Formal Verification of a V2X Privacy-Preserving Scheme using Proverif

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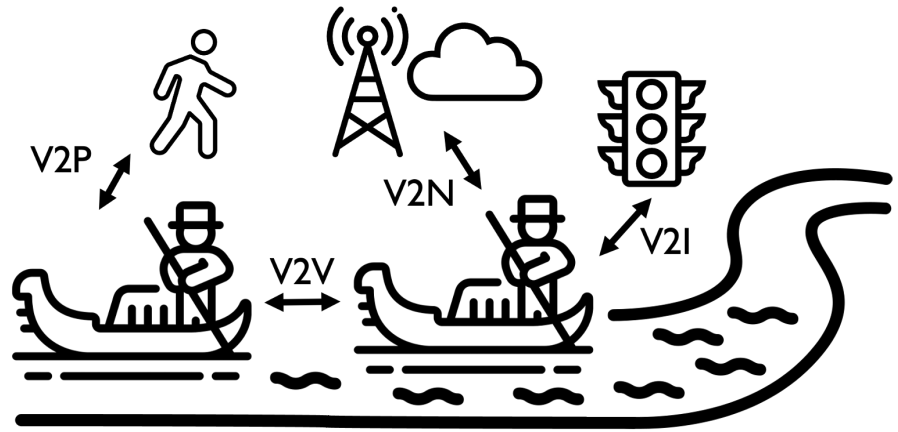
V2X Introduction

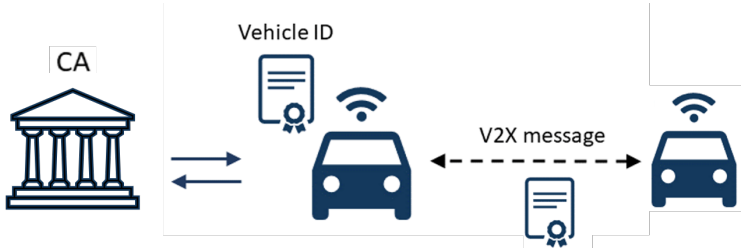
- **V2X** – Vehicle to Everything
- **Broadcast messages** sent to surrounding neighbours
- … vehicle **speed, position, direction** …
- Applications = Road safety and Traffic flow optimization
- Being sensitive, a compromise of this data can impact the **safety** of involved actors
- Mechanisms are needed to protect it



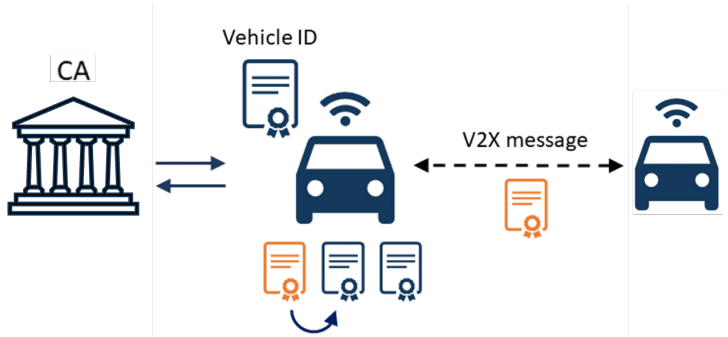
In particular, message authentication and integrity

V2X Privacy Issues

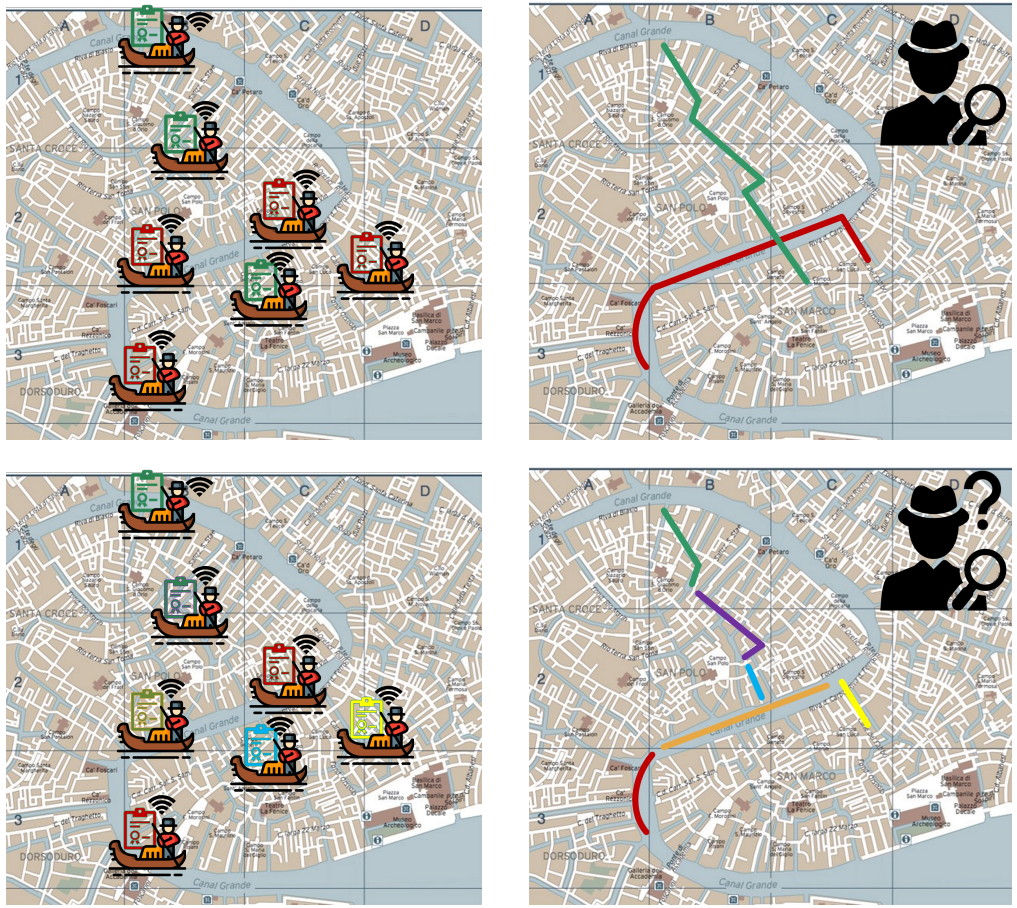
- Traditional network protocols use **Digital signatures** and **certificates**



- **Privacy** issues! Easy to **track** vehicle position
- **Anonymity** is needed



- Solution with **Pseudonymous certificates**
- Still some **problems**: Refill problem, Pseudonyms revocation …



Formal Verification gap and Objective of the work

- Many **v2x schemes** have been proposed over the years
- Also, many definitions of **properties** that these schemes must satisfy

