KTH ROYAL INSTITUTE
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SECMACE: Scalable and Robust Identity and Credential Management Infrastructure in Vehicular Communication Systems

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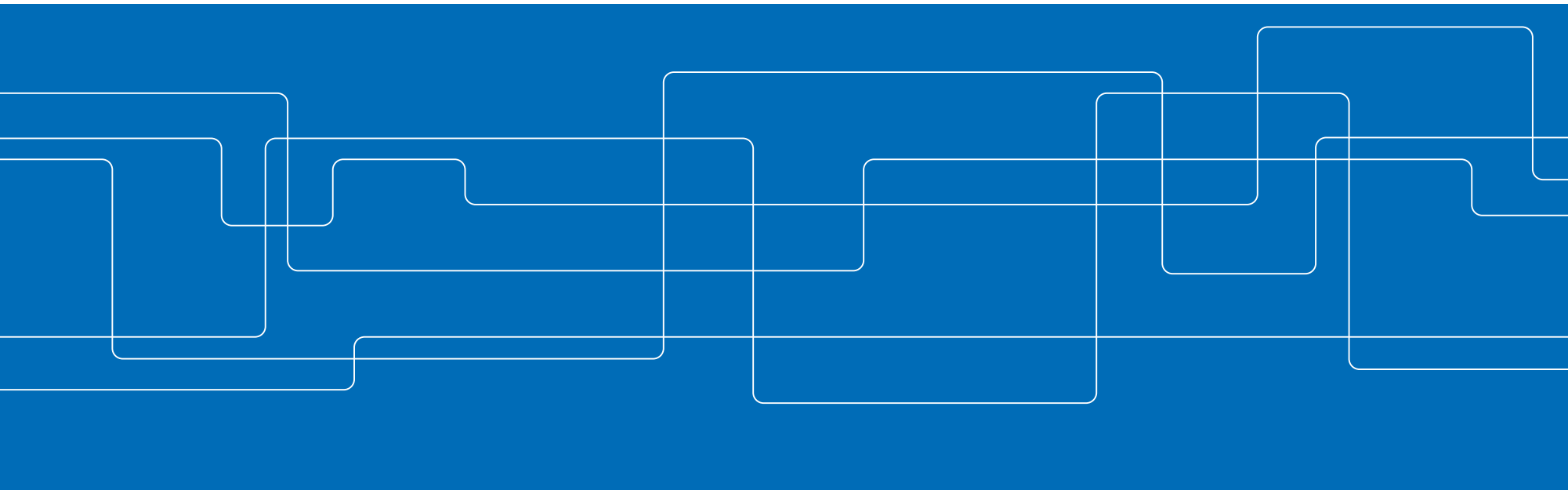


Outline

Vehicular Communication (VC) Systems

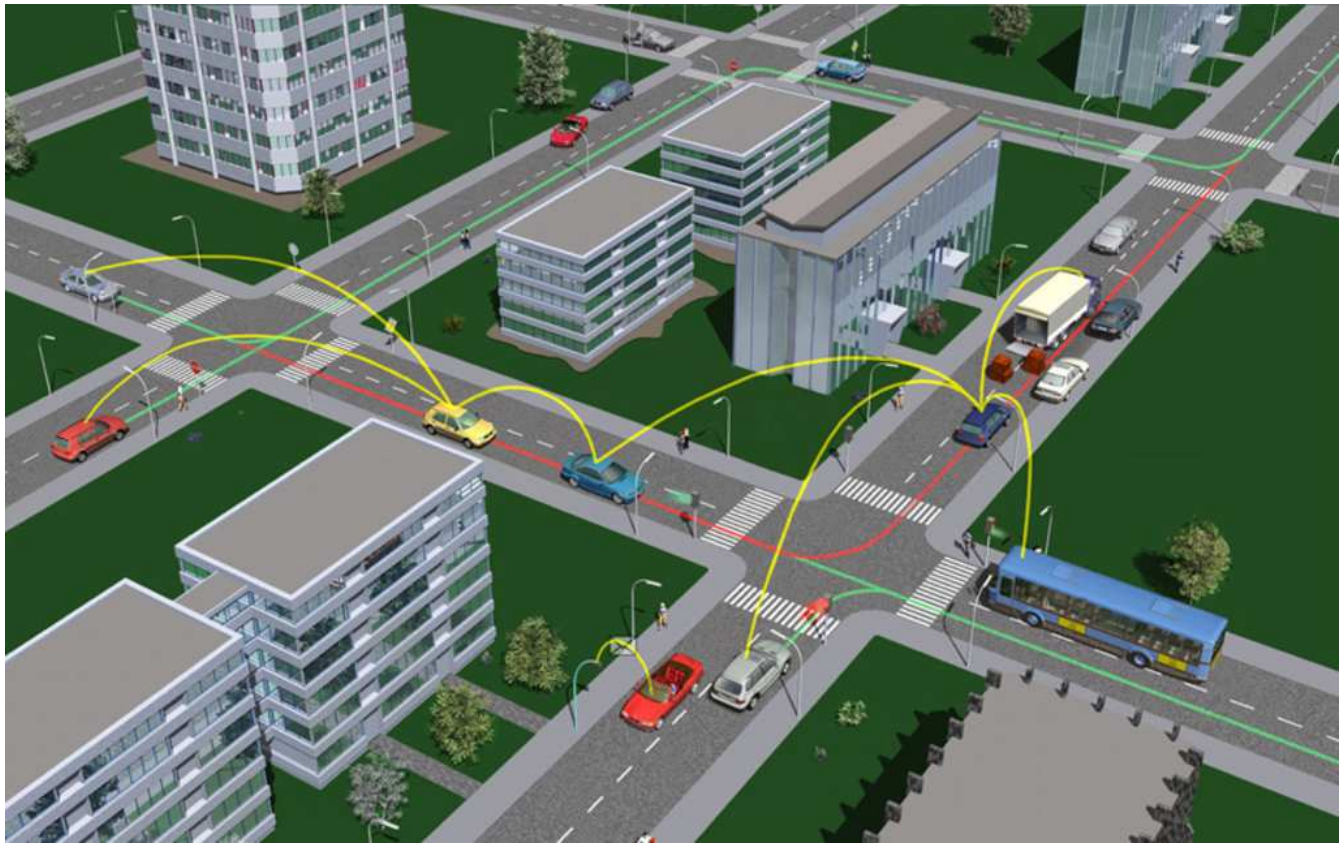
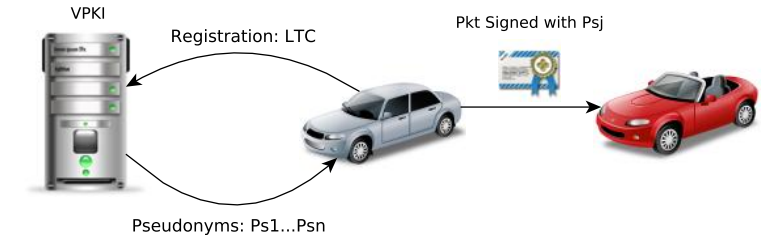


