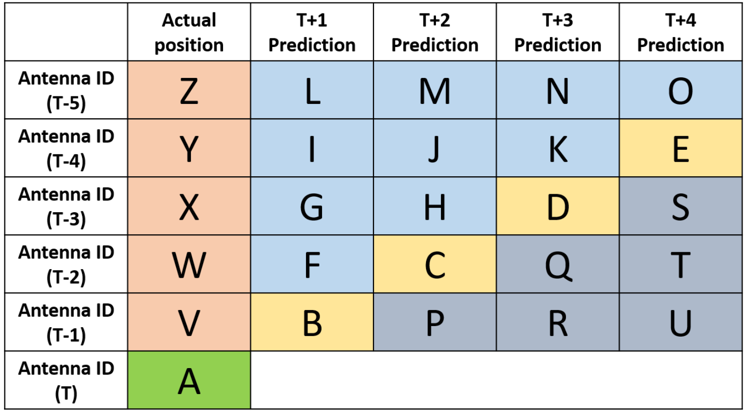




Methodology – Scenarii

3 scenarii

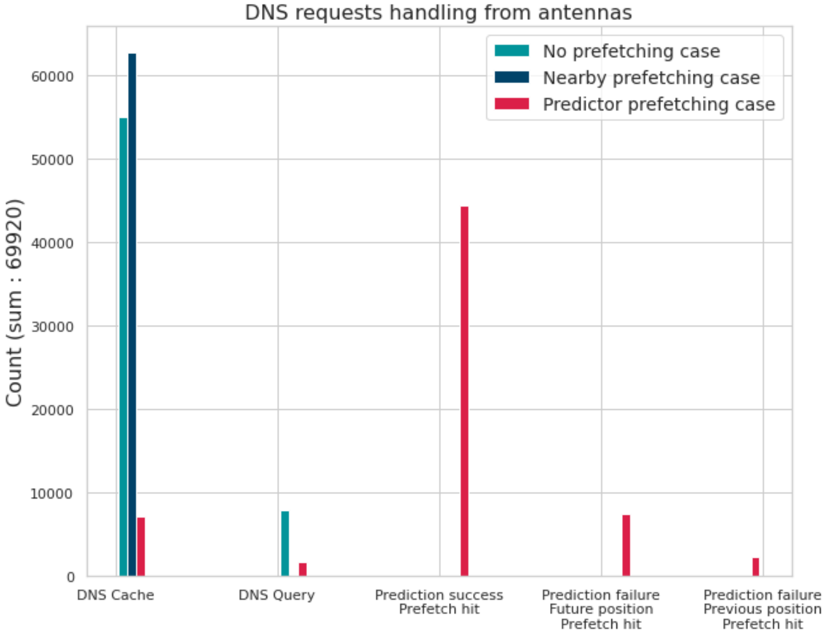
- No DNS Prefetching
- DNS prefetching on nearby gateway
- DNS prefetching using ML predictor



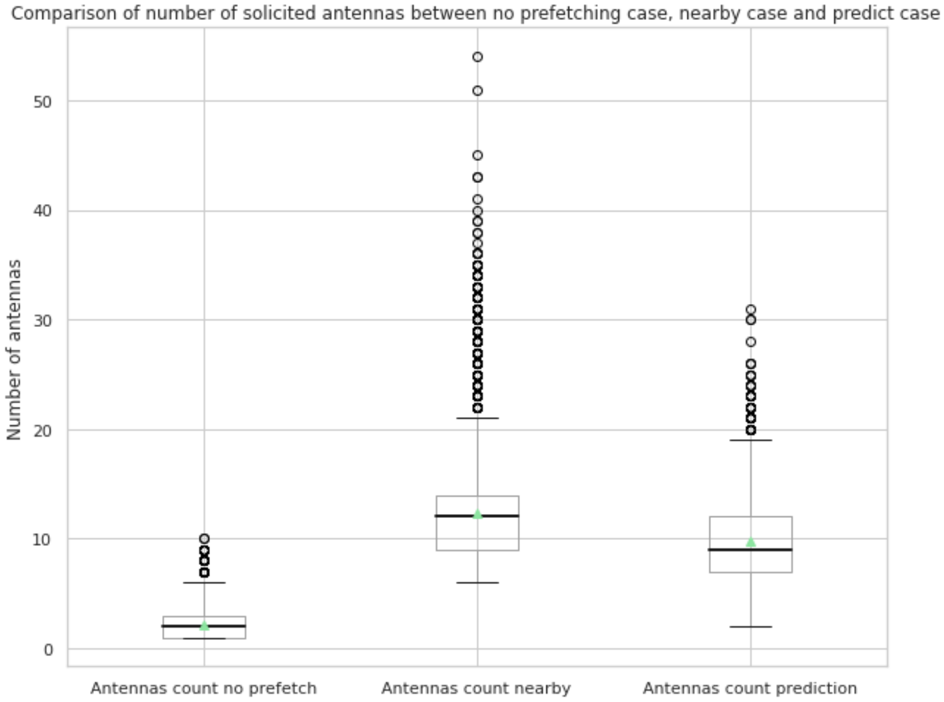
	Actual position	T+1 Prediction	T+2 Prediction	T+3 Prediction	T+4 Prediction
Antenna ID (T-5)	Z	L	M	N	O
Antenna ID (T-4)	Y	I	J	K	E
Antenna ID (T-3)	X	G	H	D	S
Antenna ID (T-2)	W	F	C	Q	T
Antenna ID (T-1)	V	B	P	R	U
Antenna ID (T)	A				

Results

- 80% On-the-fly DNS query reduction
- Over 60% exact antenna prediction success
- Over 80% prefetched cache hit
- Can save up to a second, around 20% of the time allocated in a join procedure



Results



- **18% less antenas between scenari 2 and 3**

- **Additional study on outliers might be of interest**

Contributions

- Overall system specification
- Prefetching mechanism simulations based on traffic predictor
- Caching heating scenario study
- Antennas solicitation breakdown

Further work

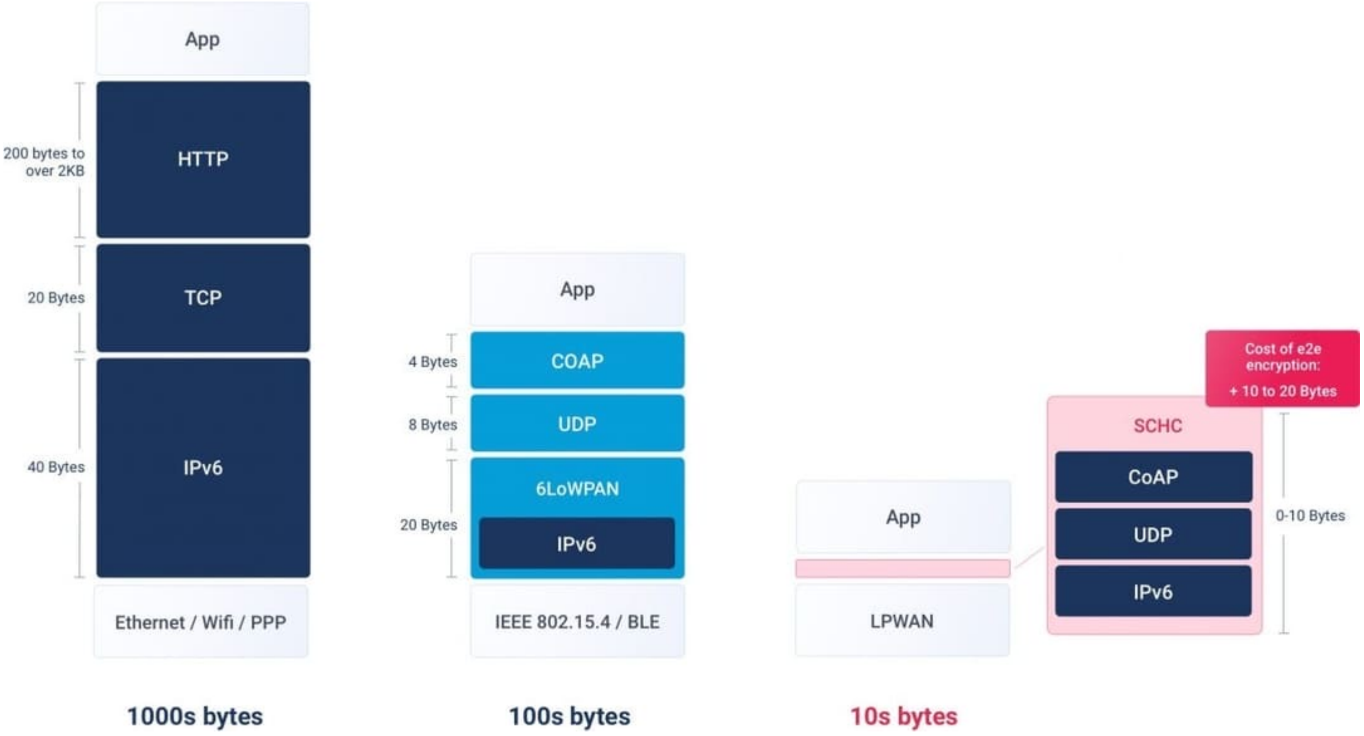
- Enhance with other traces
- Study other antennas placements
- Predictor quality impact
- More specific division between road topologies
- Impact from traffic density estimations

Internet made in France

Solve performance challenges

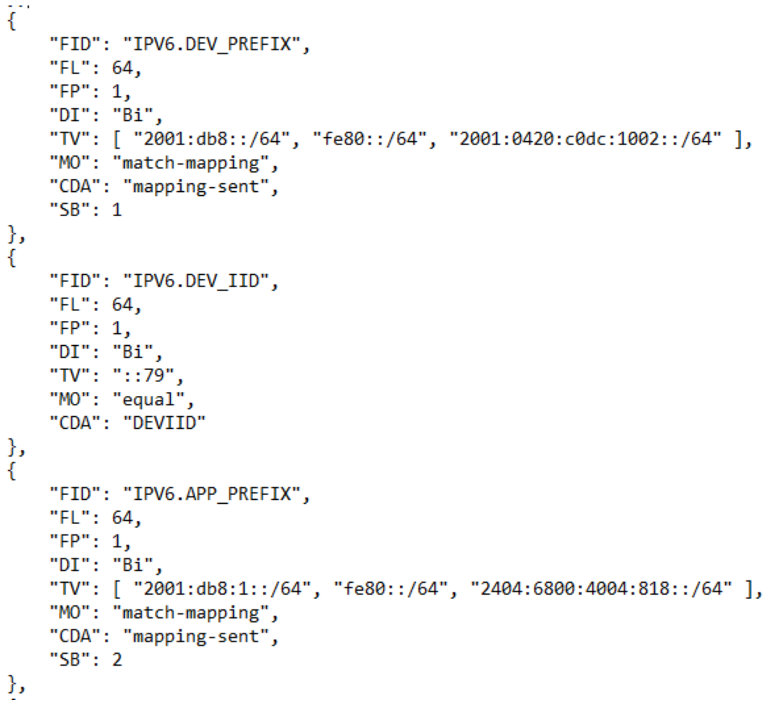
Compressing Headers

Why compress headers ?



