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Network-efficient authenticated pseudonym-based V2X communications with constant revocation costs

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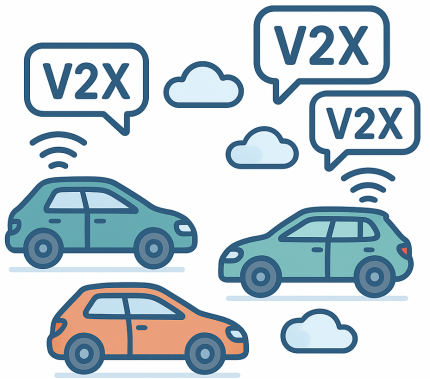
Intelligent Transportation Systems communications

- Vehicles and infrastructure exchange messages for **road safety**, **traffic management**, and **enhanced mobility**
- Performance:
  - V2X beacon messages are **frequent** and **broadcast**
    → network bandwidth is the major bottleneck

every byte matters!

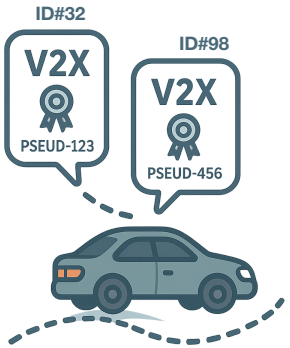


Intelligent Transportation Systems communications

- Vehicles and infrastructure exchange messages for **road safety**, **traffic management**, and **enhanced mobility**
- Performance:
  - V2X beacon messages are **frequent** and **broadcast**
    → network bandwidth is the major bottleneck
    ↳ ***every byte matters!***
- Security:
  - **Message authenticity**
  - **Conditional anonymity**
  - **Efficient revocation**
- Also, carefully balanced with: tight **latency-requirements of safety-related features**, resource constraints of wireless communication protocols, **economic costs**…

PKI-based approach: pseudonyms & linkage values

- Vehicles are provisioned with a **set of pseudonym certificates** issued by a CA
  - **Trade-off: privacy, security and scalability**
  - Full conditional anonymity not affordable in vehicular networks
- Vehicles **rotate pseudonym certificates to prevent tracking**



Protocol framework

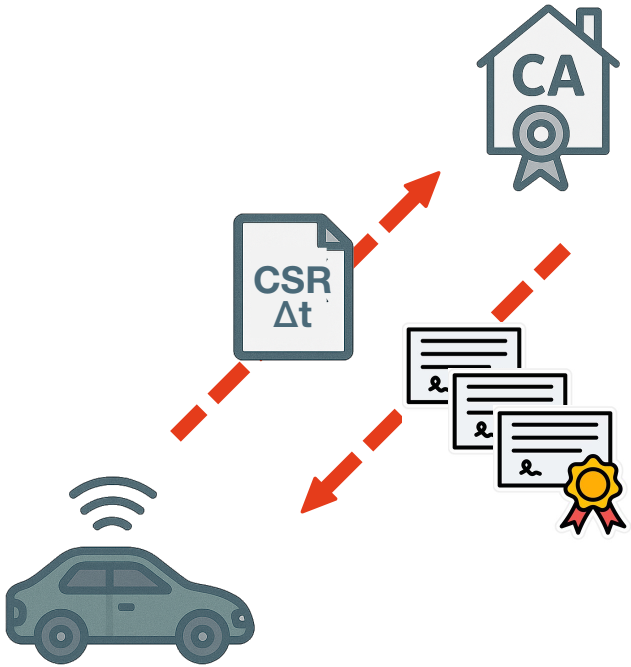
- Three sub-protocols: **pseudonym certificates release**, **revocation**, **refresh**
- Parameters:
  - CA divides time into *time periods* **t**
  - **N** is the maximum fixed number of pseudonym certificates a vehicle can obtain for each time period
  - **T** is the number of subsequent time periods for which a vehicle is requesting sets of pseudonym certificates

Pseudonym certificates release

1) **Request**: Certificate Signing Request from vehicle to CA with the number of future time periods requested Δt, $\Delta t \leq T$

2) **Generation**: the CA creates and sign N pseudonym certificates for each Δt, and sends them to the vehicle

3) **Reception**: the vehicle prepares the set of pseudonym certificates for the current time period, and stores the extra certificates for later use



