Efficient and Timely Revocation of V2X Credentials

Artifact Evaluated
NDSS SYMPOSIUM
Available
Functional
Reproduced

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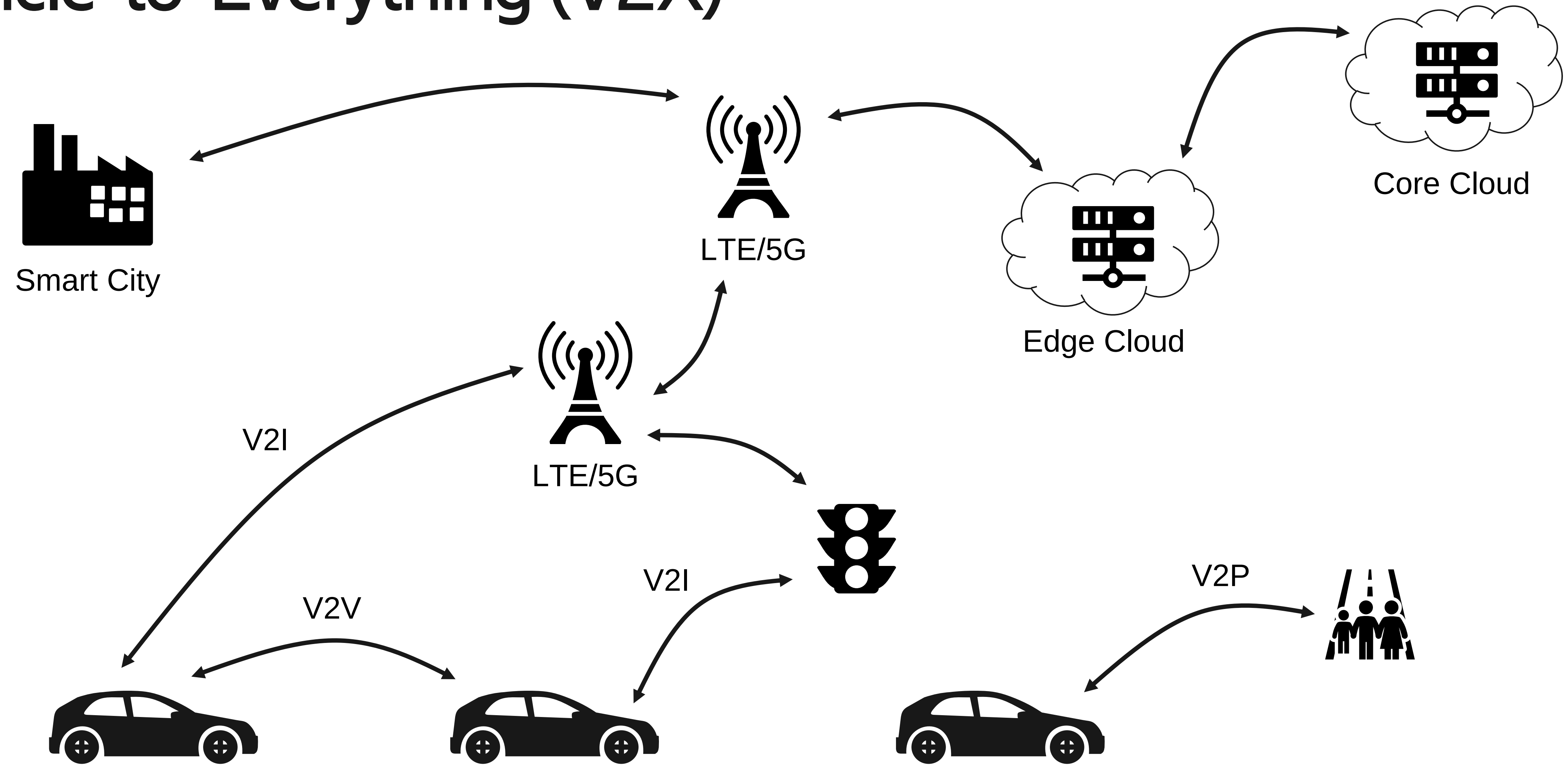
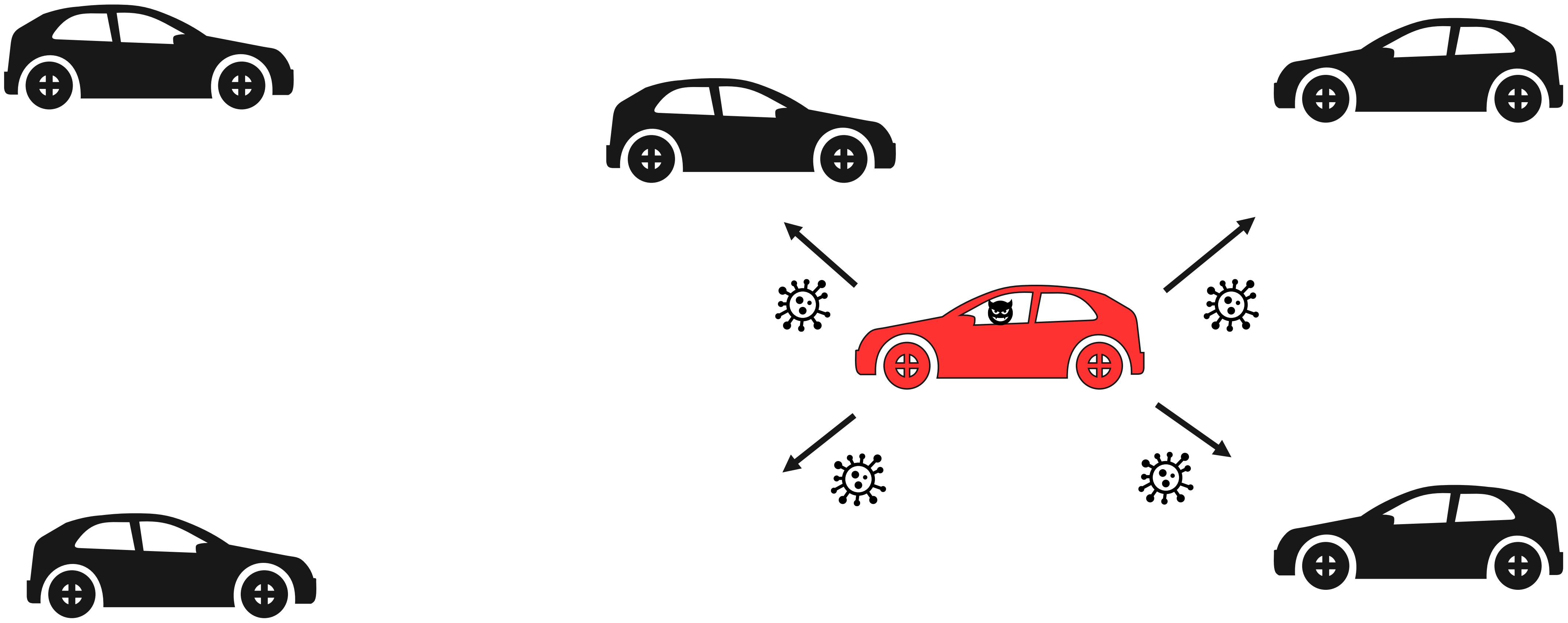
ERICSSON KU LEUVEN DistriNet ULB CYBERSECURITY RESEARCH CENTER

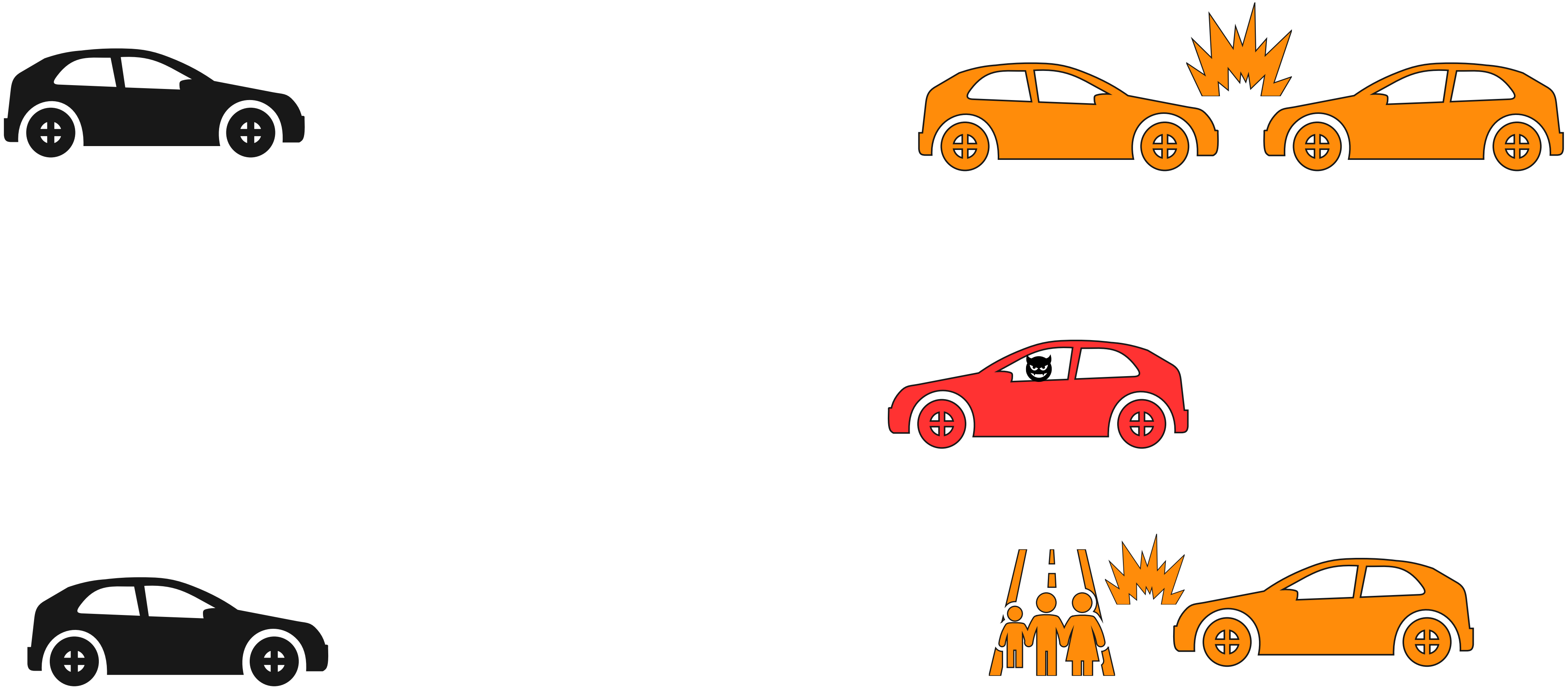
Vehicle-to-Everything (V2X)



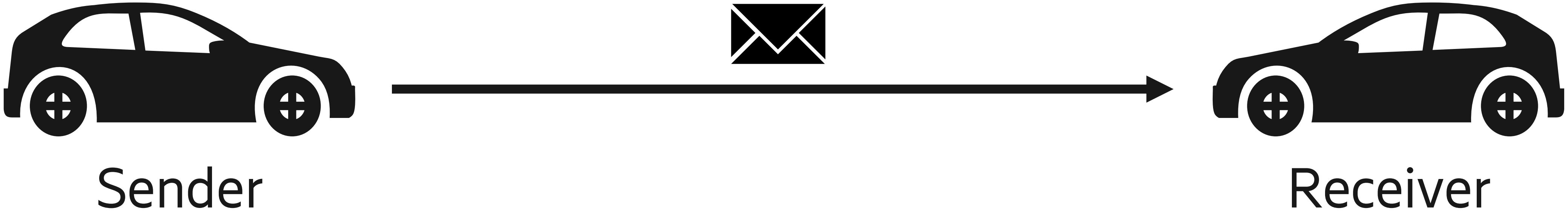
What if a vehicle is malicious?



What if a vehicle is malicious?



Vehicle communication in V2X needs to be properly protected



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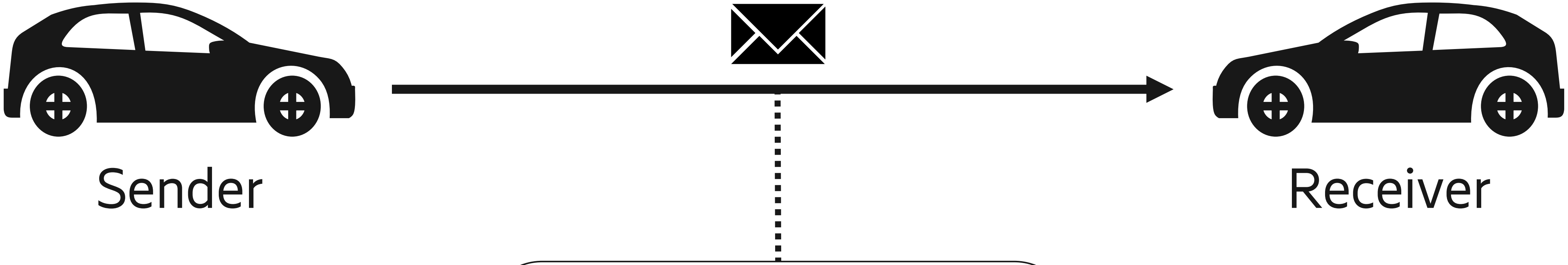

```
speed: 90
location: 23.90437, -140.51174
direction: NE
...

timestamp: 1709025600
pseudonym: deadbeef
expiration: 1711531200
signature: <some bytes>
```

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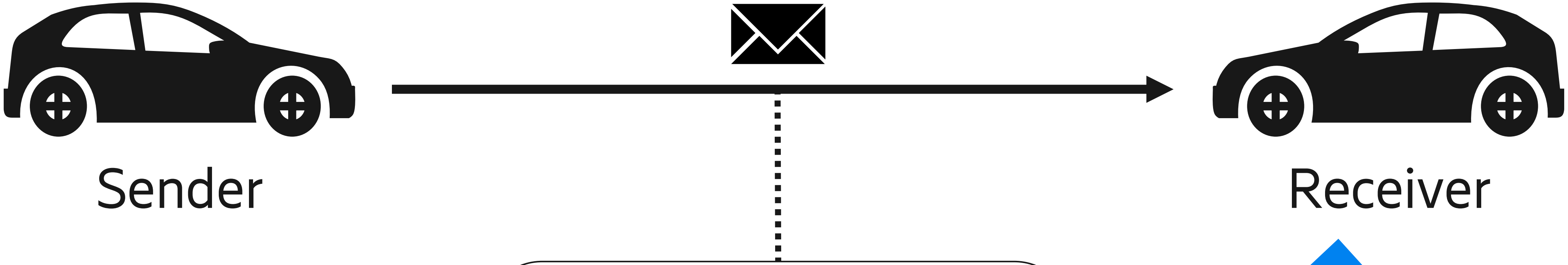

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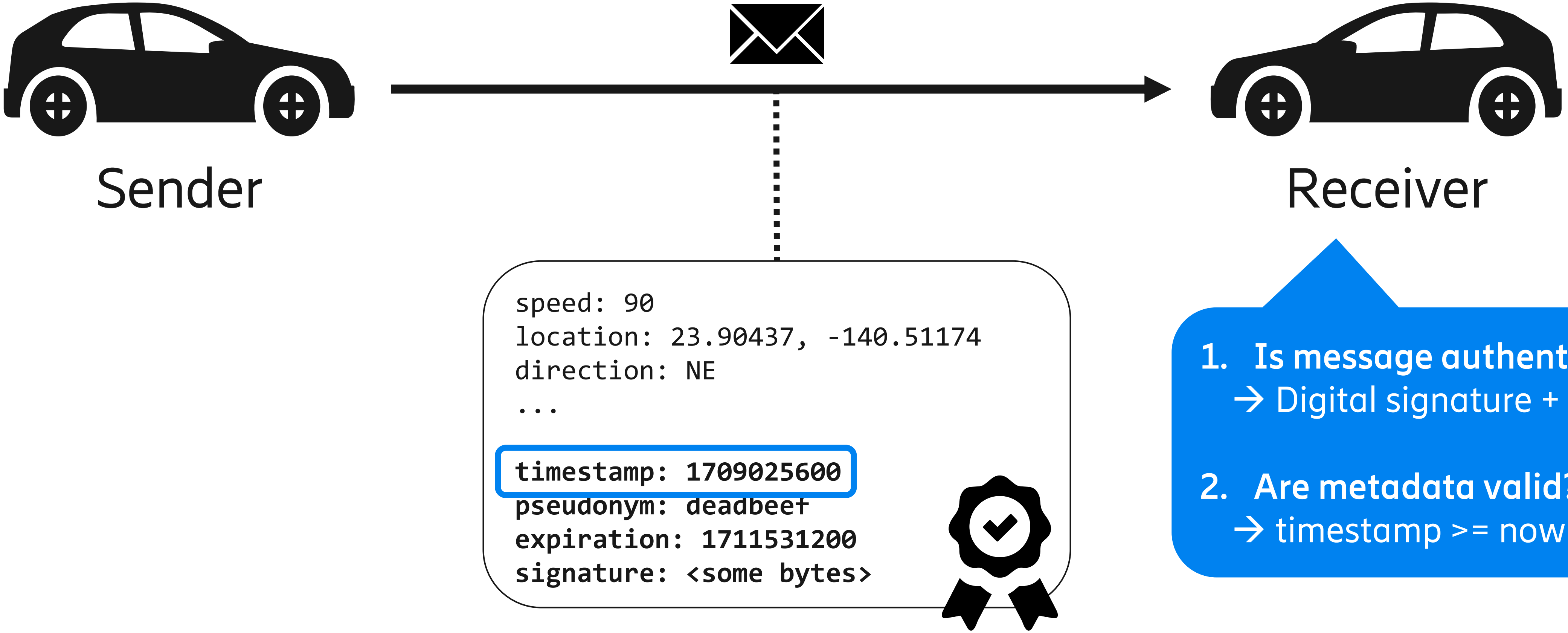
```

1. **Is message authentic?**
   → Digital signature + identity

Vehicle communication in V2X needs to be properly protected

T_V : **tolerance** for network messages



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location: 23.90437, -140.51174
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...

timestamp: 1709025600
pseudonym: deadbeef
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```
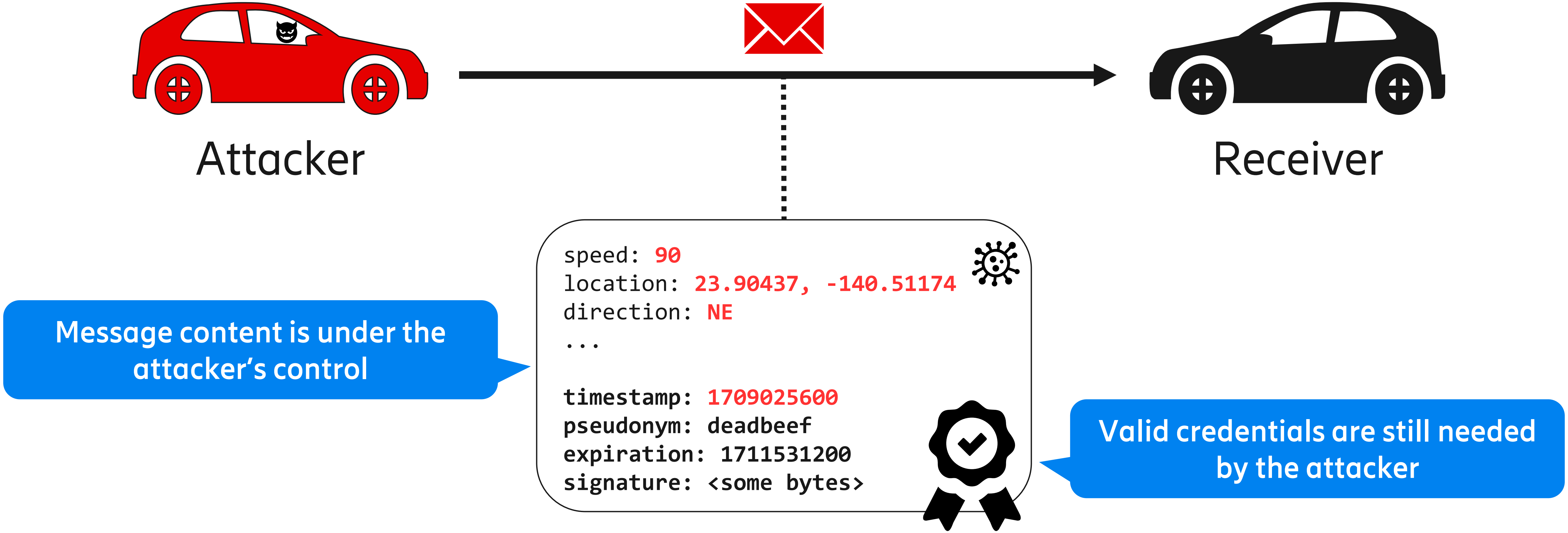

1. **Is message authentic?**
   → Digital signature + identity
2. **Are metadata valid?**
   → timestamp >= now() - T_V

Malicious participants may spread false information and cause accidents



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...

timestamp: 1709025600
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signature: <some bytes>
```

Message content is under the attacker's control

Valid credentials are still needed by the attacker

State of the art in revocation schemes for V2X

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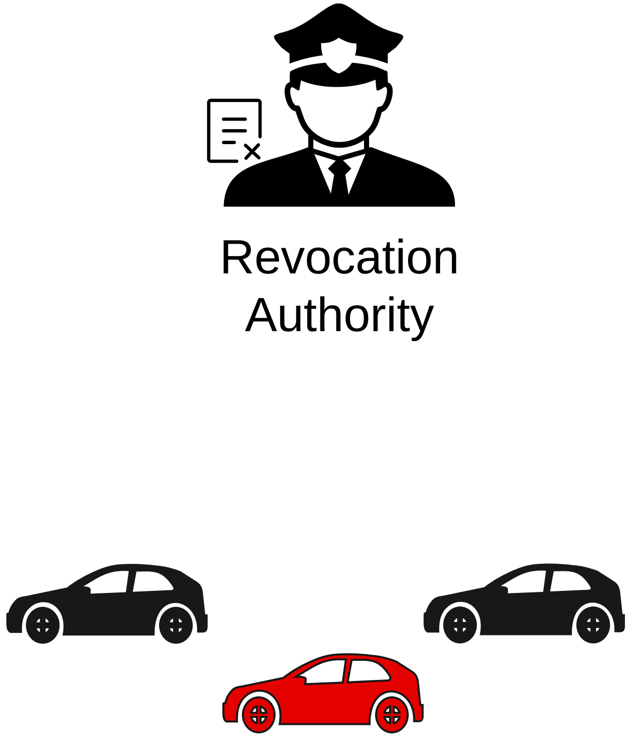
Active revocation (IEEE 1609.2.1 – SCMS [1])



[1] IEEE Std 1609.2.1-2022 "IEEE WAVE - Certificate Management Interfaces for End Entities”

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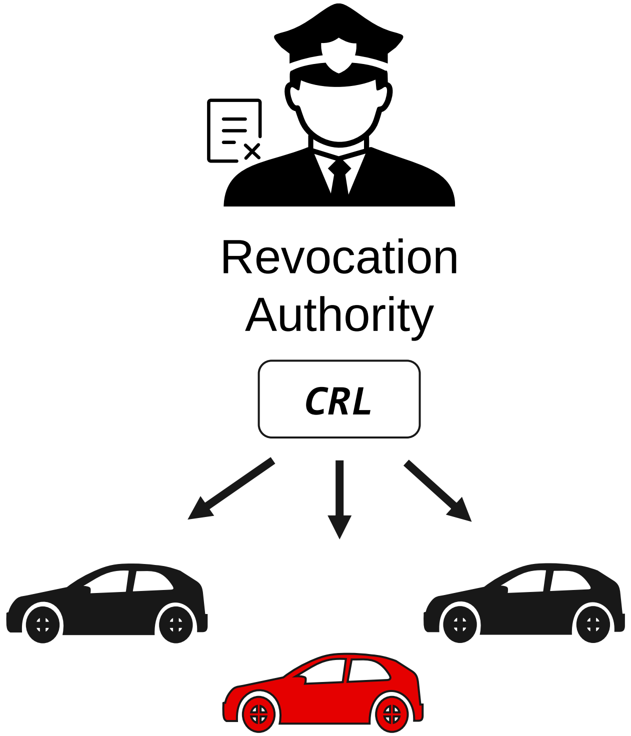

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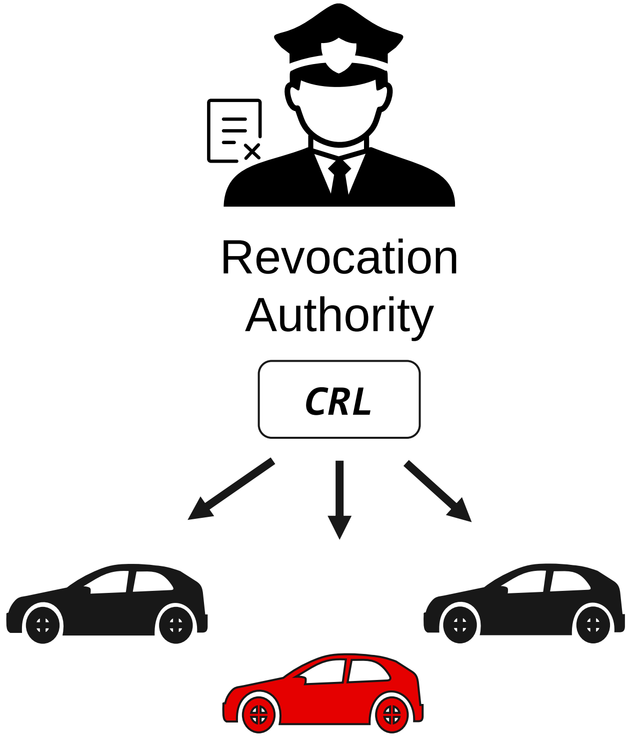
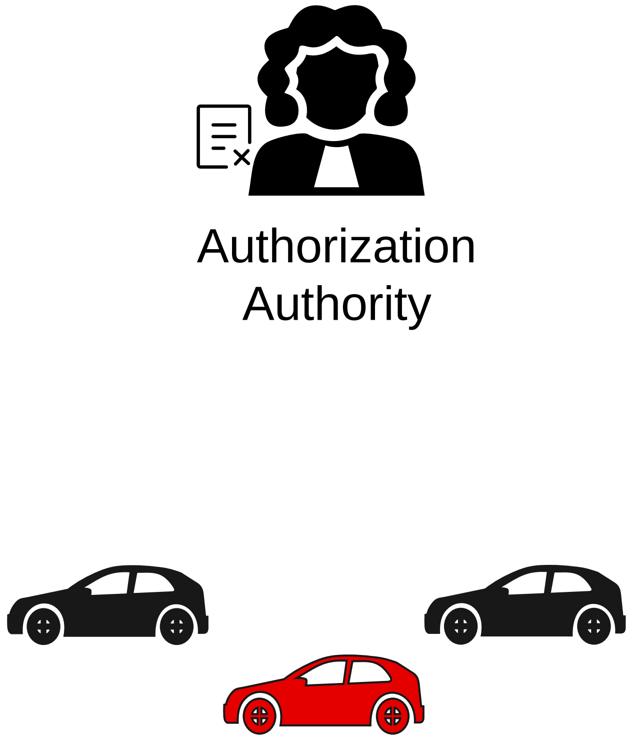