Source : https://www.ackl.io/technology/schc

SCHC rule example - extract



```
...
{
    "FID": "IPV6.DEV_PREFIX",
    "FL": 64,
    "FP": 1,
    "DI": "Bi",
    "TV": [ "2001:db8::/64", "fe80::/64", "2001:0420:c0dc:1002::/64" ],
    "MO": "match-mapping",
    "CDA": "mapping-sent",
    "SB": 1
},
{
    "FID": "IPV6.DEV_IID",
    "FL": 64,
    "FP": 1,
    "DI": "Bi",
    "TV": "::79",
    "MO": "equal",
    "CDA": "DEVIID"
},
{
    "FID": "IPV6.APP_PREFIX",
    "FL": 64,
    "FP": 1,
    "DI": "Bi",
    "TV": [ "2001:db8:1::/64", "fe80::/64", "2404:6800:4004:818::/64" ],
    "MO": "match-mapping",
    "CDA": "mapping-sent",
    "SB": 2
},
```

Source : https://github.com/openschc/openschc

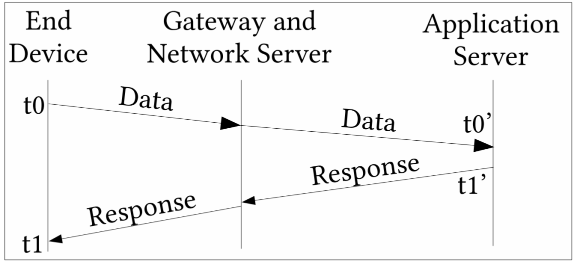
Storing compression parameters

- **Sharing compression rules**
- **Various scenarios studied**
- **Measurements**
  - Decompression Time
  - System latency

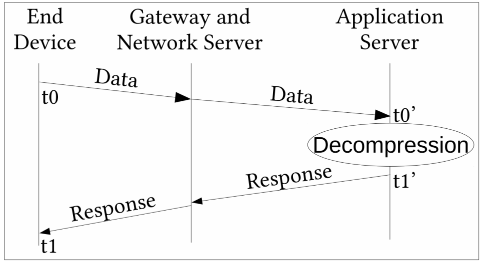
Our proposal

- Weight constraints would not allow for efficient full rule storage
- Store a signature information within the DNS
- Mutualize rules when signatures are identical
- Fallback onto a web API to get actual rules

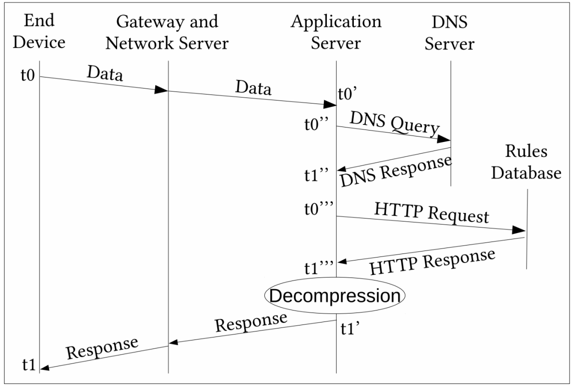
Exchanges experiments



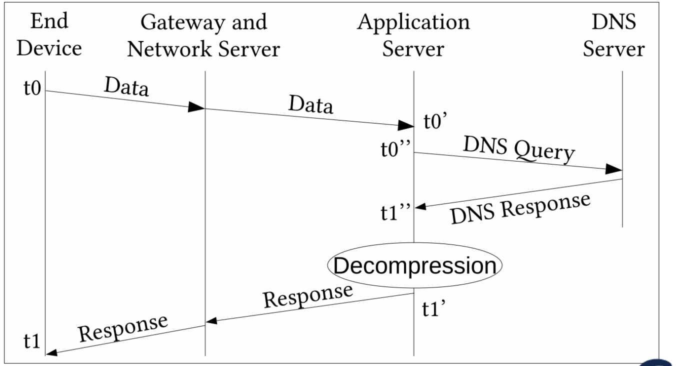
1st Experiment



2nd Experiment

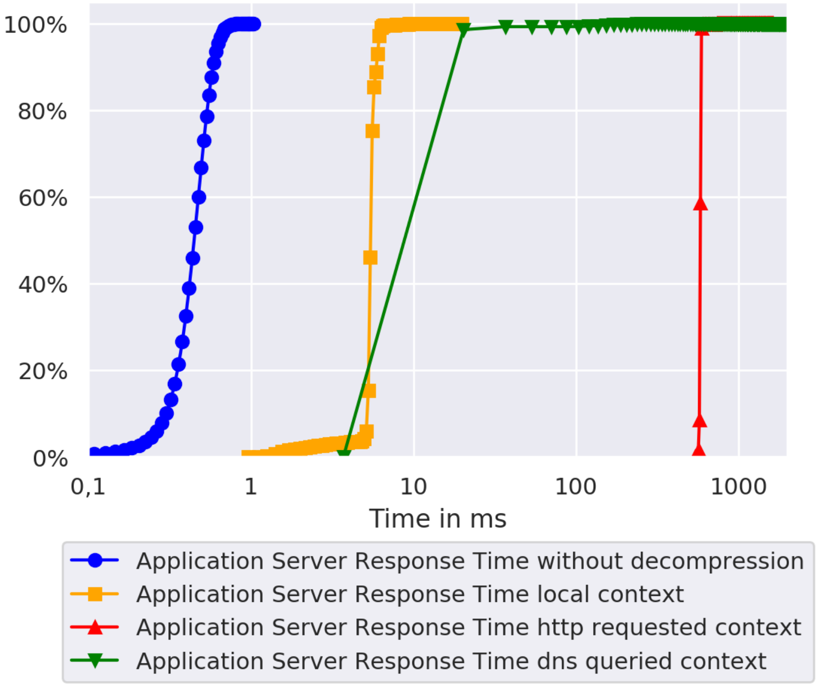


3rd Experiment



4th Experiment

Our results – Decompression Time

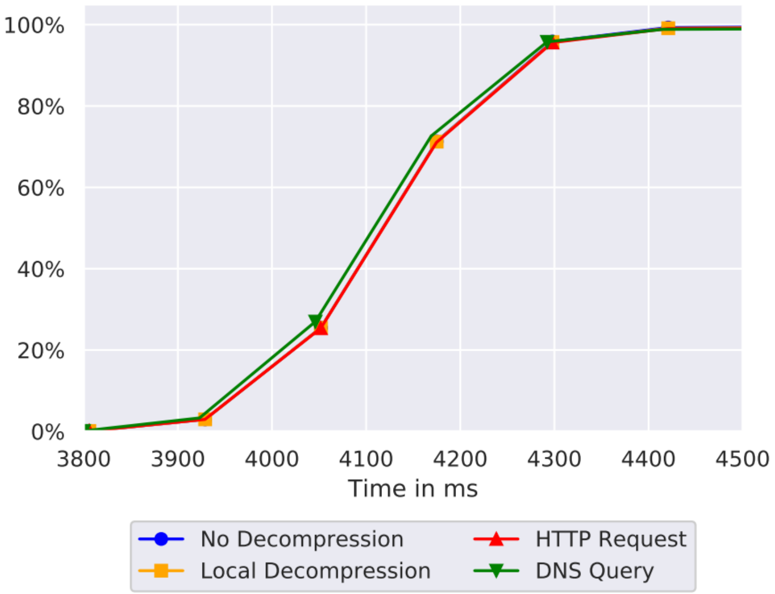


- **Adding SCHC increase packet processing time up to 8ms**
- **Using DNS to query the context would take up to 30ms**
- **HTTP requests are much slower (around 550ms)**

Our results – Global Round Trip Time

- **No incidence on the communication as the limiting factor is the reception window.**

- **All responses are received within the same reception window on the device.**



Contribution

- SCHC decompression measurement delays
- DNS use for rules querying
- Impact from DNS querying using Atlas probes

Ideas for further work

- **Data Model for Static Context Header Compression**
  - Full rule storage within the DNS ?

- **Discuss our work with the SCHC community at the IETF**

References : https://datatracker.ietf.org/doc/html/draft-ietf-lpwan-schc-yang-data-model-05

Solve performance challenges

Compressing application payload

Minimizing traffic

Minimize network traffic from LPWAN sensors

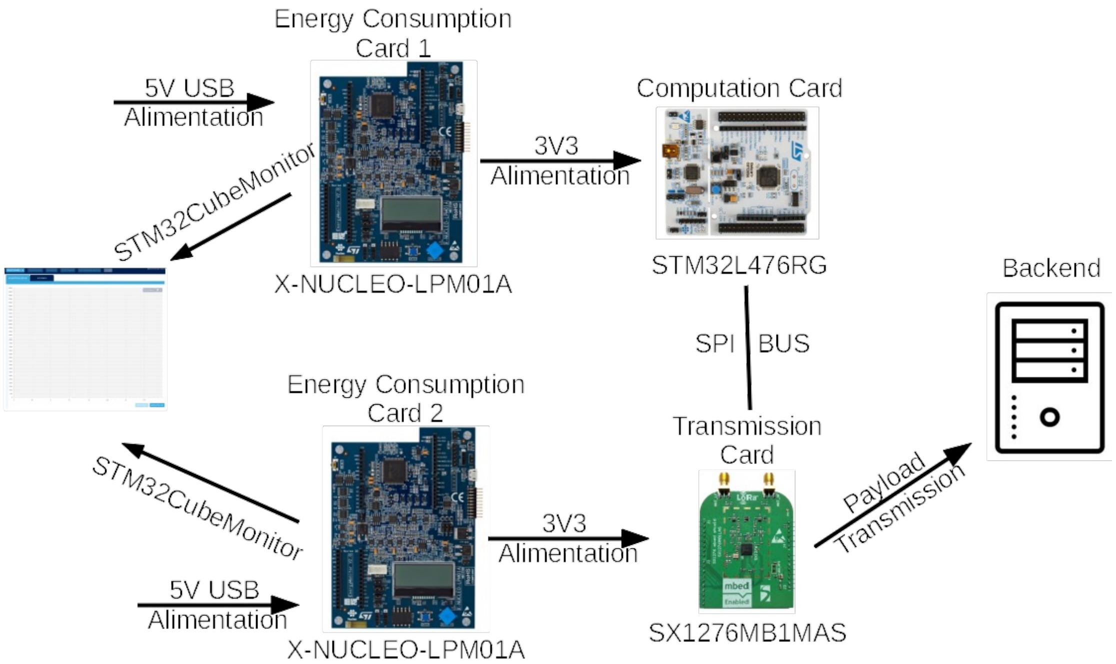
- Scarce resources
- Increase energy efficiency, save battery
- Sensors generate time-correlated data
- Exploit ML techniques to predict this data

Références

Experimentations

- Tests with various technologies
- Unsupported operations
- Discussions with the TensorFlow Lite community
- Handmade implementation to support the algorithm