Revocation

1) The **CA publishes a CRL revoking the misbehaving vehicle**

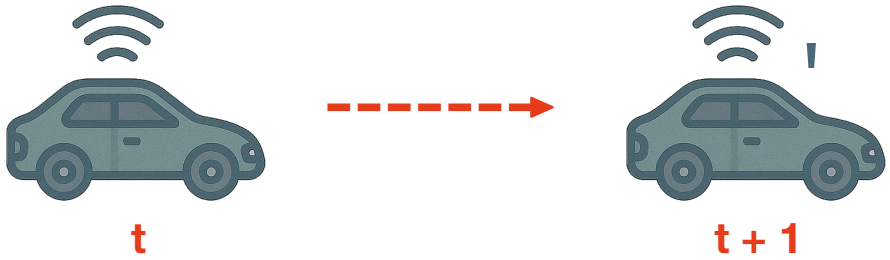
2) A vehicle can **link** all the pseudonym certificates associated with the misbehaving vehicle...

3) … and **discard V2X messages signed with a revoked key**

Refresh

At the end of each time period, the vehicle should:

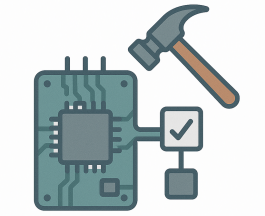
1) **prepare the new set of pseudonym certificates** for the next time period
2) **update the set of revoked pseudonym public keys** for the next time period



Weaknesses of state-of-the-art

- Revocation is not straightforward: standards include **pseudo-random indexing identifiers** within certificates (linkage values)
  - **Trade-off: smaller revocation lists vs bigger per-message overhead**

- **Pseudonym: random key pair + pseudo-random indexing identifier**
  - *Linkage value* is included in each V2X message → network bandwidth is the **major bottleneck** in vehicular networks
  - Depends on hash functions' collision resistance → resizing may be needed in the future to support higher traffic workloads and privacy guarantees



Contributions

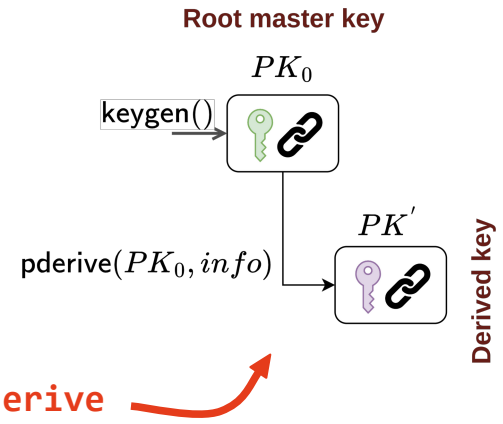
- ***What?*** *Conditionally unlinkable* **pseudo-random** keys in pseudonym certificates
- ***How?*** Pseudonym keys are derived via **Hierarchical deterministic homomorphic Key Derivation** (HKD)
  - Mostly known for deterministic wallets in the context of blockchains (see Bitcoin Improvement Proposal #32)
- ***So?***
  - No linkage values required → **reduced network overhead**
  - Revocation via single master public key → **constant network cost**

Network-efficient HKD-based protocol specification

- *Conditionally unlinkable* pseudo-random keys derived via **Hierarchical deterministic homomorphic Key Derivation (HKD)**
  - Same sub-protocols: **pseudonym certificates release**, **revocation**, **refresh**
  - Same parameters: *time periods*, **N** pseudonym certificates for each time period, **T** subsequent time periods in certificate request

HKD scheme

- Three routines
  - **key generation:** `⟨sk,PK⟩ ←$ keygen()`
  - **public key derivation:** `PK' ← pderive(PK,info)`
  - **secret key derivation:** `sk' ← sderive(sk,PK,info)`



Example with `pderive`

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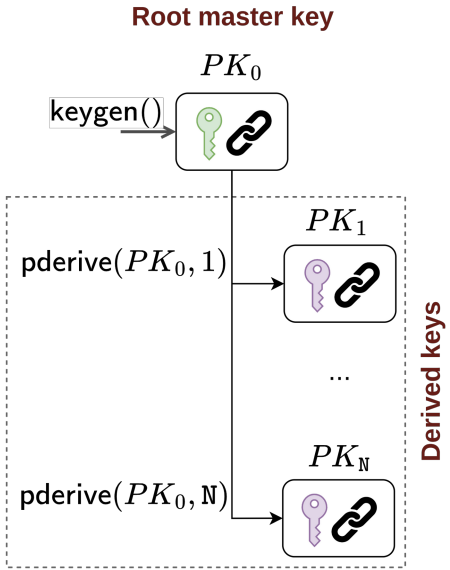
- Subsequent calls to **`pderive`** and **`sderive`** allows to derive several key pairs from a single master key pair