Revocation Authority

CRL

Passive revocation (ETSI TS 102 941 [2])



Authorization Authority

[1] IEEE Std 1609.2.1-2022 "IEEE WAVE - Certificate Management Interfaces for End Entities”

[2] ETSI TS 102 940 version 2.1.1, “Intelligent Transport Systems (ITS); Security, ITS communications security architecture and security management”

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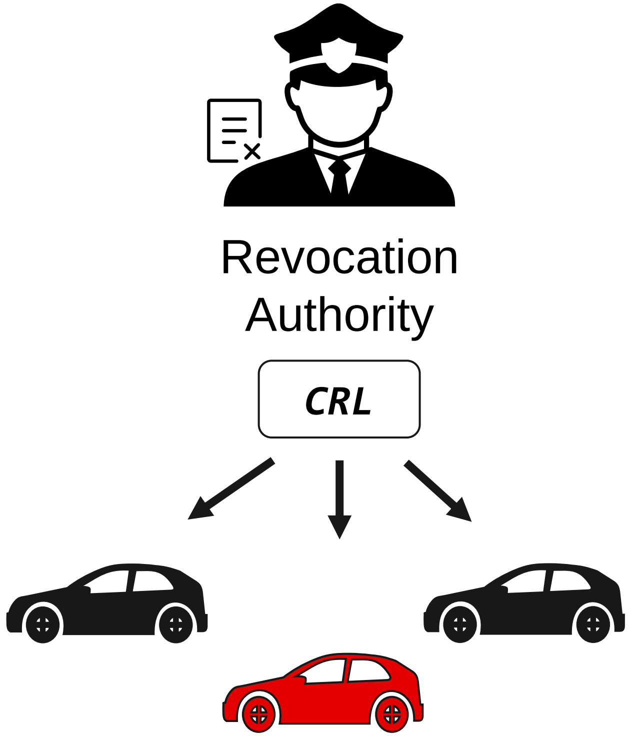
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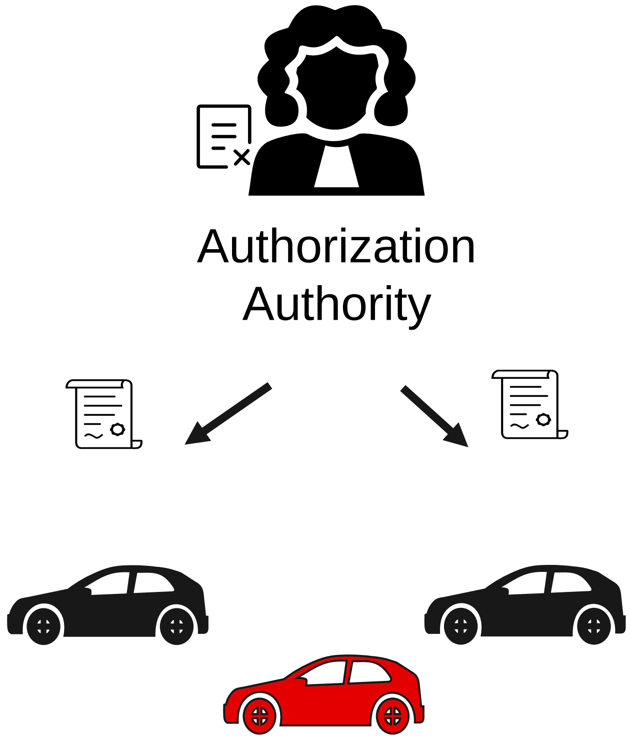
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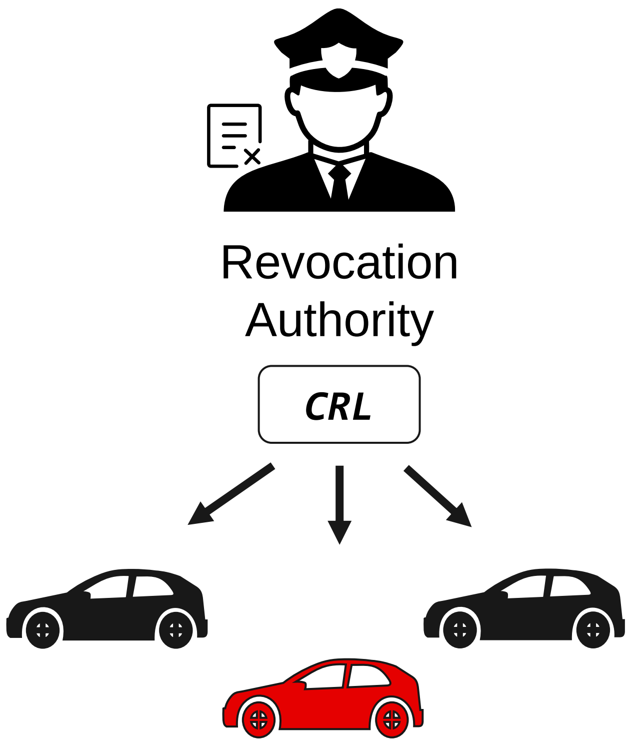

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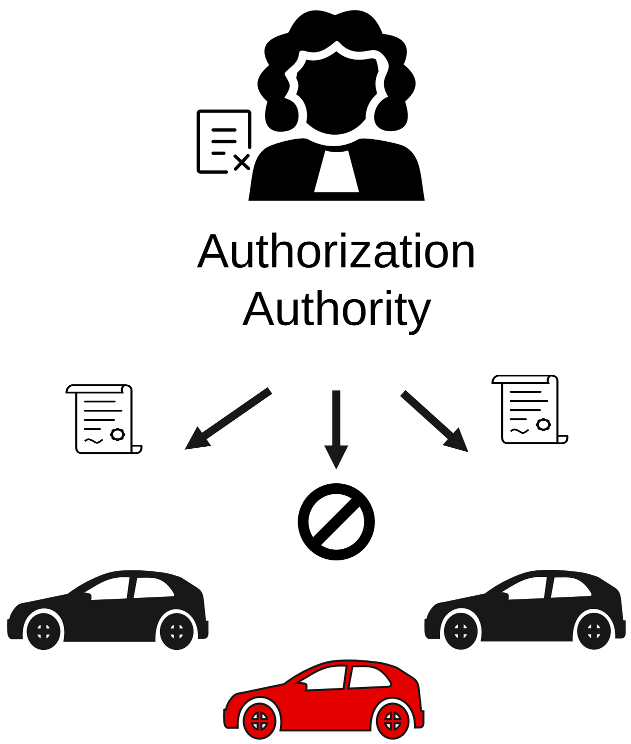

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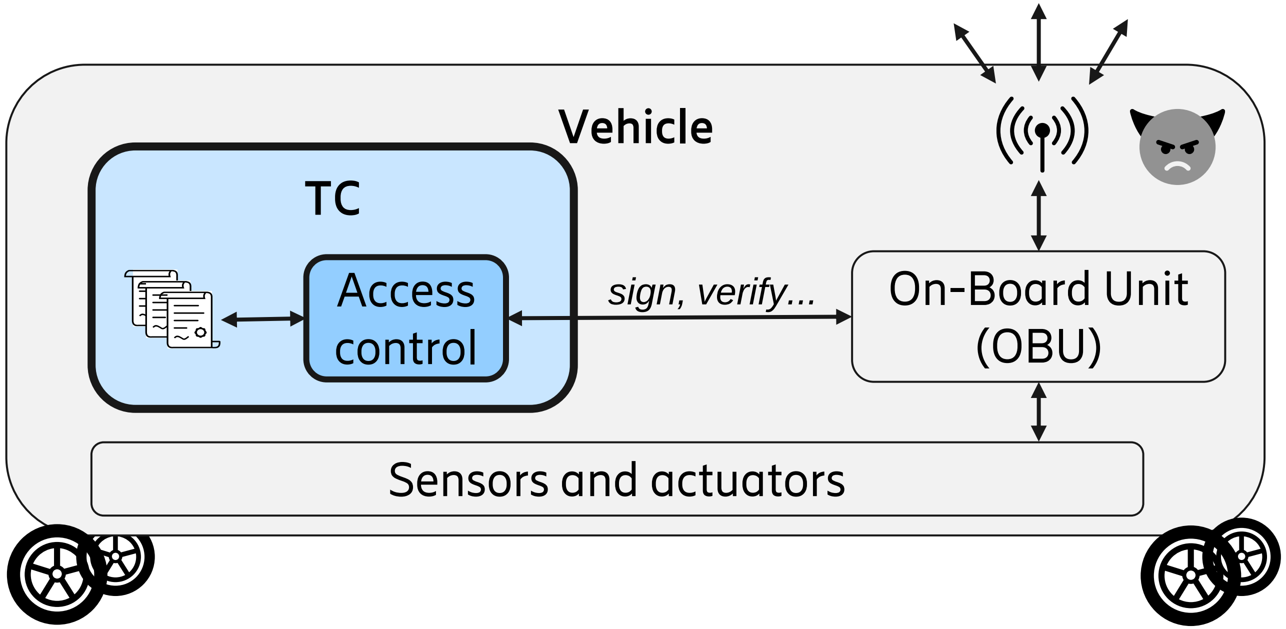
[2] ETSI TS 102 940 version 2.1.1, "Intelligent Transport Systems (ITS); Security, ITS communications security architecture and security management"

Putting trust in vehicles: Trusted Computing and Self-Revocation

- Vehicles equipped with a **Trusted Component (TC)**
- Credentials + message metadata are managed by the TC
- Academic proposals leverage TPMs and Direct Anonymous Attestation (DAA) [3]

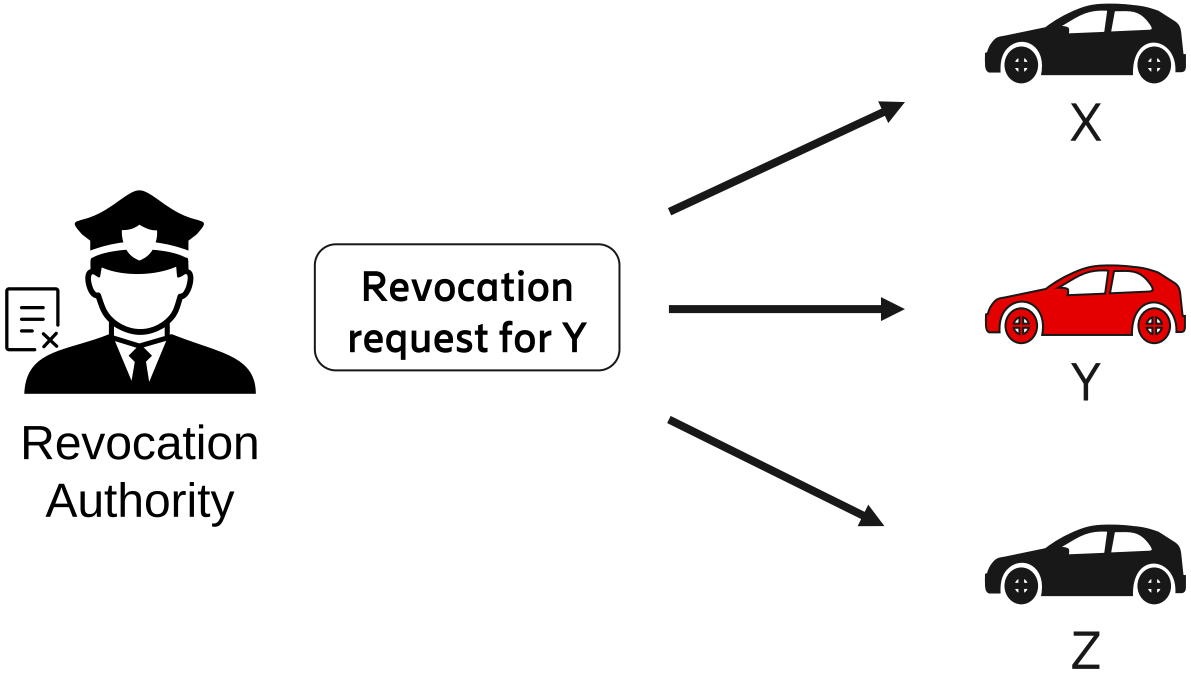


[3] Larsen et al., "Direct Anonymous Attestation on the Road: Efficient and Privacy-Preserving Revocation in C-ITS", WiSec '21.

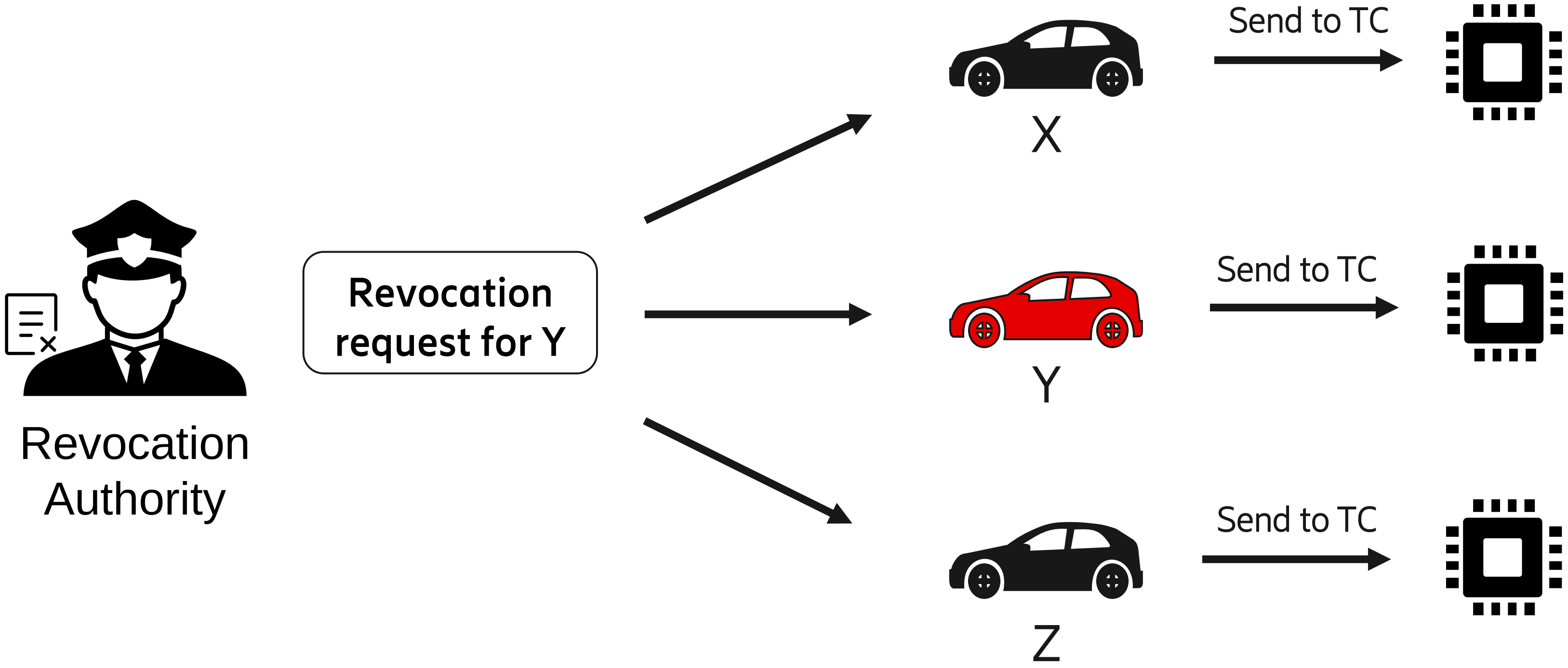
Self-revocation in practice

X
Y
Z
Revocation Authority

Self-revocation in practice



Self-revocation in practice



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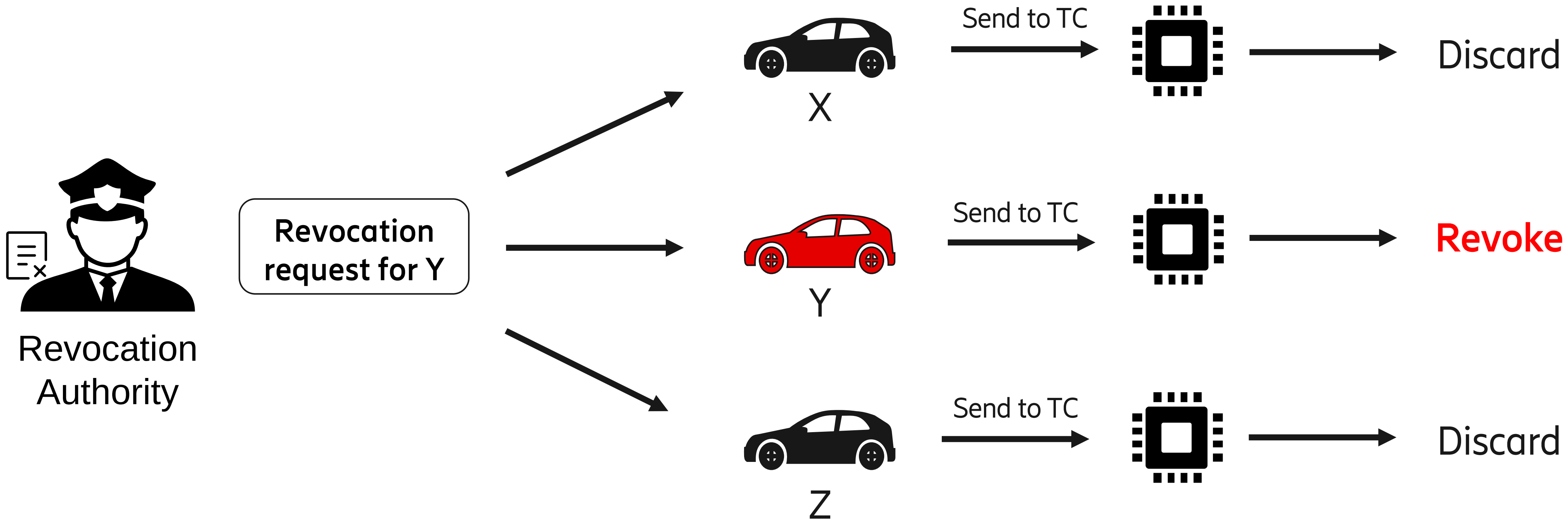
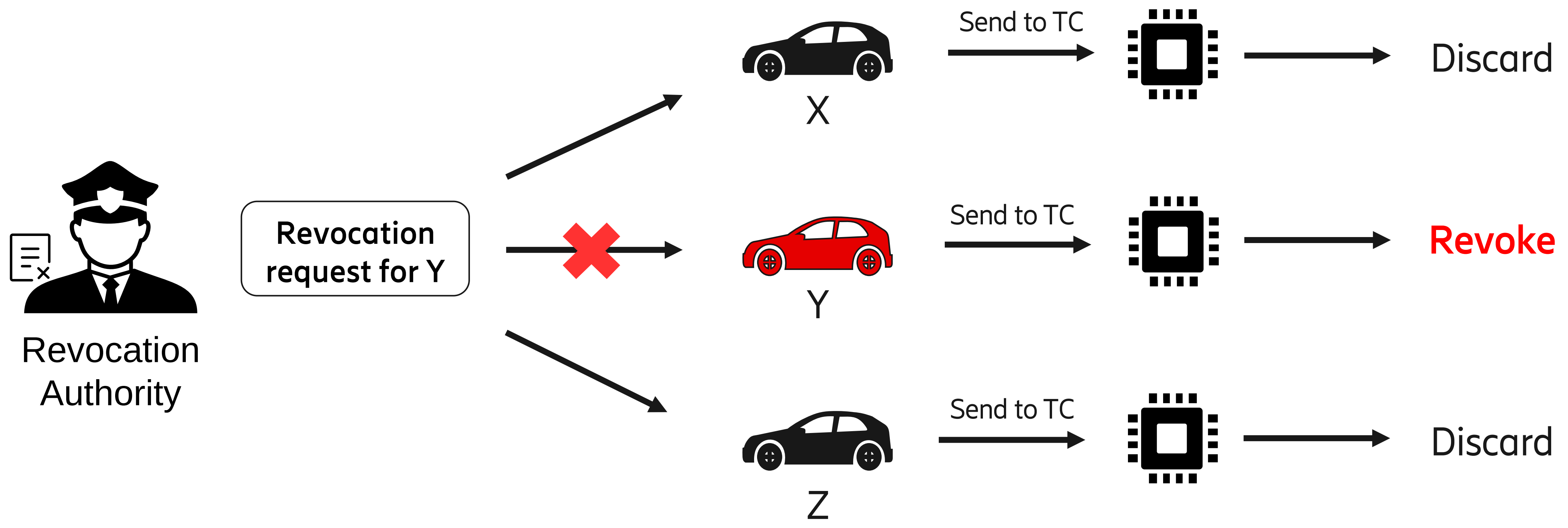


Self-revocation in practice

Dolev-Yao attacker



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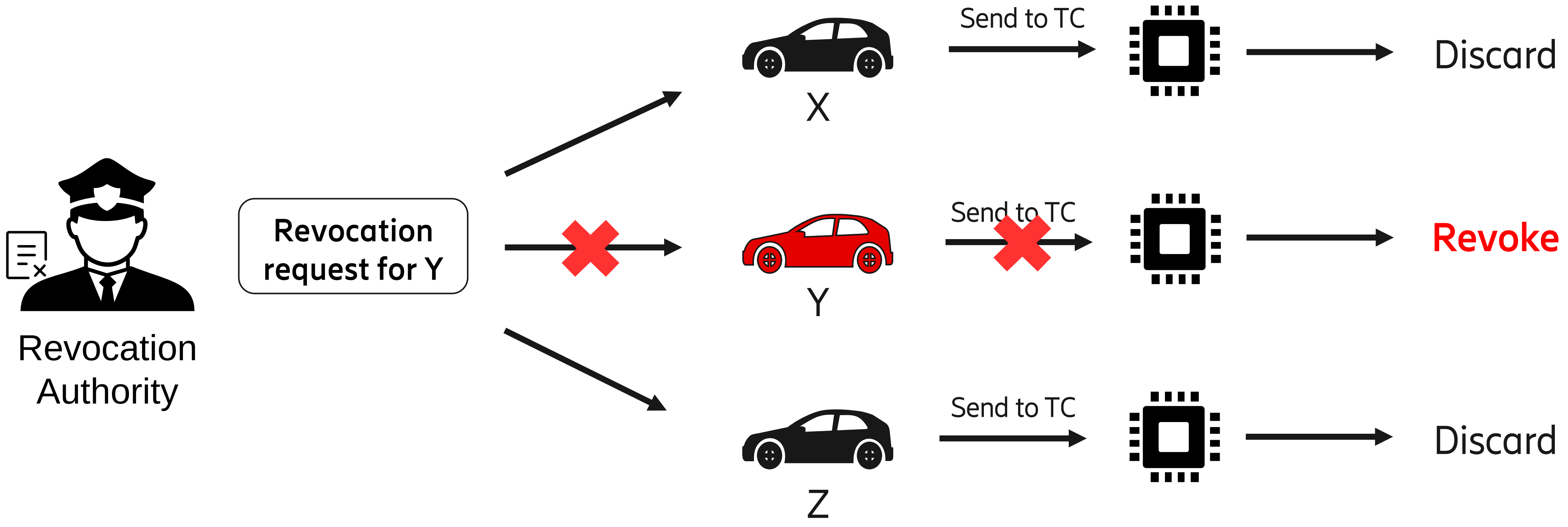

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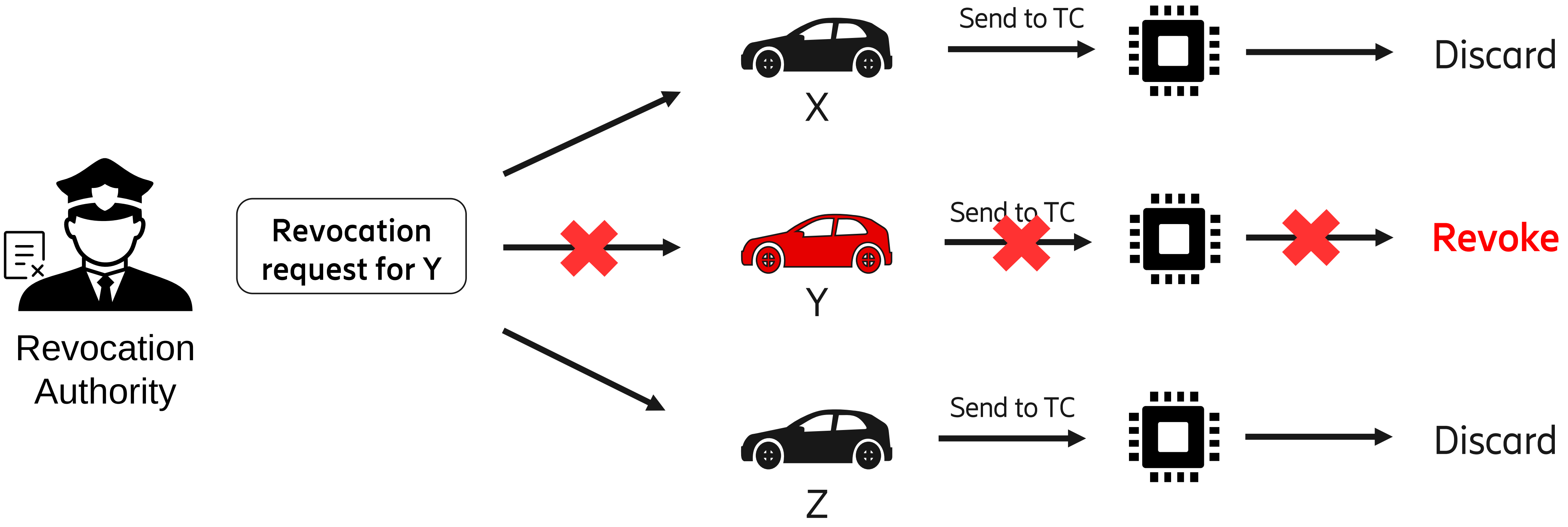