Experimental setup



Energy Consumption Card 1

5V USB Alimentation

X-NUCLEO-LPM01A

STM32CubeMonitor

3V3 Alimentation

Computation Card

STM32L476RG

SPI BUS

Energy Consumption Card 2

STM32CubeMonitor

5V USB Alimentation

X-NUCLEO-LPM01A

3V3 Alimentation

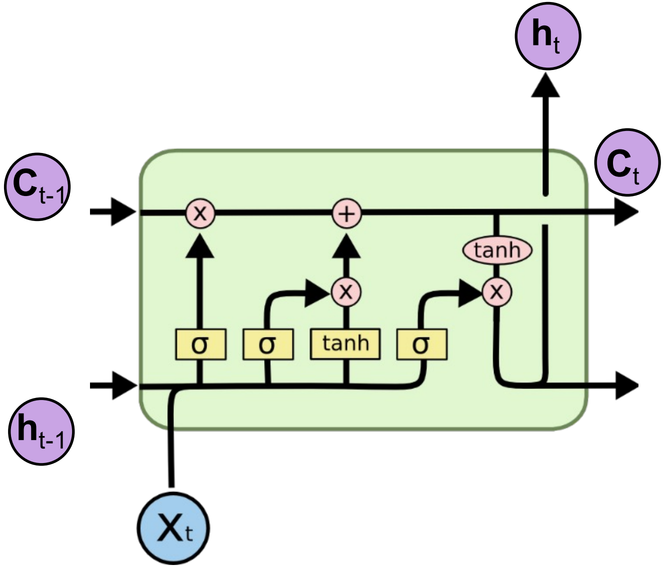
Transmission Card

SX1276MB1MAS

Payload Transmission

Backend

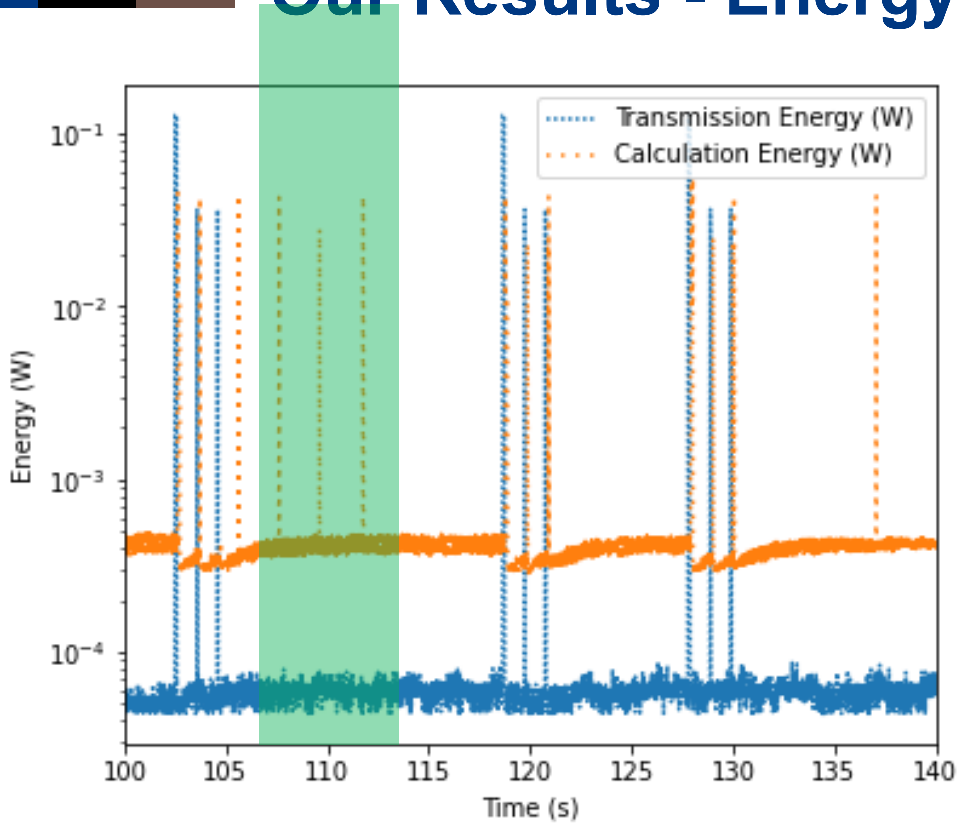
LSTMs and our uses



- **LSTM are tools that can correlate Long Term dependancies with Short Term information**
- **Used in our work to obtain rough time-serie estimation**

Source : Christopher Olah, Understanding LSTM Networks, **2015**
https://colah.github.io/posts/2015-08-Understanding-LSTMs/

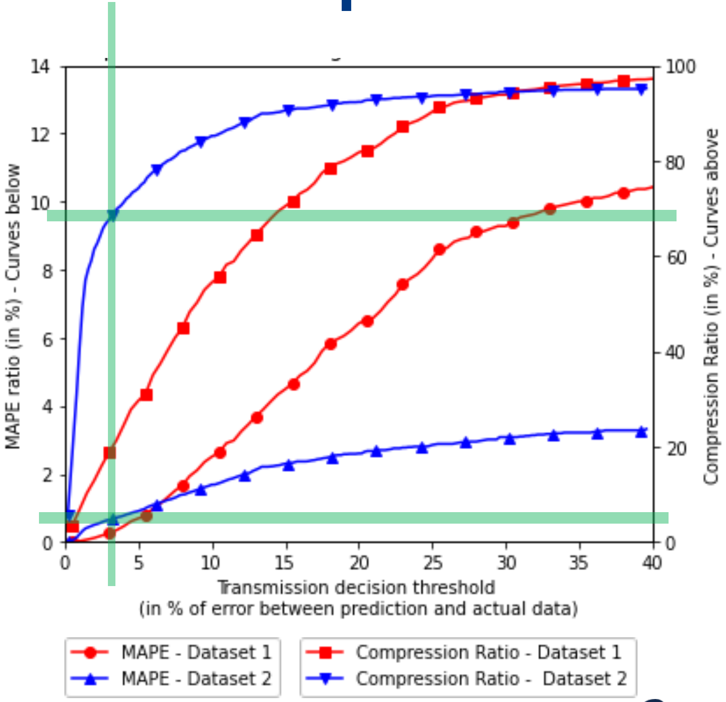
Our Results - Energy



- **Two states**
- **Less activity spikes on the transmission card**
- **Transmission prevented in the green area**
- **Energy savings**

Our Results – Compression capabilities

- Experimenting with various transmission threshold
- Measuring MAPE & Compression ratio
- Two datasets studied



Results

- Reduction in energy consumed
- Efficient overall with sufficient training data
- No significance from the number of cells in neural network
- Quantification is efficient and does not hinder the predictor
- Embedding these algorithms by hand is feasible

Key contributions

- Implementation of LSTM compatible with MBED OS
- Energy measurements
- Experimental proof of ML compression schemes applied to networks

Conclusions and Further work

Conclusions

- **Do not underestimate DNS**
  - Efficient
  - Reliable
  - Secure
- **Roaming is possible within a federated architecture**
- **DNS can store protocol parameters**
- **DNS Prefetching works with predictors**
- **Complex Machine Learning algorithms can be implemented on sensors**

Main contributions

- Tests around roaming for LoRaWAN network including a proposition for IoT Roaming Federation
- Design and performance study of a DNS prefetching scheme based on vehicular traffic prediction
- Design and performance evaluation of a traffic minization scheme based on a sensed data predictor.
- Tests and validation of DNS use for SCHC rules resolution
- LSTM implementation on MBED device and rules sharing

Communications

- Antoine BERNARD, “La découverte de service à l’aide du DNS”, JCSA 2019
- Antoine BERNARD, “LoRaWAN Experimentations”, Doctoral student day @ Telecom SudParis 2019
- Antoine BERNARD, “LPWANs tools to scale up IoT solutions from Smart Buildings to Smart Cities”, E4C Summer school: From smart buildings to smart cities, July 2021
- Antoine BERNARD, “Embedding ML Algorithms onto LoRaWAN Sensors”, LoRa Alliance Academic WG, Oct 2021

International conferences

- Antoine Bernard, Sandoche Balakrichenan, Michel Marot, and Benoit Ampeau, « DNS-based dynamic context resolution for SCHC », IEEE ICC 2020
- Antoine Bernard, Aicha Dridi, Michel Marot, Hossam Afifi, and Sandoche Balakrichenan, « Embedding ML Algorithms onto LPWAN Sensors for Compressed Communications », IEEE PIMRC 2021
- Sandoche Balakrichenan, Antoine Bernard, Michel Marot, and Benoît Ampeau, « IoTRoam – Design and implementation of an openLoRaWAN roaming architecture », IEEE Globecom 2021
- Antoine Bernard, Mohammed Laroui, Michel Marot, Sandoche Balakrichenan, Hassine Moungla, Benoit Ampeau, Hossam Afifi and Monique Becker, « Prefetching of mobile devices information - a DNS perspective », IEEE ICC 2022 (Submitted)

Possible further work based on this thesis

Expand work on DNS storage [1]

Experiment further on LSTM for MBED device, expanding the work on number of layers and quantification

.

References : https://datatracker.ietf.org/doc/html/draft-ietf-lpwan-schc-yang-data-model-05

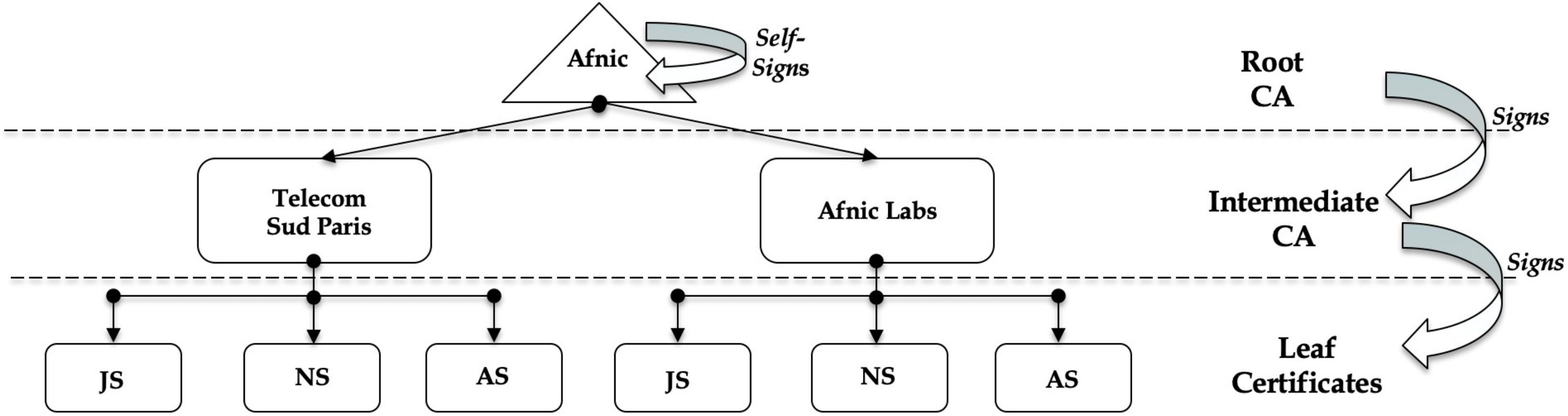
Questions ?