To our knowledge, a formal analysis of the security of these schemes is missing

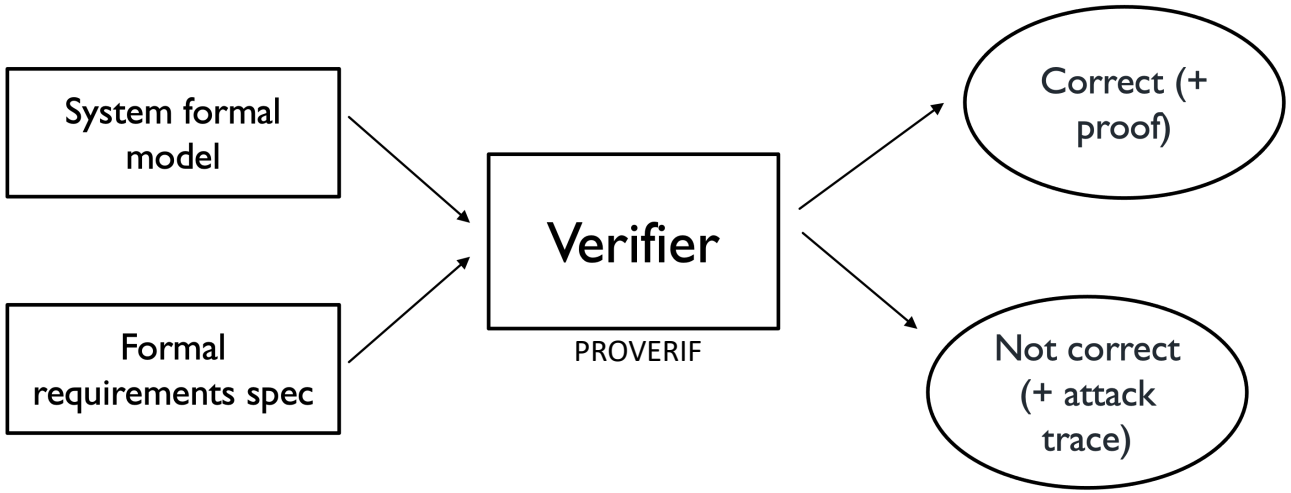
- **Objective** of the work:
  - Consider **one** of the proposed schemes existing in the literature
  - **Complete** the scheme to get a **formal specification** of the protocol
  - **Formally** define the security/privacy **properties** it must enforce
  - Run the **formal verification** using **Proverif**

The verification revealed some issues. Some of them are well-known in the literature and common to other schemes; other specific to the modeled protocol.

Formal Verification

- Static **analysis** of a system **formal model**

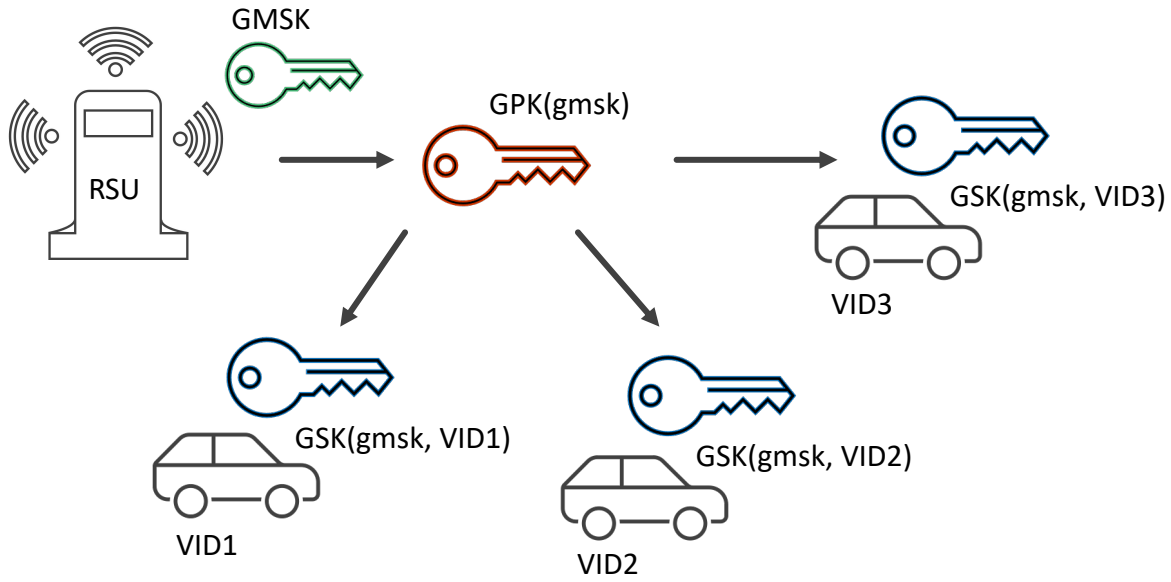
1. **Formal Specification**: from the real system to its formal abstract model
2. **Formal Verification**: check if the model satisfies some formal properties (e.g., its security requirements)



- Why formal verification?
- Designing security protocols is error prone
- Several flaws are constantly being found
- Formal verification today is required to submit most protocols
- Formal methods **increase the confidence** in the security by giving high assurance