Revocation Authority

Revocation request for Y

Goals

Security

Guaranteed revocation with fixed upper bound

⬇

Formal verification

Goals

Security

Guaranteed revocation with fixed upper bound

↓

Formal verification

Usability

Resistant against network delays and interruptions

↓

Simulation

Goals

Security

Guaranteed revocation with fixed upper bound

↓

Formal verification

Usability

Resistant against network delays and interruptions

↓

Simulation

Efficiency

Small overhead, scalable with large number of revocations

↓

Probabilistic model

Constraints

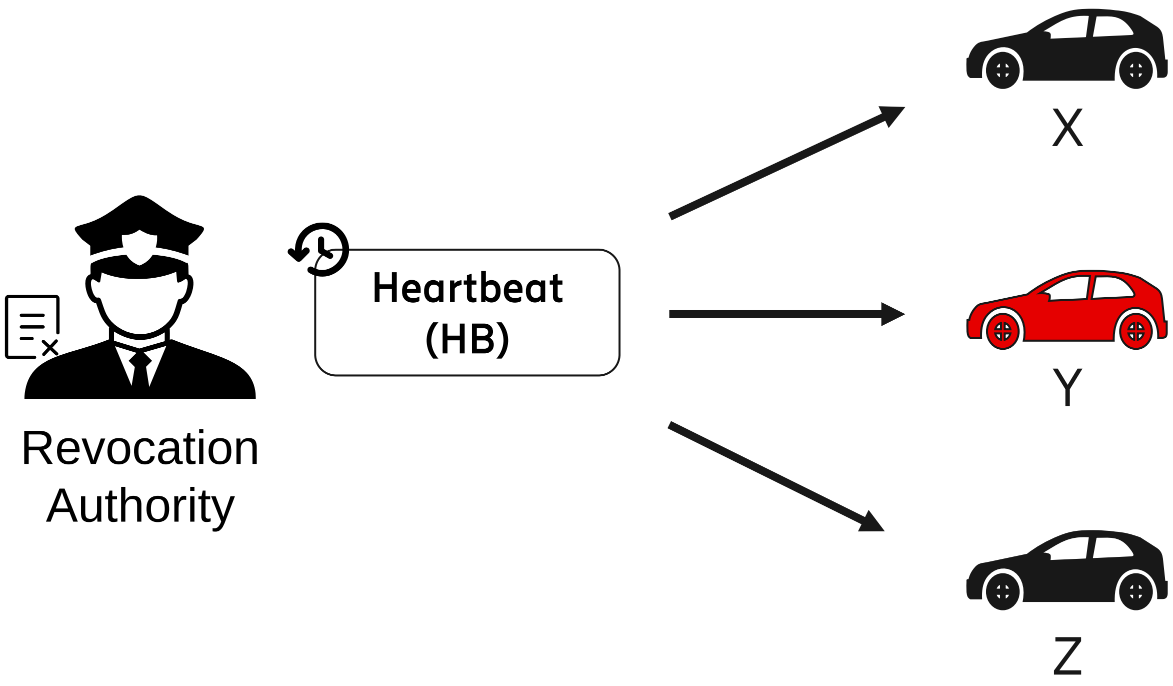
- TC does **not** have access to a trusted time source
  - Common issue with most TEEs

Constraints

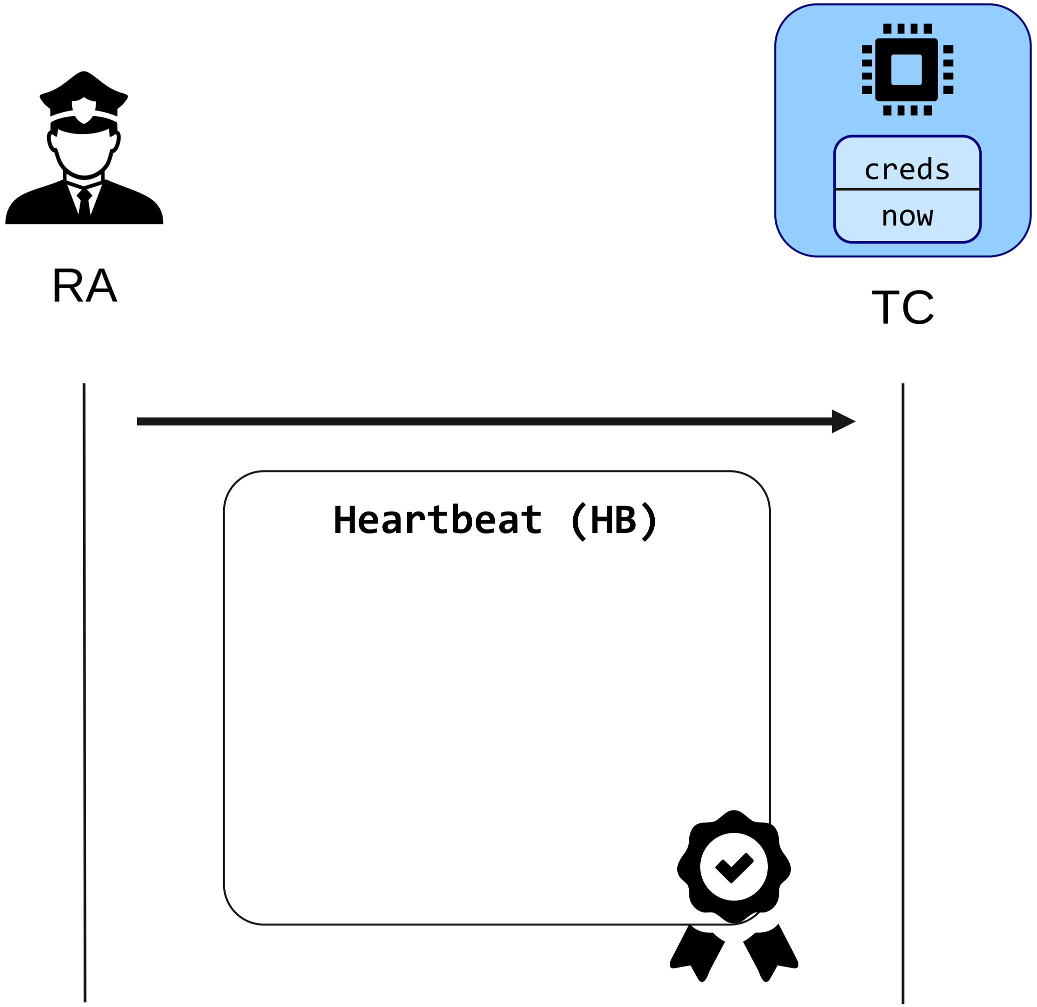
- TC does **not** have access to a trusted time source
  - Common issue with most TEEs

- TC is a **passive device**
  - Process request from untrusted host (e.g., *sign*), return response

Our approach: periodic heartbeats (HBs)



Processing a HB



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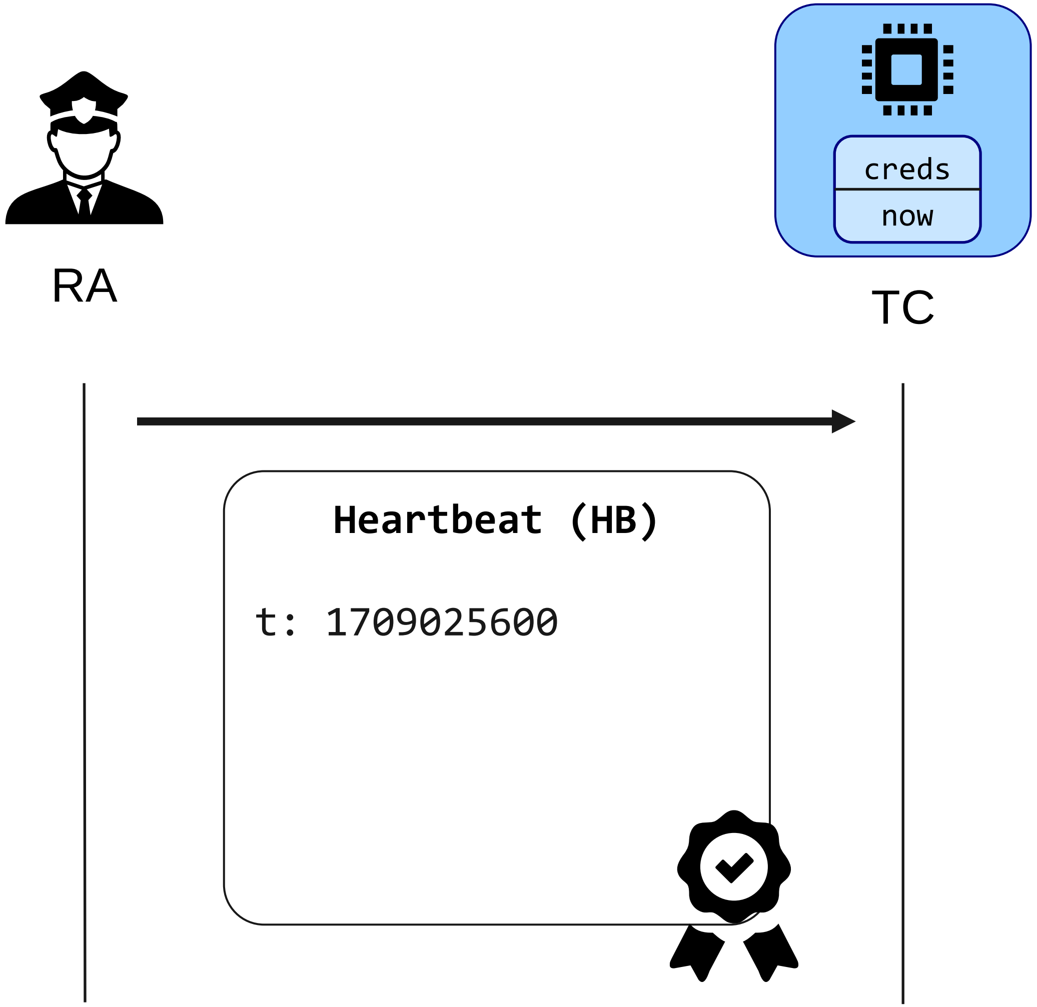


Heartbeat (HB)

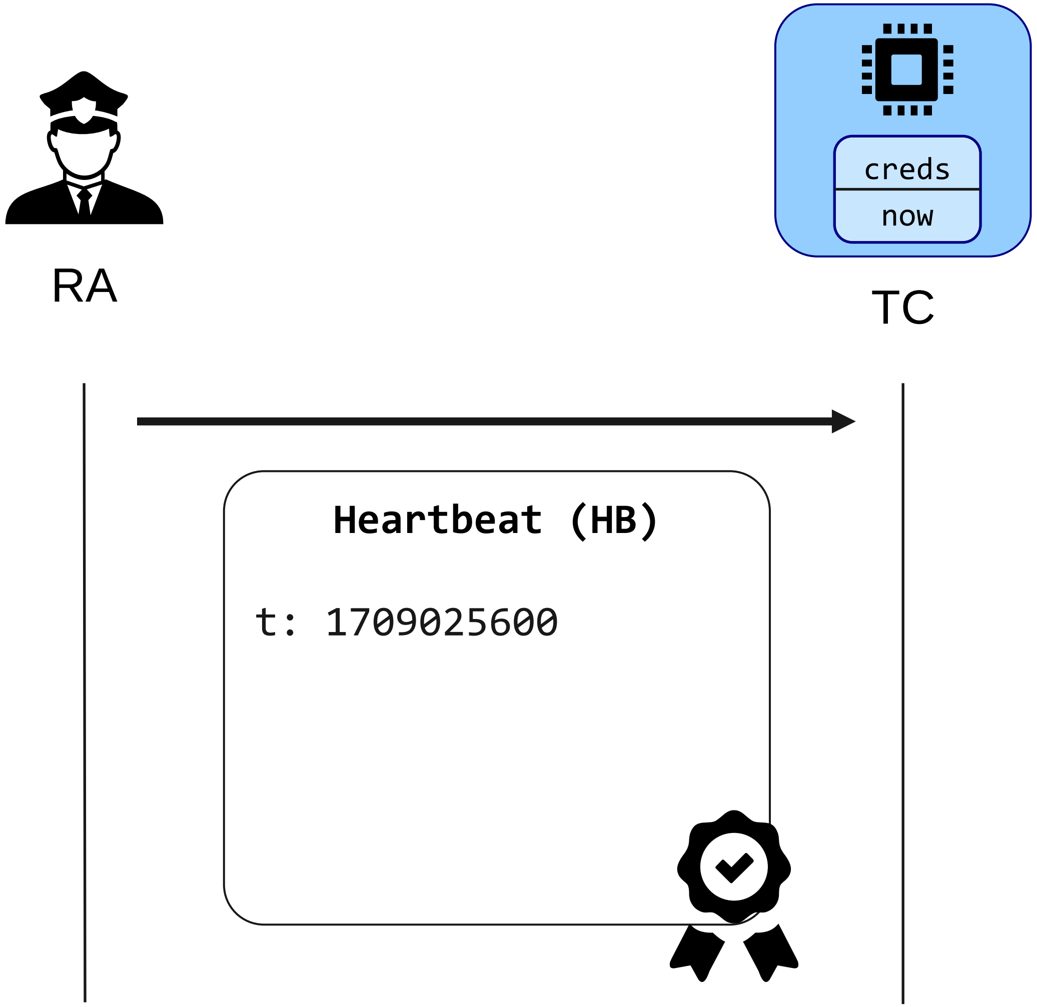
t: 1709025600

Signature check

Freshness check

$t >= \mathrm{now} - T_v$

Processing a HB



Signature check

Freshness check

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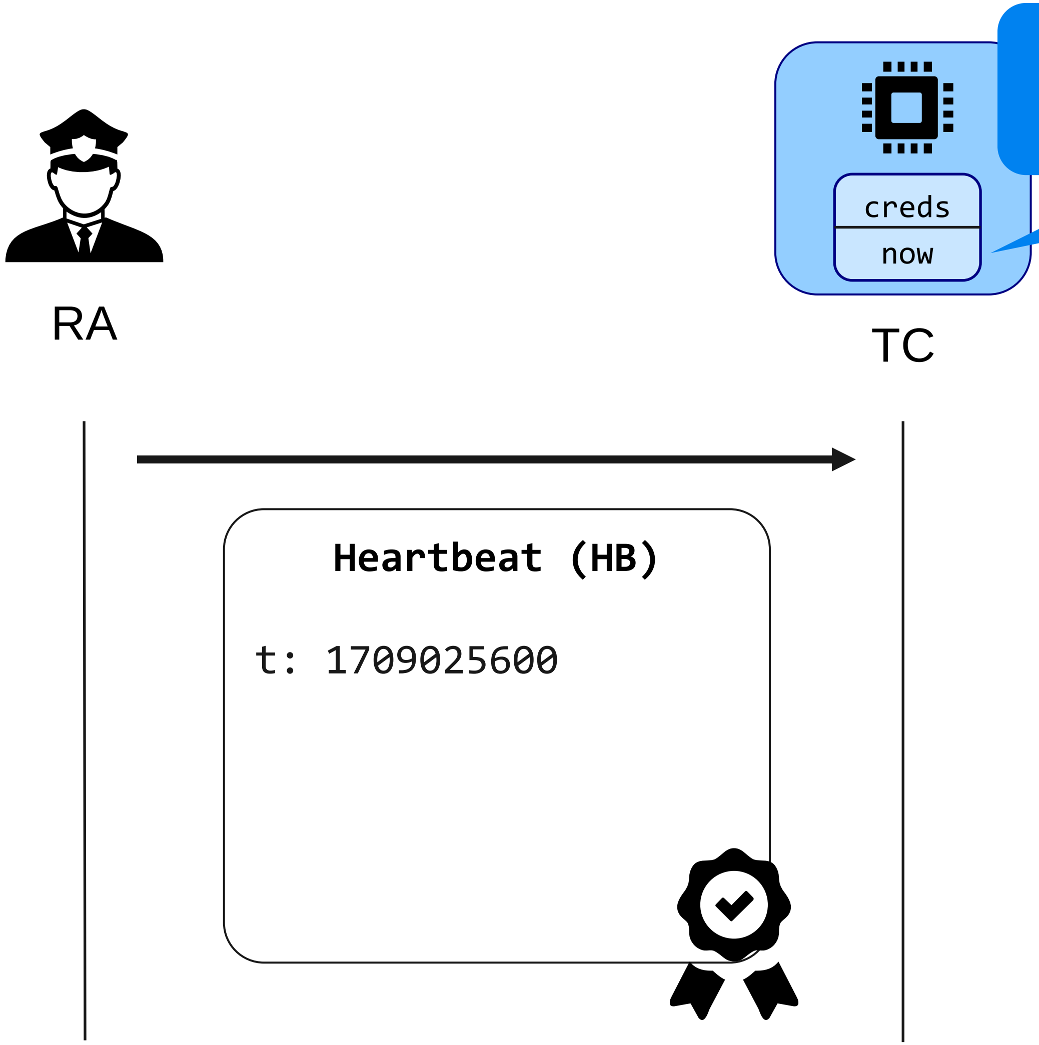
Time synchronization

$\text{now} = t$

Processing a HB



RA

TC

creds

now

Heartbeat (HB)

t: 1709025600

Initial timestamp (epoch) given during initialization (e.g., enrolment)

check

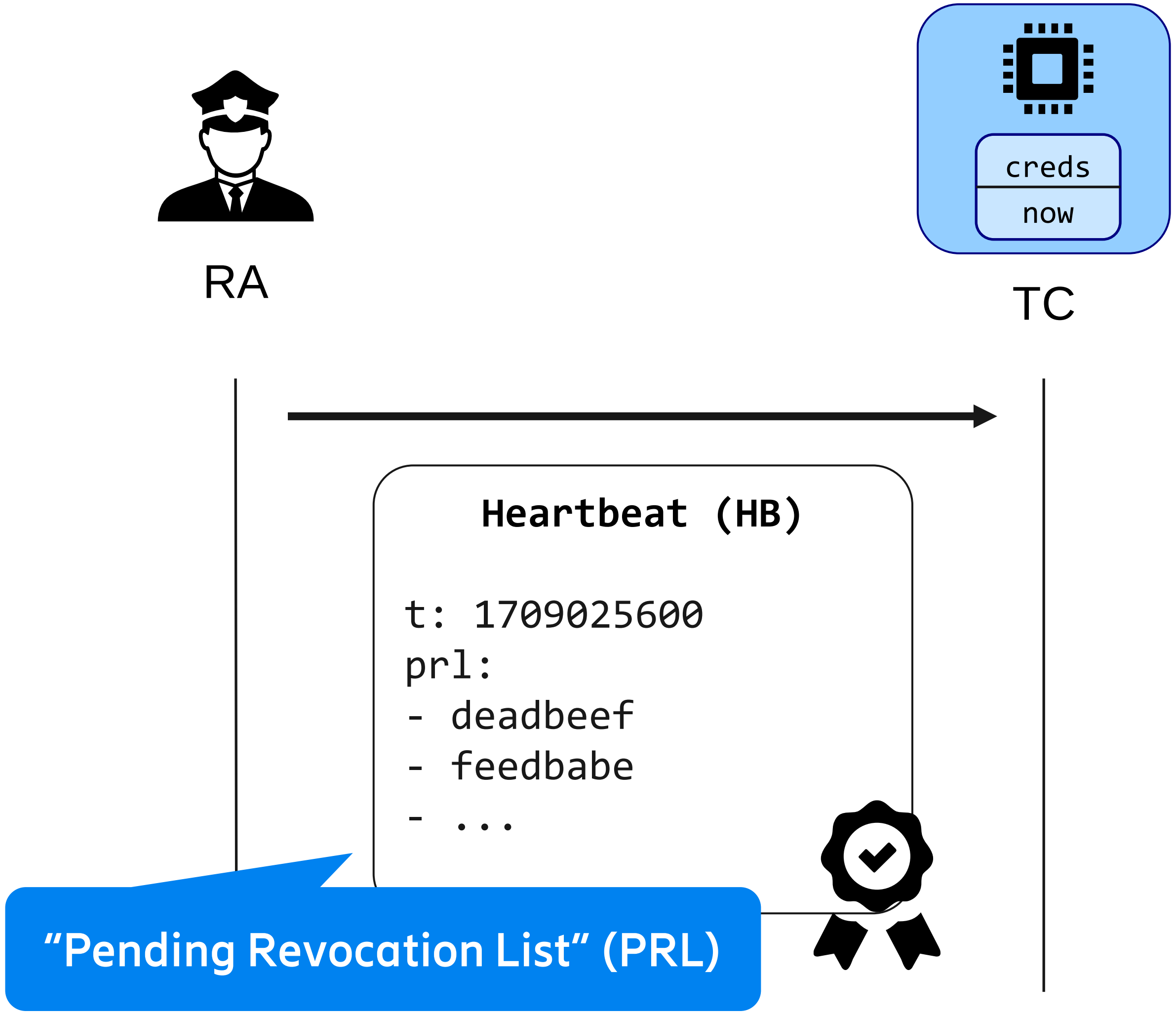
Freshness check

`t >= now - `T_v

Time synchronization

`now = t`

Processing a HB



Heartbeat (HB)

```
t: 1709025600
prl:
- deadbeef
- feedbabe
- ...
```

"Pending Revocation List" (PRL)

Signature check

Freshness check

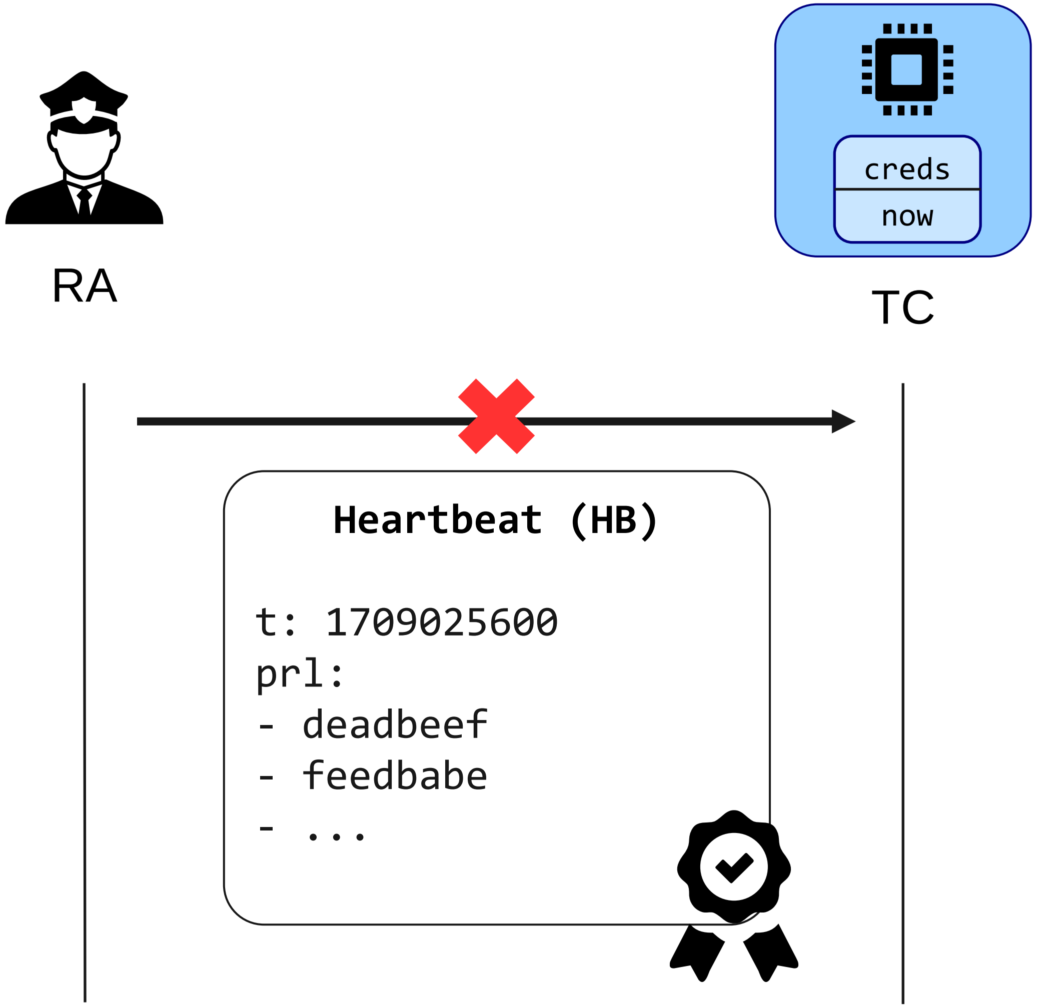
$t >= now - T_v$

Time synchronization

$now = t$

Revocation check

(Not) Processing a HB



Heartbeat (HB)

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Time synchronization

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Revocation check

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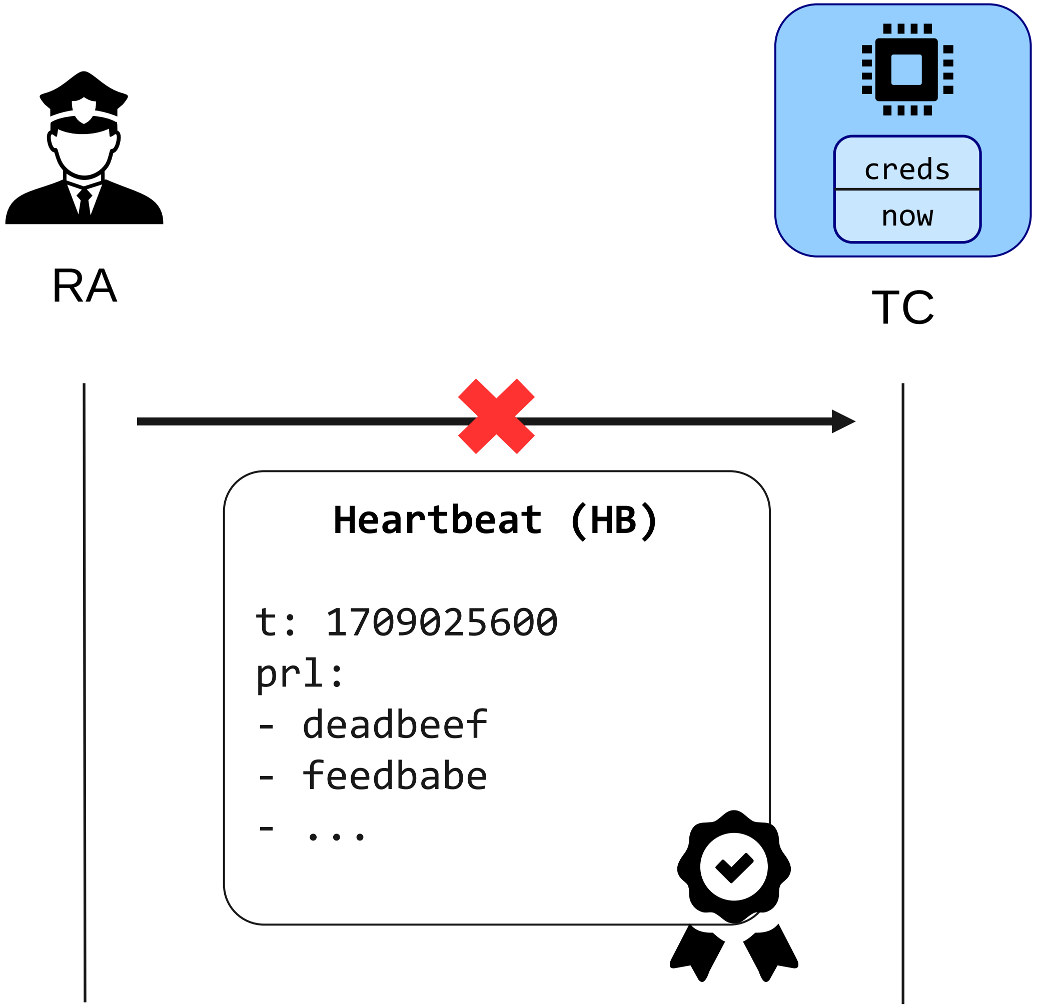