Thanks for your attention

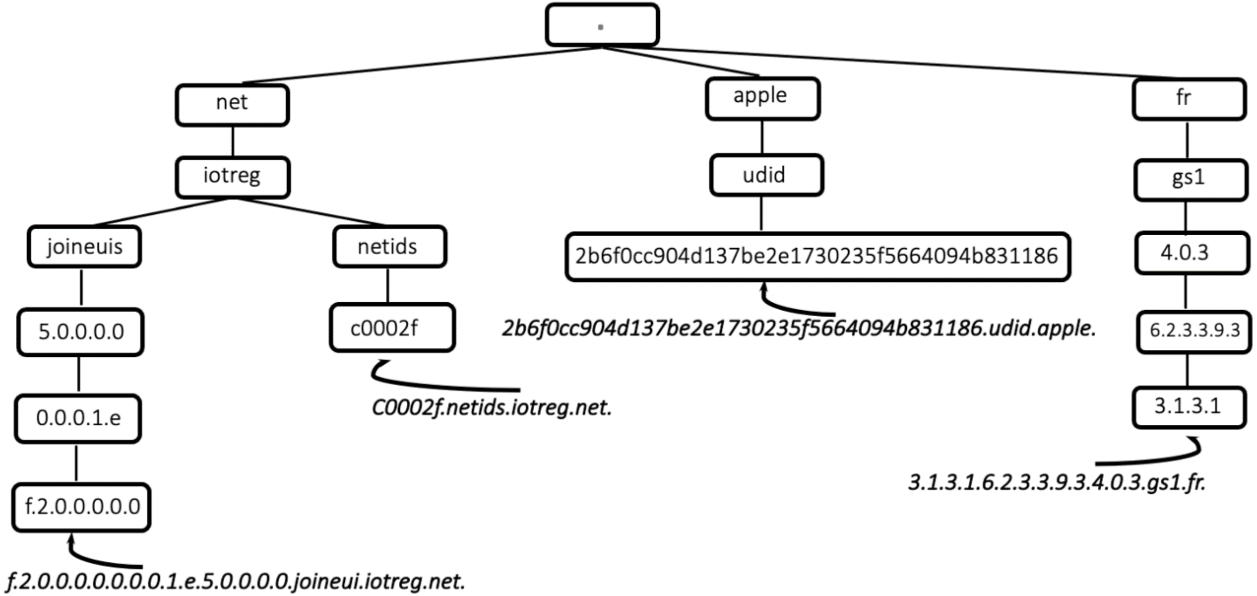
If you need to contact me after this presentation :
thesis@a-bernard.fr
these@a-bernard.fr

Annexes

Certificate signing policy



Identifier provisionning through DNS



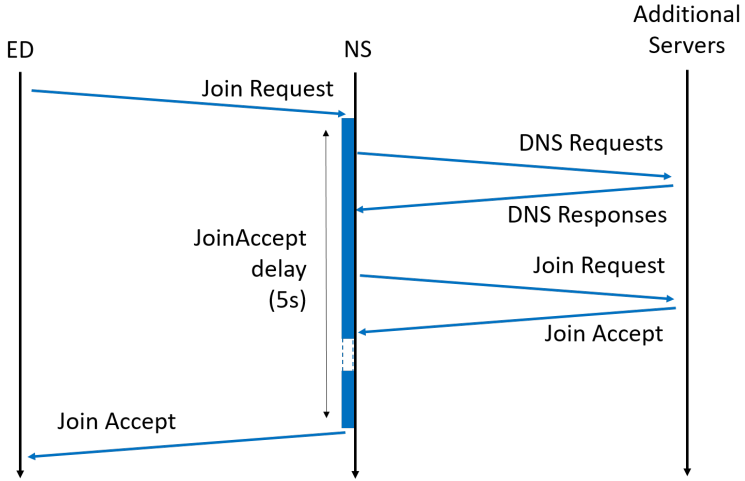
2b6f0cc904d137be2e1730235f5664094b831186.udid.apple.

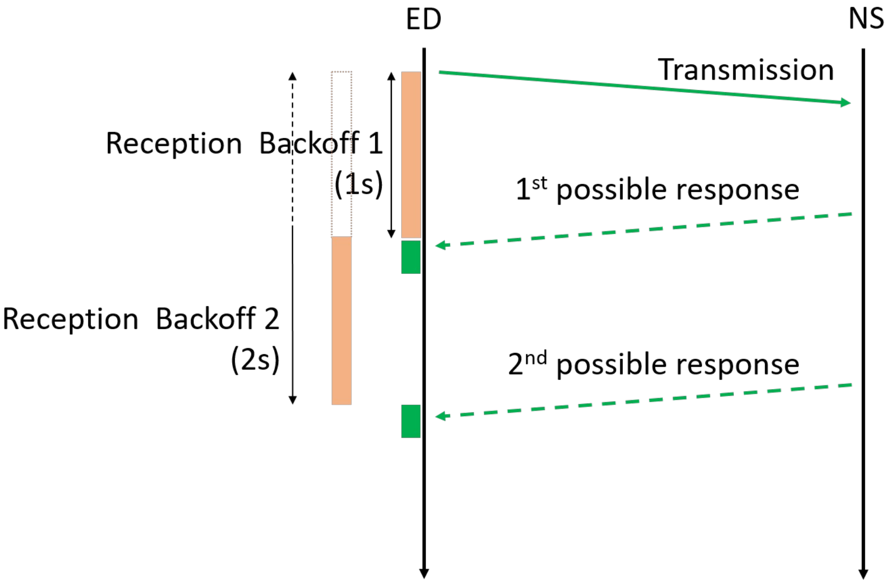
C0002f.netids.iotreg.net.

3.1.3.1.6.2.3.3.9.3.4.0.3.gs1.fr.

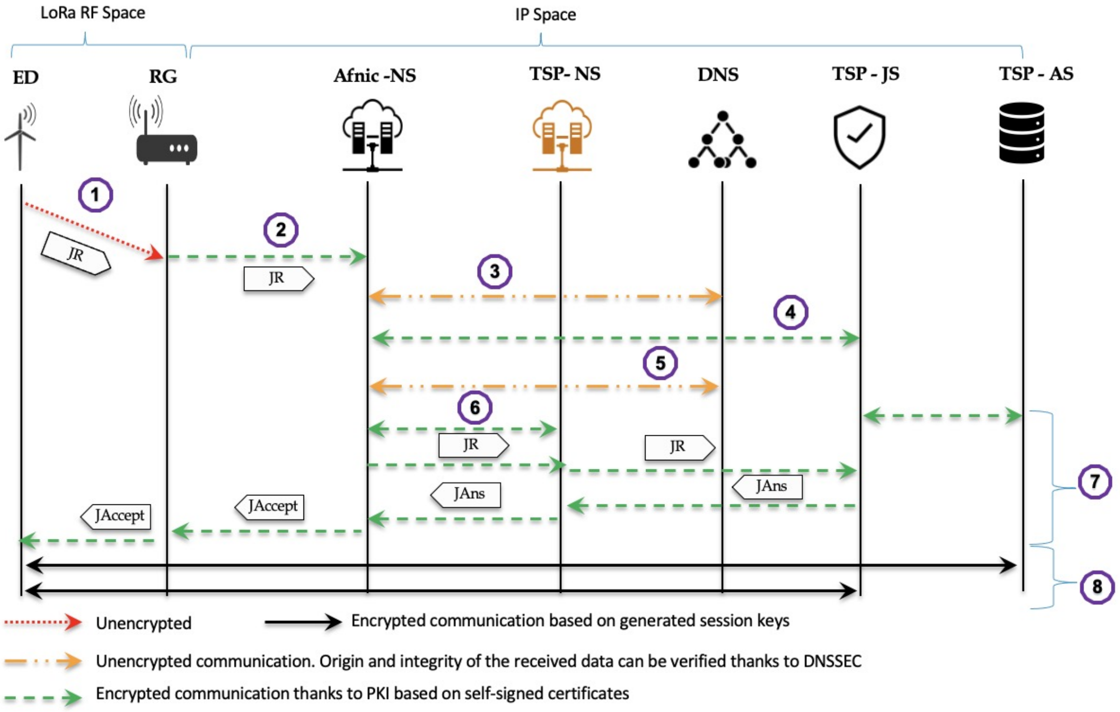
f.2.0.0.0.0.0.0.0.1.e.5.0.0.0.0.joineui.iotreg.net.