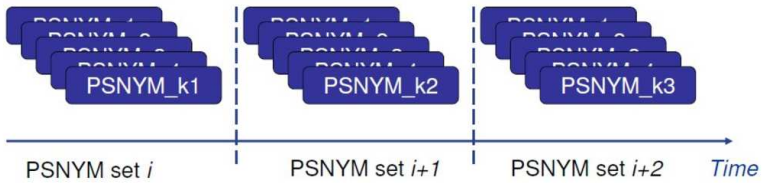
Figure: Photo Courtesy of the Car2Car Communication Consortium (C2C-CC)

Security and Privacy for VC Systems[1]

Basic Requirements

- Message authentication & integrity
- Message non-repudiation
- Access control
- Entity authentication
- Accountability
- Privacy protection



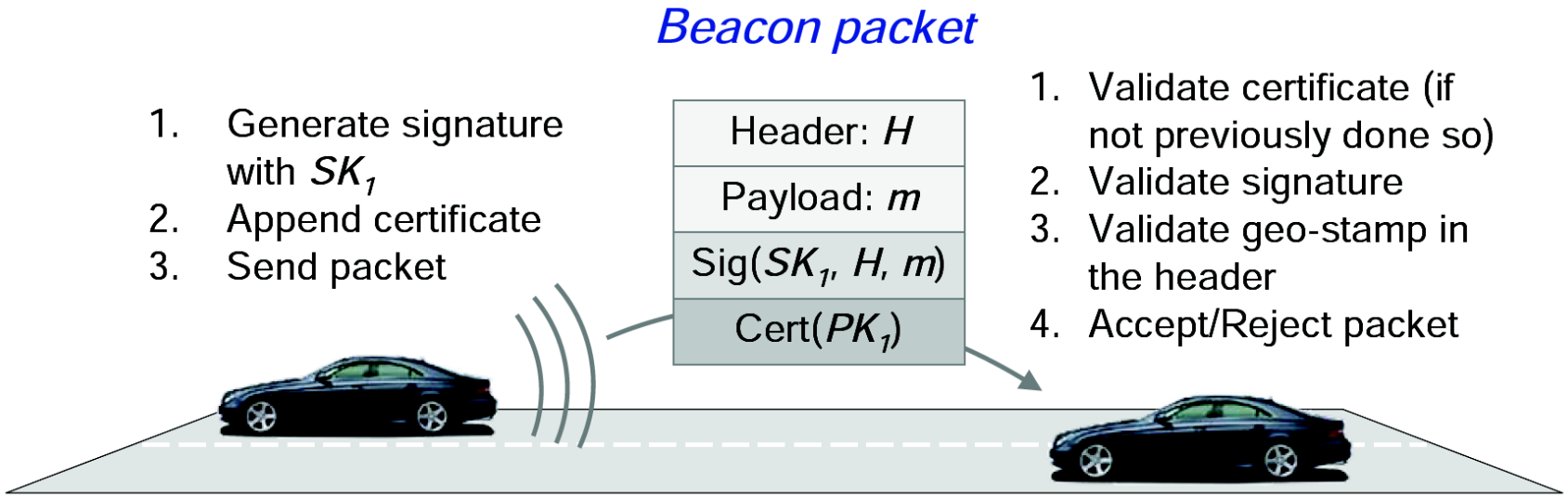


Vehicular Public-Key Infrastructure (VPKI)

- Pseudonymous authentication
- Trusted Third Party (TTP):
  - Certification Authority (CA)
  - Issues credentials & binds users to their pseudonyms

[1] P. Papadimitratos, et al. "Securing Vehicular Communications - Assumptions, Requirements, and Principles," in ESCAR, Berlin, Germany, pp. 5-14, Nov. 2006.
P. Papadimitratos, et al. "Secure Vehicular Communication Systems: Design and Architecture," in IEEE Communications Magazine, vol. 46, no. 11, pp. 100-109, Nov. 2008.

Security and Privacy for VC Systems (cont'd)



- Sign packets with the private key, corresponding to the current valid pseudonym
- Verify packets with the valid pseudonym
- Cryptographic operations in a Hardware Security Module (HSM)

State-of-the-art

Standardization and harmonization efforts

- IEEE 1609.2 [1], ETSI [2] and C2C-CC [3]
- VC related specifications for security and privacy-preserving architectures

Projects

- SEVECOM, EVITA, PRECIOSA, OVERSEE, DRIVE-C2X, Safety Pilot, PRESERVE, CAMP-VSC3

Proposals

- V-Token, CoPRA, SCMS , SEROSA, PUCA

Outline

Problem Statement and Motivation
The design of a VPKI

- Resilience
- Stronger adversarial model (than fully-trustworthy entities)
  - User privacy protection against *"honest-but-curious"* entities
  - User privacy enhancement and service unlinkability (inference of service provider or time)
- Pseudonym acquistion policies
  - How should each vehicle interact with the VPKI, e.g., how frequently and for how long?
  - Should each vehicle itself determine the pseudonym lifetime?
- Operation across multiple domains, thus a scalable design
- Efficiency and robustness

Security and Privacy Requirements for the VPKI Protocols

- Authentication, communication integrity and confidentiality
- Authorization and access control
- Non-repudiation, accountability and eviction (revocation)
- Privacy
  - Anonymity (conditional)
  - Unlinkability
- Thwarting Sybil-based misbehavior
- Availability

Adversarial Model

External adversaries

Internal adversaries

Stronger adversarial model

Protection against *honest-but-curious* VPKI entities

- Correct execution of protocols but motivated to profile users
- Concealing pseudonym provider identity and acquisition time, and reducing pseudonyms linkability (inference based on time)

Multiple VPKI entities could collude

Outline

Secure VC System

- Root Certification Authority (RCA)
- Long Term CA (LTCA)
- Pseudonym CA (PCA)
- Resolution Authority (RA)
- Lightweight Directory Access Protocol (LDAP)
- Roadside Unit (RSU)
- Trust established with RCA, or through cross certification