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Heartbeat (HB)

t: 1709025600
prl:
- deadbeef
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- ...
```

Signature check

Freshness check

t >= now – T_v

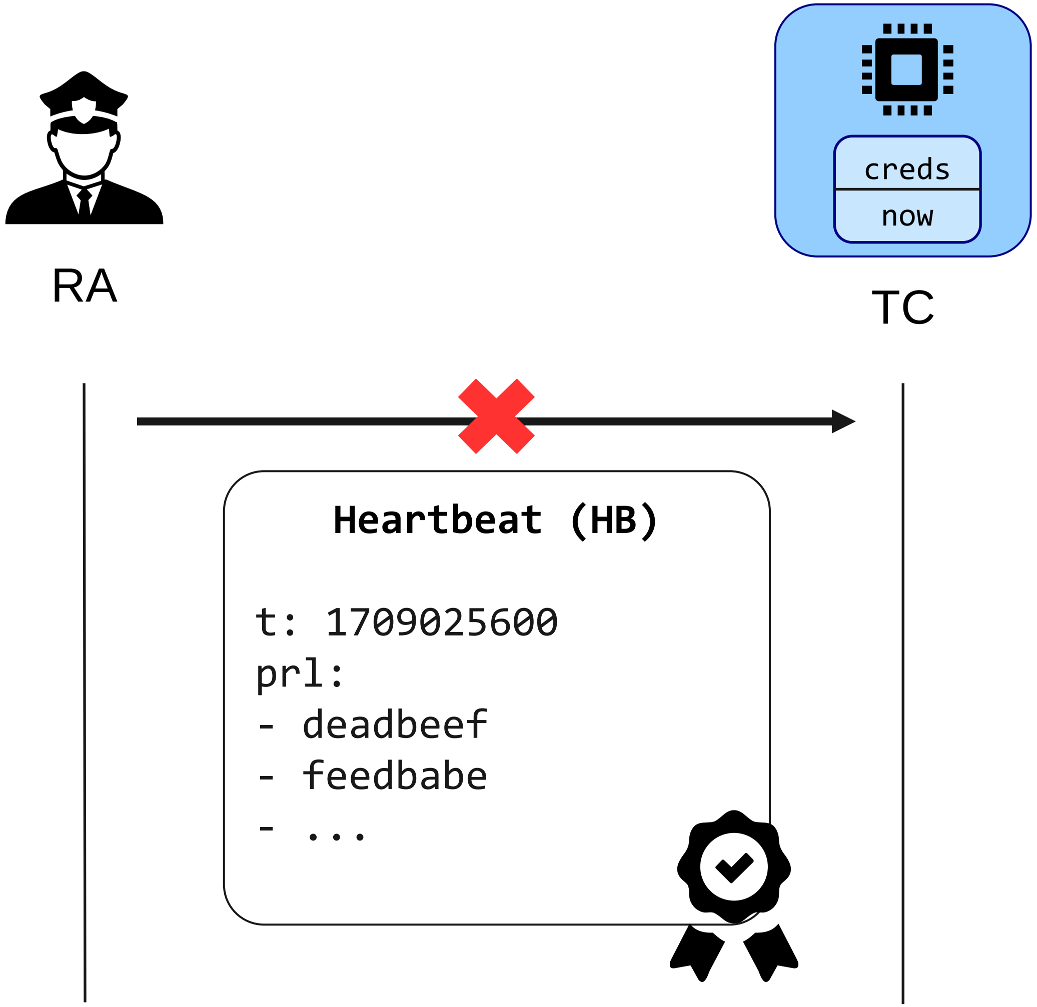
Time synchronization

now = t

✗ Revocation check

Good for attacker: credentials remain valid

(Not) Processing a HB



Heartbeat (HB)

```
t: 1709025600
prl:
- deadbeef
- feedbabe
- ...
```

Signature check

Freshness check

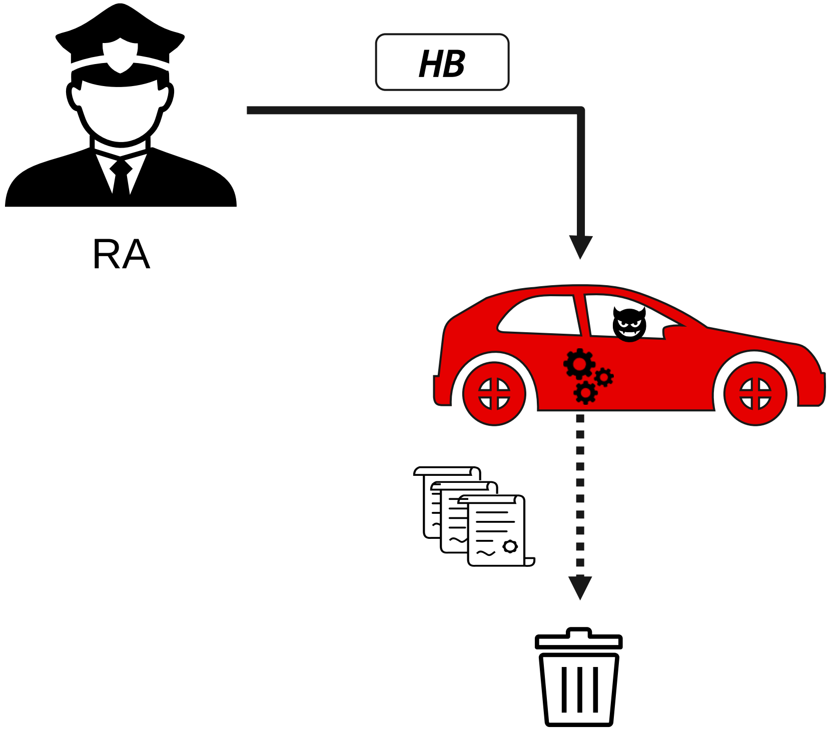
Bad for attacker: TC not in sync with other vehicles

Time synchronization

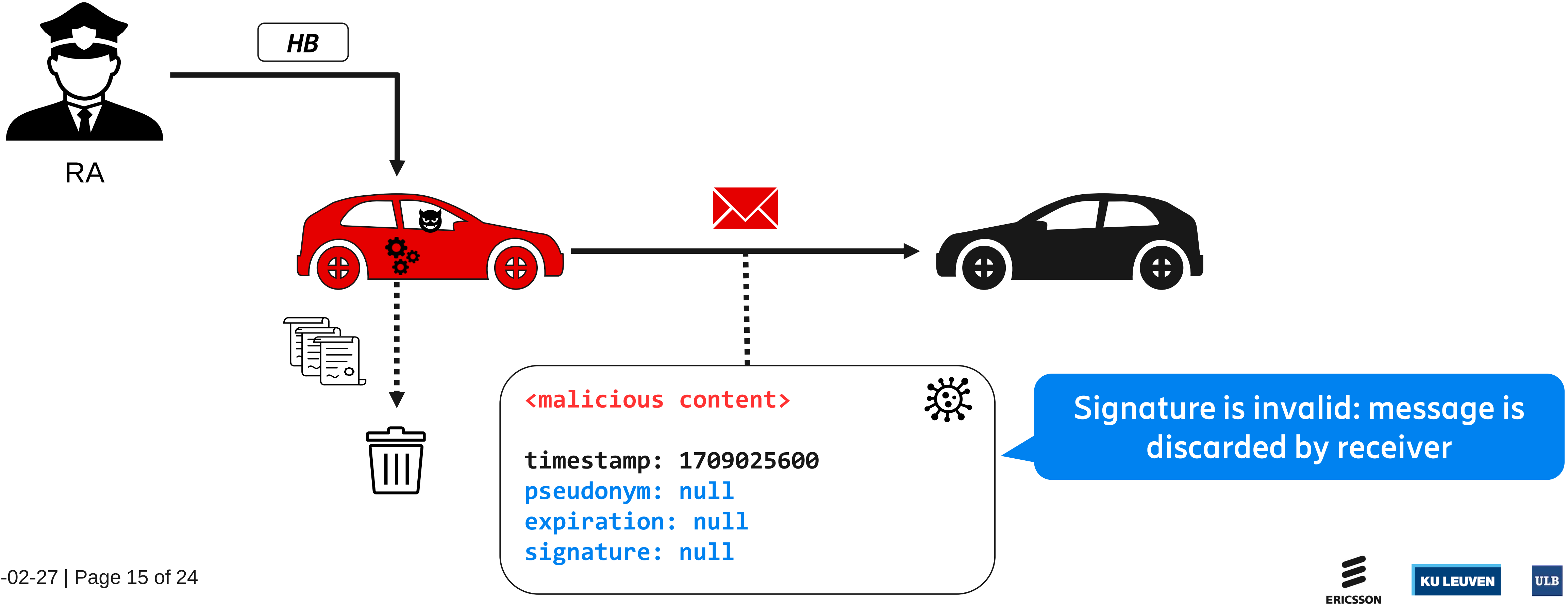
`now = t`

Revocation check

“Cooperative” attacker: HBs are forwarded to the TC and credentials self-revoked



“Cooperative” attacker: HBs are forwarded to the TC and credentials self-revoked

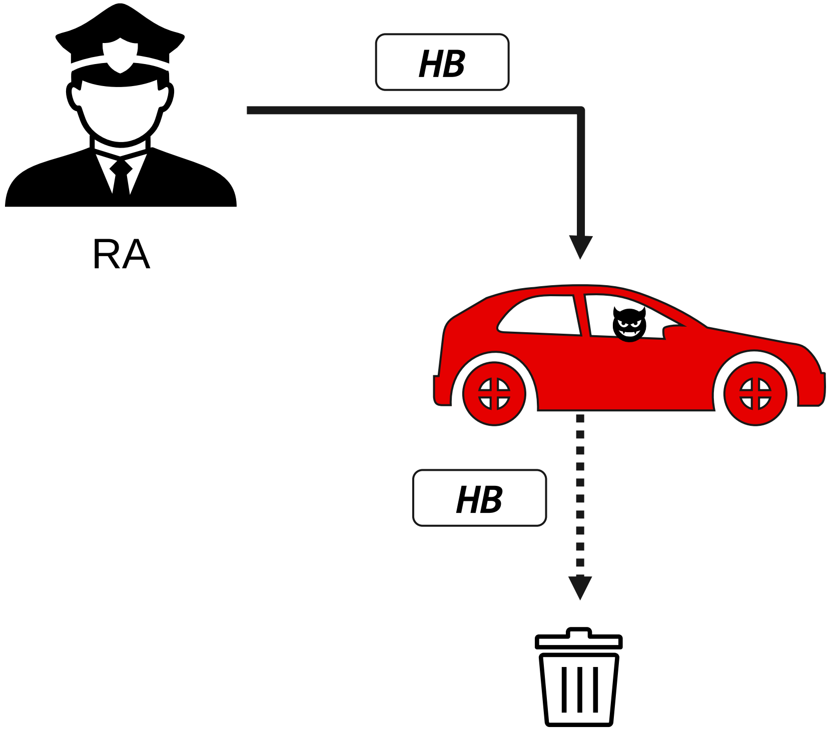


```
<malicious content>

timestamp: 1709025600
pseudonym: null
expiration: null
signature: null
```

Signature is invalid: message is discarded by receiver

“Non-cooperative” attacker: HBs are dropped to elude revocation



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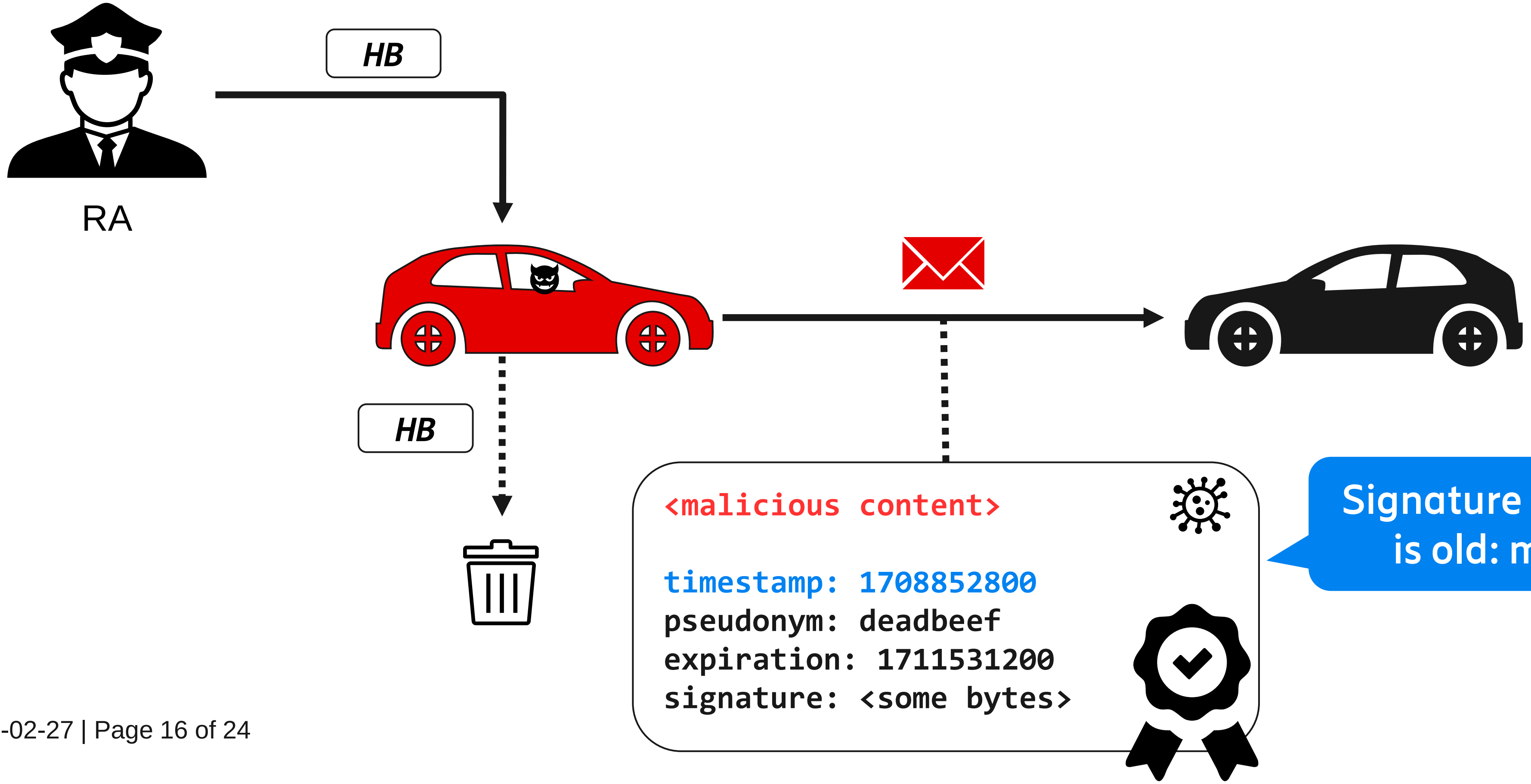
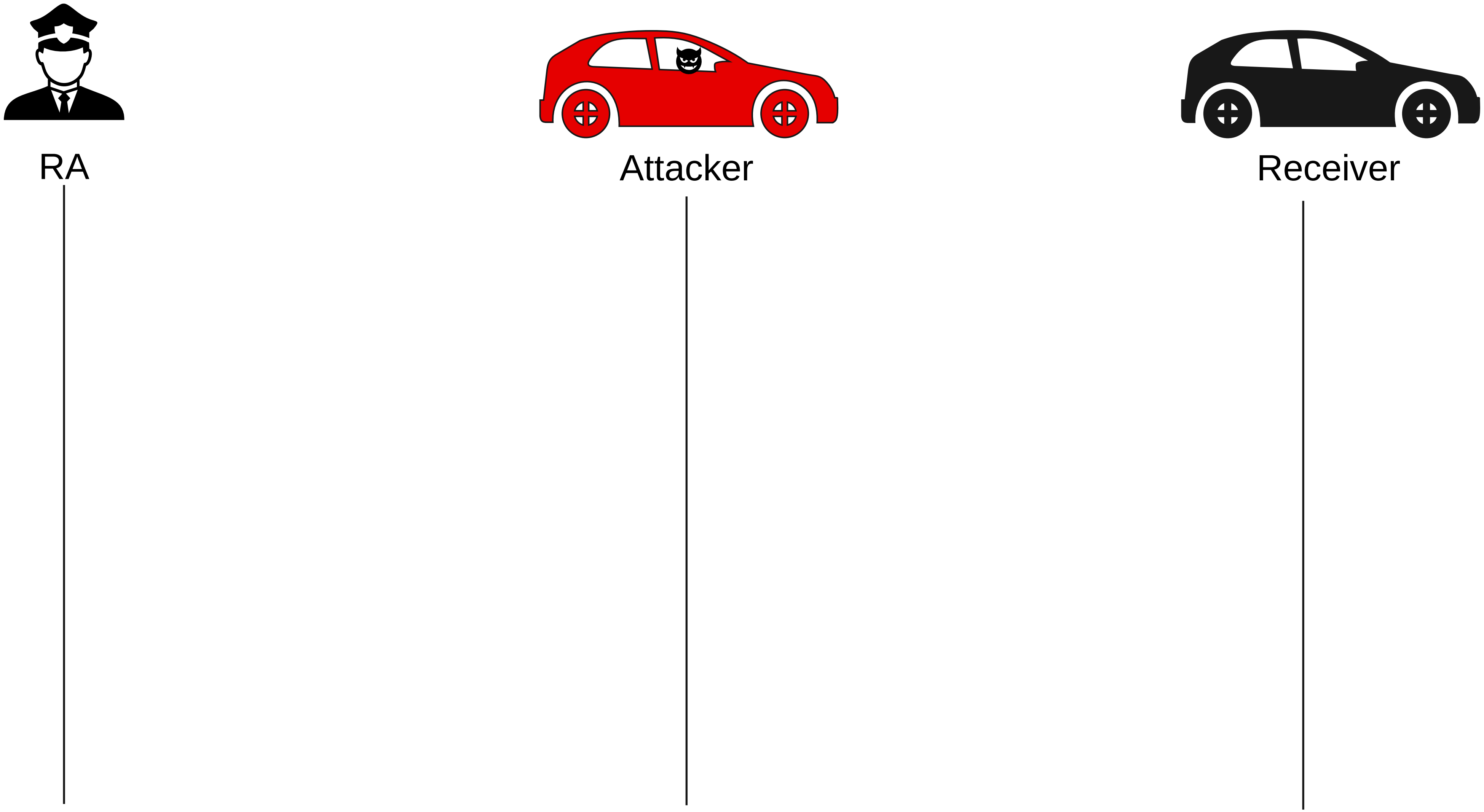