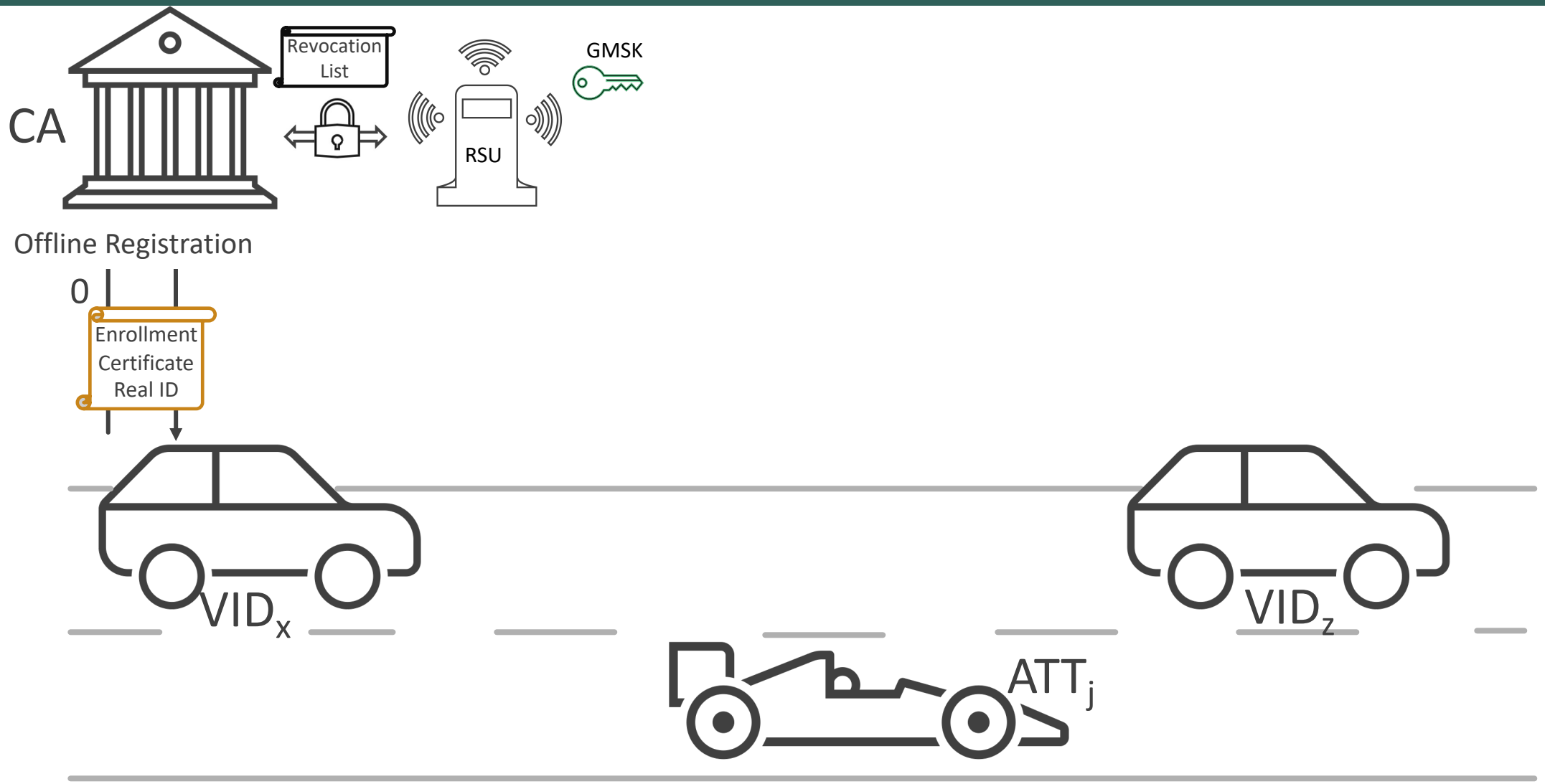
The Verified Scheme

- "Efficient and robust pseudonymous authentication in vanet" (reference paper)
- **Pseudonymous certificates** (Asymmetric encryption and Digital signatures)
- Pseudonyms are **generated** and **self-certified** by each vehicle using **group signatures**
  - Avoid the refill problem !
  - Groups are managed by a **RSU** (group master)



- Group signature properties
- A single signature is anonymous within the group (**anonymity**)
- Multiple signatures cannot be linked (**unlinkability**)
- Only the group master can reveal the group private key that performed a signature (**conditional accountability**)
- Unfortunately, complex and expensive operations

The Verified Scheme (in more details)



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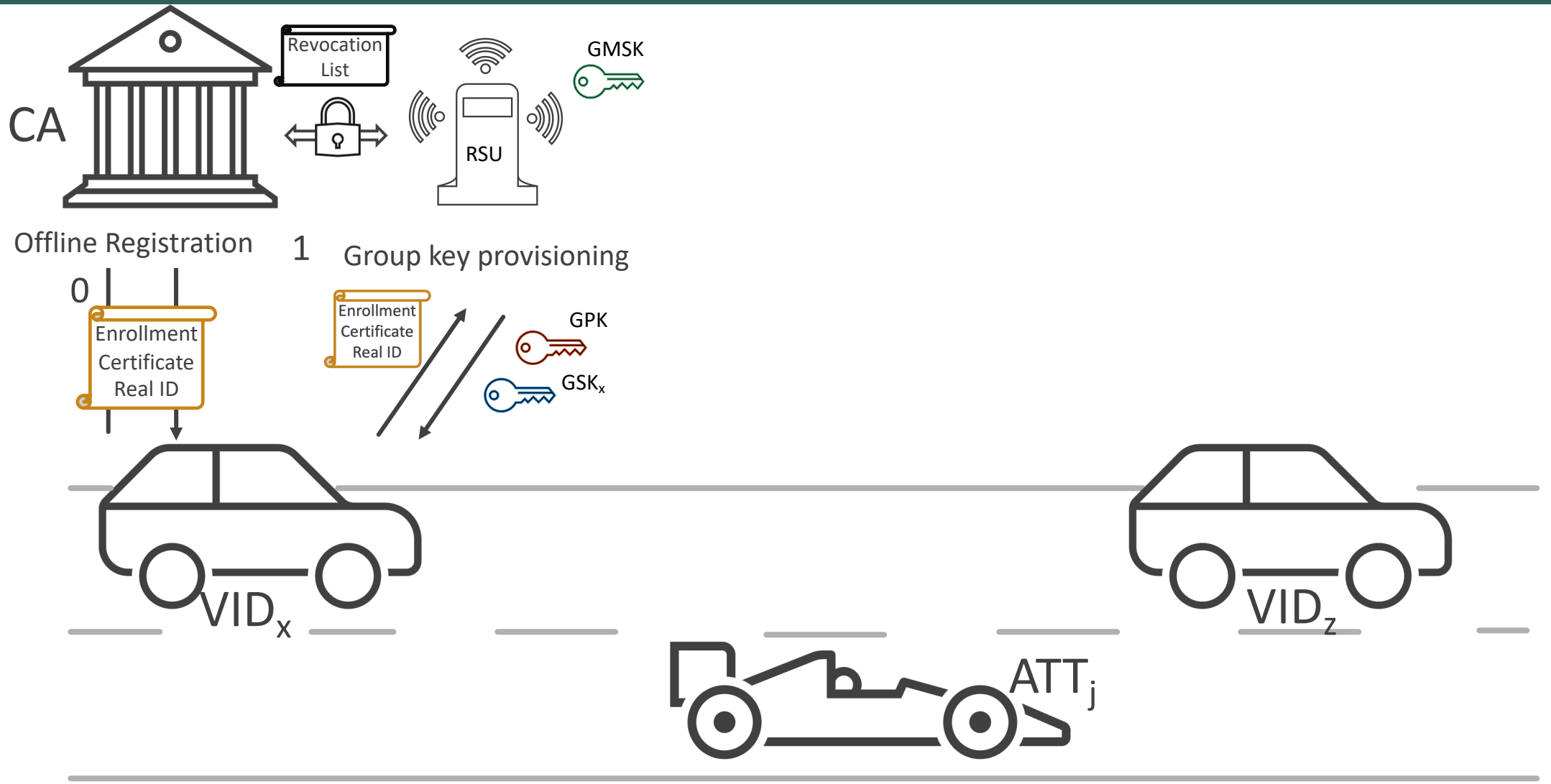