IoTRoam OTAA & Uplink delays

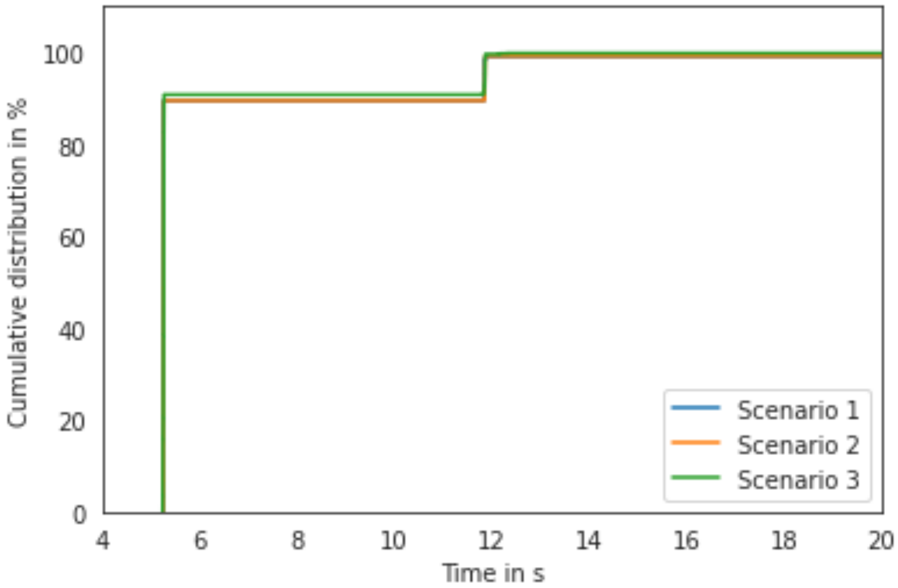




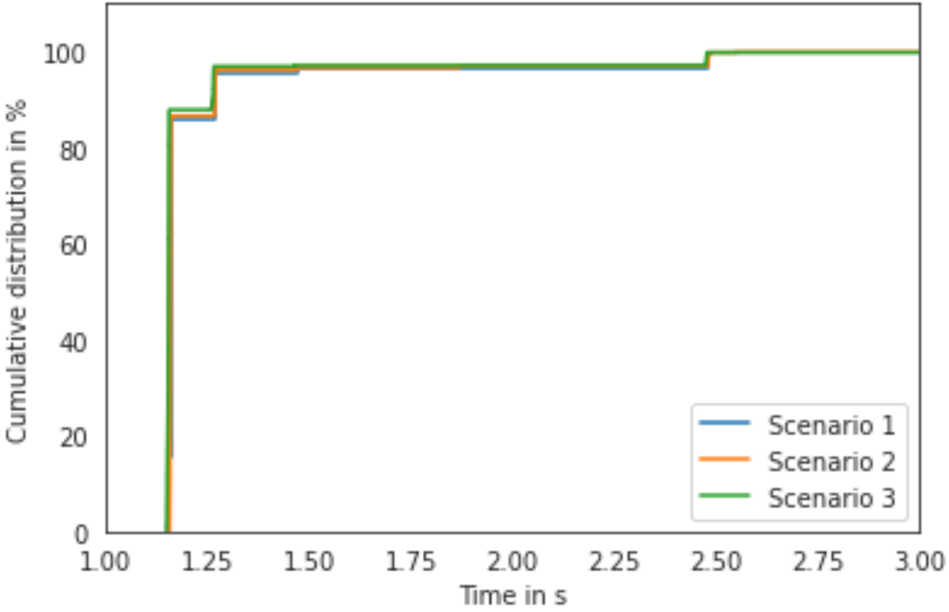
Roaming message flow



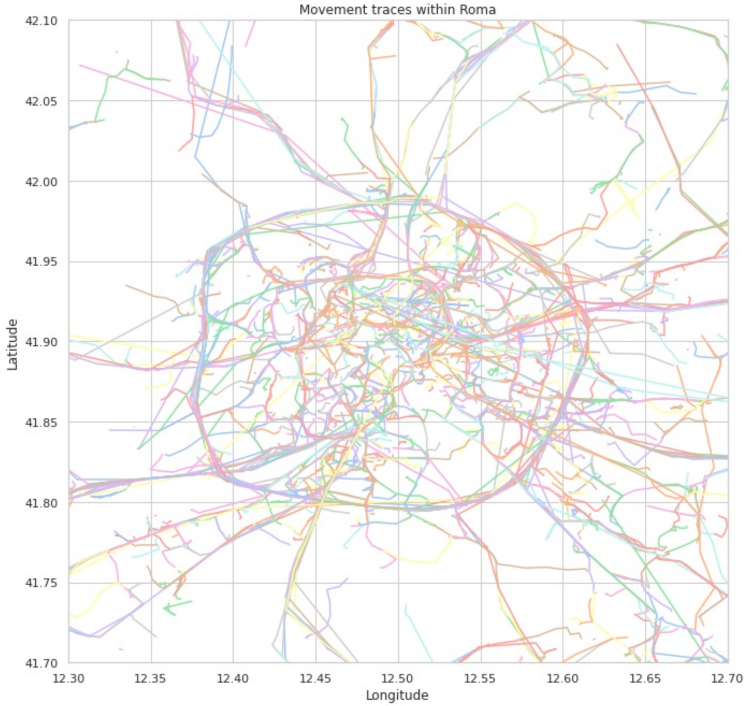
Activation time repartition



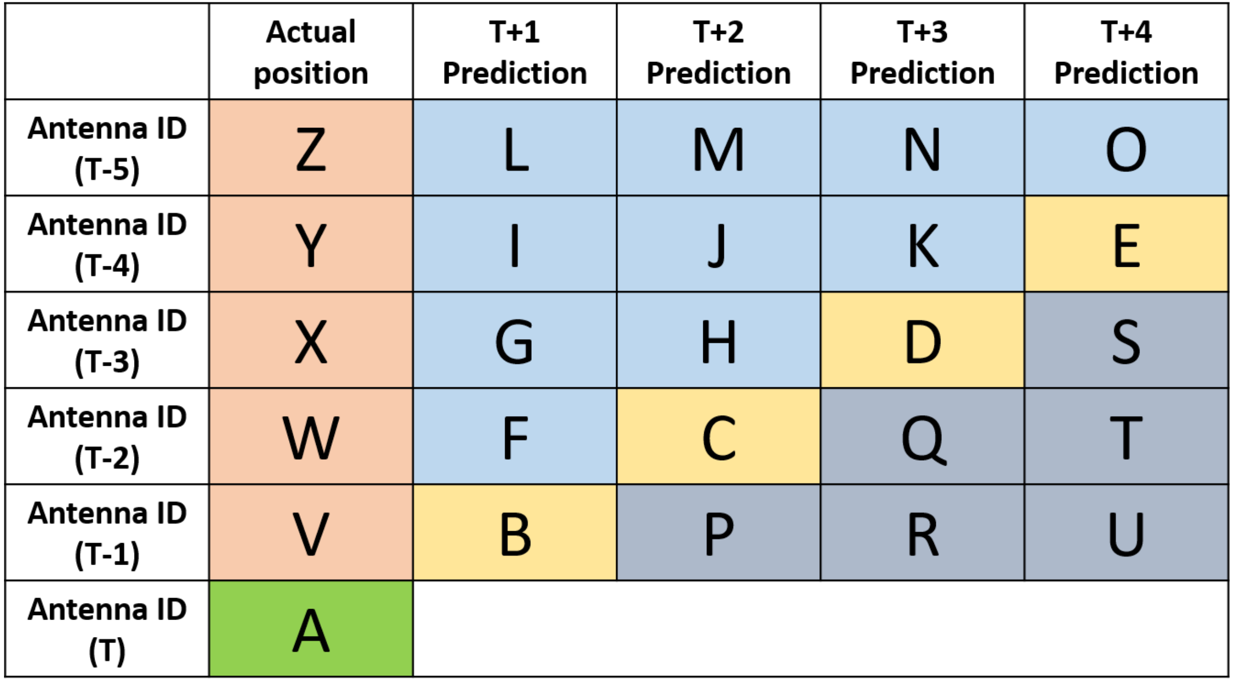
First uplink - Ack repartition



Movement traces

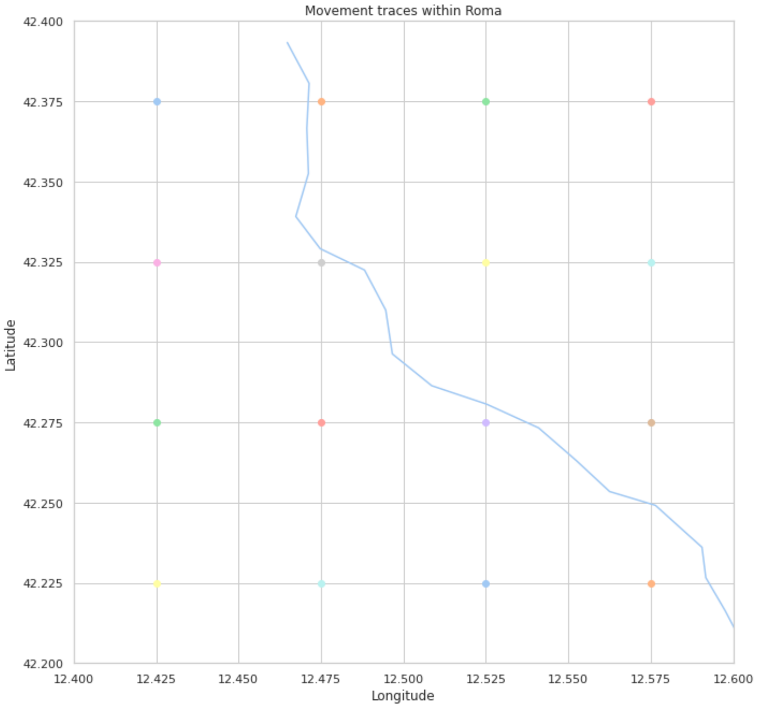


Cache disposition based on predictor

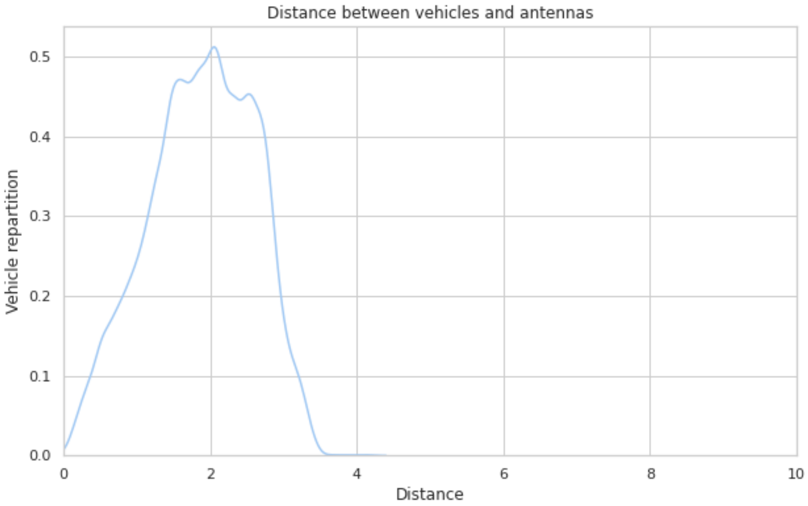


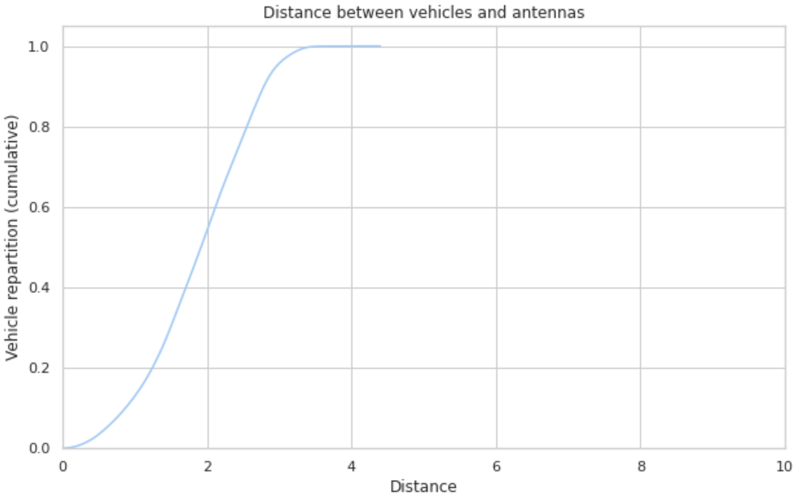
	Actual position	T+1 Prediction	T+2 Prediction	T+3 Prediction	T+4 Prediction
Antenna ID (T-5)	Z	L	M	N	O
Antenna ID (T-4)	Y	I	J	K	E
Antenna ID (T-3)	X	G	H	D	S
Antenna ID (T-2)	W	F	C	Q	T
Antenna ID (T-1)	V	B	P	R	U
Antenna ID (T)	A				