```
<malicious content>

timestamp: 1708852800
pseudonym: deadbeef
expiration: 1711531200
signature: <some bytes>
```

Signature is valid, but timestamp is old: message is discarded

Effective revocation time

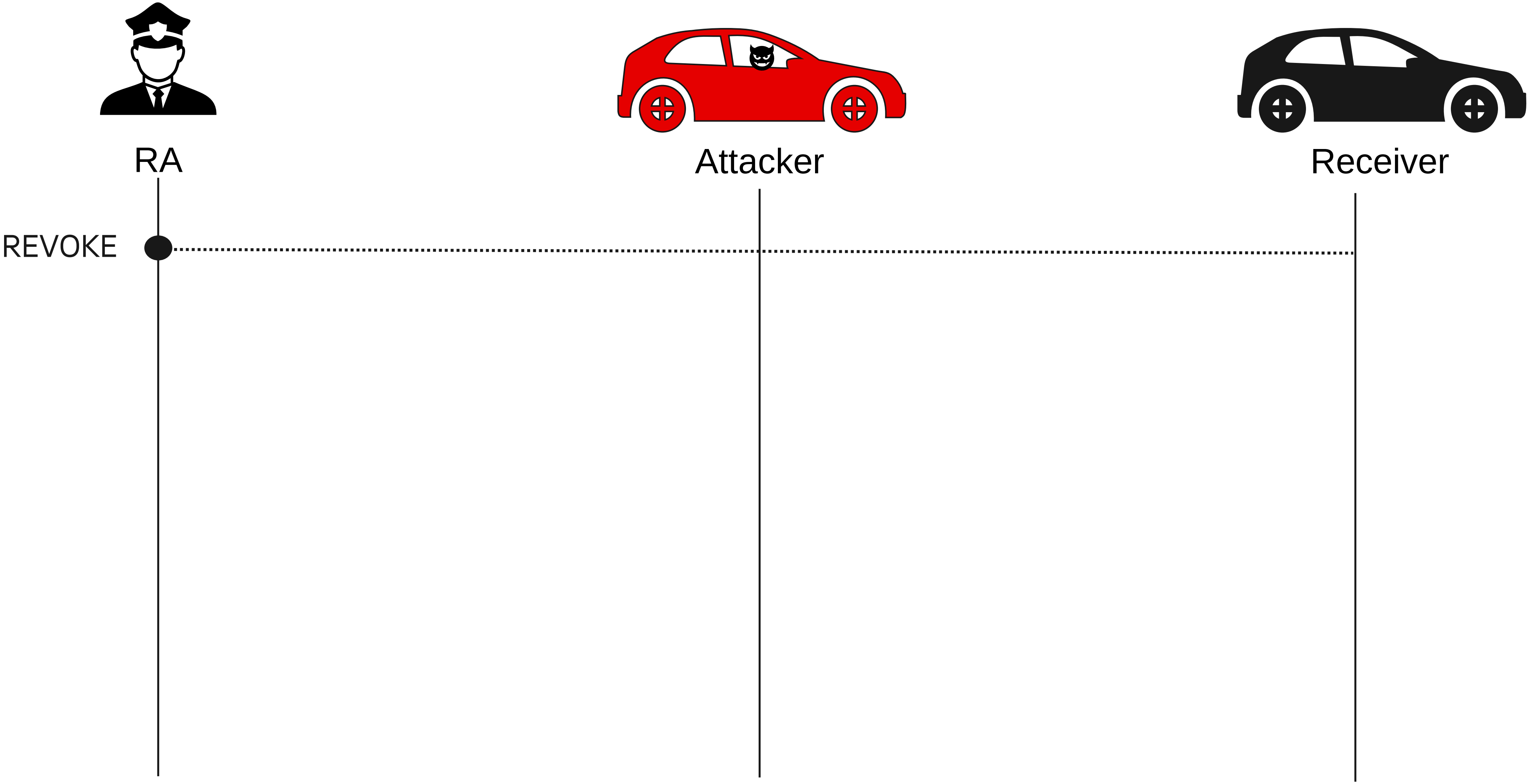


RA

Attacker

Receiver

Effective revocation time



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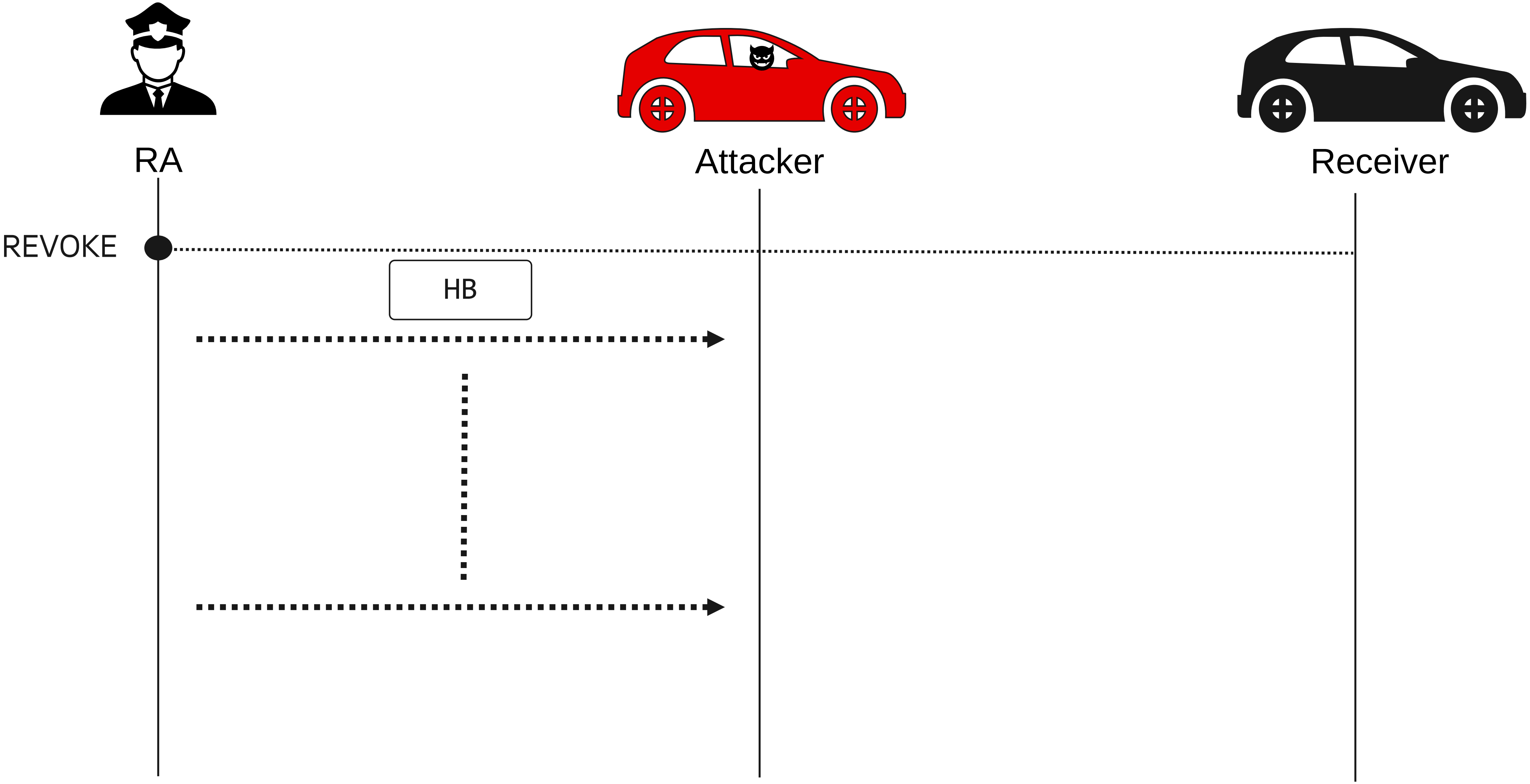

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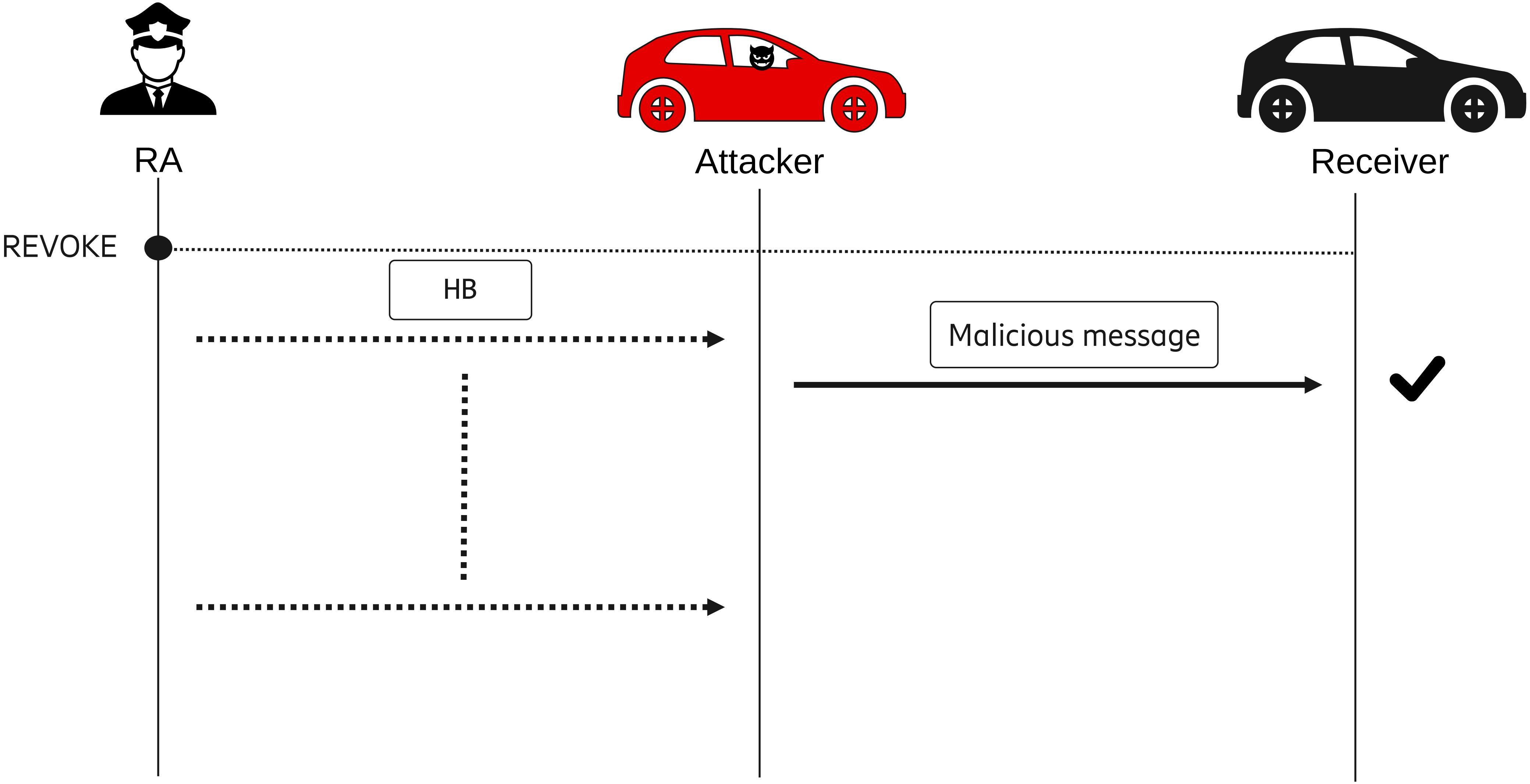

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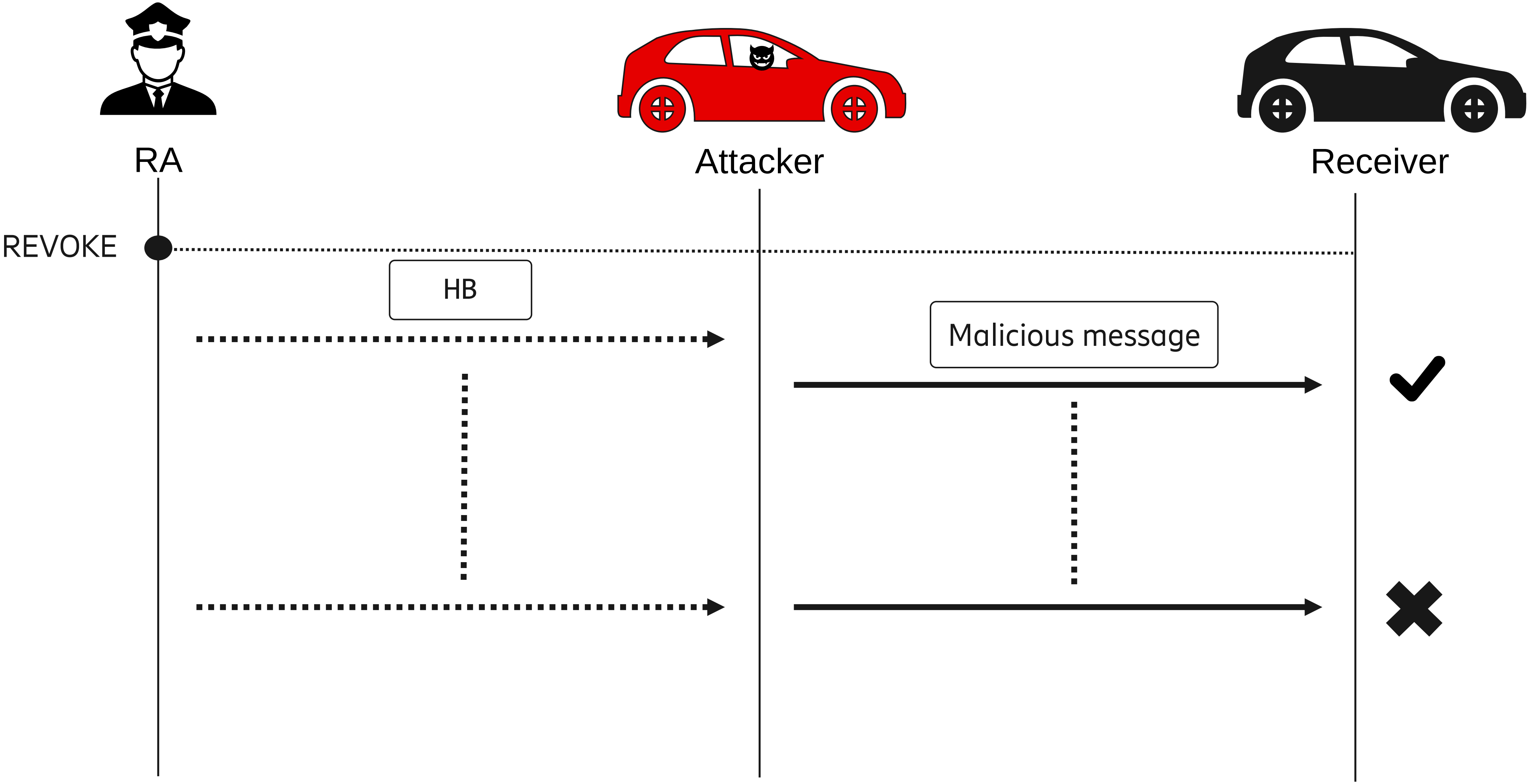

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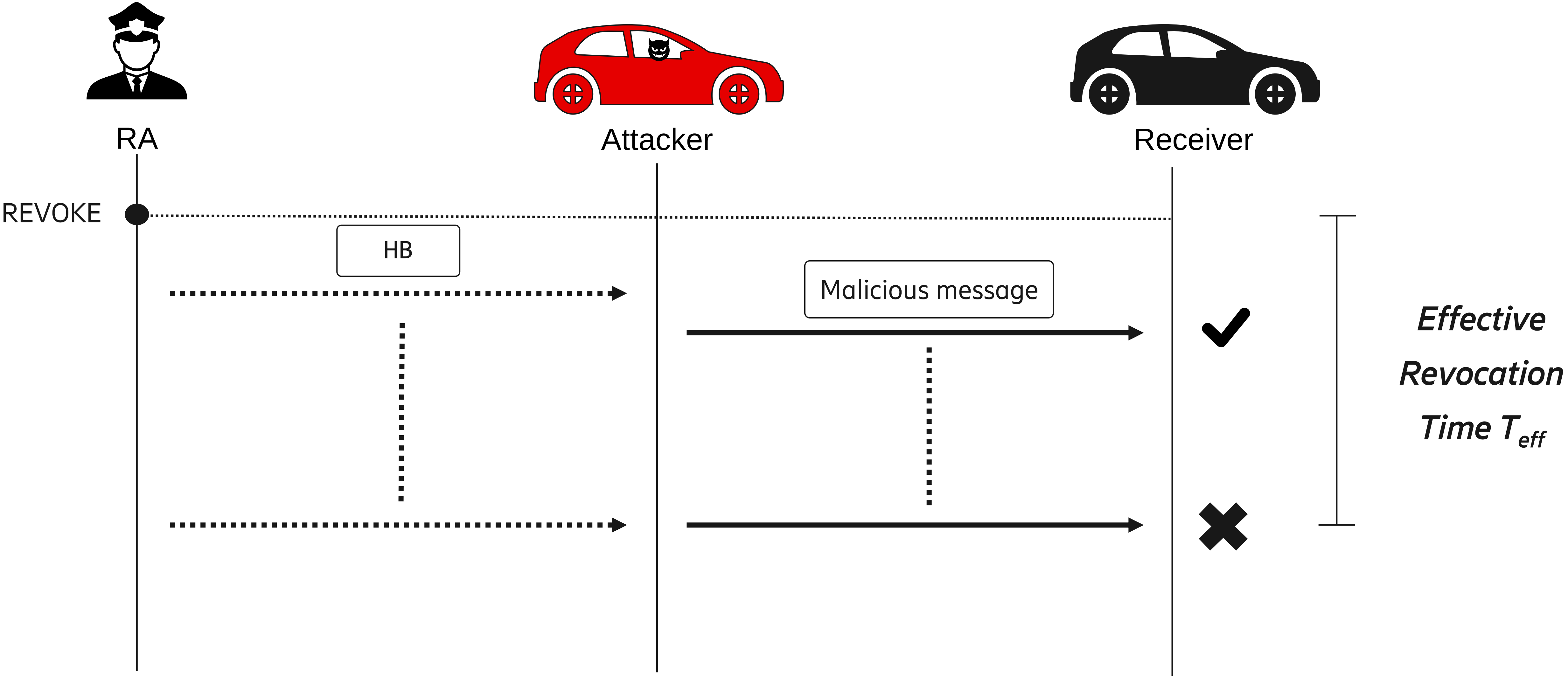

Goal #1: Security

Tamarin Prover. https://tamarin-prover.com

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```
lemma effective_revocation [heuristic=o "oracle.py"]:
"
All msg ps t #i . MessageAccepted(msg, ps, t)@i ==>
    Ex tv #j . SystemInitialized(tv)@j & j<i
    & not (
      Ex ps2 t_rev #k . RevocationIssued(ps2, t_rev)@k
        & GreaterThan(t, t_rev + tv)
    )
"
```

*If revocation occurs at time **t**, a receiver will discard all messages from the attacker when its internal time reaches* $\boldsymbol{t + T_v}$

Tamarin Prover. https://tamarin-prover.com

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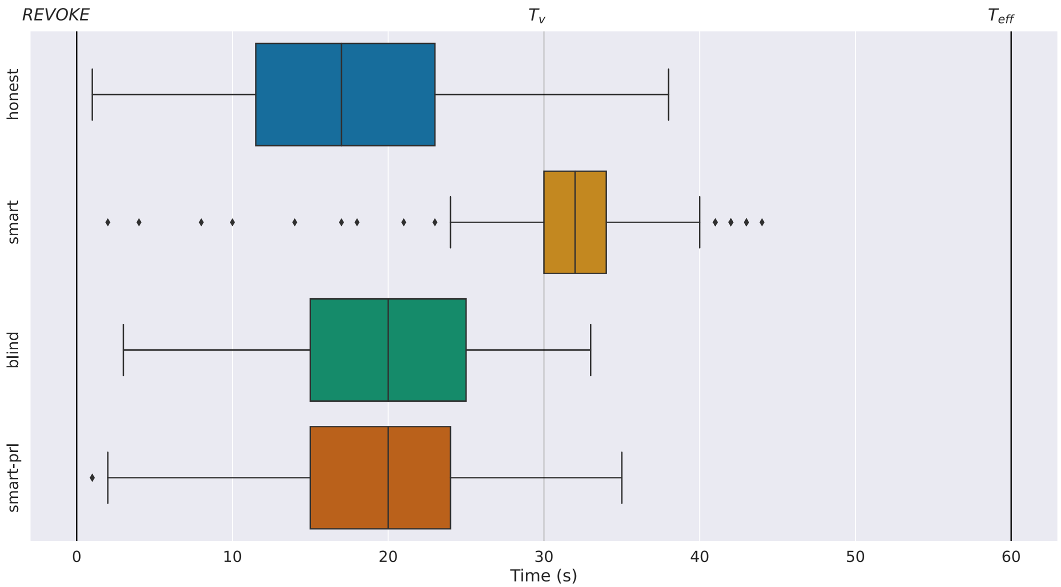
*If revocation occurs at time **t**, a receiver will discard all messages from the attacker when its internal time reaches* $\boldsymbol{t + T_v}$

→ Assuming that honest receivers are at most T_V behind the RA time: $T_{eff} = 2T_v$

Tamarin Prover. https://tamarin-prover.com

Goal #2: Usability

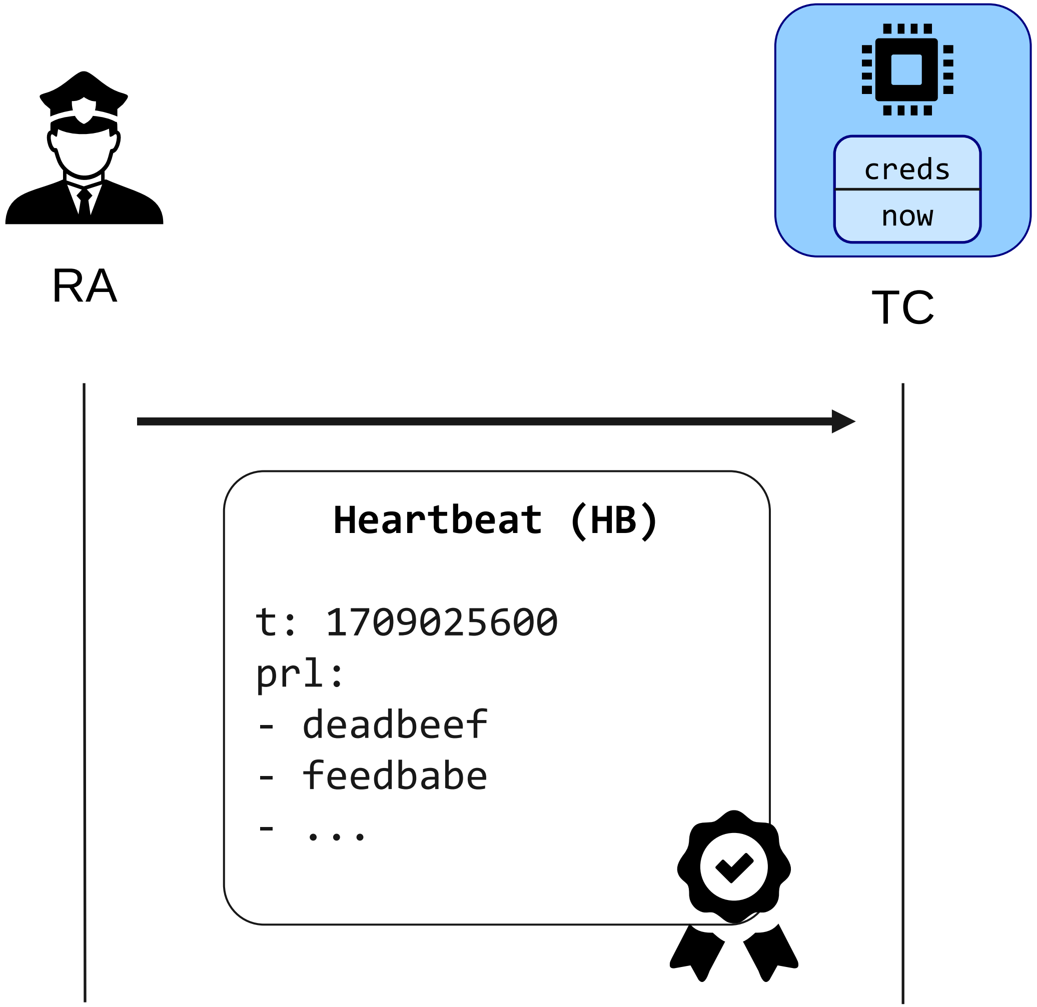


Distribution of revocation times for each class of attacker (lower is better)

- Simulation of a small V2X network in Kubernetes
  - Severe network malfunctions (delays, interruptions)
  - Attackers trying to evade revocation
- Evaluated different scenarios with different parameters → **more info on the paper!**

Kubernetes. https://www.kubernetes.io

What about efficiency?



Heartbeat (HB)

```
t: 1709025600
prl:
- deadbeef
- feedbabe
- ...
```

Signature check

Freshness check

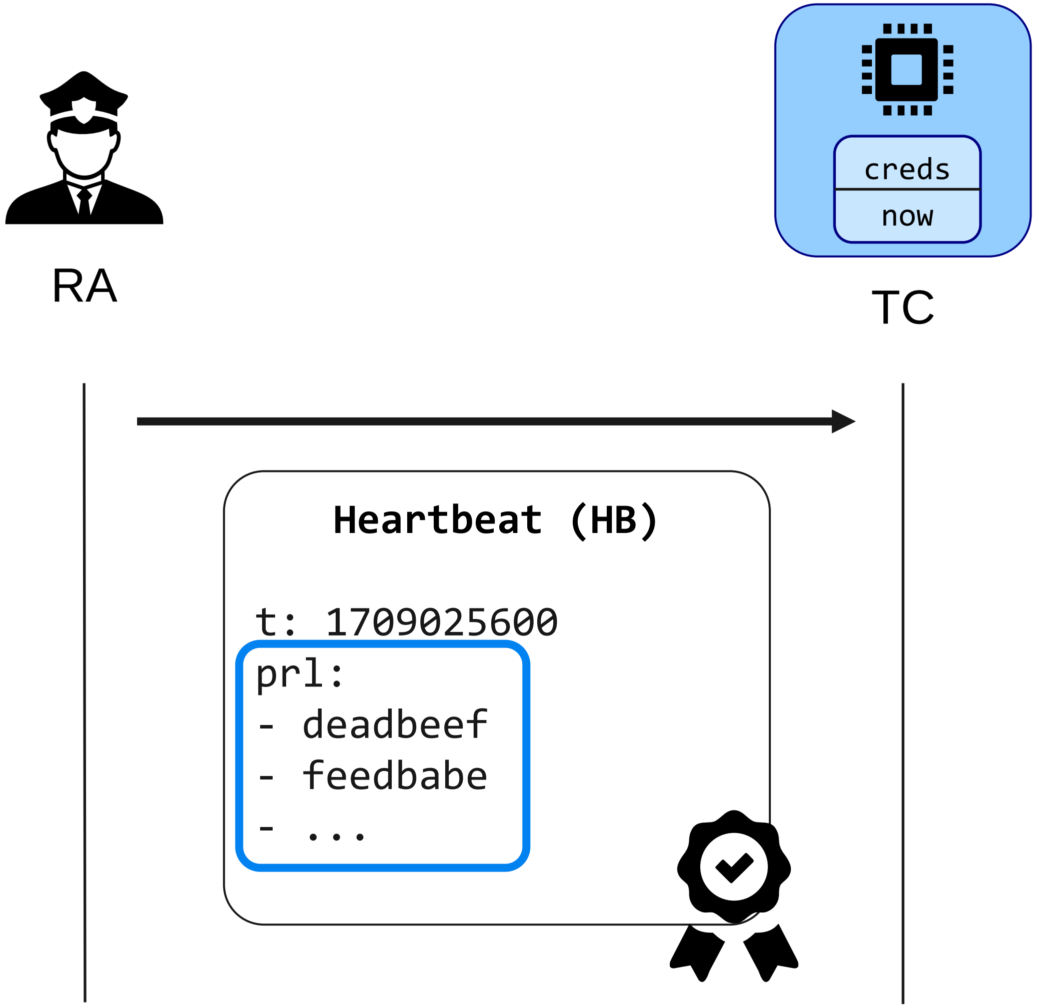
$t >= now - T_v$

Time synchronization

$now = t$

Revocation check

What about efficiency?



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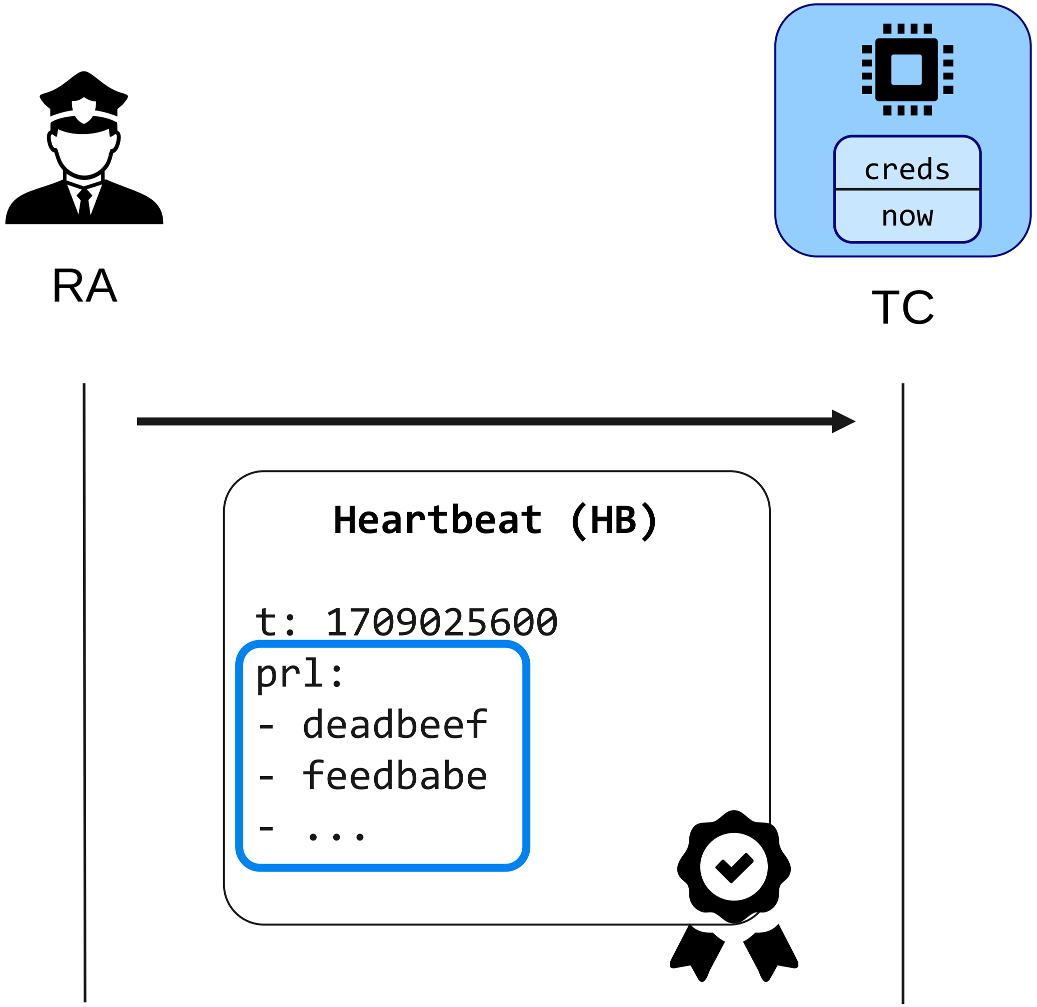
Revocation check

What about efficiency?