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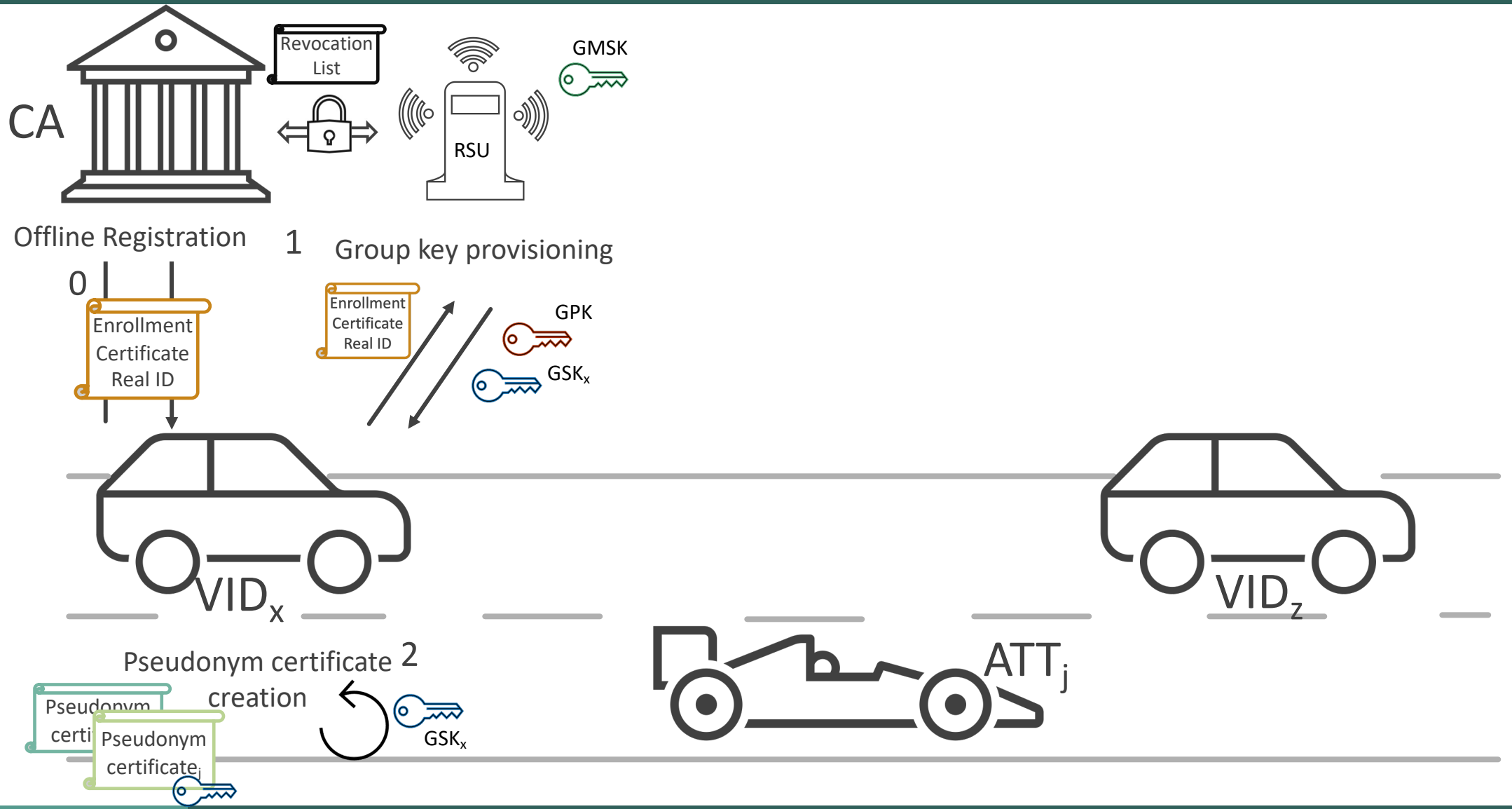