Movement trace and antennas

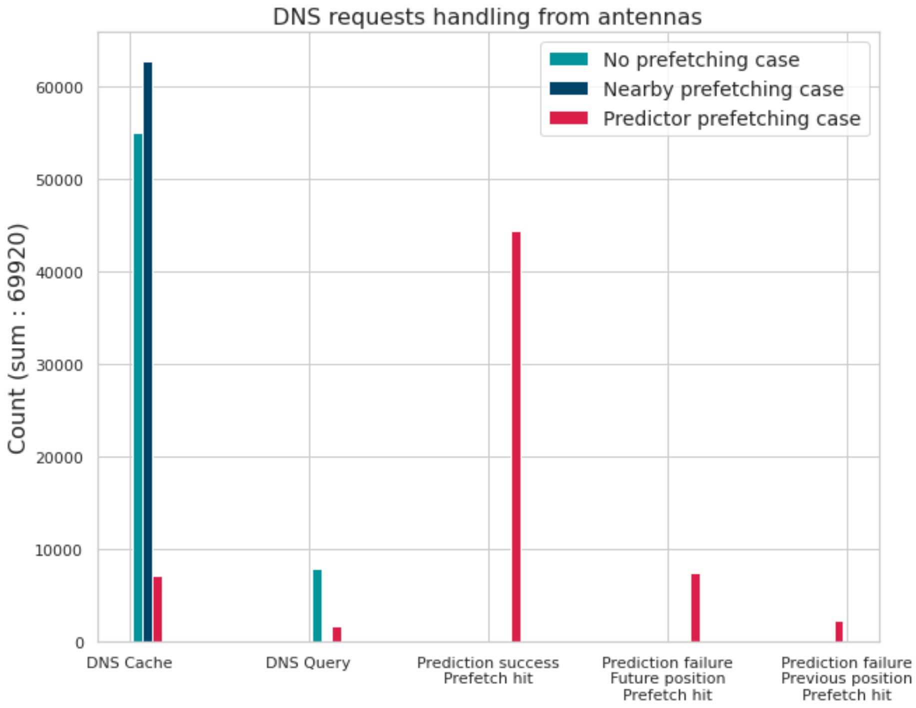


Antenna-vehicule distance

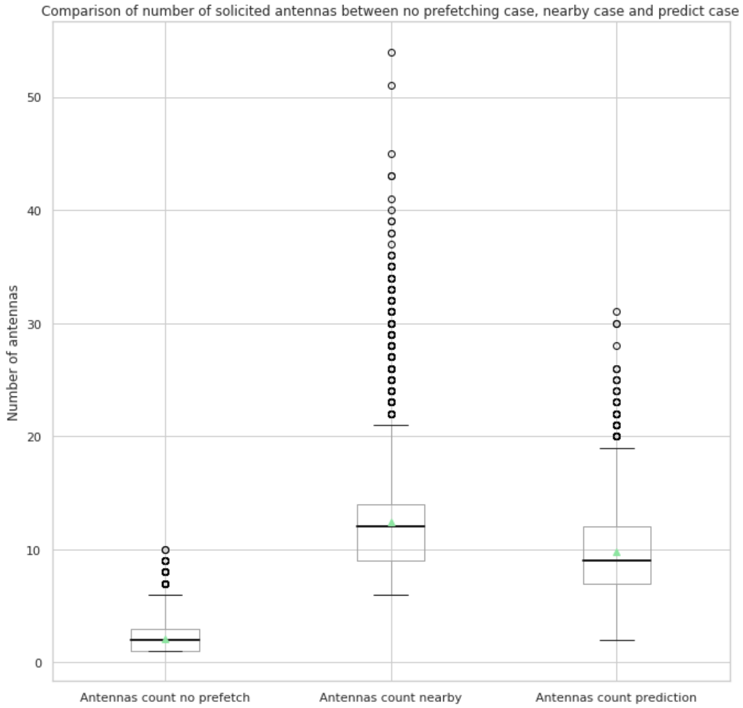




DNS Queries between scenarios

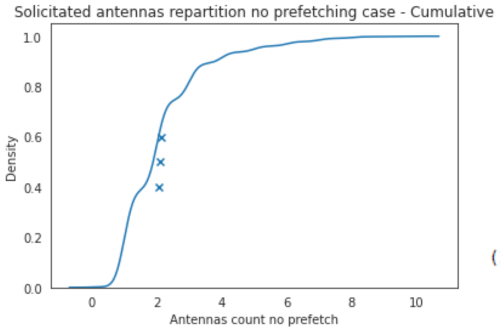


Number of antennas solicited



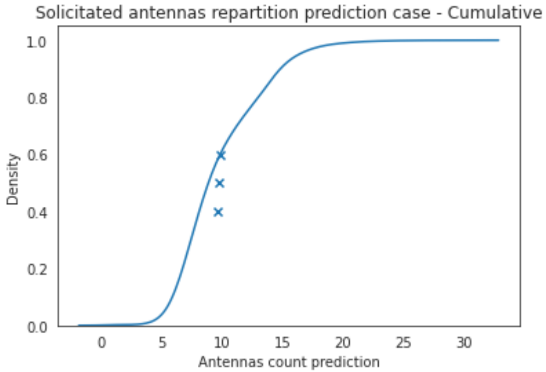
Antennas solicitation

```
(2.0738689084017174, 2.1058789954337898, 2.137889082465862)
```



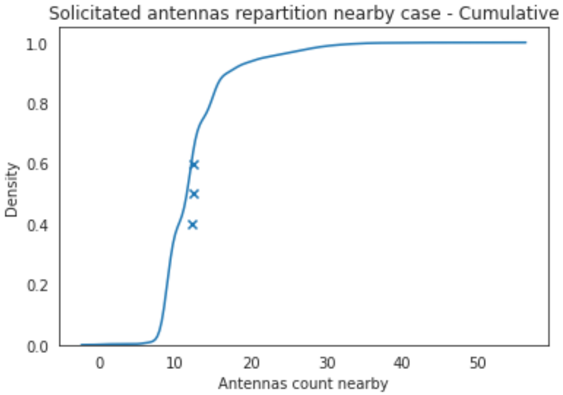
Solicitated antennas repartition no prefetching case - Cumulative

```
(9.6714542796611, 9.754994292237443, 9.838534304813786)
```



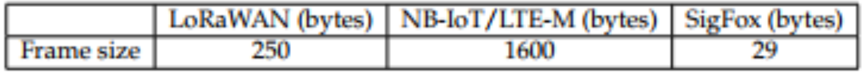
Solicitated antennas repartition prediction case - Cumulative

```
(12.259453278600654, 12.367294520547945, 12.475135762495237)
```



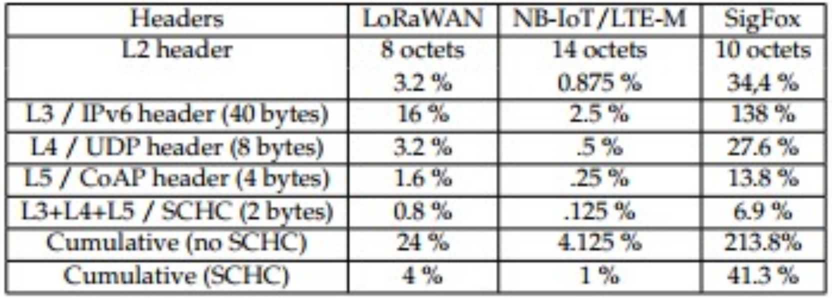
Solicitated antennas repartition nearby case - Cumulative

Frame size LPWANs



	LoRaWAN (bytes)	NB-IoT/LTE-M (bytes)	SigFox (bytes)
Frame size	250	1600	29

TABLE 4.1: Max Frame size from the main LPWANs technologies



Headers	LoRaWAN	NB-IoT/LTE-M	SigFox
L2 header	8 octets 3.2 %	14 octets 0.875 %	10 octets 34,4 %
L3 / IPv6 header (40 bytes)	16 %	2.5 %	138 %
L4 / UDP header (8 bytes)	3.2 %	.5 %	27.6 %
L5 / CoAP header (4 bytes)	1.6 %	.25 %	13.8 %
L3+L4+L5 / SCHC (2 bytes)	0.8 %	.125 %	6.9 %
Cumulative (no SCHC)	24 %	4.125 %	213.8%
Cumulative (SCHC)	4 %	1 %	41.3 %

TABLE 4.2: Frame Header Occupationas percentage of frame size for the main LPWANs technologies

Explaining SCHC

SCHC rule example

```
Rule 0
 +----------------+--+--+--+---------+--------+------------++------+
 | Field          |FL|FP|DI| Value   | Match  | Comp Decomp|| Sent |
 |                |  |  |  |         | Opera. | Action     ||[bits]|
 +----------------+--+--+--+---------+---------------------++------+
 |IPv6 Version    |4 |1 |Bi|6        | ignore | not-sent   ||      |
 |IPv6 DiffServ   |8 |1 |Bi|0        | equal  | not-sent   ||      |
 |IPv6 Flow Label |20|1 |Bi|0        | equal  | not-sent   ||      |
 |IPv6 Length     |16|1 |Bi|         | ignore | compute-*  ||      |
 |IPv6 Next Header|8 |1 |Bi|17       | equal  | not-sent   ||      |
 |IPv6 Hop Limit  |8 |1 |Bi|255      | ignore | not-sent   ||      |
 |IPv6 DevPrefix  |64|1 |Bi|FE80::/64| equal  | not-sent   ||      |
 |IPv6 DevIID     |64|1 |Bi|         | ignore | DevIID     ||      |
 |IPv6 AppPrefix  |64|1 |Bi|FE80::/64| equal  | not-sent   ||      |
 |IPv6 AppIID     |64|1 |Bi|::1      | equal  | not-sent   ||      |
 +================+==+==+==+=========+========+============++======+
```

SCHC measurement platform

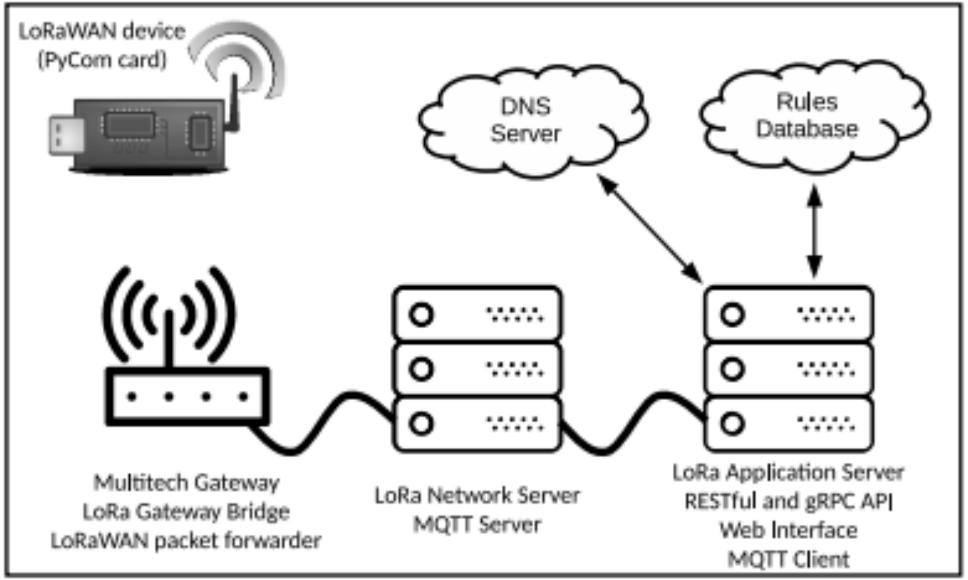
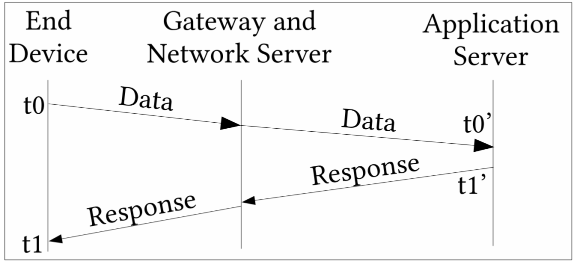
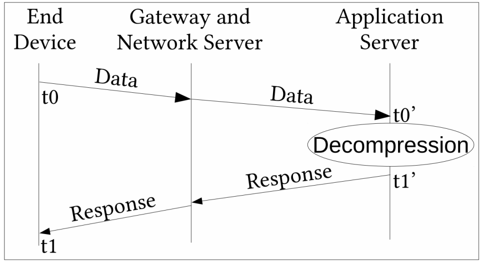