Heartbeat (HB)

```
t: 1709025600
prl:
- deadbeef
- feedbabe
- ...
```

Fail? Discard, TC is out of sync
(re-synchronization needed, e.g., via re-enrollment)

Freshness check

$t >= now - T_v$ && $t <= now + T_v$

Time synchronization

now = t

Revocation check

Goal #3: Efficiency

```
lemma no_heartbeats_processed_after_tolerance [heuristic=o
"oracle.py"]:
"
All prl t_hb t #i . HeartbeatProcessed(<prl, t_hb>, t)@i ==>
    Ex tv #j . SystemInitialized(tv)@j & j<i
    & not (
      Ex ps t_rev #k . RevocationIssued(ps, t_rev)@k
        & k<i
        & GreaterThan(t_hb, t_rev + tv)
    )
"
```

If revocation occurs at time ***t****, the attacker will not be able to process any HBs containing timestamp >=* ***t*** **+** T_v

Goal #3: Efficiency

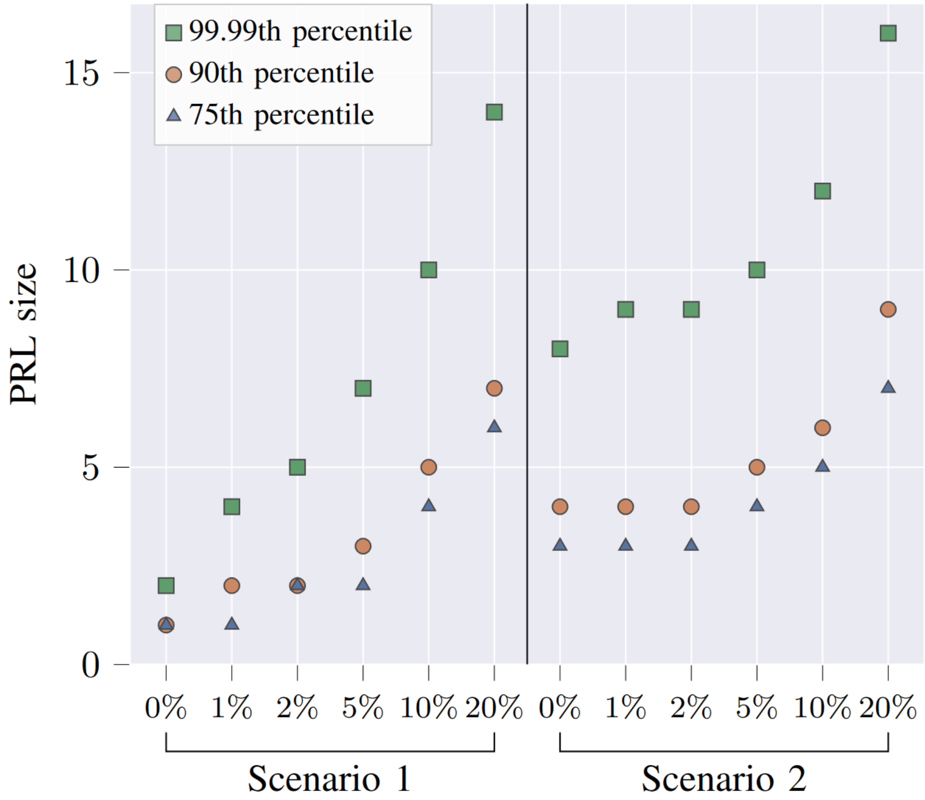
```
lemma no_heartbeats_processed_after_tolerance [heuristic=o
"oracle.py"]:
"
All prl t_hb t #i . HeartbeatProcessed(<prl, t_hb>, t)@i ==>
    Ex tv #j . SystemInitialized(tv)@j & j<i
    & not (
      Ex ps t_rev #k . RevocationIssued(ps, t_rev)@k
        & k<i
        & GreaterThan(t_hb, t_rev + tv)
    )
"
```

*If revocation occurs at time **t**, the attacker will not be able to process any HBs containing timestamp >=* $\boldsymbol{t} + T_v$

→ Each revoked credential can be safely removed from the HB after $T_{prl} = T_v$ since insertion

Goal #3: Efficiency

Lower is better



% of attackers in the network

(n = 800, T_{prl} = 30)

- PRL as a Markov Model
  - Adding elements with probability *p*
  - Removing elements with probability *$1/T_{prl}$*

- Evaluated different scenarios with different parameters → **more info on the paper!**

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  - Requires changes in V2X standards

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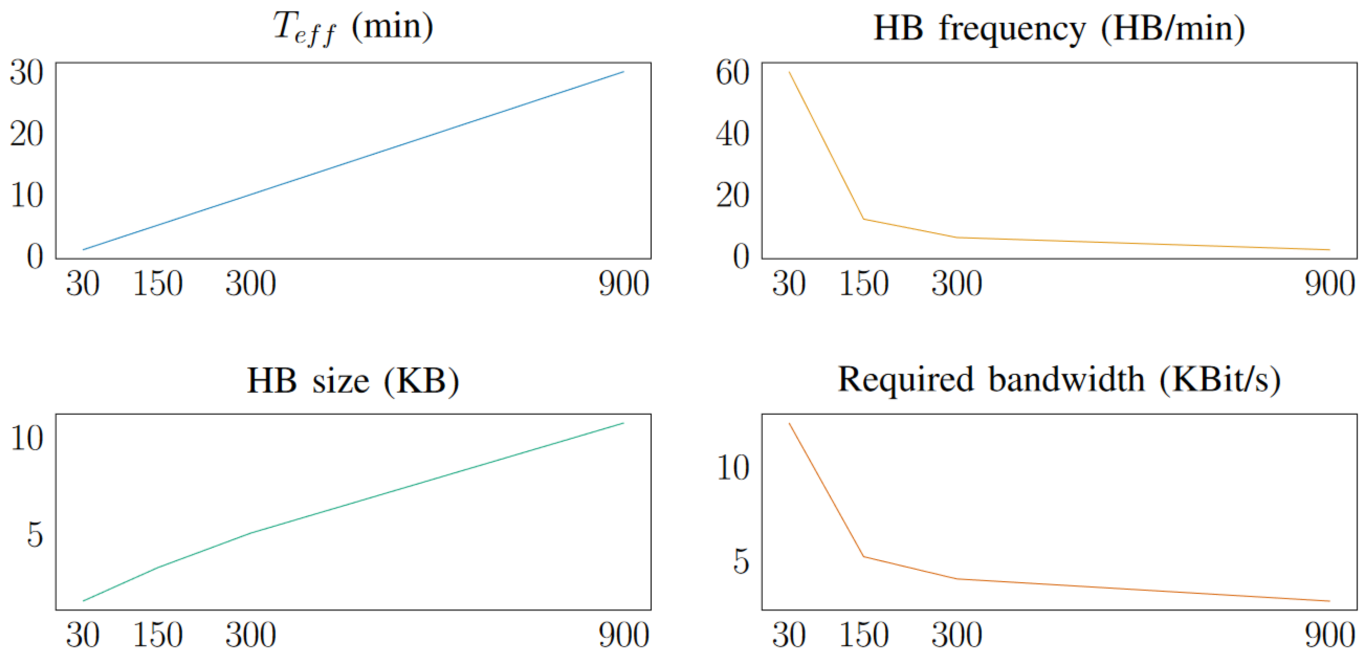


X axis: values of T_V in seconds

Efficient and Timely Revocation of V2X Credentials

Artifact Evaluated
NDSS
Available
Functional
Reproduced

- A formally verified revocation scheme based on trusted computing and self-revocation
- Guaranteed upper bound on revocation time (*“effective revocation”*)
- Tolerance parameter T_V gives a trade-off between security, usability and efficiency
- Open-source!*

Paper & Artifacts

Gianluca Scopelliti, Christoph Baumann, Fritz Alder, Eddy Truyen, Jan Tobias Mühlberg.

Network and Distributed System Security (NDSS) Symposium 2024. San Diego, CA.

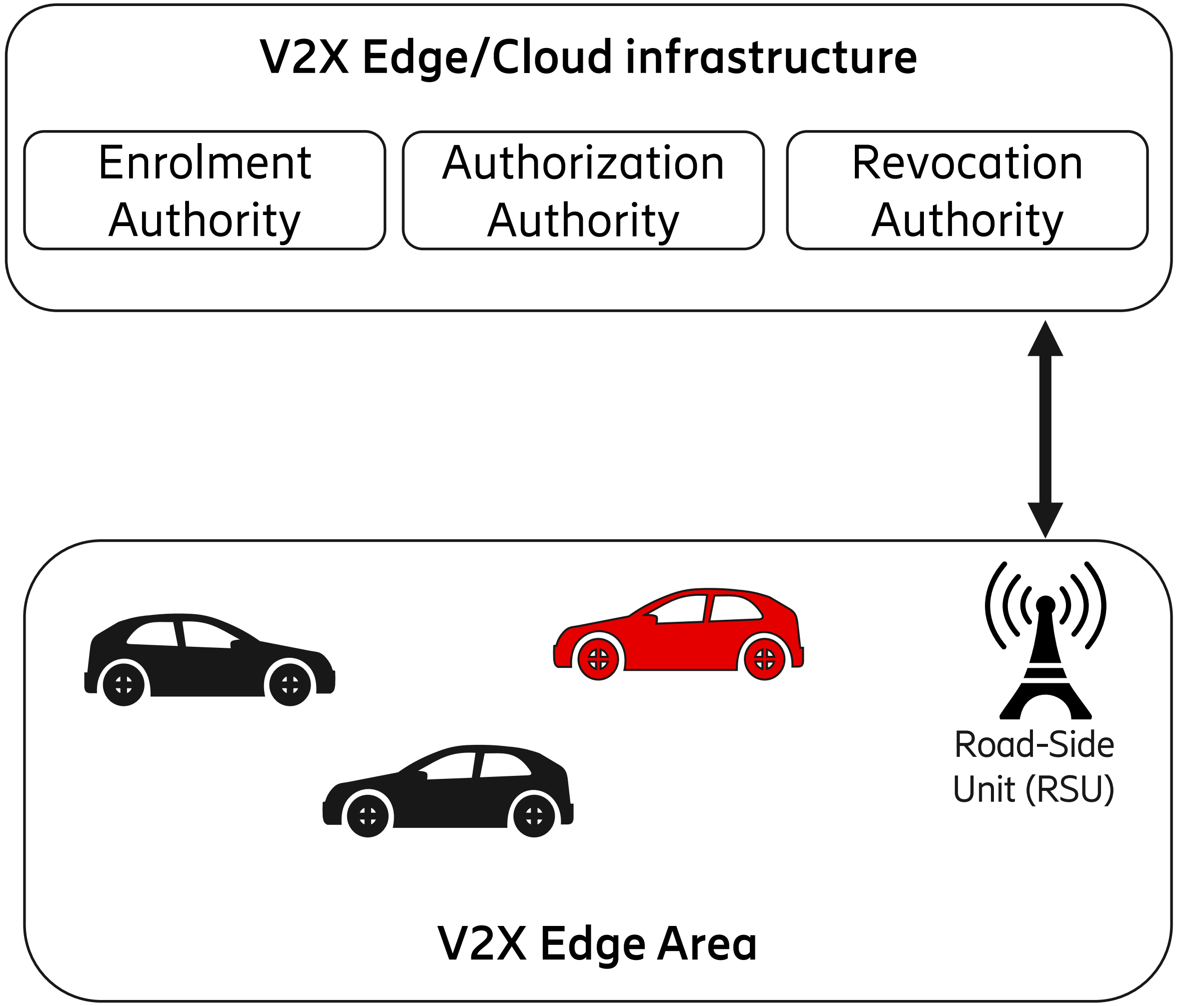
gianluca.scopelliti@ericsson.com

*github.com/EricssonResearch/v2x-self-revocation

ERICSSON   KU LEUVEN   DistriNet   ULB   CYBERSECURITY RESEARCH CENTER

Backup

System and attacker model

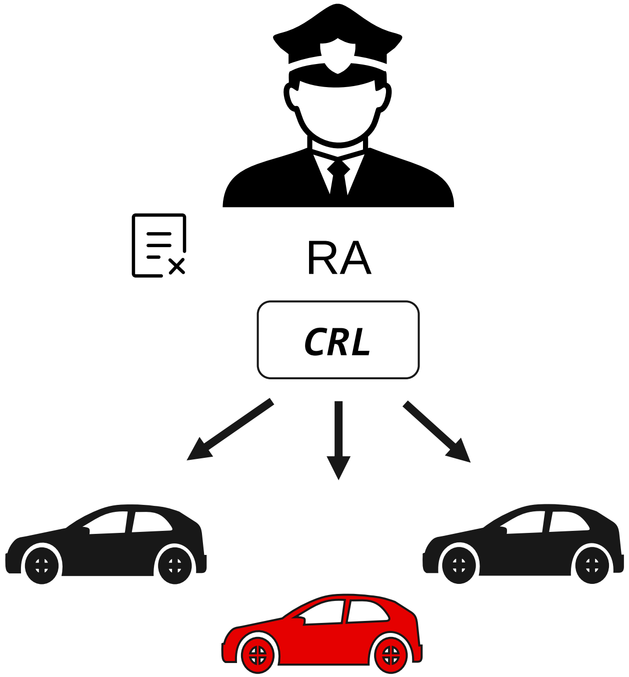


- **Attacker model:**
  - V2X Edge/Cloud infrastructure: **trusted**
  - Vehicles: **potentially malicious**

- **Attacker's goal:**
  - Obtain V2X credentials / compromise vehicle
  - Spread malicious information

State of the art in revocation schemes

Active revocation (IEEE 1609.2.1 – SCMS [1])



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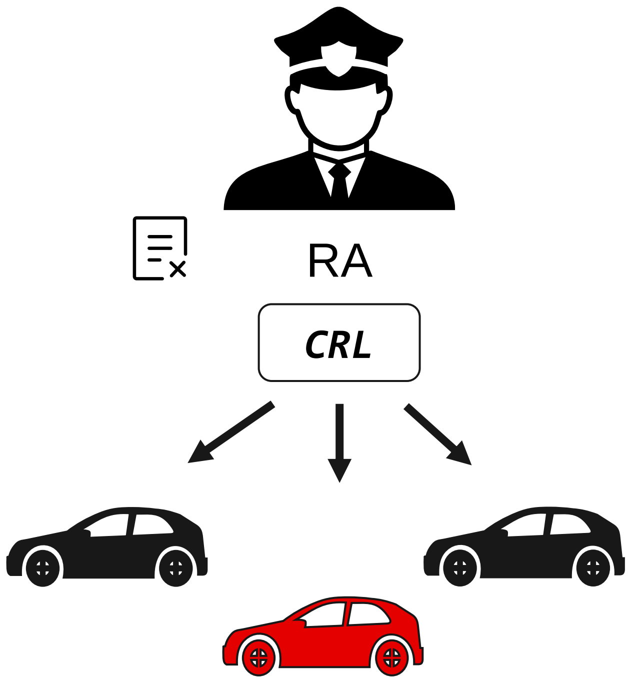

- **Relatively fast response**: revocation is achieved as soon as CRL update is received
  - Delays? Network interruptions?

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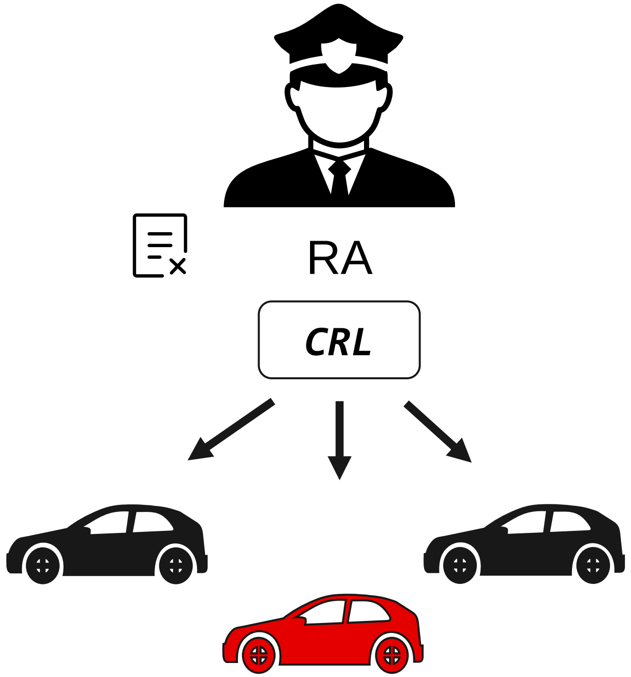

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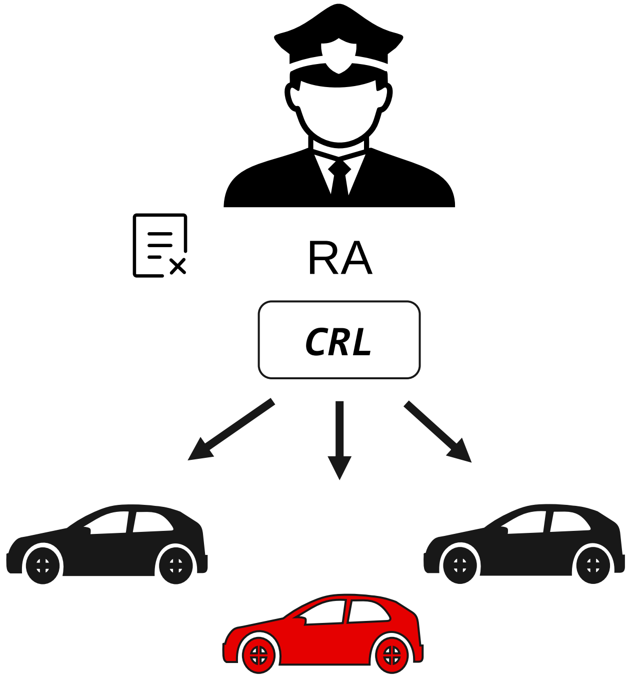

- **Relatively fast response**: revocation is achieved as soon as CRL update is received
  - Delays? Network interruptions?
- **High latency:** each received message requires checking the pseudonym against the CRL
- **Not scalable**: CRLs grow bigger and bigger over time

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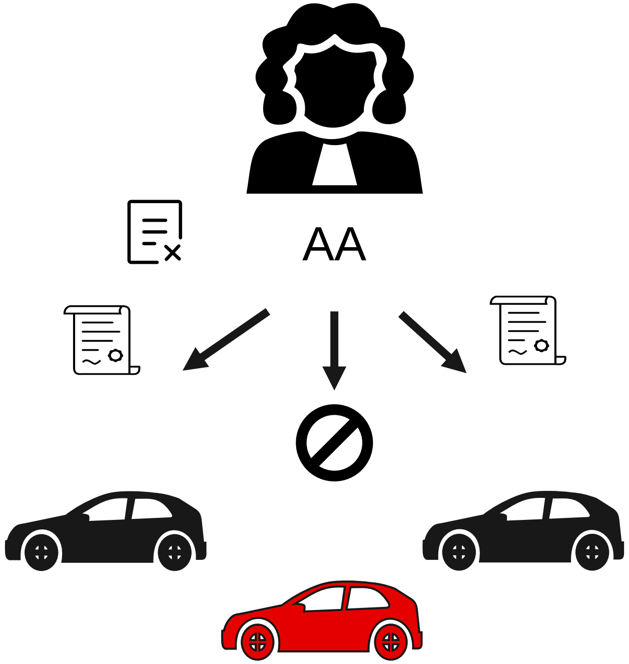
State of the art in revocation schemes

Passive revocation (ETSI TS 102 941 [2])



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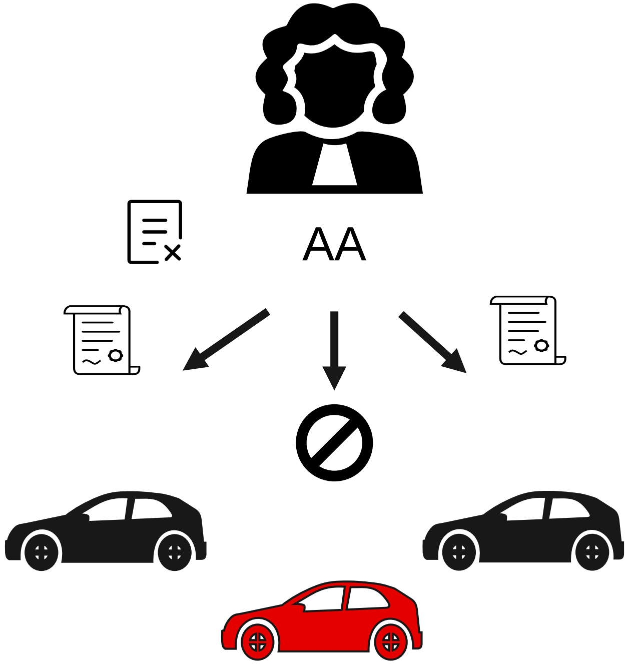

- **Slow response**: revocation is achieved when all the attacker’s pseudonyms have expired

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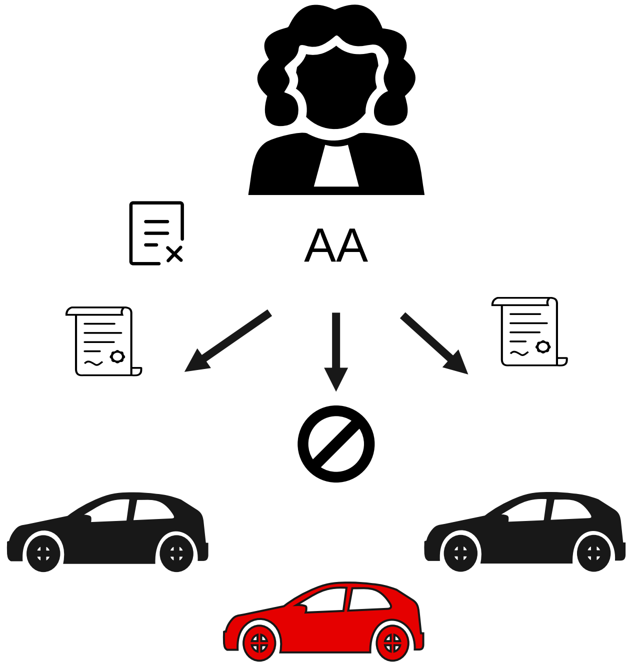

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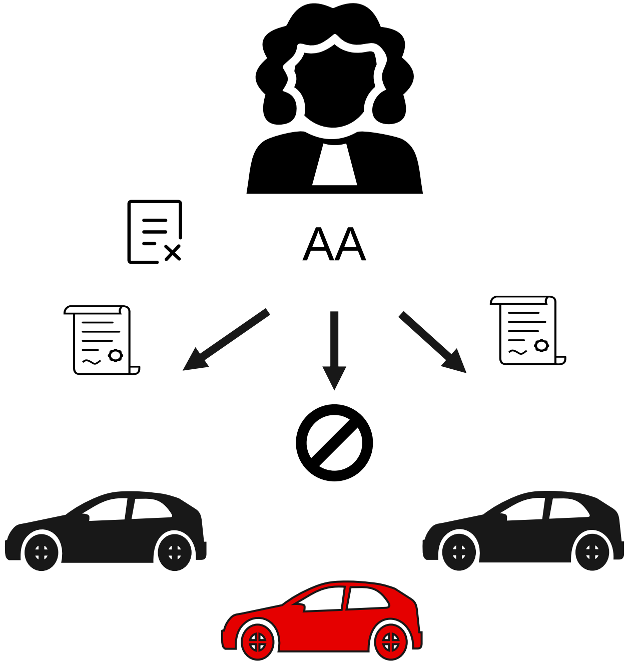

- **Slow response**: revocation is achieved when all the attacker’s pseudonyms have expired
- **Low latency:** no additional verification checks are required
- **Not scalable**: Increased traffic and computational resources due to frequent pseudonym change

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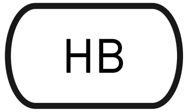
Processing a HB: flowchart



HB

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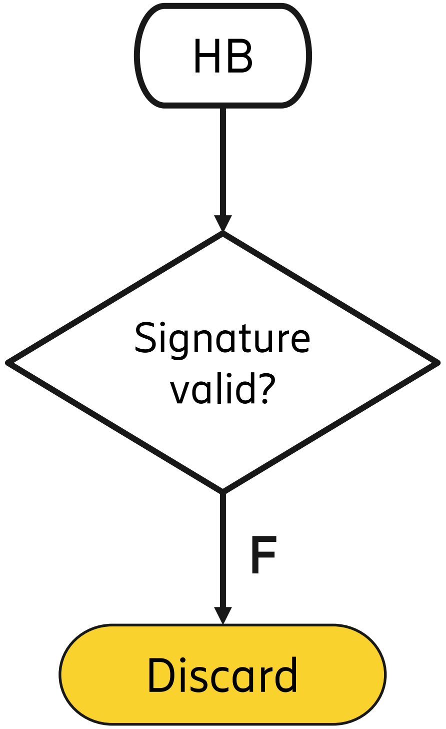

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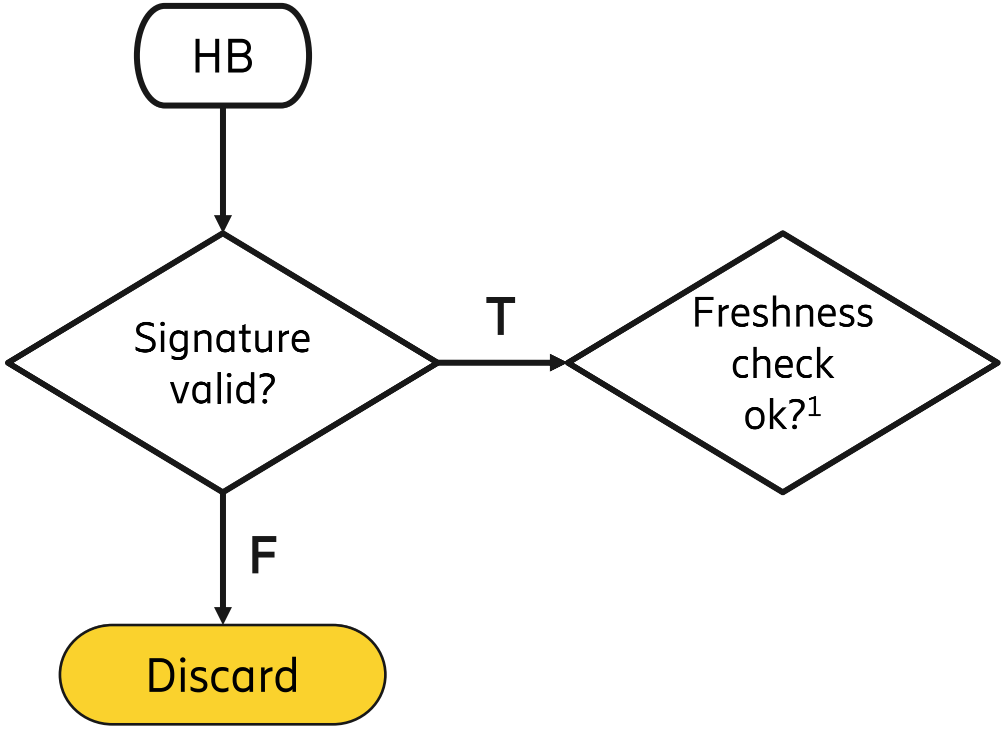
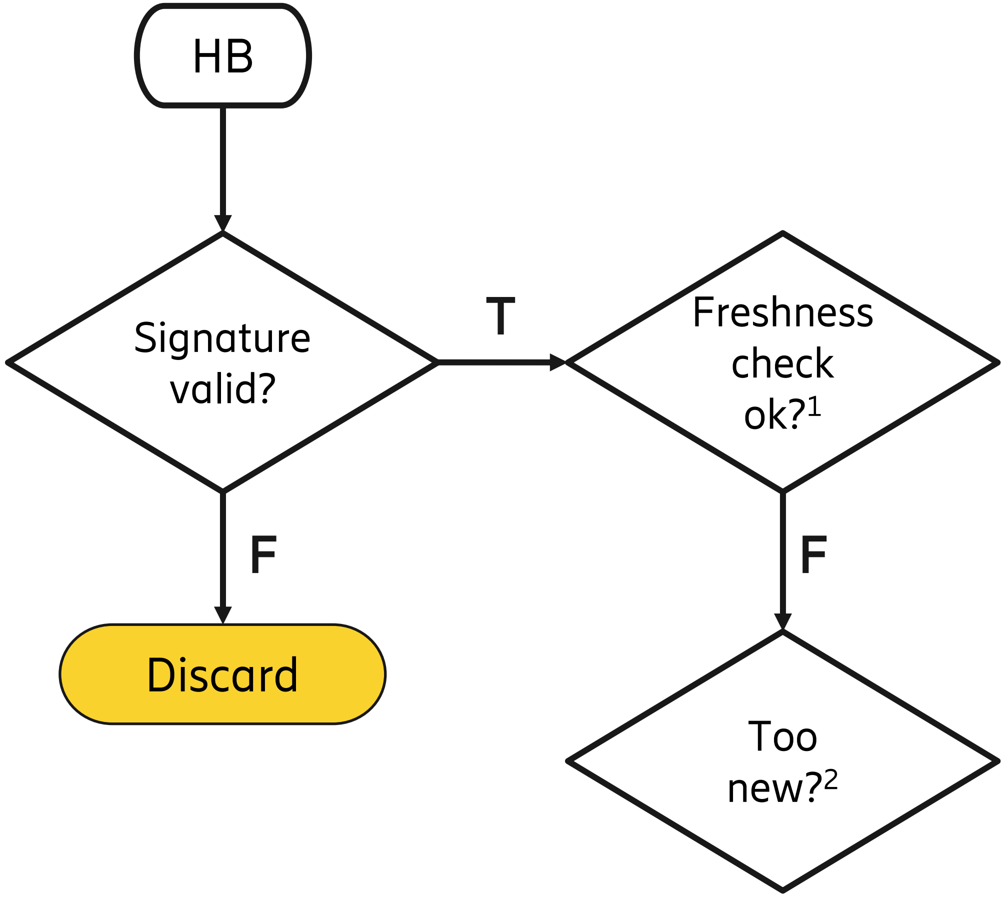