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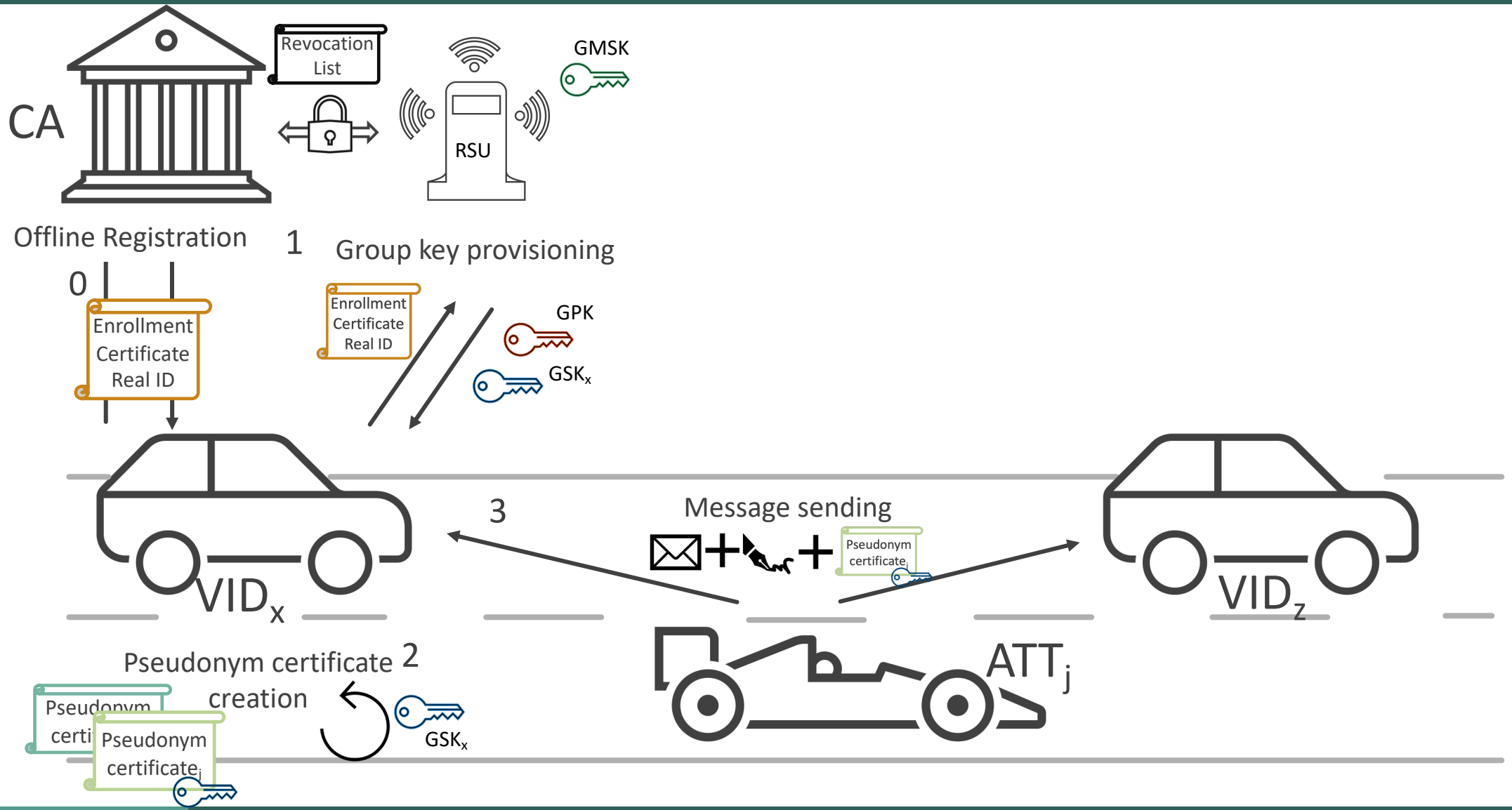
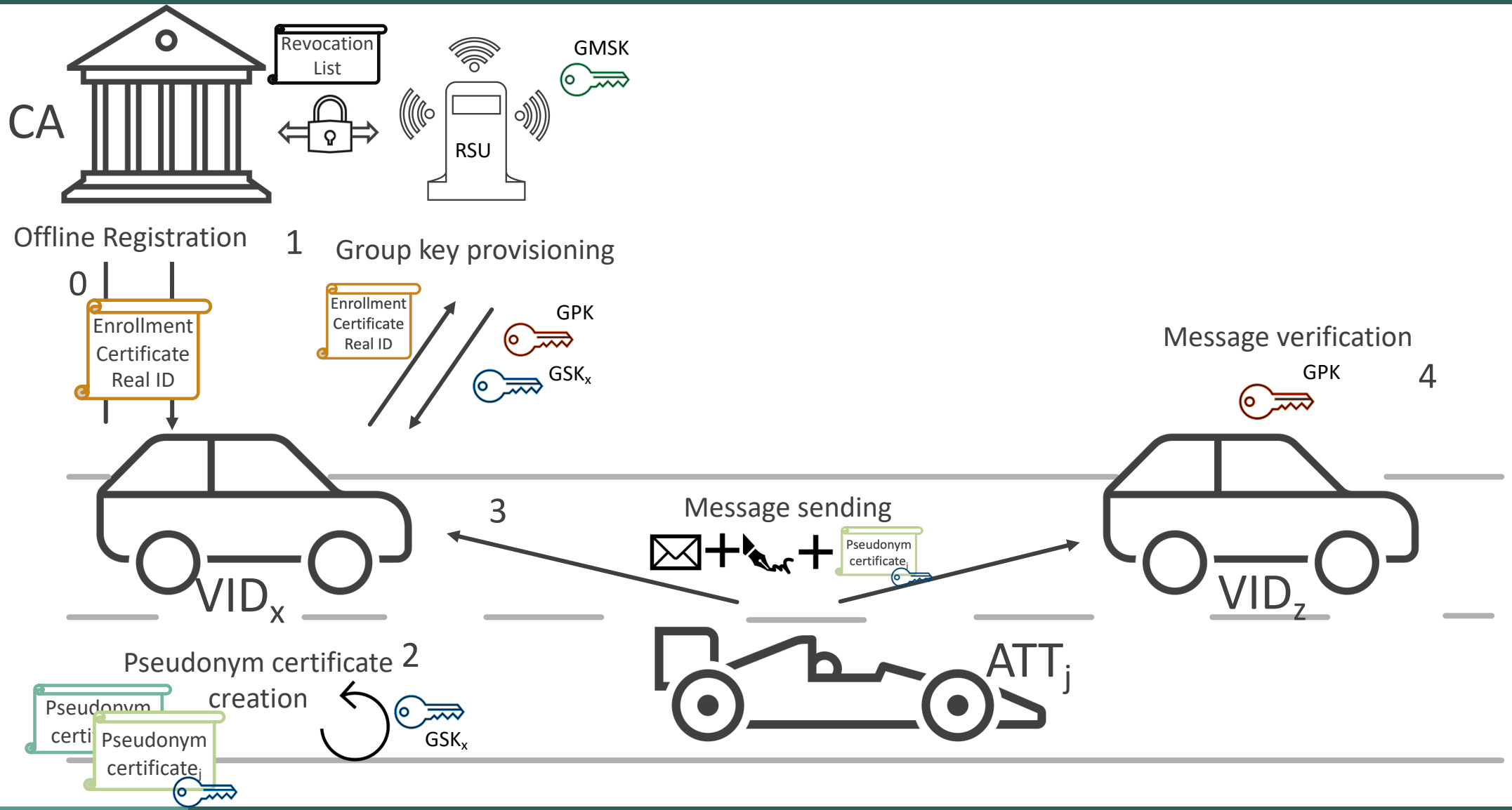
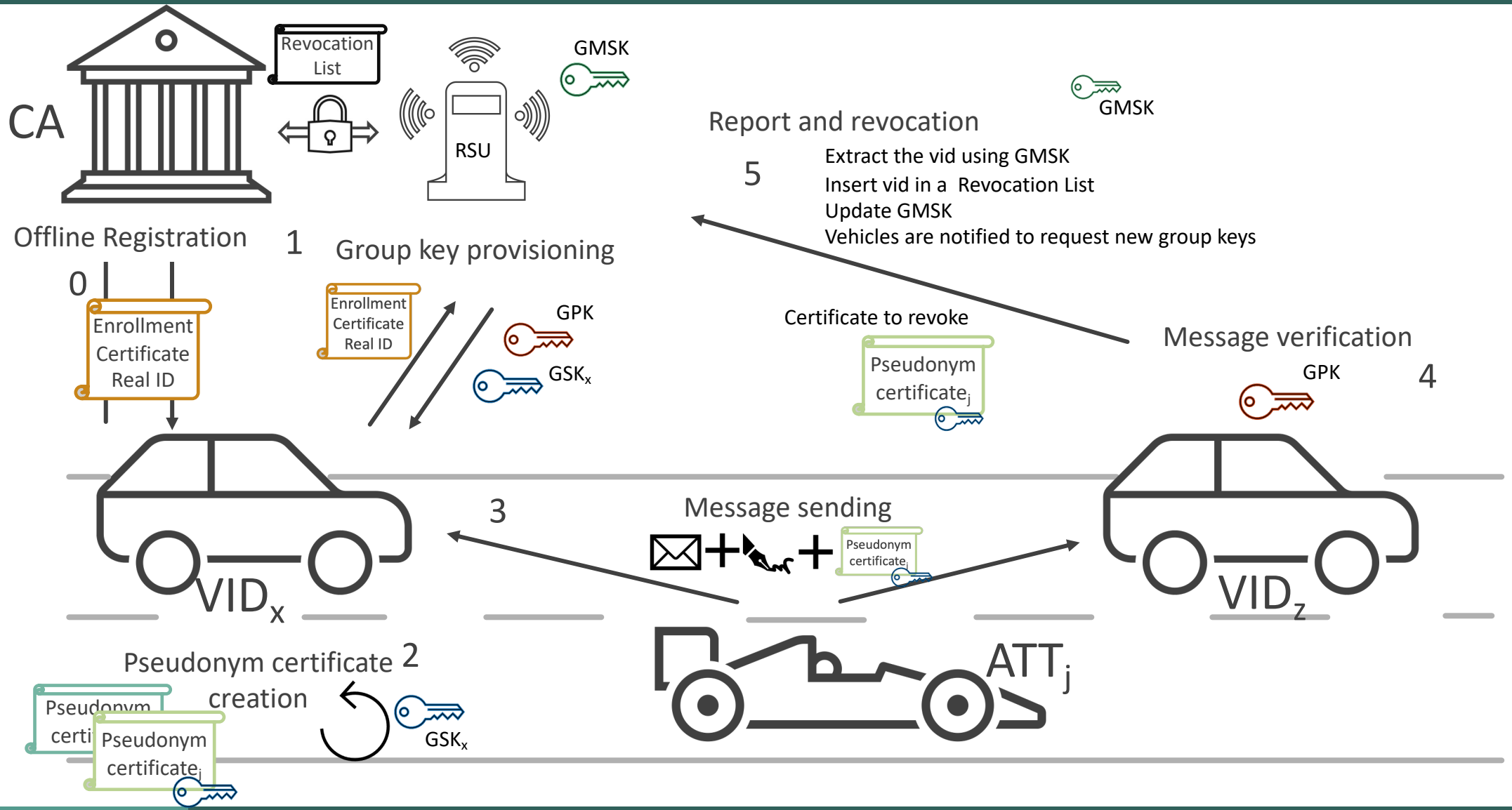