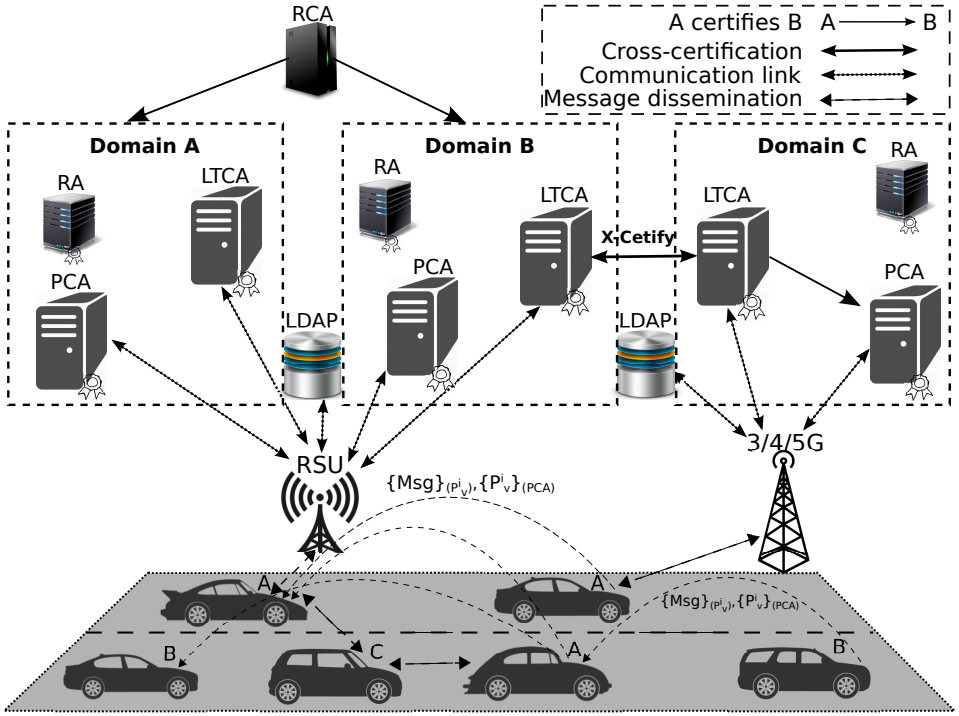


Figure: VPKI Overview

System Model

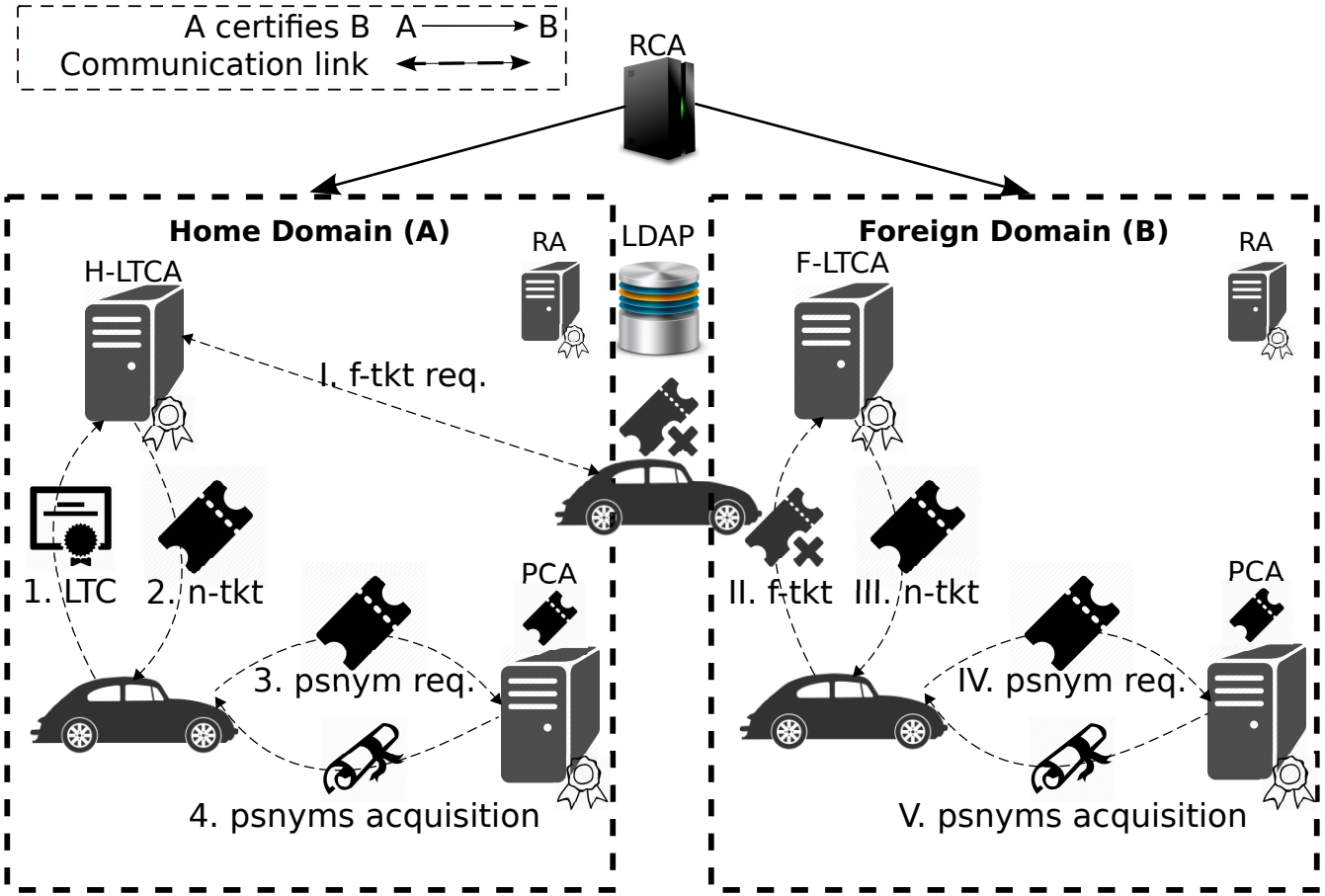


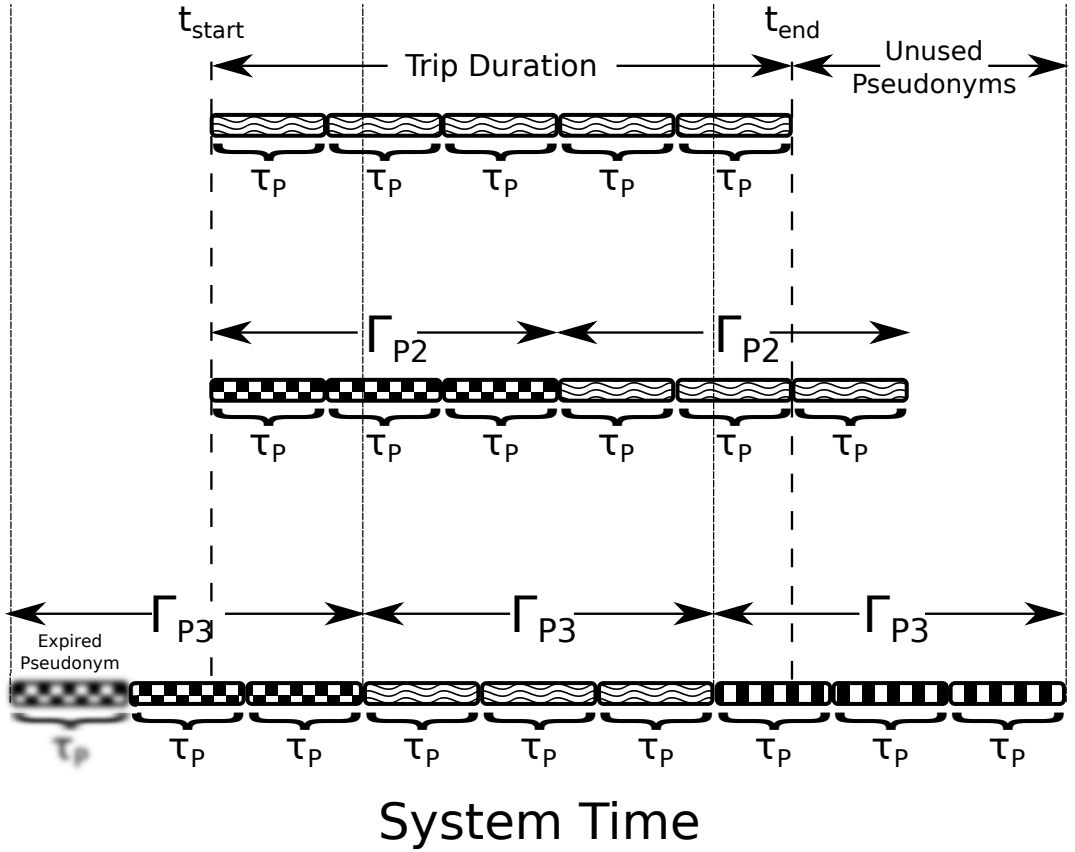
Figure: VPKI Architecture

Pseudonym Acquisition Policies

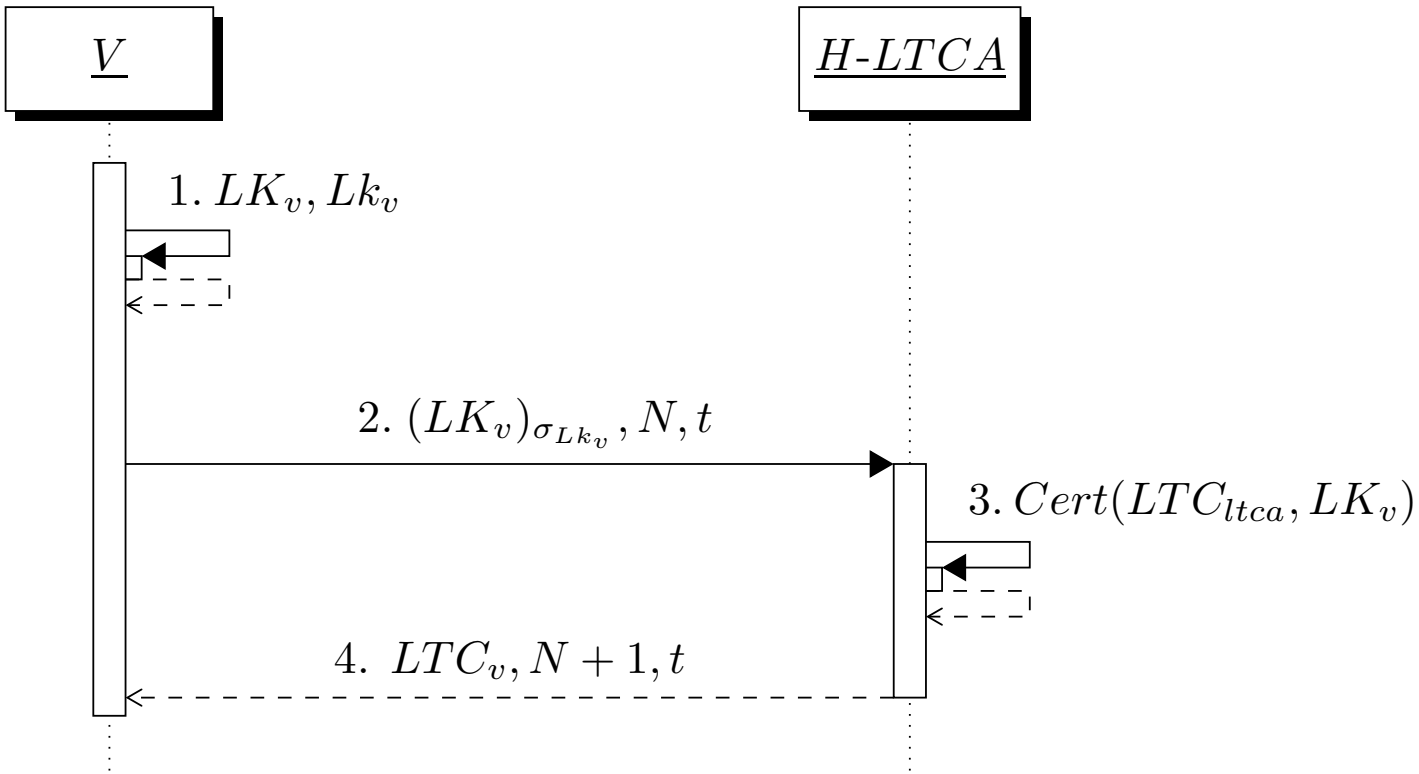
User-controlled policy (P1)

Oblivious policy (P2)

Universally fixed policy (P3)



Vehicle Registration and Long Term Certificate (LTC) Update



Ticket Acquisition Protocols

Protocol 1 Ticket Request (from the LTCA)

1: **procedure** REQTICKET($P_x, \Gamma_{Px}, t_s, t_e, t_{date}$)
2: **if** $P_x = P1$ **then**
3: $(t_s, t_e) \leftarrow (t_s, t_e)$
4: **else if** $P_x = P2$ **then**
5: $(t_s, t_e) \leftarrow (t_s, t_s + \Gamma_{P2})$
6: **else if** $P_x = P3$ **then**
7: $(t_s, t_e) \leftarrow (t_{date} + \Gamma^{i}_{P3}), t_{date} + \Gamma^{i+1}_{P3})$
8: **end if**
9: $\zeta \leftarrow (Id_{tkt\text{-}req}, H(Id_{PCA} || Rnd_{tkt}), t_s, t_e)$
10: $(\zeta)_{\sigma_v} \leftarrow Sign(Lk_v, \zeta)$
11: **return** $((\zeta)_{\sigma_v}, \text{LTC}_v, N, t_{now})$
12: **end procedure**

- Run over Transport Layer Security (TLS) with mutual authentication