[1] $t - T_V <= t_{HB} <= t + T_V$

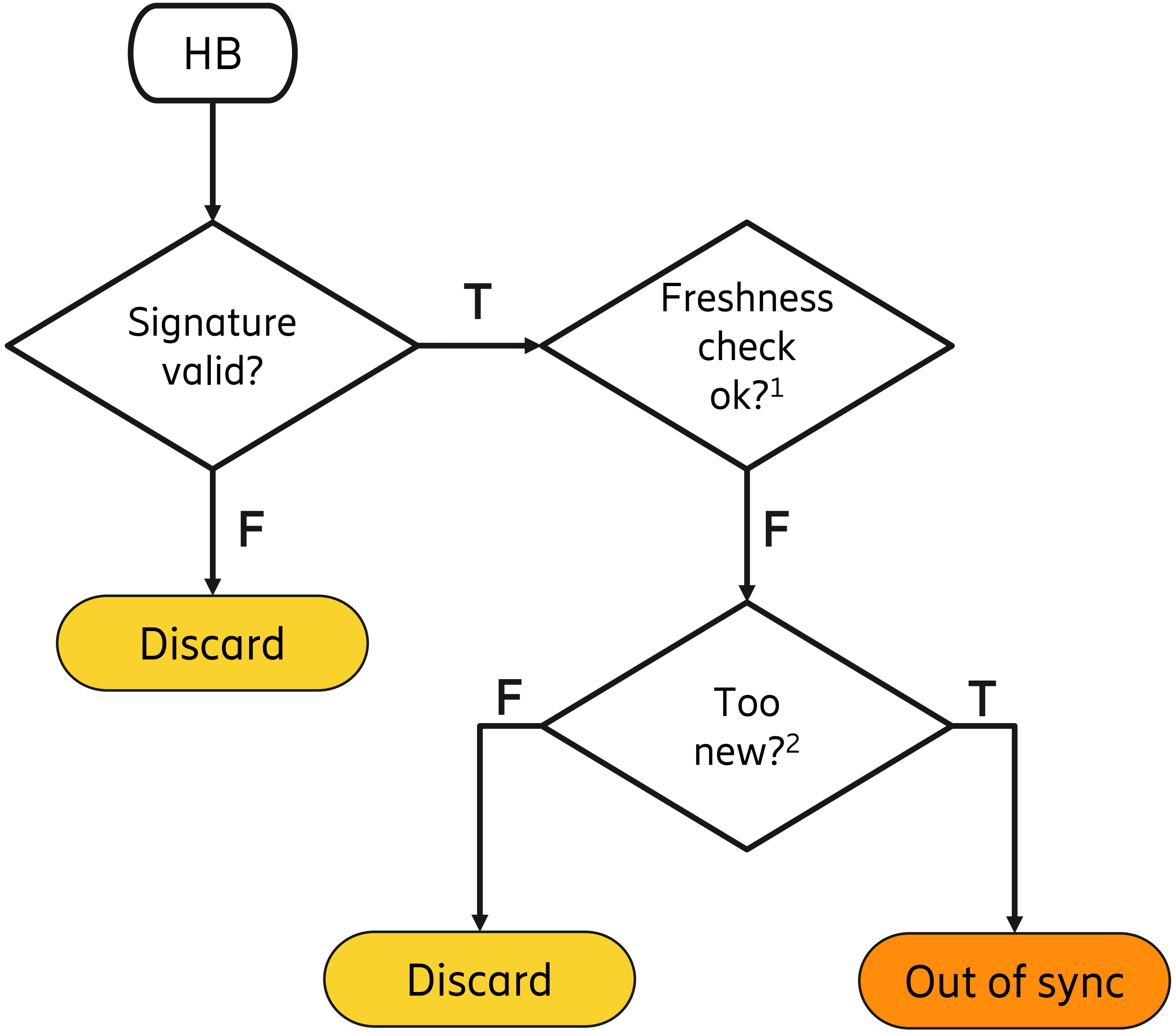
Processing a HB: flowchart



1) $t - T_V <= t_{HB} <= t + T_V$

2) $t_{HB} > t + T_V$

Processing a HB: flowchart



Needs communication with infrastructure (e.g., re-enrolment)

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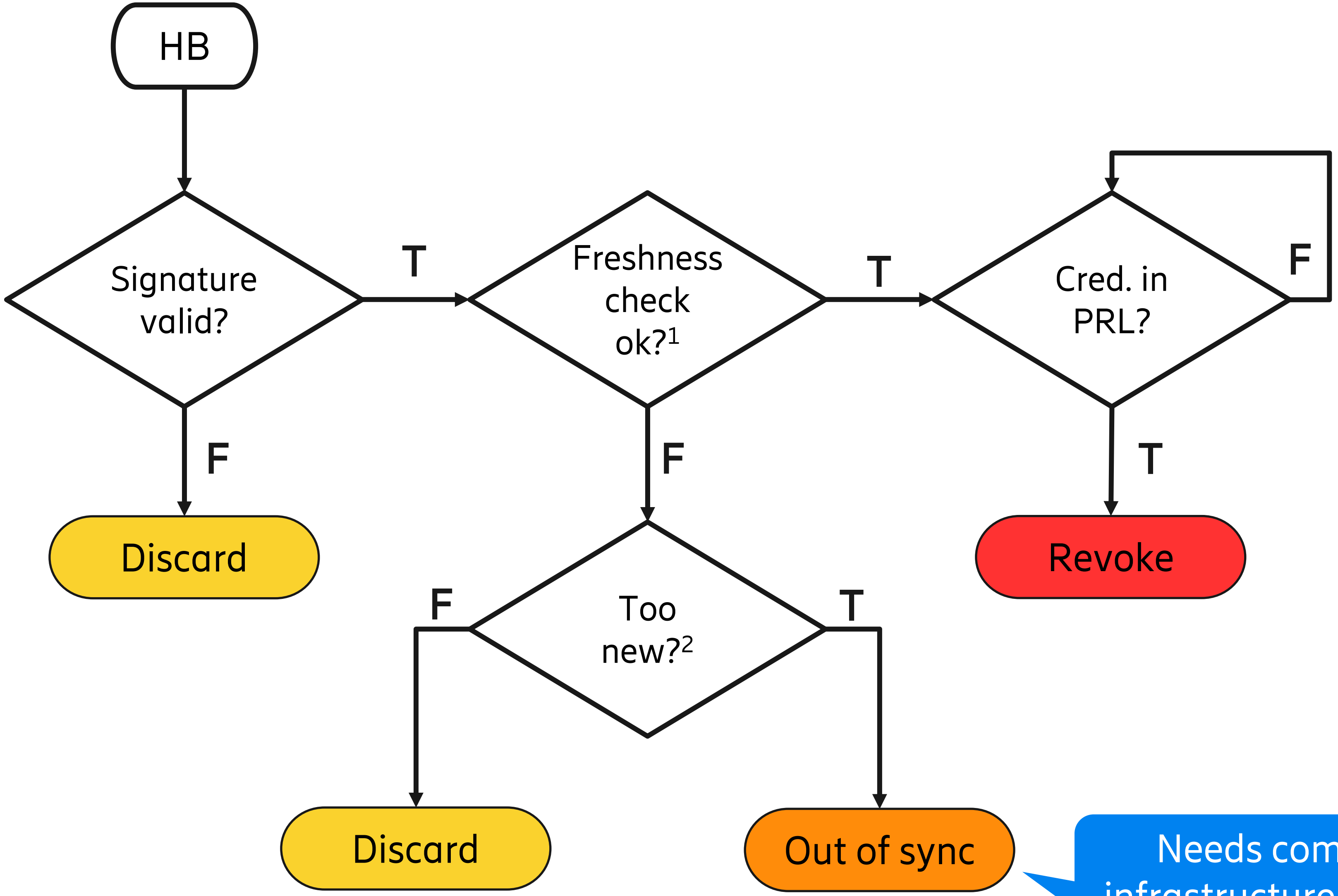

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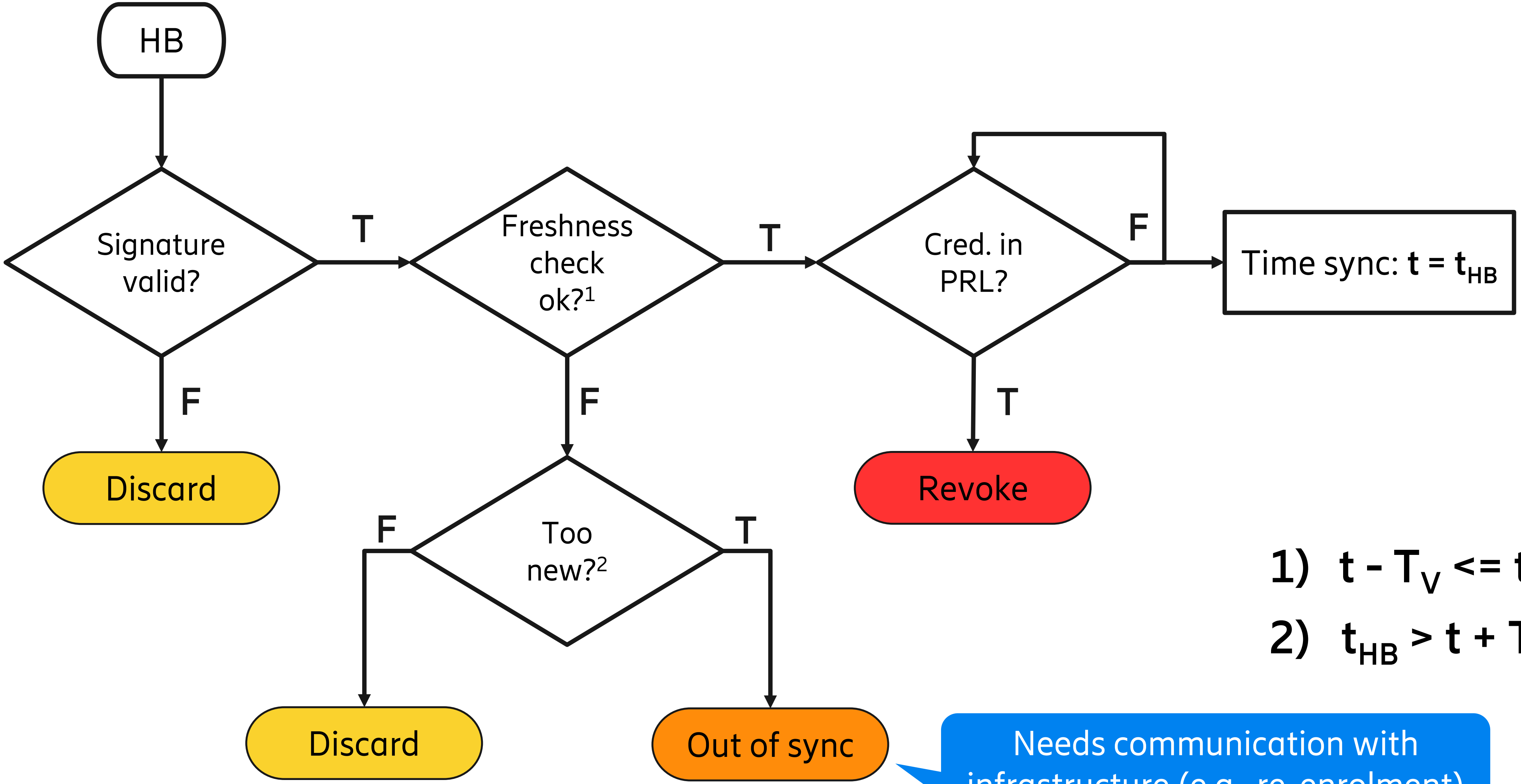

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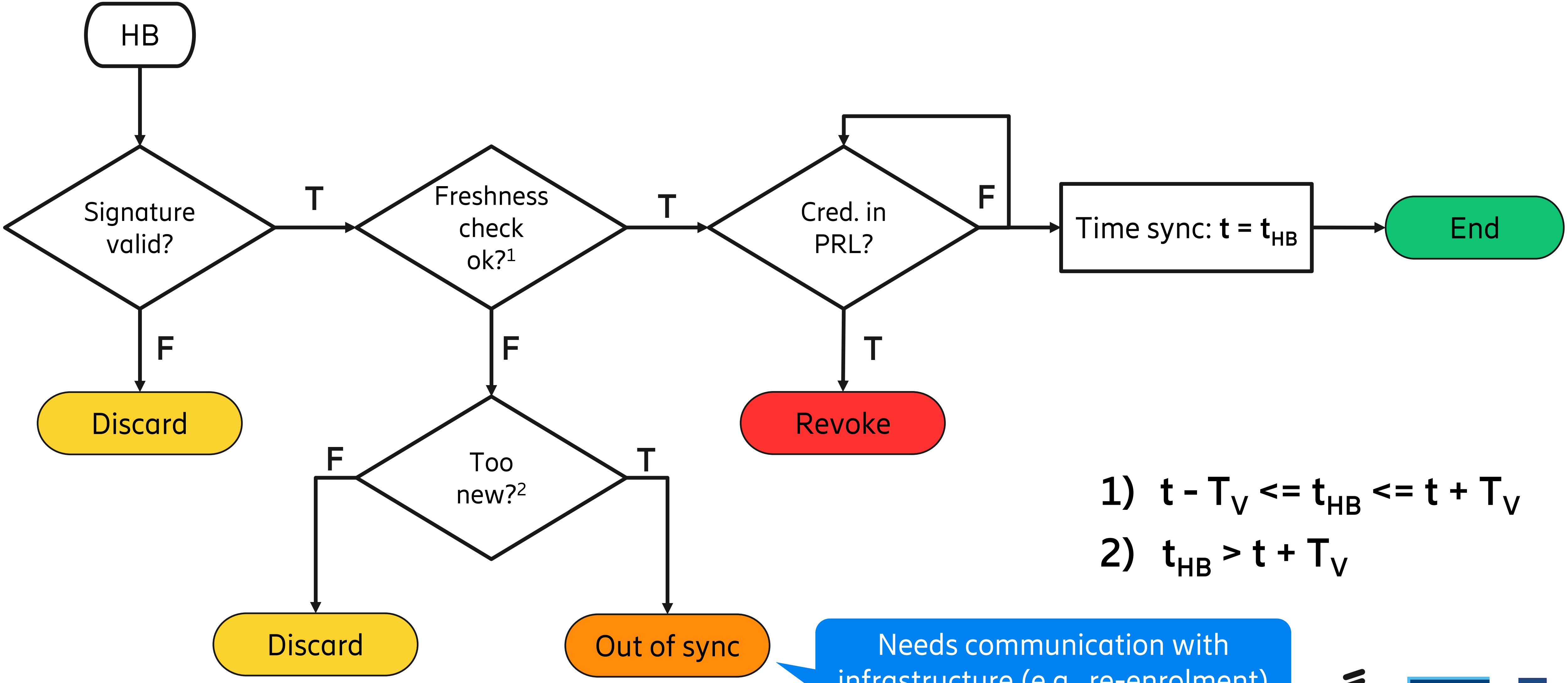

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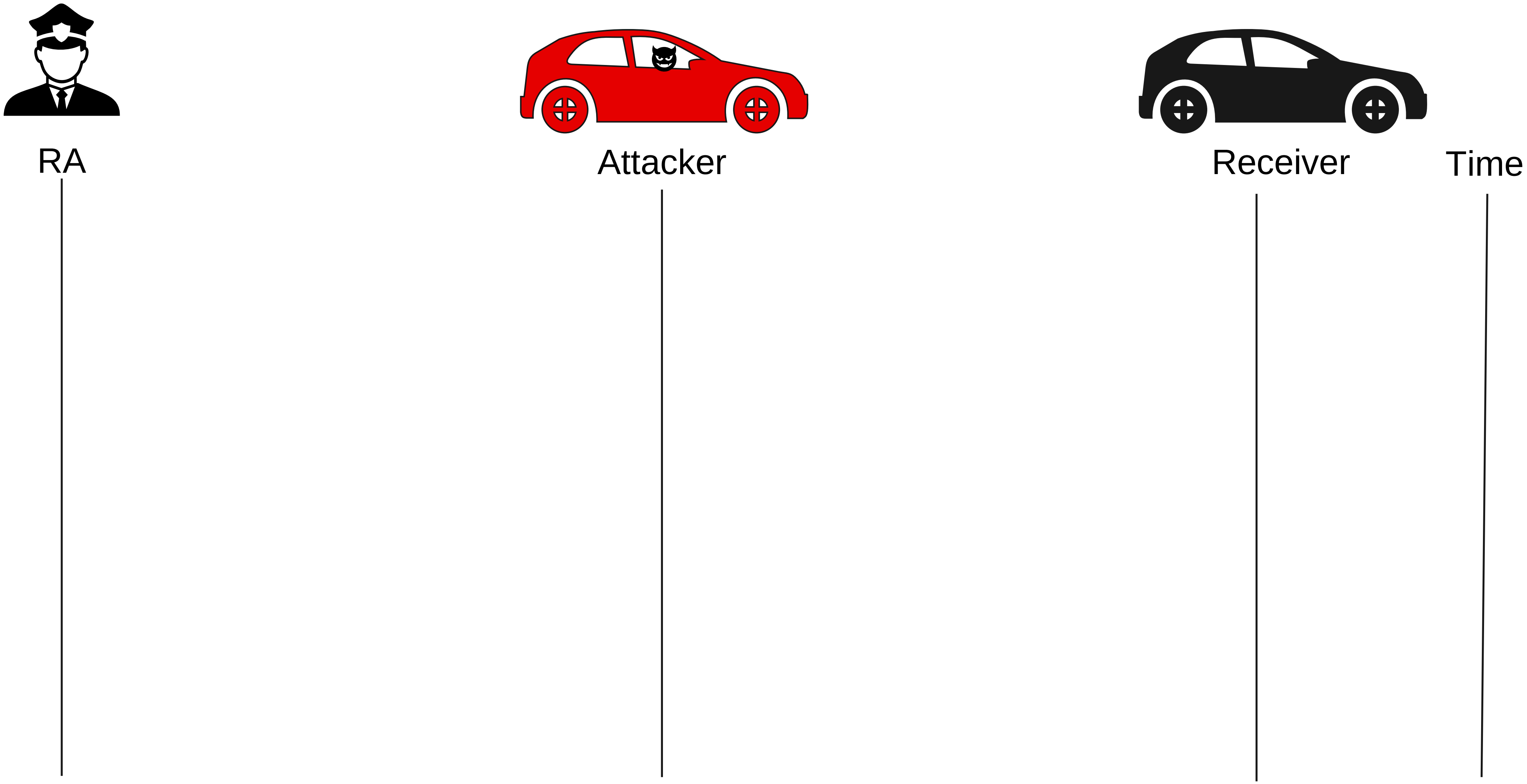
Worst-case T_{eff}



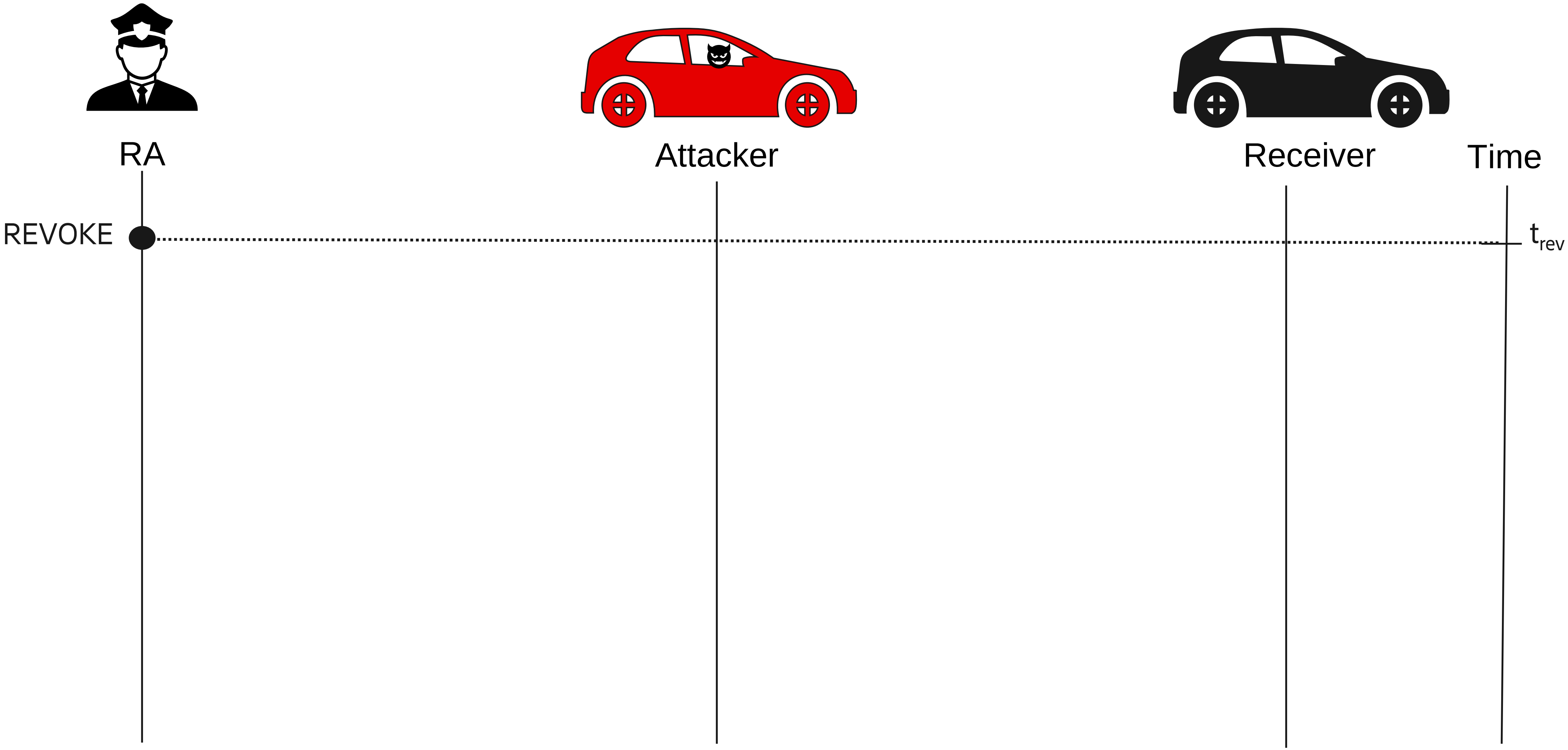
RA

Attacker

Receiver

Time

Worst-case T_{eff}



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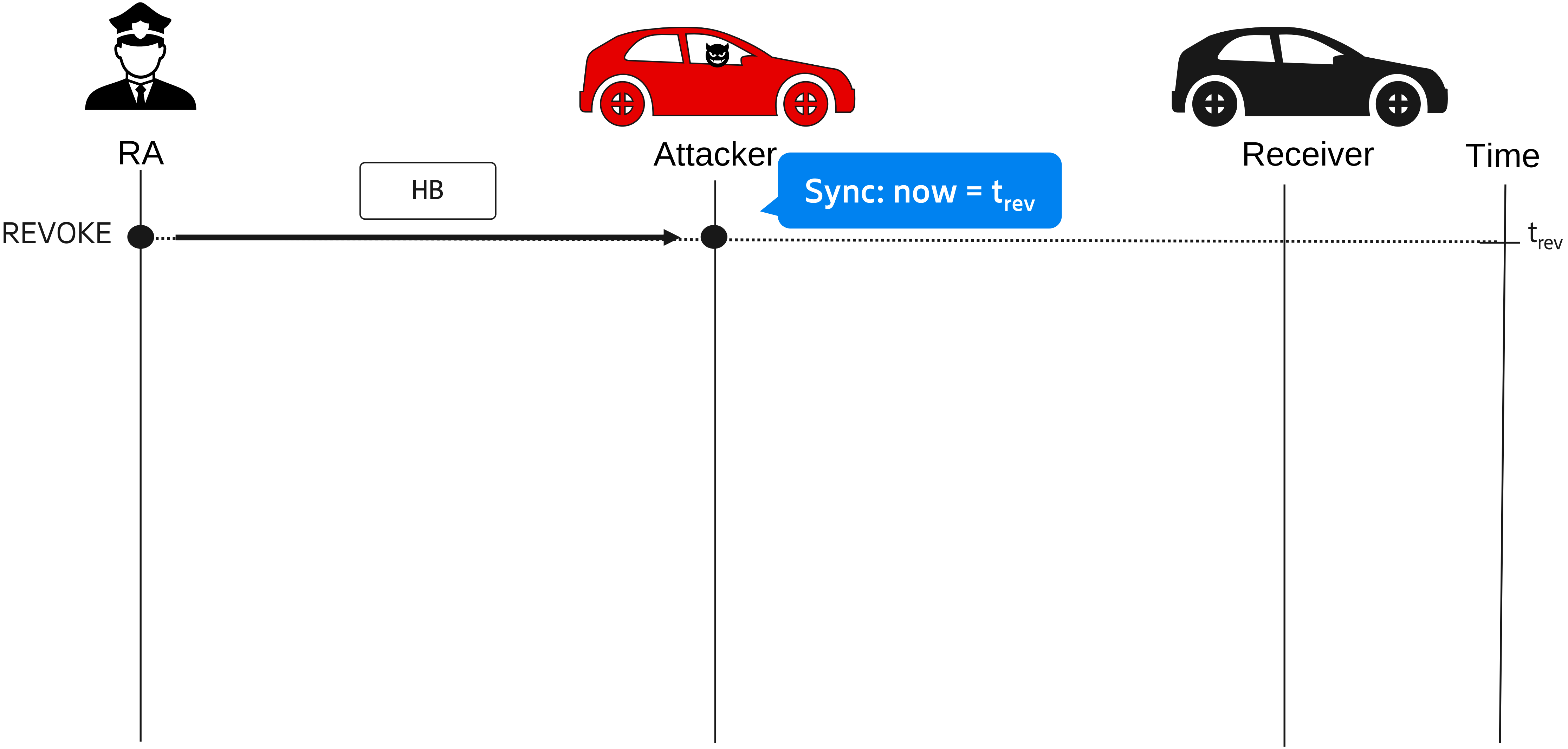