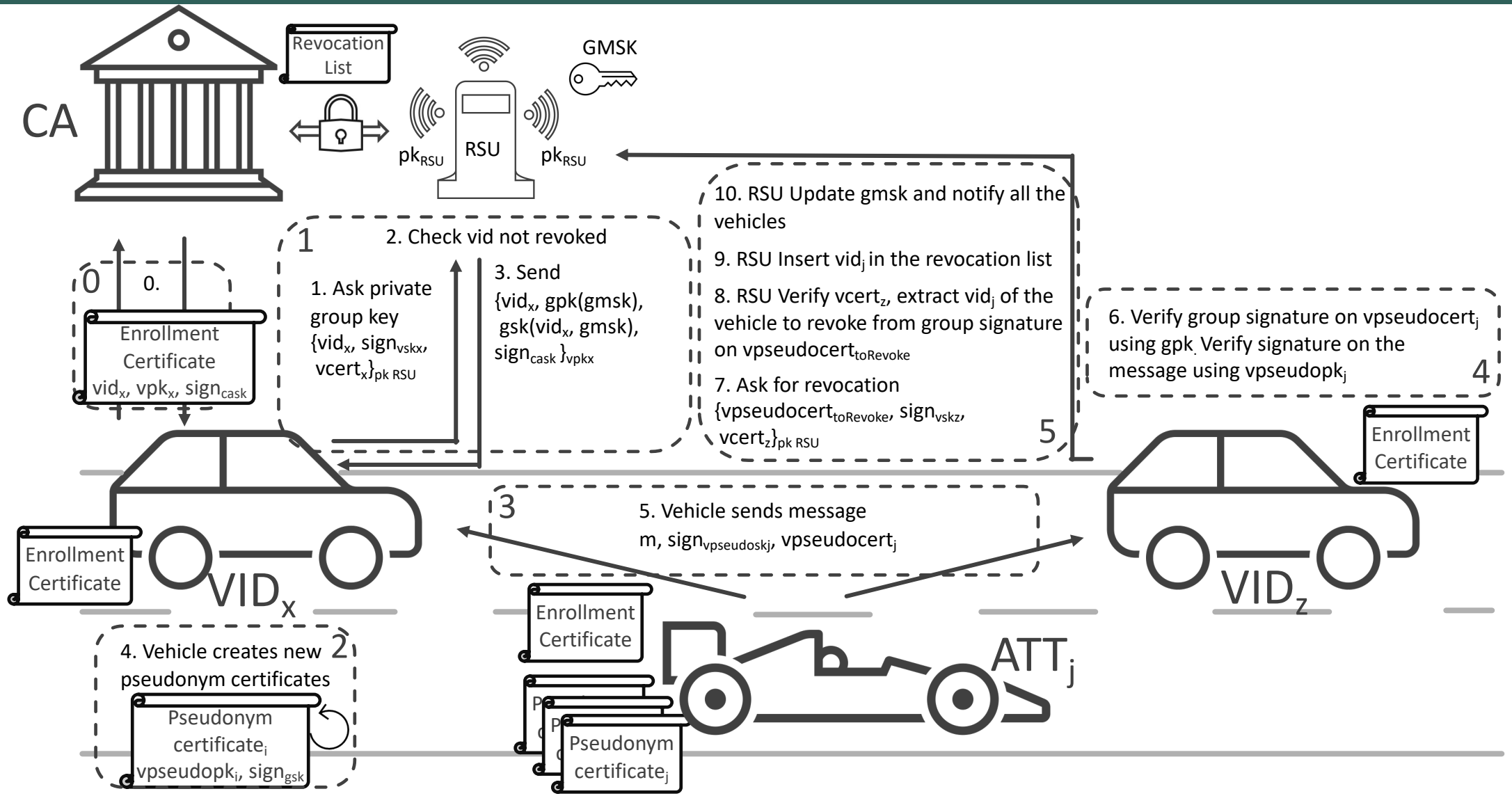
The Verified Scheme (in more details)



The Verified Scheme (in more details)