FIGURE 4.3: Measurement Platform's Network and system architecture (rework this scheme)

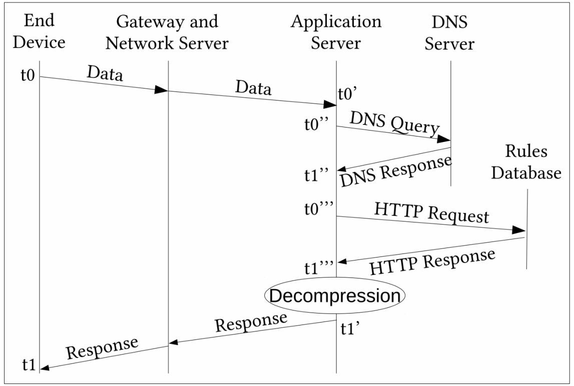
SCHC measurements scenarii



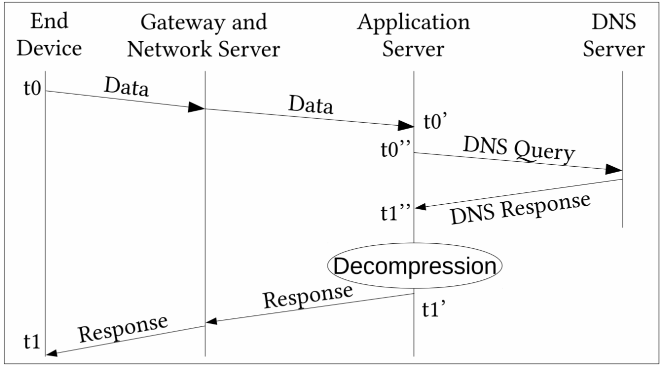
1st Experiment



2nd Experiment



3rd Experiment



4th Experiment

AS response time – decompression impact

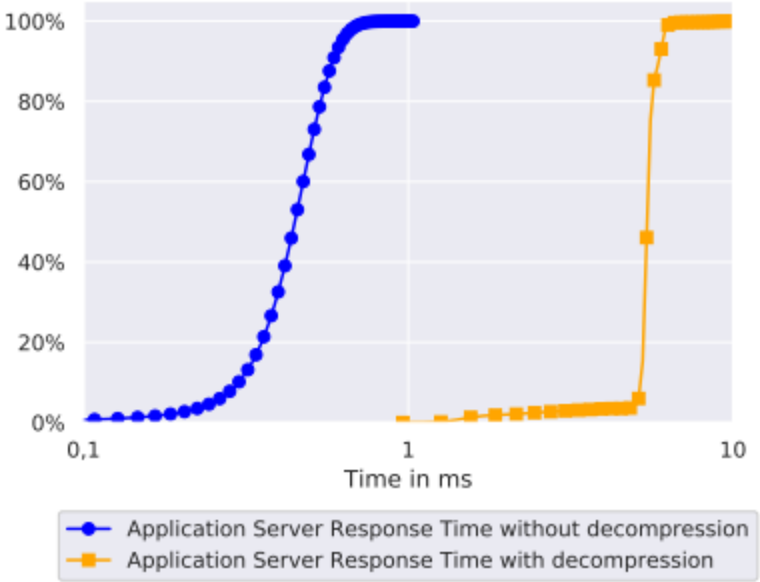


FIGURE 4.8: Cumulative distribution function of the AS Response Time $t1' - t0'$ (in %) against time in ms for Scenarios 1 and 2

AS response time – remote querying impact

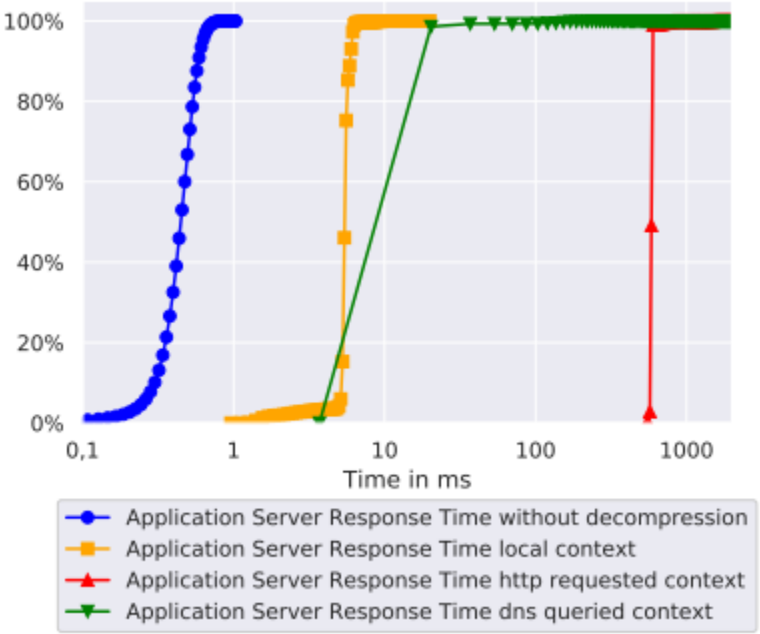


FIGURE 4.9: Cumulative distribution function of the AS Response Time $t1' - t0'$ (in %) against time in ms for all scenarios

DNS Response Time using Atlas probes

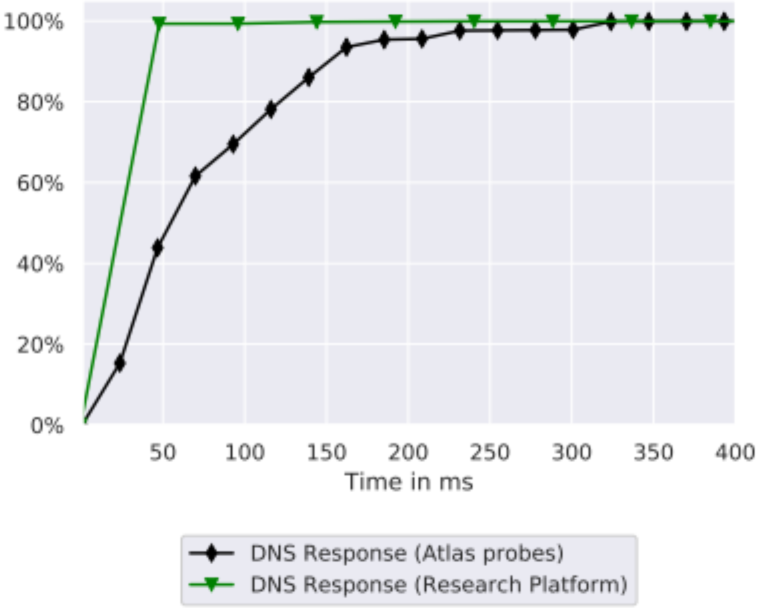


FIGURE 4.10: Cumulative distribution function of the DNS Response Time $t1'' - t0''$ (in %) against time in ms for Scenario 3 compared and from RIPE Atlas [327] Measurements

Global RTT

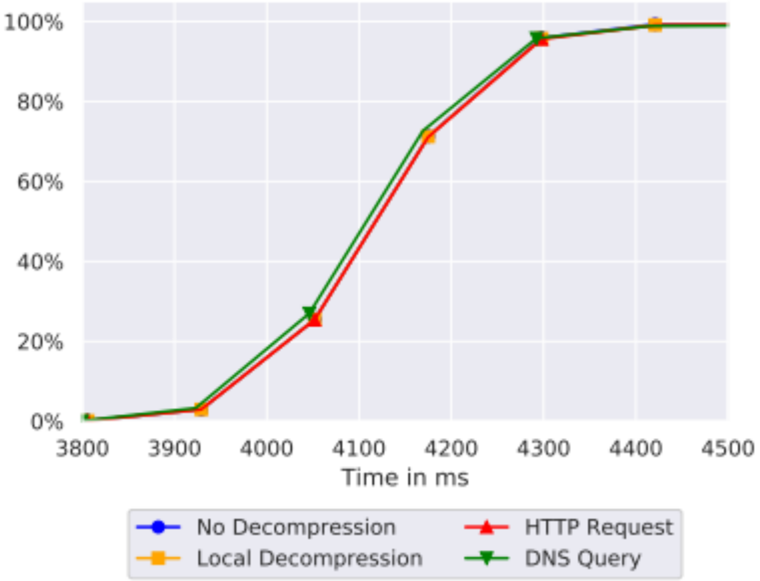
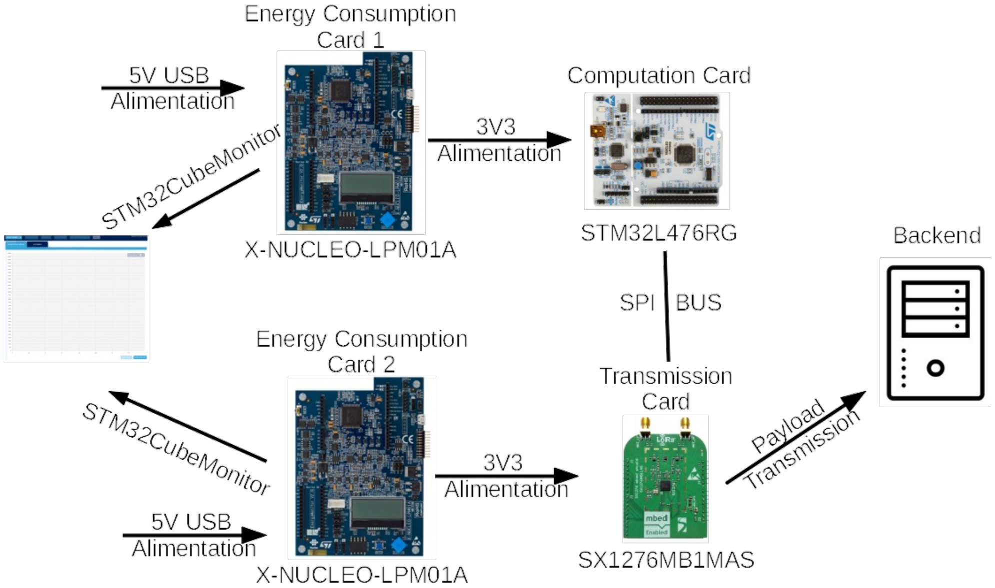
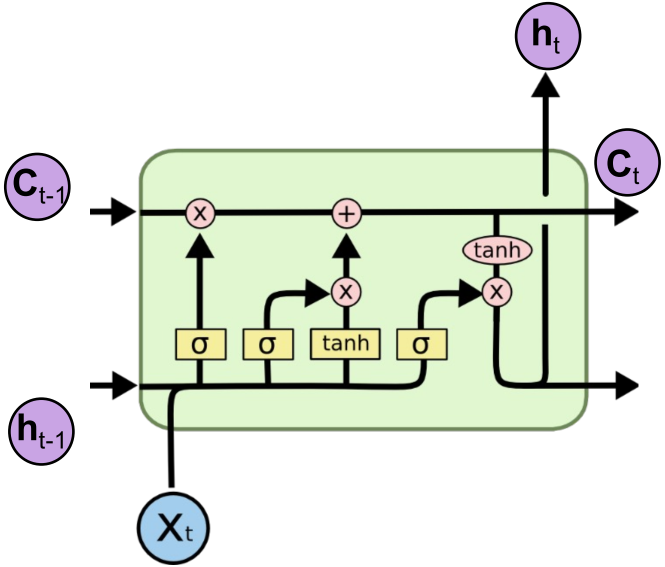