RA

Attacker

Receiver

Time

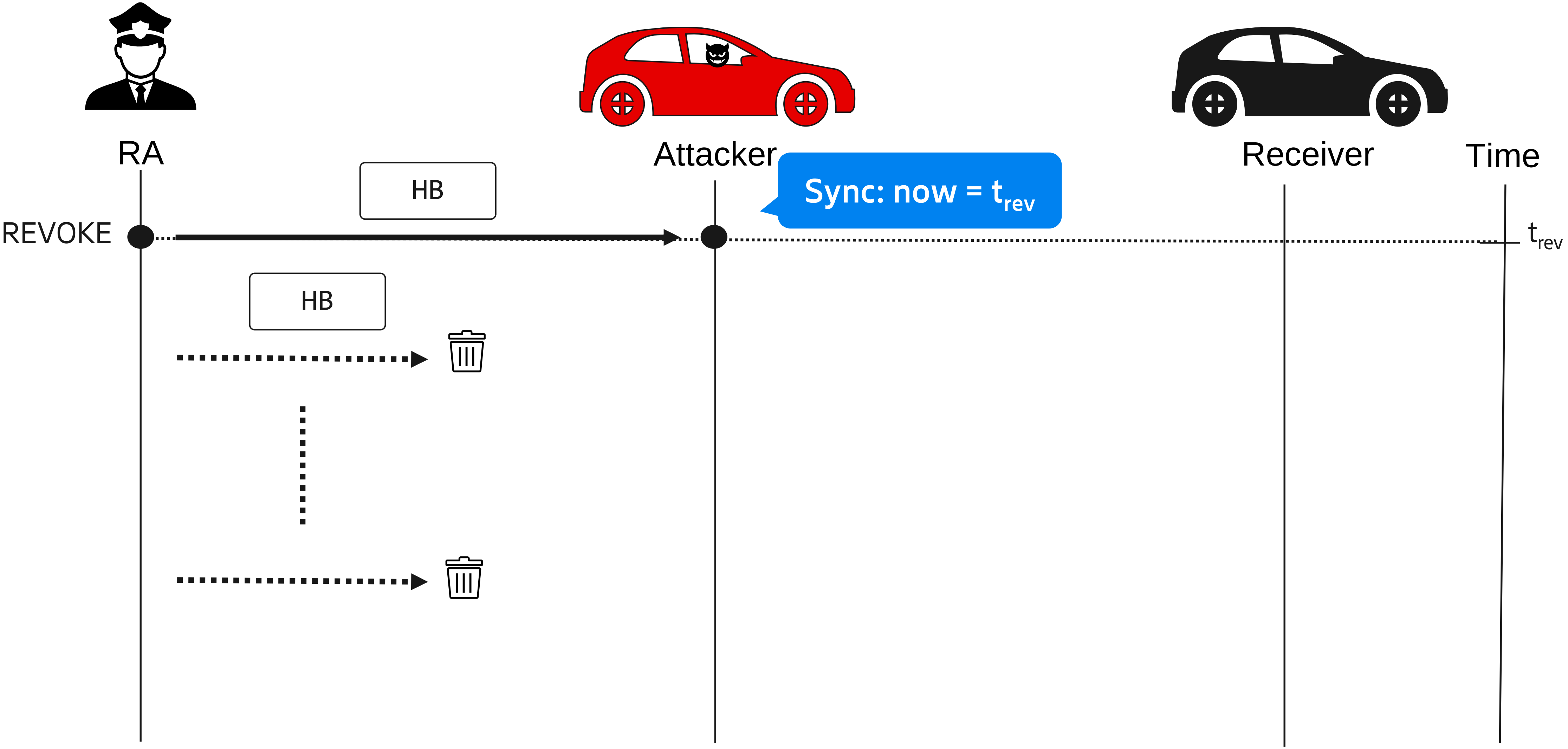
HB

REVOKE

Sync: now = t_{rev}

t_{rev}

Worst-case T_{eff}



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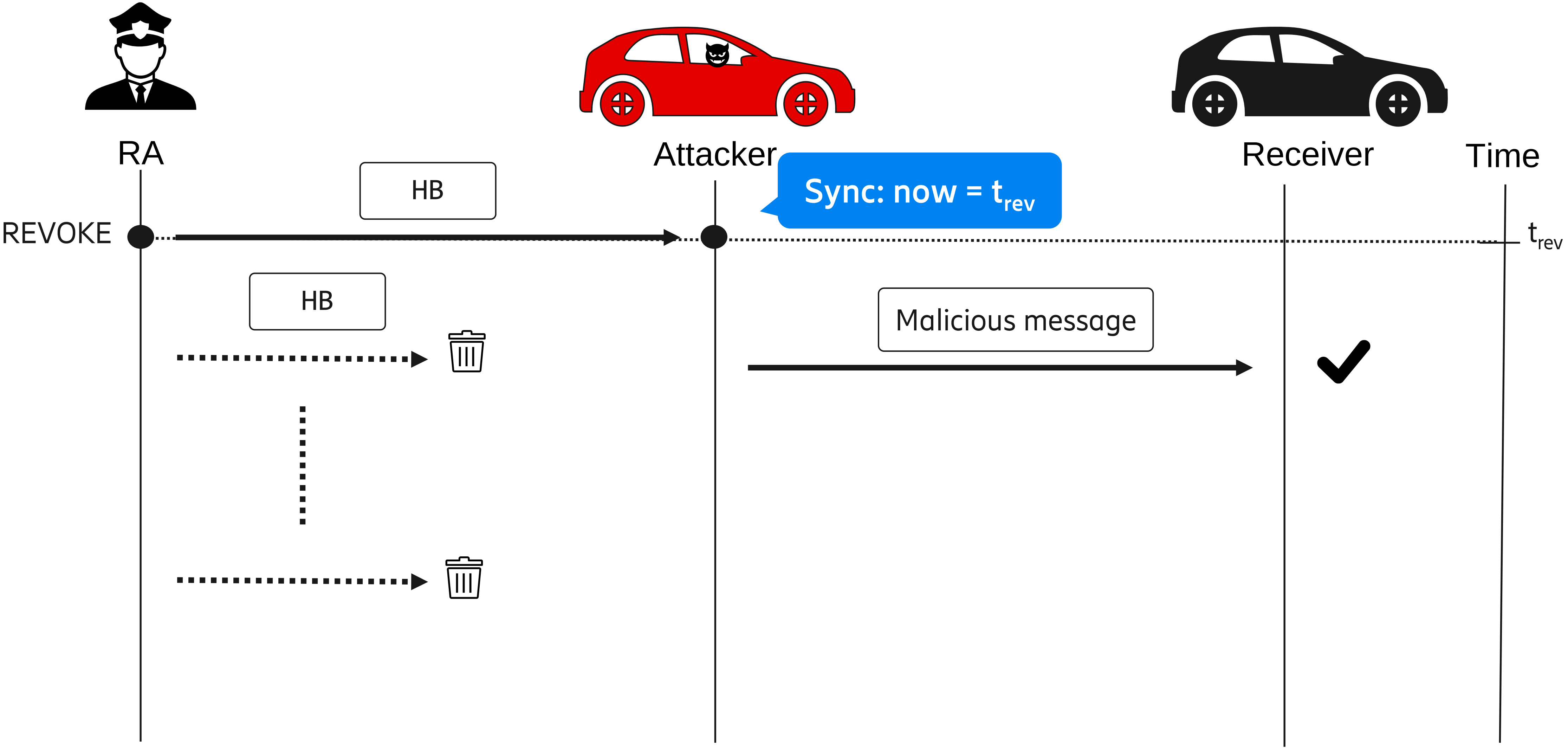

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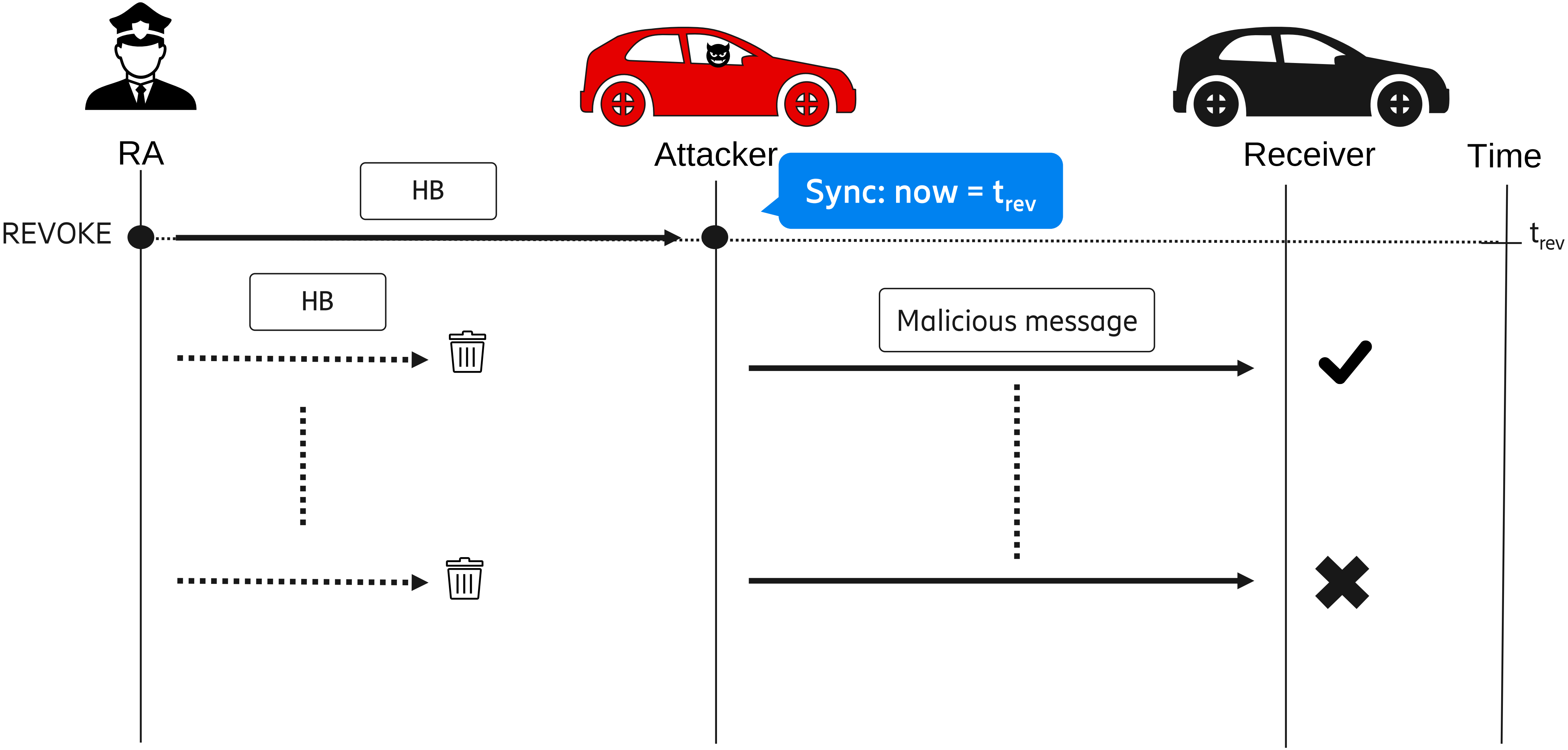

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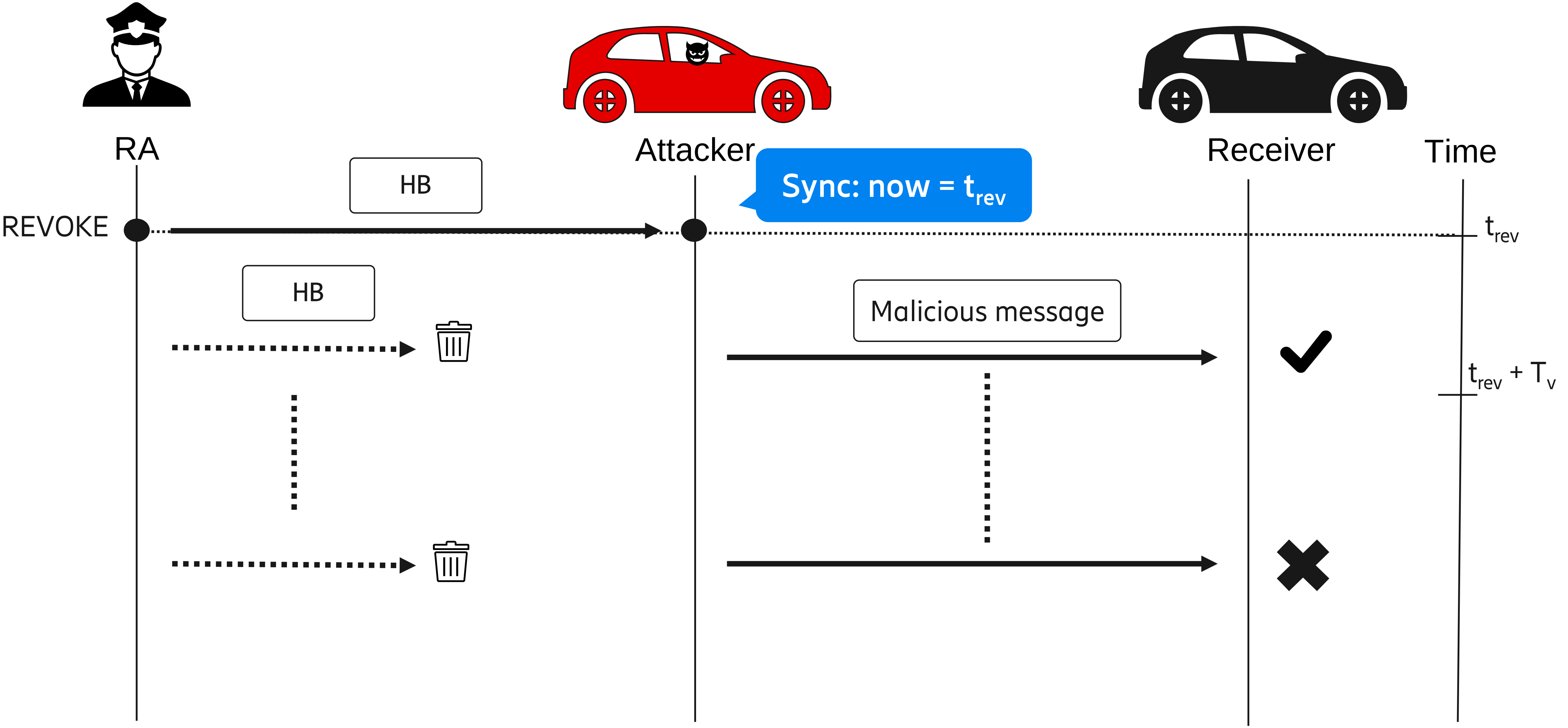
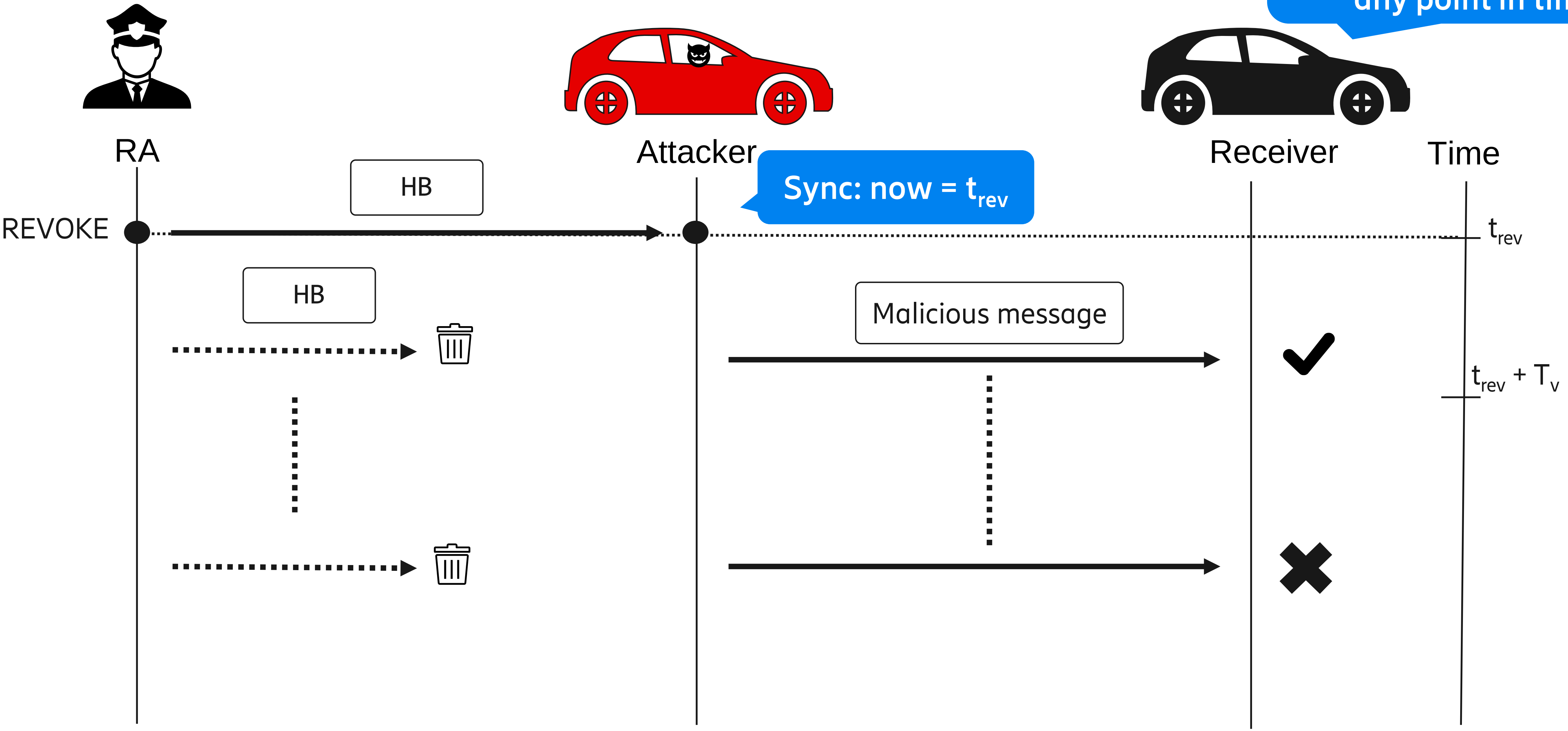


Worst-case T_{eff}

Assumption: receiver is at most T_v behind the RA at any point in time



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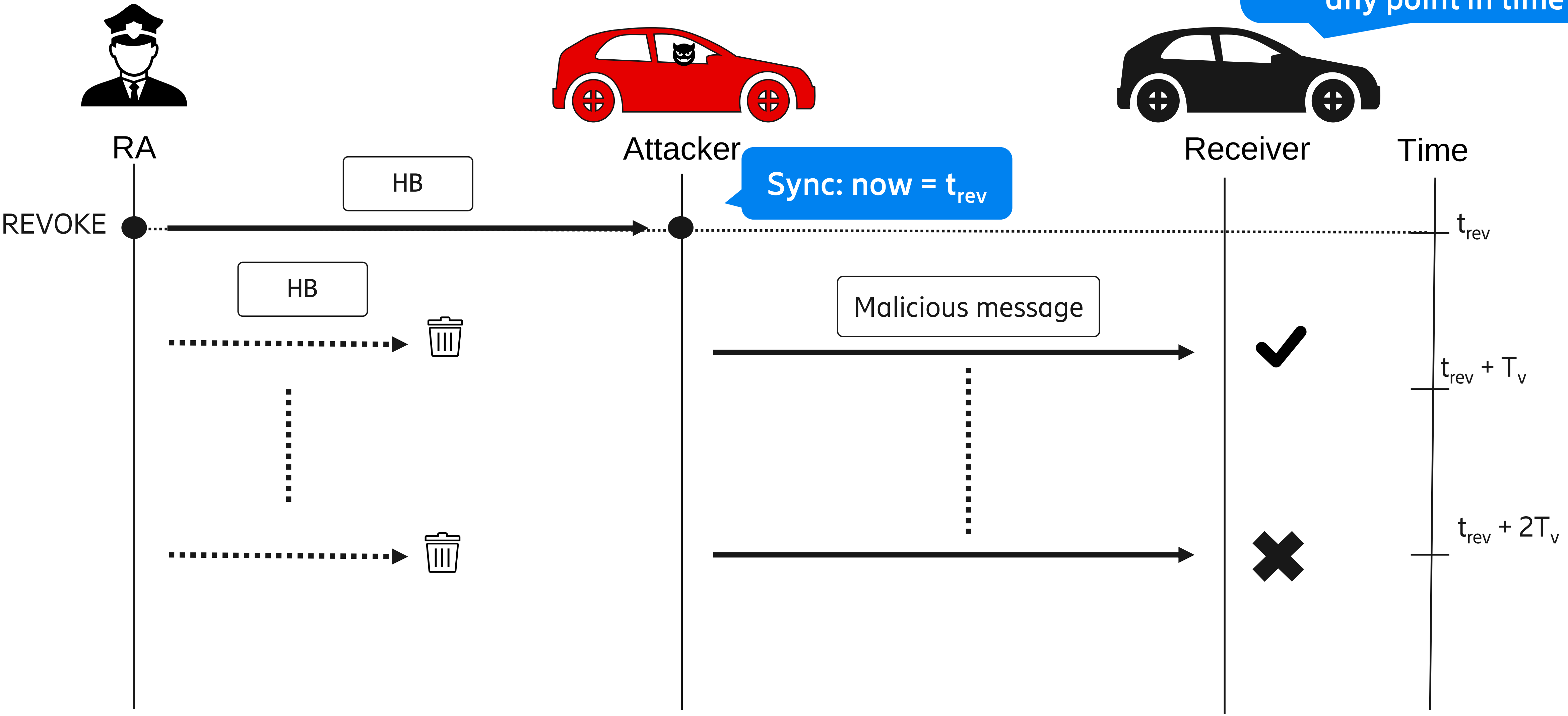

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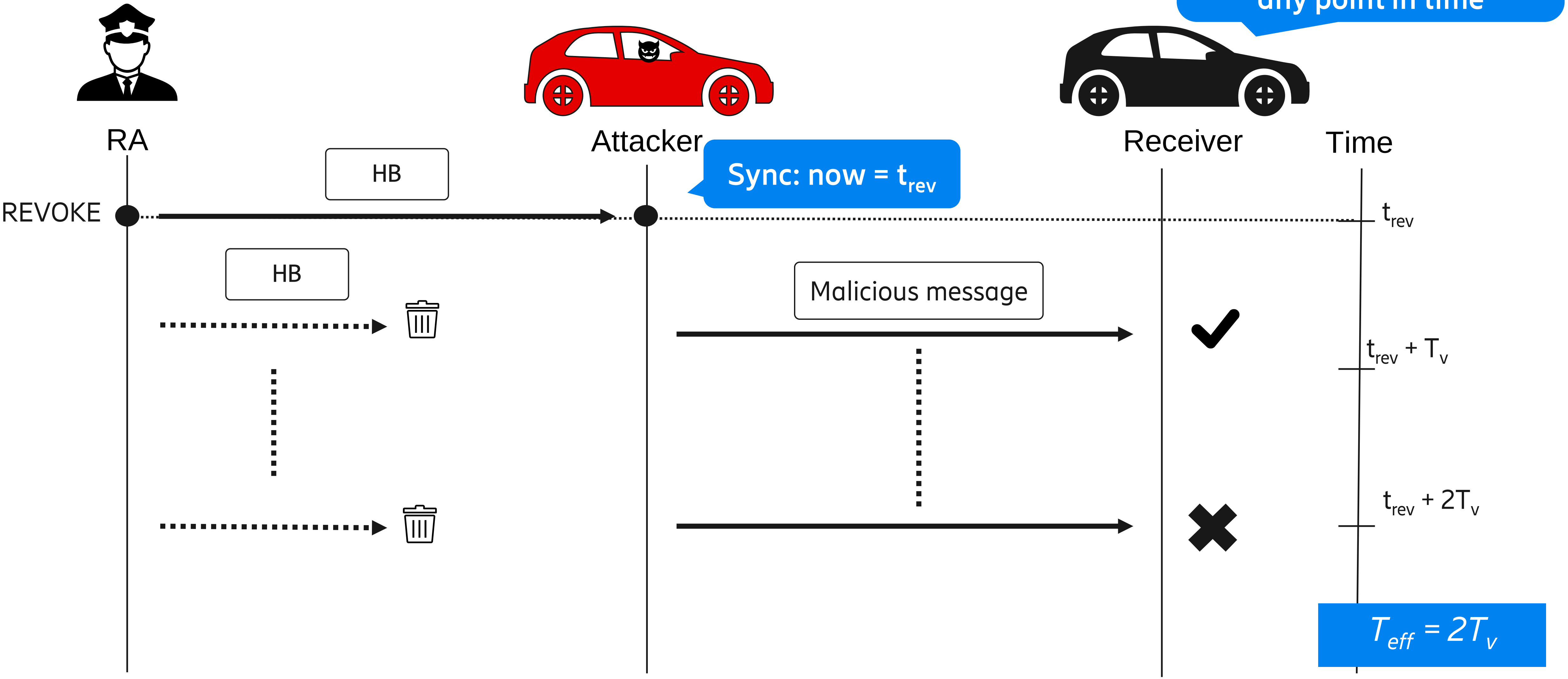

Sync: now = t_{rev}

$T_{eff} = 2T_v$