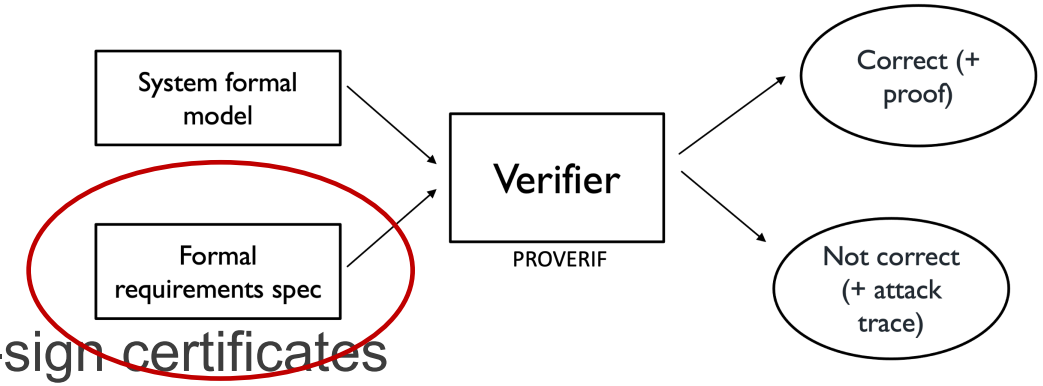


The Verified Scheme (in more and more details)



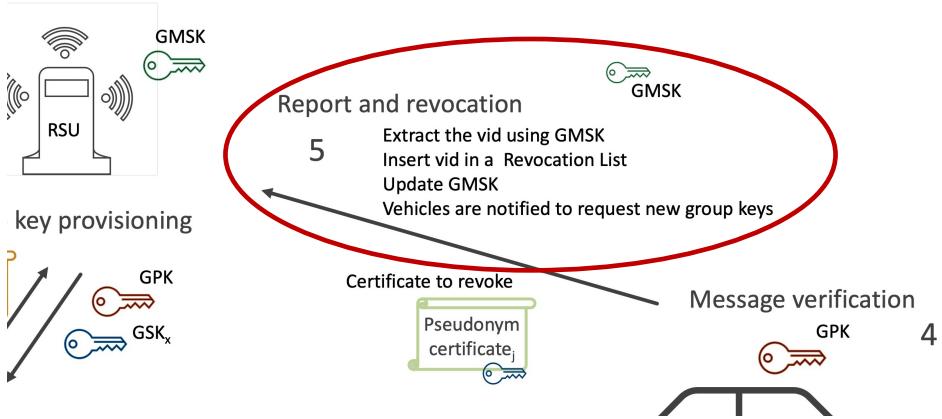
The Verified Properties

- **Confidentiality**
  - Of vehicle real identity and private keys
- **Anonymity**
  - When the vehicle uses group private keys to self-sign certificates and when it signs messages using pseudonymous certificates
- **Unlinkability**
  - In the use of different pseudo certificates to sign different messages and in the use of a single group key to certify multiple certificates



Verification results (i)

- **RESULT 1**: *Vehicle continues to be considered valid even after being removed*
  - After the RSU has added the revoked vid to the RL
    but before it updates the GMSK
  - OR after the RSU has updated the GMSK
    but before vehicles request new group keys



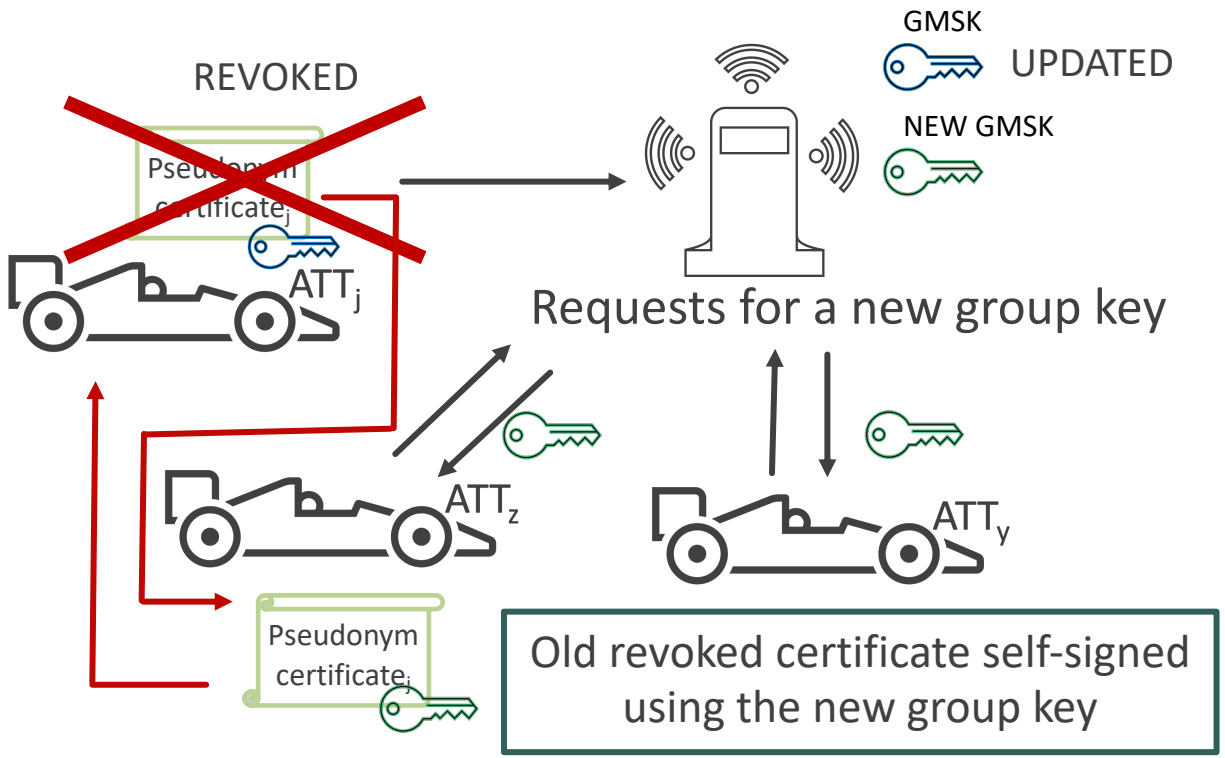
  - An attacker in this period can continue to use its old group key and vehicles would continue to accept it as a valid vehicle

Well-known Window of Exposure problem, common to other schemes

  - Adopted solutions: Group keys with short life (drawback of requiring more key updates and interactions with the RSU)

Verification results (ii)

- **RESULT 2**: *Pseudonymous certificate continues to be used even after the vehicle has been revoked*
  - When there are multiple attacker vehicles



- This process can continue as long as there are ”valid” attackers within the group
- Once all attackers are revoked one by one, the process ends
- No one can request and obtain updated group keys