Protocol 2 Issuing a Ticket (by the LTCA)

1: **procedure** ISSUETICKET($(msg)_{\sigma_v}, \text{LTC}_v, N, t_{now}$)
2: Verify($\text{LTC}_v, (msg)_{\sigma_v}$)
3: $IK_{tkt} \leftarrow H(\text{LTC}_v || t_s || t_e || Rnd_{IK_{tkt}})$
4: $\zeta \leftarrow (SN, H(Id_{PCA} || Rnd_{tkt}), IK_{tkt}, Rnd_{IK_{tkt}}, t_s, t_e, Exp_{tkt})$
5: $(tkt)_{\sigma_{ltca}} \leftarrow Sign(Lk_{ltca}, \zeta)$
6: **return** $((tkt)_{\sigma_{ltca}}, N + 1, t_{now})$
7: **end procedure**

- *"ticket identifiable key"* (IK_{tkt}) binds a ticket to the corresponding LTC
- Preventing a compromised LTCA from mapping a different LTC during resolution process

Pseudonyms Acquisition Protocols

Protocol 3 Pseudonym Request (from the PCA)

1: **procedure** REQPSNYMS($t_s, t_e, (tkt)_{\sigma_{ltca}}$)
2: **for** i:=1 to **n do**
3: **Begin**
4: Generate(K_v^i, k_v^i)
5: $(K_v^i)_{\sigma_{k_v^i}} \leftarrow$ Sign(k_v^i, K_v^i)
6: **End**
7: $psnymReq \leftarrow (Id_{req}, Rnd_{tkt}, t_s, t_e, (tkt)_{\sigma_{ltca}}, \{(K_v^1)_{\sigma_{k_v^1}}, ..., (K_v^n)_{\sigma_{k_v^n}}\}, N, t_{now})$
8: **return** *psnymReq*
9: **end procedure**