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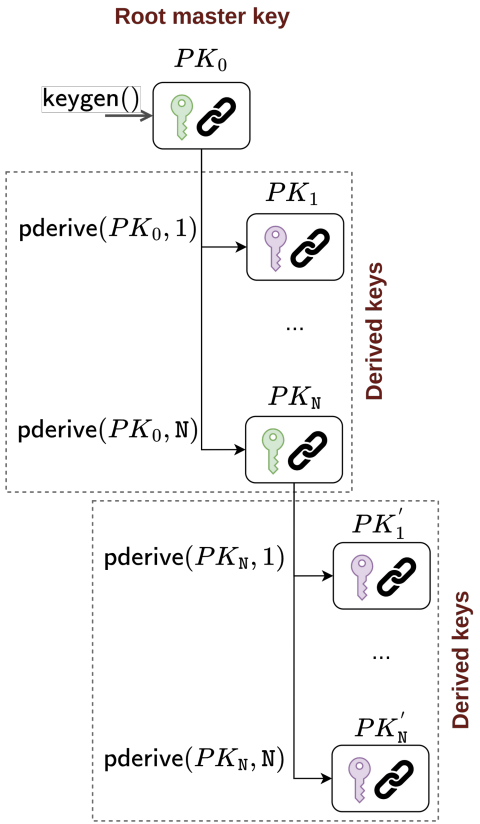
- Subsequent calls to **`pderive`** and **`sderive`** allows to derive several key pairs from a single master key pair
- *Hierarchical?* A derived key can be used as a master key for further derivation → **hierarchical sub-tree of derived keys** by recursively calling **`sderive`** and **`pderive`** to a derived node

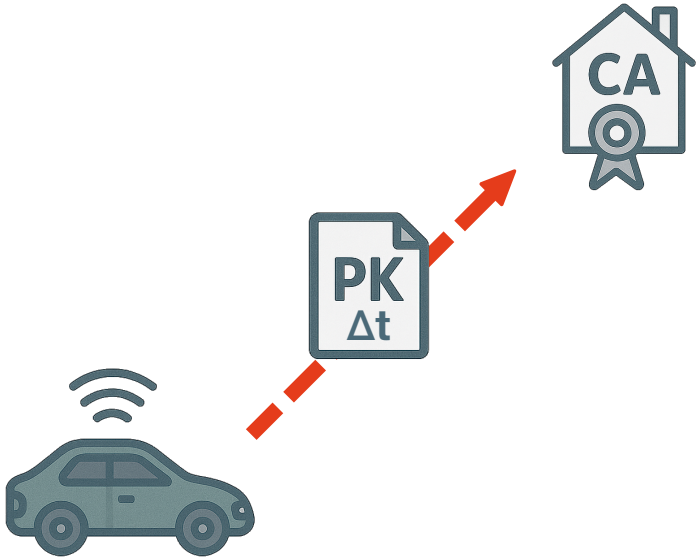


Pseudonym certificates release

1) **Request**: the vehicle sends to the CA its **master public key PK** and the number of future time periods for which is requesting pseudonym certificates Δt, $\Delta t \leq T$

2) Generation

3) Reception

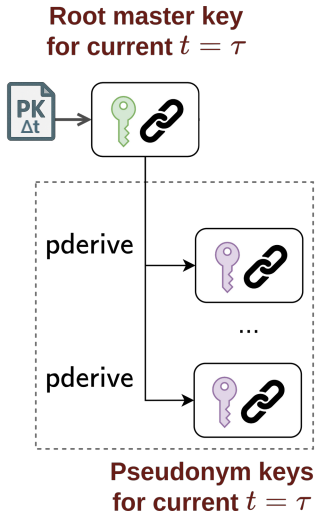


Pseudonym certificates release

1) Request

2) **Generation**: the CA derives N pseudonym public keys using `pderive`. For each subsequent time period derives the next master public key and the N pseudonym public keys. Sends the signatures back to the vehicle