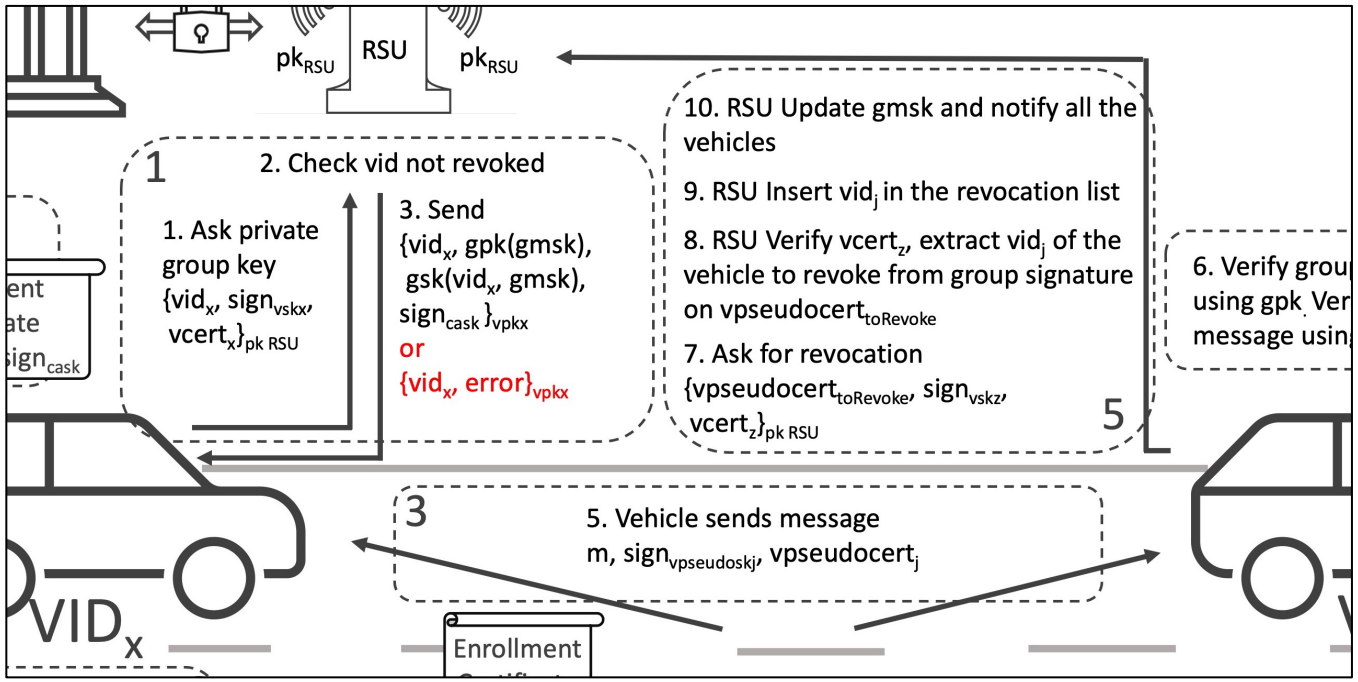
Verification results (iii)

- **RESULT 3**: *Anonymity issue in the revocation phase*
  - If the RSU receives a group key request from a revoked vehicle
  - It “should” reply with an error message and not simply ignore the request
  - ATTACK TRACE
    - Attacker intercepts and stores an initial request sent by a vehicle
    - Then, the vehicle is revoked
    - RSU notifies all vehicles to update their keys
    - By replying the initial request, attacker can understand if the revoked vehicle is the one it intercepted at the beginning

      based on whether it can get a response from the RSU

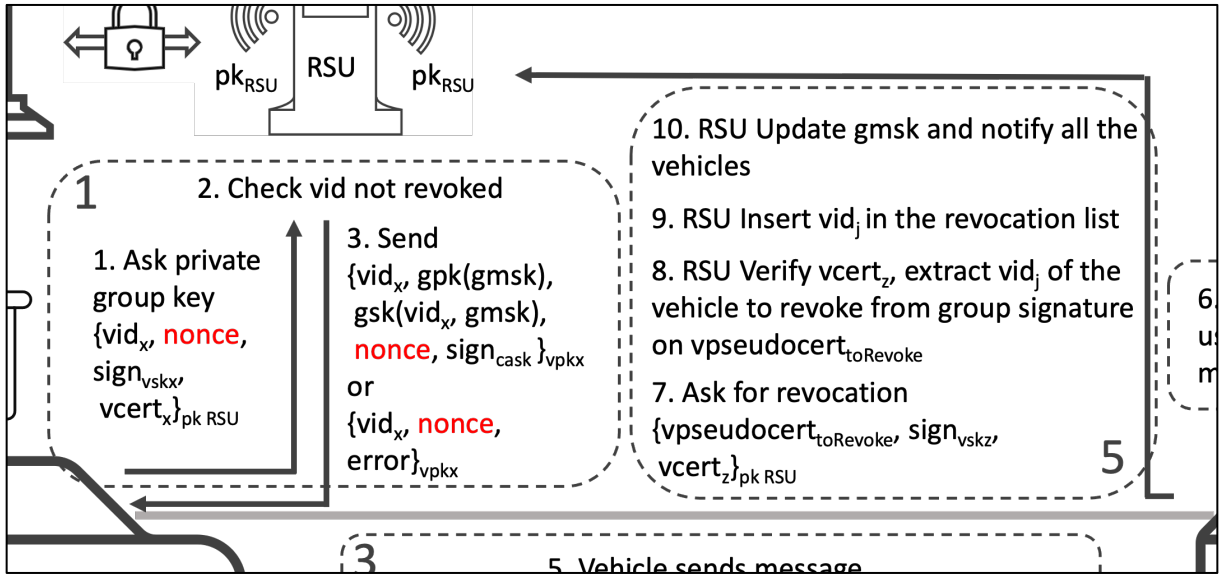
Verification results (iii)

- **RESULT 3**: *Anonymity issue in the revocation phase*
  - If attacker can link the initial intercepted request to the real identity of the vehicle (e.g., traffic-free road),
  - There is a violation of anonymity of the revoked vehicle
  - Solution



Verification results (iv)

- **RESULT 4**: *Linkability issue in the request for a group key*
  - Requests for a group key contain: vehicle id, enrollment certificate and signature using the enrollment certificate
  - These are all constant data
  - Two different requests are therefore identical and can be linked (tracking the vehicle through its requests to the RSU)
  - Solution



Conclusions

- We formally **modeled** and **analyzed** a v2x scheme existing in the literature
- The aim of the work is to show how **formal verification** can be used to analyze the **security** of a protocol
- The **model** we built for this protocol and the **related privacy properties** can be **adapted** to analyze other v2x protocols **as future work**

Thanks for your attention!

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