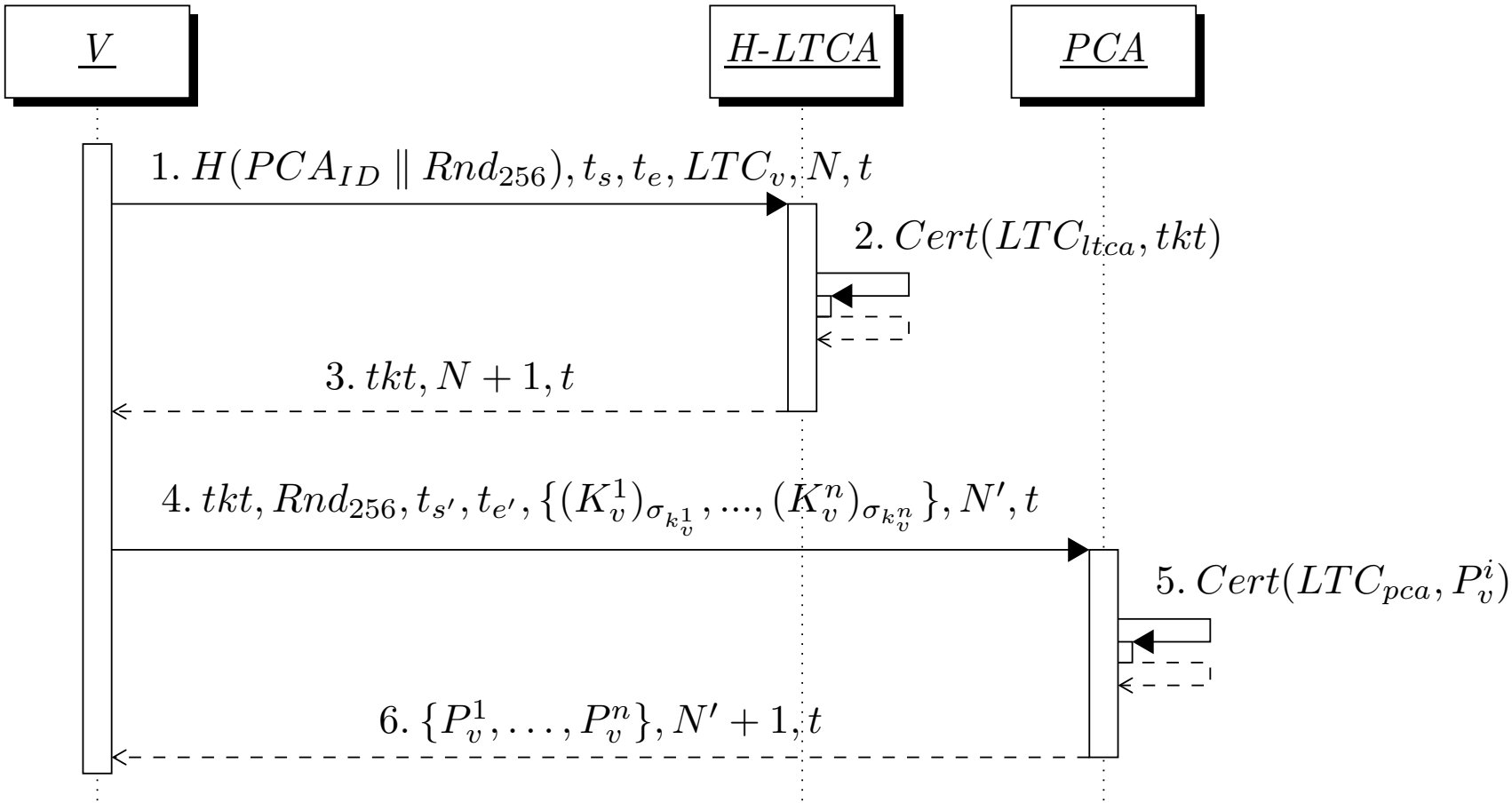
- Run over TLS with unidirectional (server-only) authentication

Protocol 4 Issuing Pseudonyms (by the PCA)

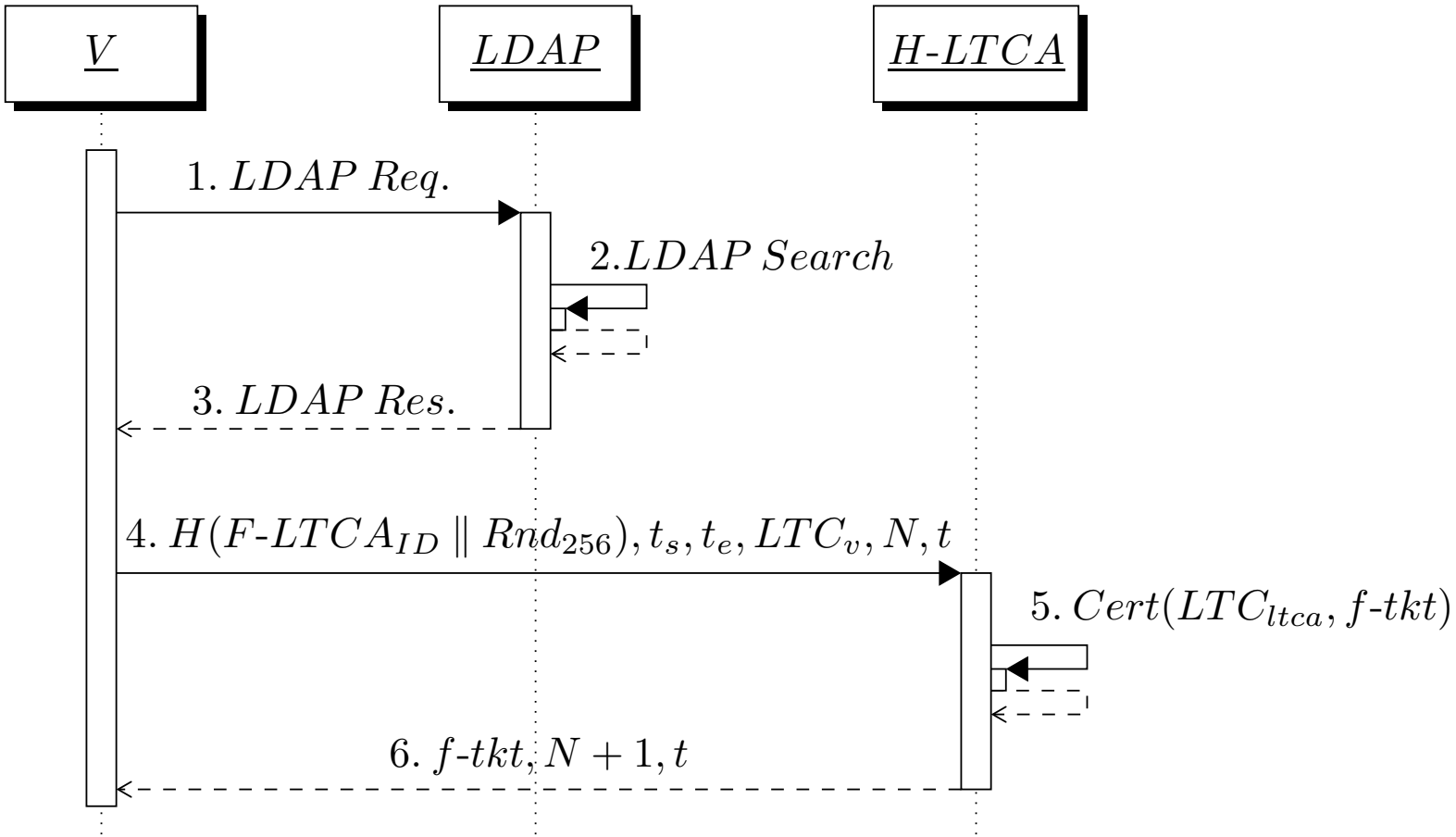
1: **procedure** ISSUEPSNYMS(*psnymReq*)
2: $psnymReq \rightarrow (Id_{req}, Rnd_{tkt}, t_s, t_e, (tkt)_{\sigma_{ltca}}, \{(K_v^1)_{\sigma_{k_v^1}}, ..., (K_v^n)_{\sigma_{k_v^n}}\}, N, t_{now})$
3: Verify($LTC_{ltca}, (tkt)_{\sigma_{ltca}}$)
4: $H(Id_{this\text{-}PCA} || Rnd_{tkt}) \stackrel{?}{=} H(Id_{PCA} || Rnd_{tkt})$
5: $[t_s,\ t_e] \stackrel{?}{=} ([t_s, t_e])_{tkt}$
6: **for** i:=1 to **n do**
7: **Begin**
8: Verify($K_v^i, (K_v^i)_{\sigma_{k_v^i}}$)
9: $IK_{P^i} \leftarrow H(IK_{tkt} || K_v^i || t_s^i || t_e^i || Rnd_{IK_v^i})$
10: $\zeta \leftarrow (SN^i, K_v^i, IK_{P^i}, Rnd_{IK_v^i}, t_s^i, t_e^i)$
11: $(P_v^i)_{\sigma_{pca}} \leftarrow Sign(Lk_{pca}, \zeta)$
12: **End**
13: **return** $(\{(P_v^1)_{\sigma_{pca}}, \ldots, (P_v^n)_{\sigma_{pca}}\}, N{+}1, t_{now})$
14: **end procedure**