3) Reception



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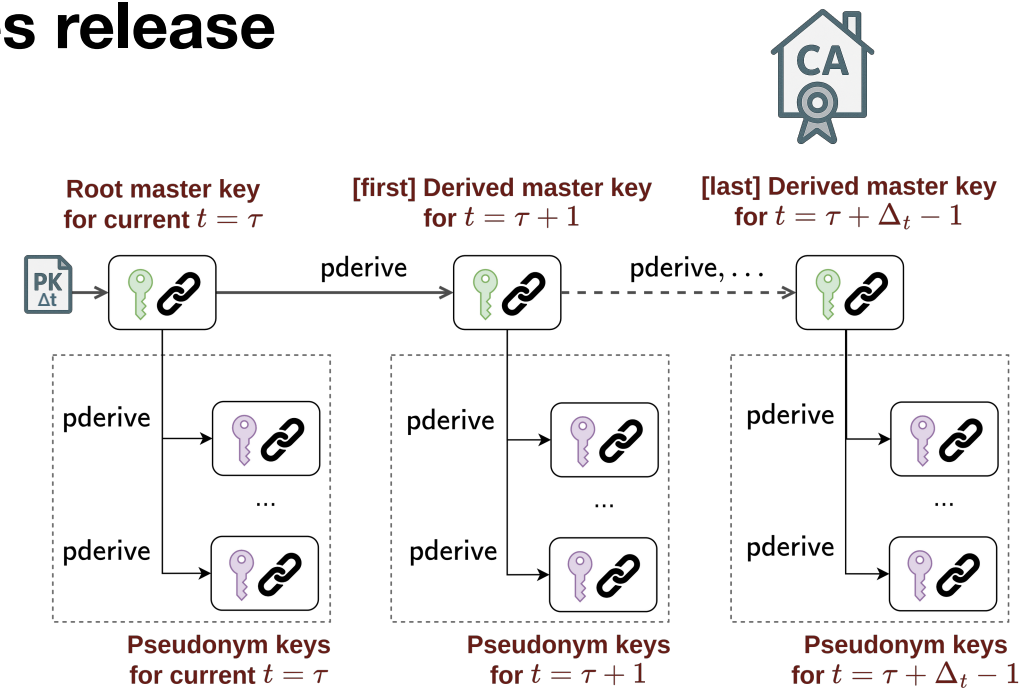

Pseudonym certificates release

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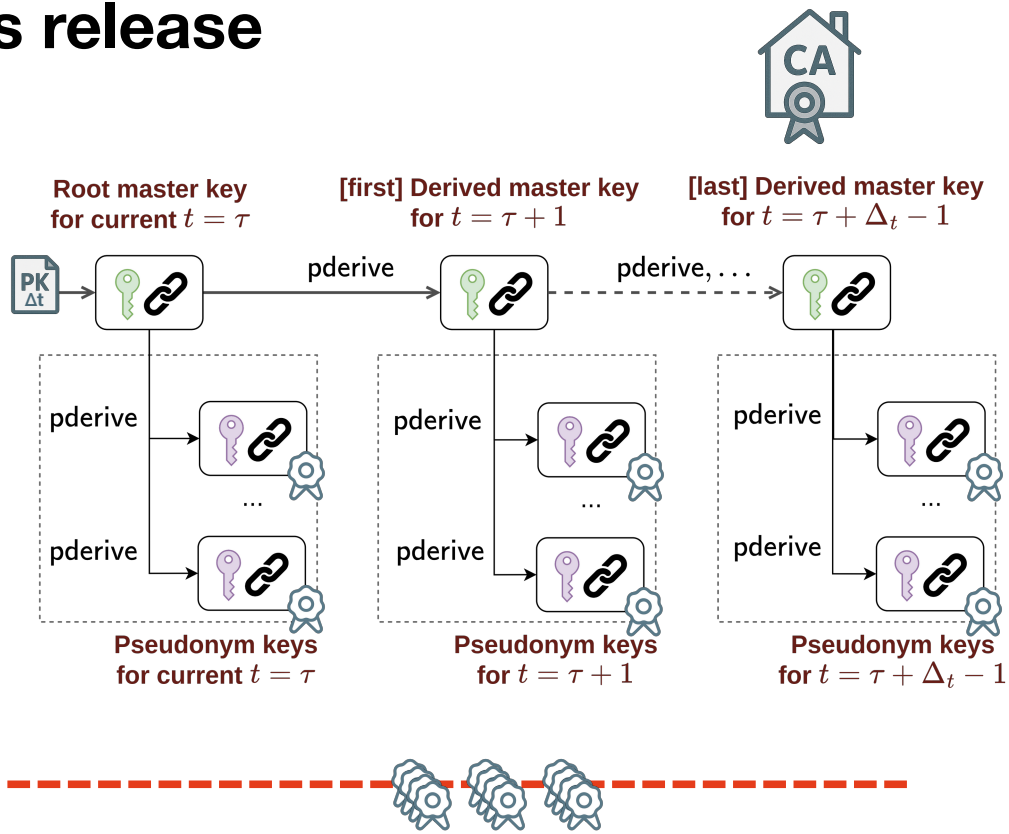
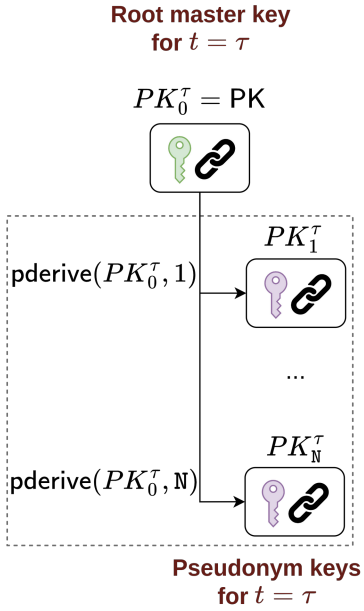