FIGURE 4.11: Cumulative distribution function of the RTT $t1 - t0$ (in %) against time in ms for all scenarios (all the curves are the superposed)

ML Energy Measurements platform



LSTM



forget gate : $f_t = \sigma\left(W_f \,.\, [h_{t-1}, x_t] + b_f\right)$

input gate : $i_t = \sigma(W_i \,.\, [h_{t-1}, x_t] + b_i)$

candidate value: $\tilde{C}_t = tanh(W_C \,.\, [h_{t-1}, x_t] + b_C)$

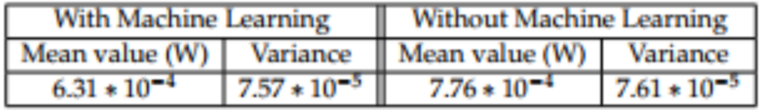
new cell state: $C_t = f_t * C_{t-1} + i_t * \tilde{C}_t$

output: $h_t = \sigma(W_o \,.\, [h_{t-1}, x_t] + b_o) * \ tanh(C_t)$

Christopher Olah, Understanding LSTM Networks, **2015**
https://colah.github.io/posts/2015-08-Understanding-LSTMs/

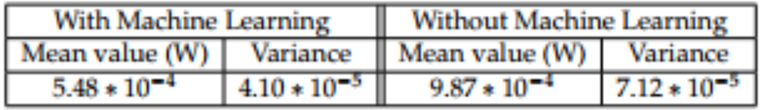
Energy consumption

TABLE 5.1: Comparison of the mean energy consumption of the calculation card and its variance, with and without LSTM-based compression (in Watts)



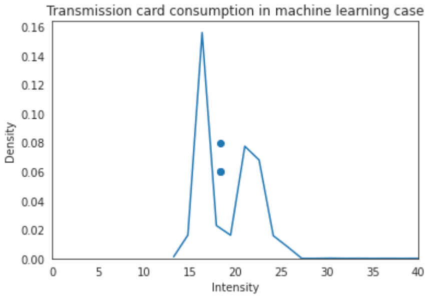
With Machine Learning		Without Machine Learning	
Mean value (W)	Variance	Mean value (W)	Variance
$6.31 * 10^{-4}$	$7.57 * 10^{-5}$	$7.76 * 10^{-4}$	$7.61 * 10^{-5}$

TABLE 5.2: Comparison of the mean energy consumption of the transmission card and its variance, with and without LSTM-based compression (in Watts)

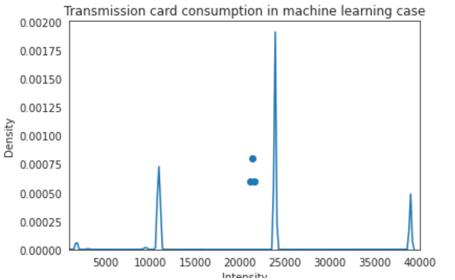


With Machine Learning		Without Machine Learning	
Mean value (W)	Variance	Mean value (W)	Variance
$5.48 * 10^{-4}$	$4.10 * 10^{-5}$	$9.87 * 10^{-4}$	$7.12 * 10^{-5}$

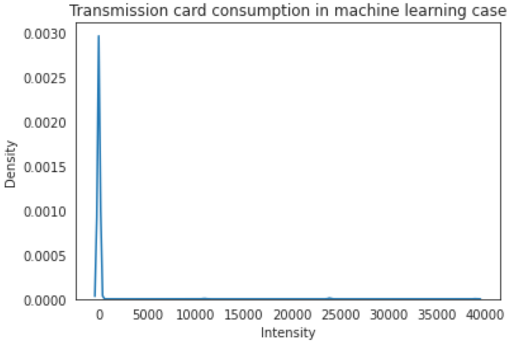
```
(18.28661818163327, 18.293796941822553, 18.300975702011836)
```



```
(21060.063789409185, 21337.932378854624, 21615.800968300064
```



```
(161.61508877972426, 166.319445587194, 171.02380239466373)
```



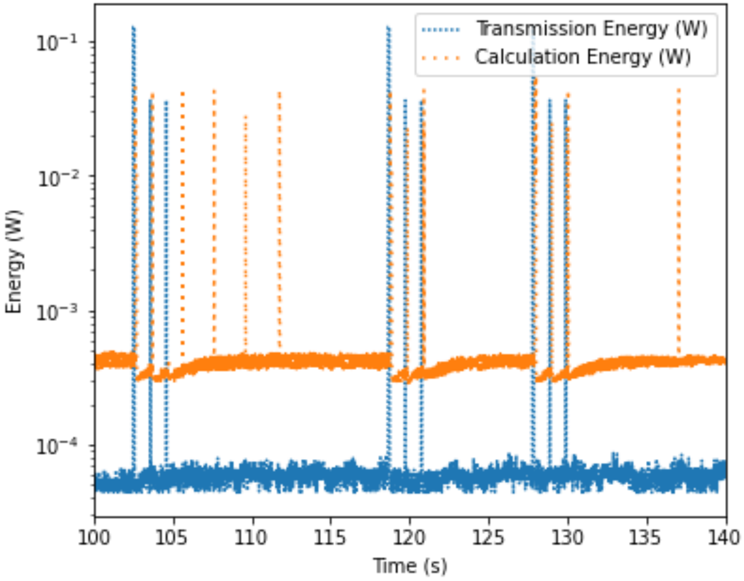
afnic
Internet made in France

TELECOM SudParis

IP PARIS

Energy consumption

Power passing through by our electronic cards in W (against time in s)



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(18.28661818163327, 18.293796941822553, 18.300975702011836)
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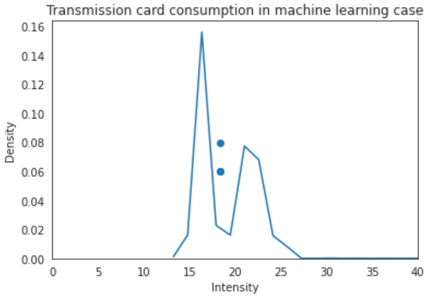

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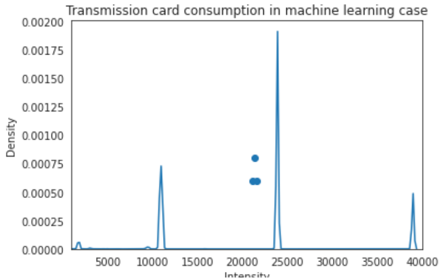
(21060.063789409185, 21337.932378854624, 21615.800968300064
```



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(161.61508877972426, 166.319445587194, 171.02380239466373)
```

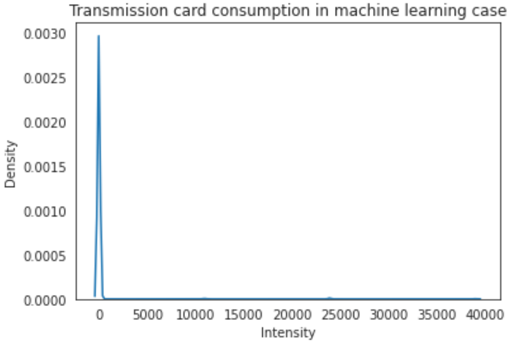

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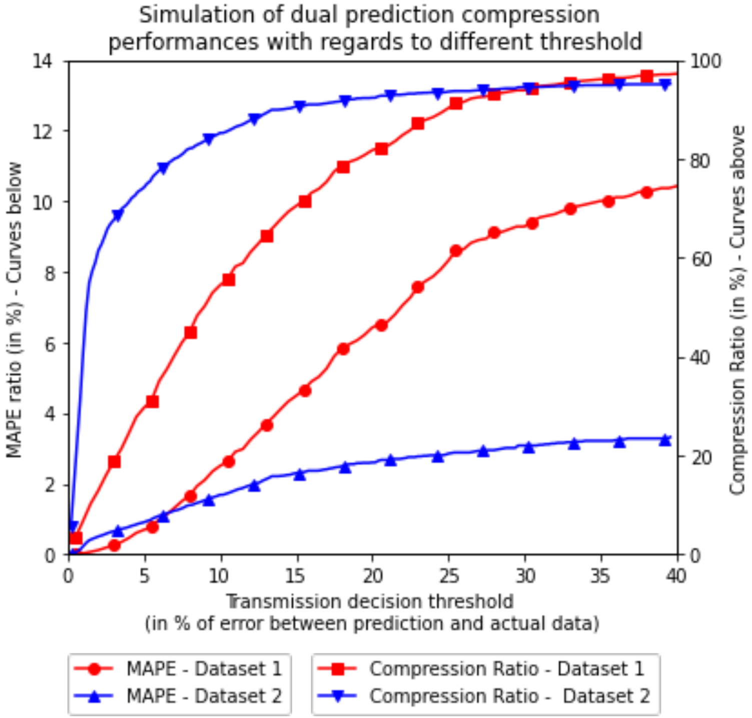
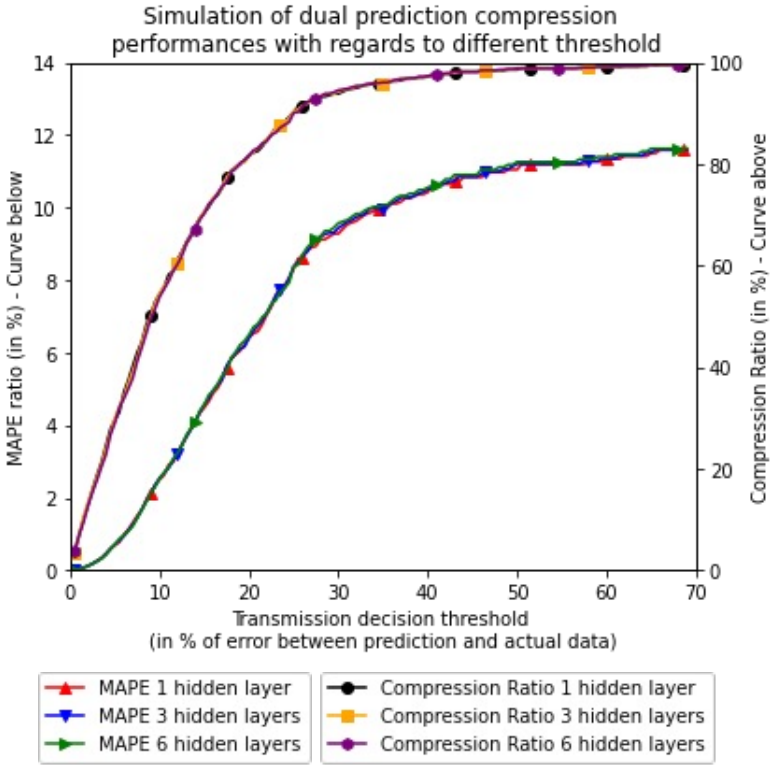
Compression performance & Error rate



Compression performance & threshold



Quantification results