- *"pseudonym identifiable key"* (IK_{P^i}) binds a pseudonym to the corresponding ticket
- Preventing a compromised PCA from mapping a different ticket during resolution process

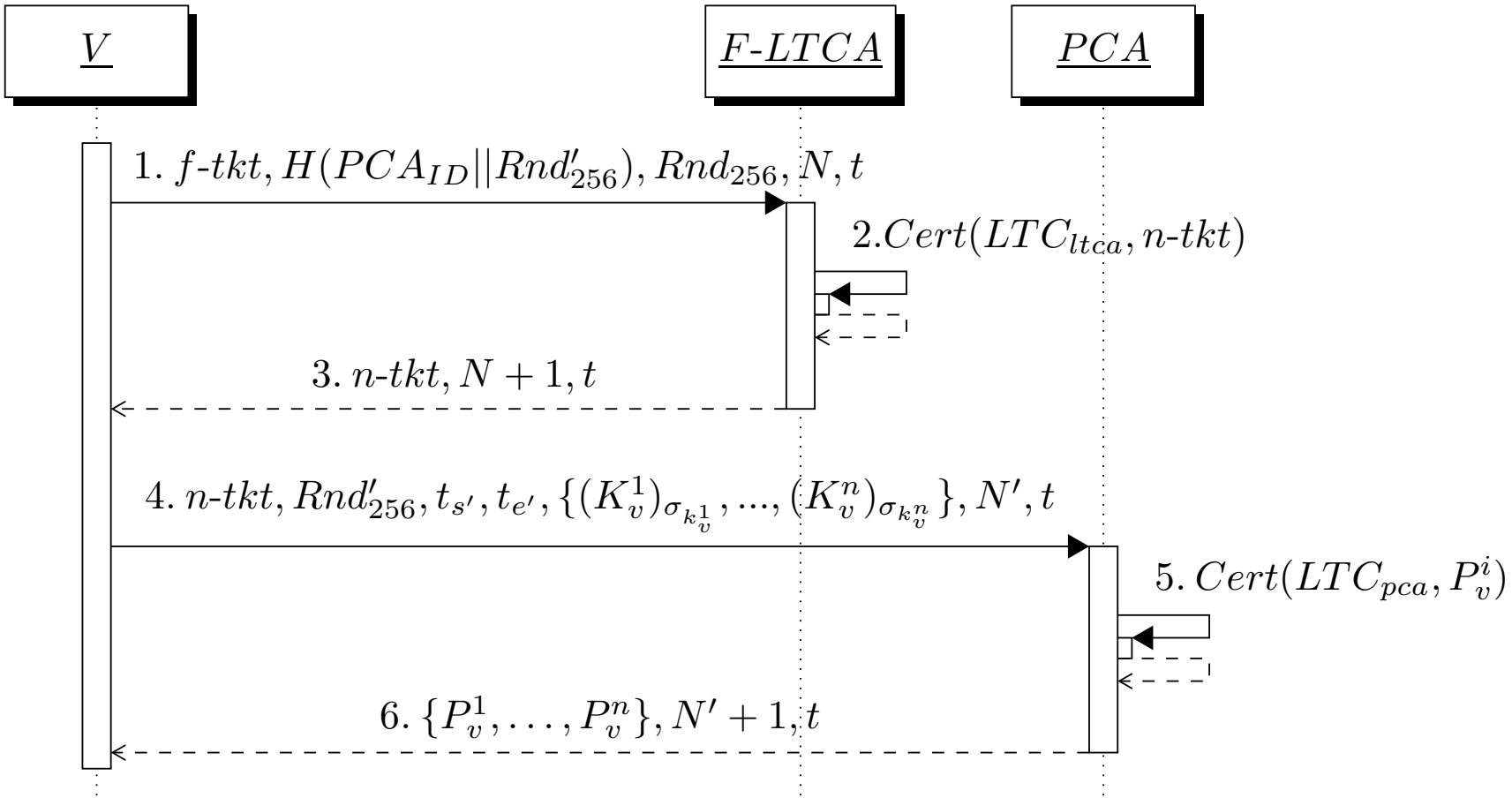
Ticket and Pseudonym Acquisition



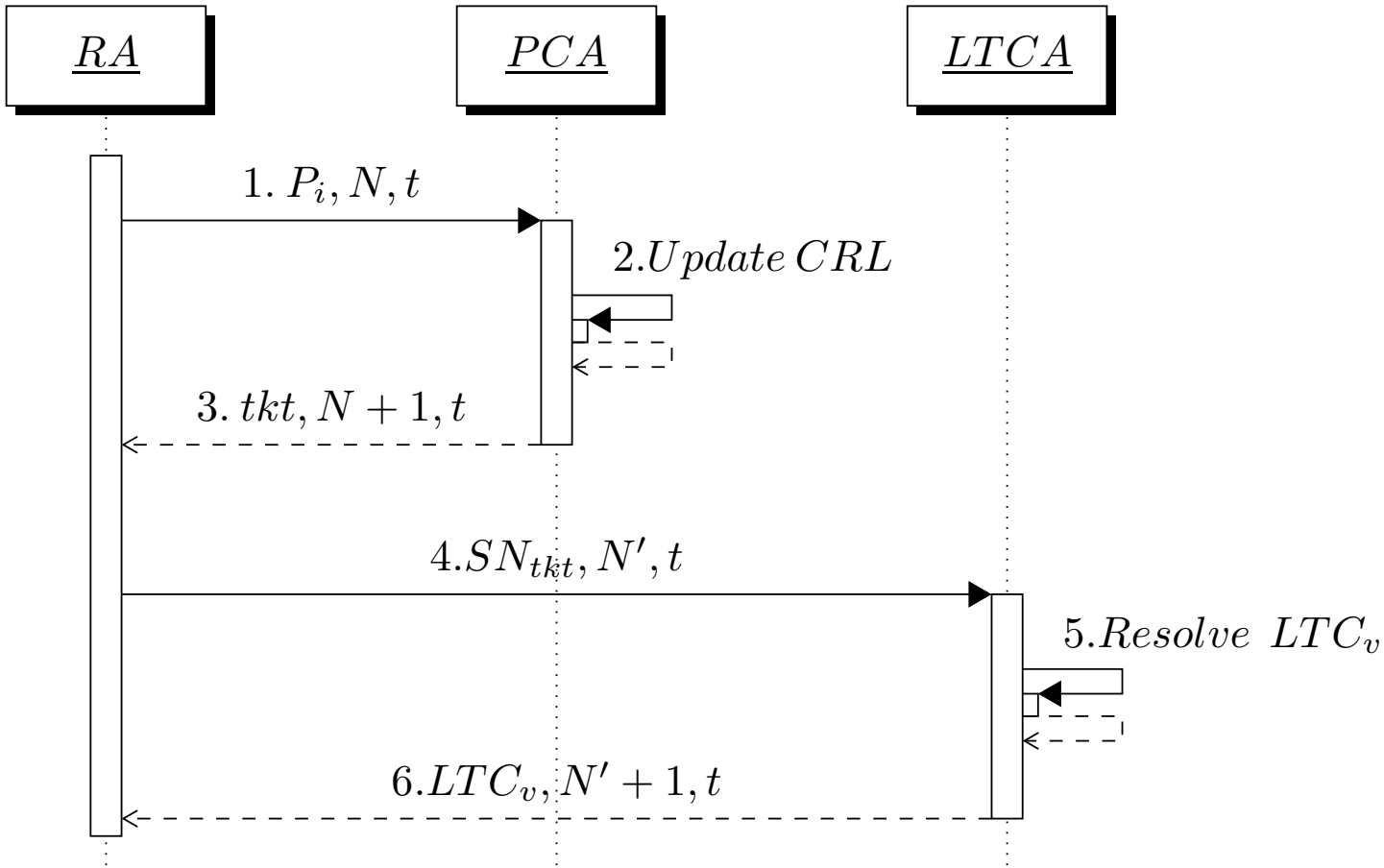
Roaming User: Foreign Ticket Authentication



Native Ticket and Pseudonym Acquisition in the Foreign Domain



Pseudonym Revocation and Resolution

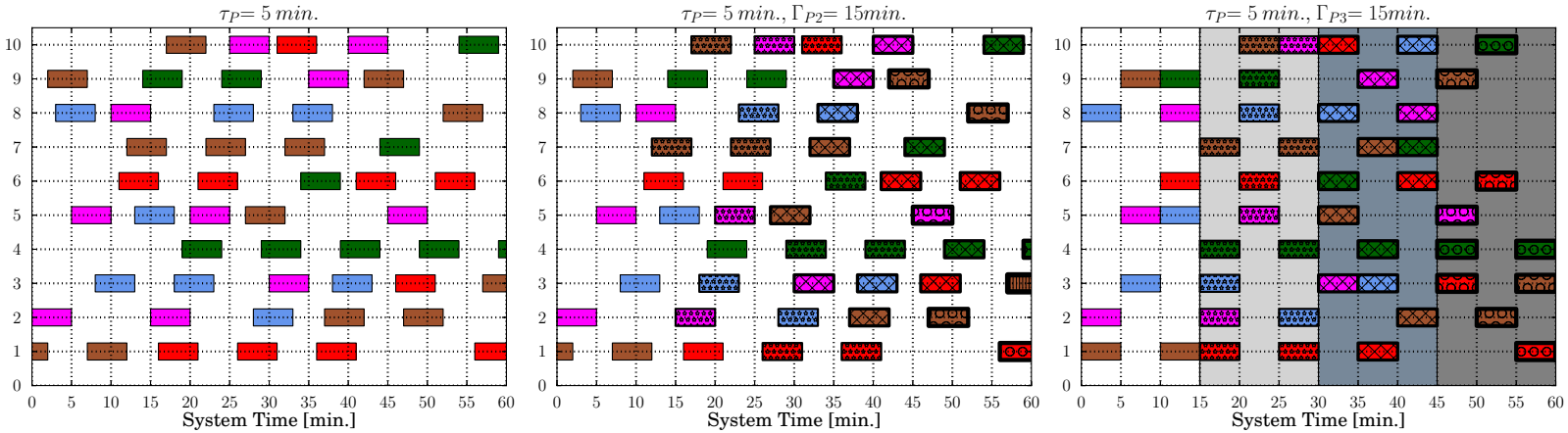


Outline

Security and Privacy Analysis

- Communication integrity, confidentiality, and non-repudiation
  - Certificates, TLS and digital signatures
- Authentication, authorization and access control
  - LTCA is the *policy decision and enforcement point*
  - PCA grants the service
  - Security association discovery through LDAP
- Concealing PCAs, F-LTCA, actual pseudonym acquisition period
  - Sending $H(PCA_{id} \| Rnd_{256})$, t_s, t_e, LTC_v to the H-LTCA
  - PCA verifies if $[t'_s,\ t'_e] \subseteq [t_s,\ t_e]$
- Thwarting Sybil-based misbehavior
  - LTCA never issues valid tickets with overlapping lifetime (for a given domain)
  - A ticket is bound to a specific PCA
  - PCA keeps records of ticket usage

Linkability based on Timing Information of Credentials



(a) P1: User-controlled policy (b) P2: Oblivious policy (c) P3: Universally fixed policy

- Non-overlapping pseudonym lifetimes from eavesdroppers' perspective
- P1 & P2: Distinct lifetimes per vehicle make linkability easier (requests/pseudonyms could act as user *'fingerprints'*)
- P3: Uniform pseudonym lifetime results in no distinction

Outline

Experimental Setup

- **VPKI testbed**
  - Implementation in C++
  - OpenSSL: TLS and Elliptic Curve Digital Signature Algorithm (ECDSA)-256 according to the standard [1]
- **Network connectivity**
  - Varies depending on the actual OBU-VPKI connectivity
  - Reliable connectivity to the VPKI (e.g., RSU, Cellular, opportunistic WiFi)