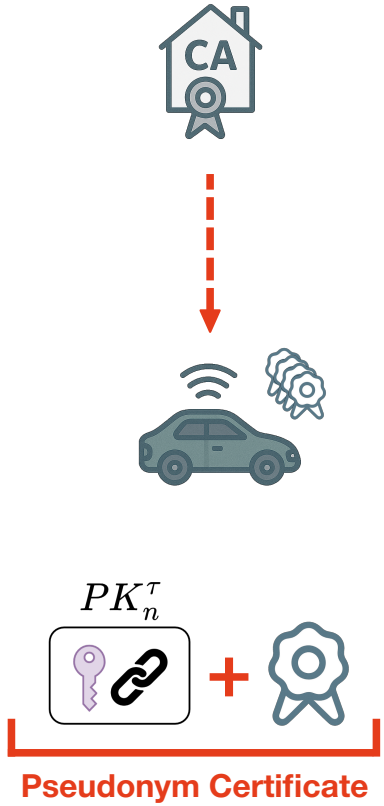
Pseudonym certificates release

1) Request

2) Generation

3) **Reception**: the vehicle derives the pseudonym public keys **only** for the current time period, creates the set of pseudonym certificates for the current time period, and stores the unused signatures for later use



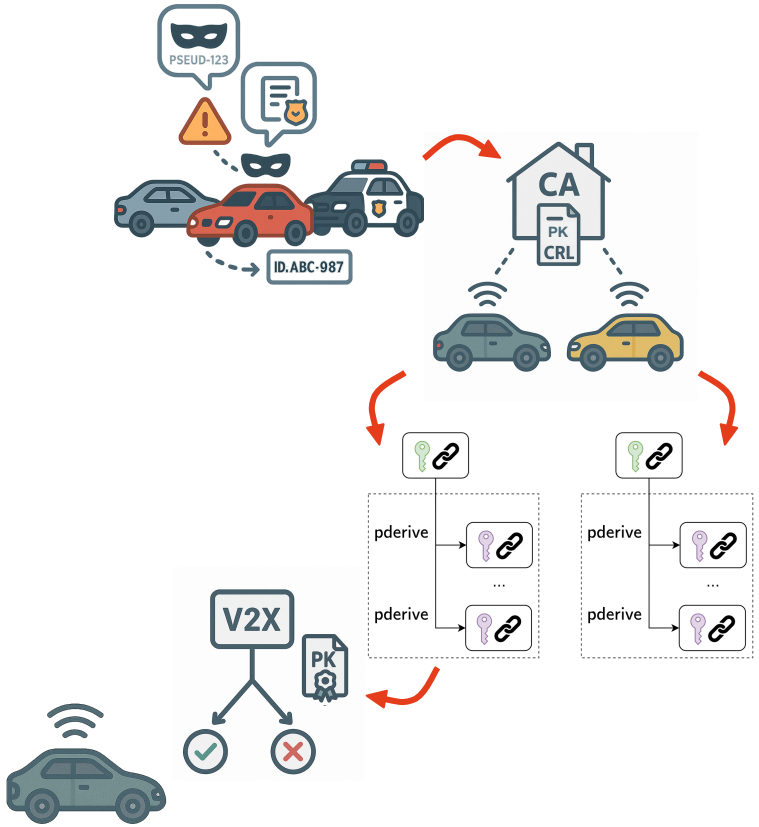


Revocation

1) The **CA revokes the misbehaving vehicle by publishing its master public key**

2) A vehicle can derive all the pseudonym public keys of the misbehaving vehicle using the **`pderive`** routine

3) Discard a received V2X message **if signed with a revoked key**

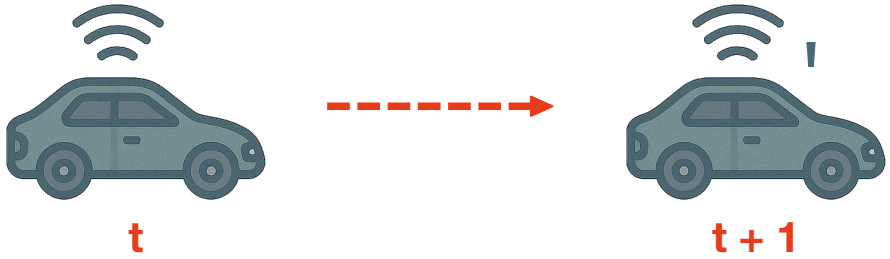


Refresh

At the end of each time period, the vehicle should:

1) **derive the master key pair** for the next time period, **derive all the pseudonym public keys** for the next time period, **create the certificates** (public key + CA signature)

2) **update the set of revoked pseudonym public keys** for the next time period



Cost evaluation: asymptotic analysis

Protocol	Procedure	Computation cost	Made by
Release	pcreq	$O(1)$	Vehicle
	pcrec	$O(\mathtt{N})$	
	pcgen	$O(\mathtt{N} \cdot \mathtt{T})$	CA
Revocation	revoke	$O(1)$ or $O(\mathtt{N})$	
	crlupdate	$O(\mathtt{N})$	Vehicle
Refresh	crtrefresh	$O(\mathtt{N})$	
	crlrefresh	$O(\mathtt{N} \cdot \mathtt{T})$	

CA is less constrained than a vehicle

Computation

Protocol	Network cost
Release	$O(\mathtt{N} \cdot \mathtt{T})$
Revocation	$O(1)$
Refresh	-

Network cost is constant!

Network

Vehicle can derive secret keys on-demand

Type of data	Storage	Storage cost
Pseudonym certificates valid in τ	$\langle crt \rangle$	$O(\mathtt{N})$
Certificates revoked by the CA in τ	$\langle crl \rangle$	$O(\mathtt{N} \cdot \mathtt{T})$
Certificate refresh material	crm	$O(\mathtt{N} \cdot \mathtt{T})$
Revocation refresh material	rrm	$O(\mathtt{N} \cdot \mathtt{T})$

Storage

Cost evaluation: analytic evaluation

Instantiation based on the ECDSA signature scheme with the NIST p-256 elliptic curve.
Standard evaluation scenario: 2.5×10^8 vehicles, N = 40 pseudonym certificates, revocation rate <1%.
Comparison against standards with explicit certificates.

	Network overhead		**Storage overhead**
	V2X message sent	**single CRL downloaded**	**10000 CRL entries**
US **SCMS** standard	Linkage value of **72 bits**	320 bits	3600 Kilobytes
Our proposal	*No extra data*	256 bits	12800 Kilobytes
	reduced network cost	**1.25× smaller**	**~3.5× larger**

Conclusions and future works

- Our novel protocol **reduces network overhead in all V2X messages**, while supporting **efficient revocation at constant network costs**.
- **Higher computational costs for key management are still affordable** in practice and there is **no computational overhead for securing communications**, all under the same cryptographic assumptions of current standards.
- **Future works:**
  - Further optimizations to allow even more efficient certificate management, such as using implicit certificates
  - Application to future V2X communication protocols based on post-quantum cryptography

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Q&A

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