Table: Servers and Clients Specifications

	LTCA	PCA	RA	Clients
VM Number	2	5	1	25
Dual-core CPU (Ghz)	2.0	2.0	2.0	2.0
BogoMips	4000	4000	4000	4000
Memory	2GB	2GB	1GB	1GB
Database	MySQL	MySQL	MySQL	MySQL
Web Server	Apache	Apache	Apache	-
Load Balancer	Apache	Apache	-	-
Emulated Threads	-	-	-	400

- **Use cases**
  - Pseudonym provision
  - Performing a DDoS attack

Experimental Setup (cont'd)

Table: Mobility Traces Information

	TAPASCologne	LuST [5]
Number of vehicles	75,576	138,259
Number of trips	75,576	287,939
Duration of snapshot (hour)	24	24
Available duration of snapshot (hour)	2 (6-8 AM)	24
Average trip duration (sec.)	590.49	692.81
Total trip duration (sec.)	44,655,579	102,766,924

- **Main metric**
  - End-to-end pseudonym acquisition latency from the initialization of ticket acquisition protocol till successful completion of pseudonym acquisition protocol

Table: Servers & Clients Specifications

	LTCA	PCA	Client
Number of entities	1	1	1
Dual-core CPU (Ghz)	2.0	2.0	2.0
BogoMips	4000	4000	4000
Memory	2GB	2GB	1GB
Database	MySQL	MySQL	MySQL

- N.B. PRESERVE Nexcom boxes specs: dual-core 1.66 GHz, 2GB Memory

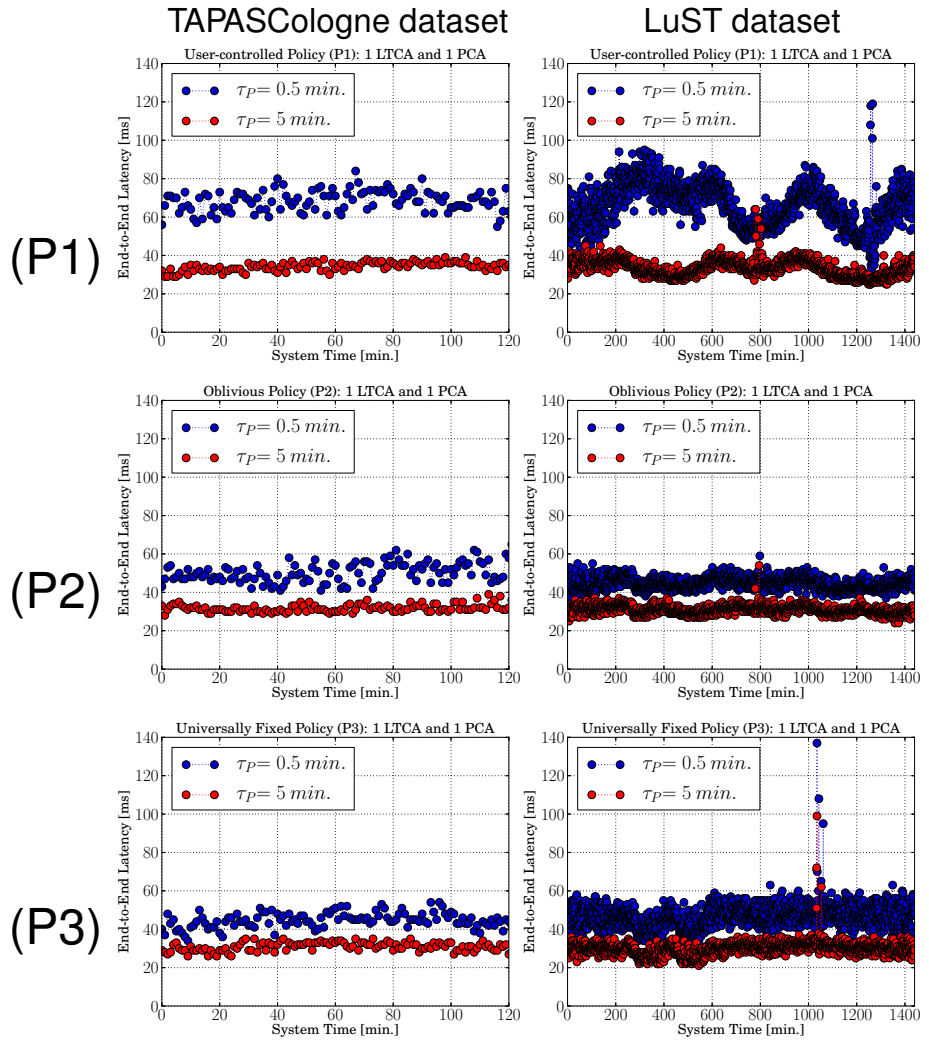
End-to-end Latency for P1, P2, and P3

Choice of parameters:

- Frequency of interaction and volume of workload to a PCA
- Γ=5 min., τ_P=0.5 min., 5 min.

LuST dataset ($\tau_P = 0.5\ min$):

- P1: $F_x(t = 167\ ms) = 0.99$
- P2: $F_x(t = 80\ ms) = 0.99$
- P3: $F_x(t = 74\ ms) = 0.99$



Latency Comparison for Different Policies

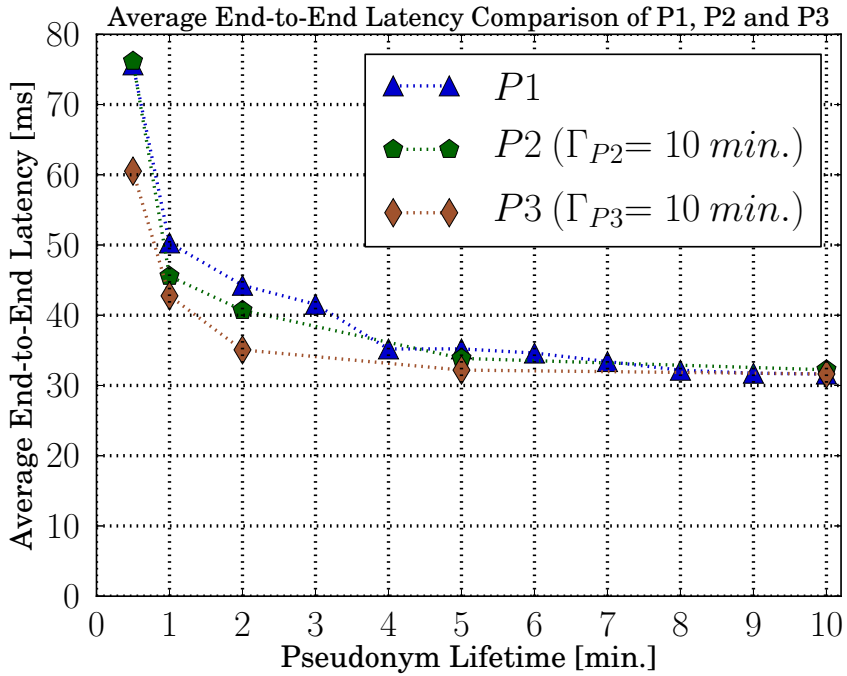
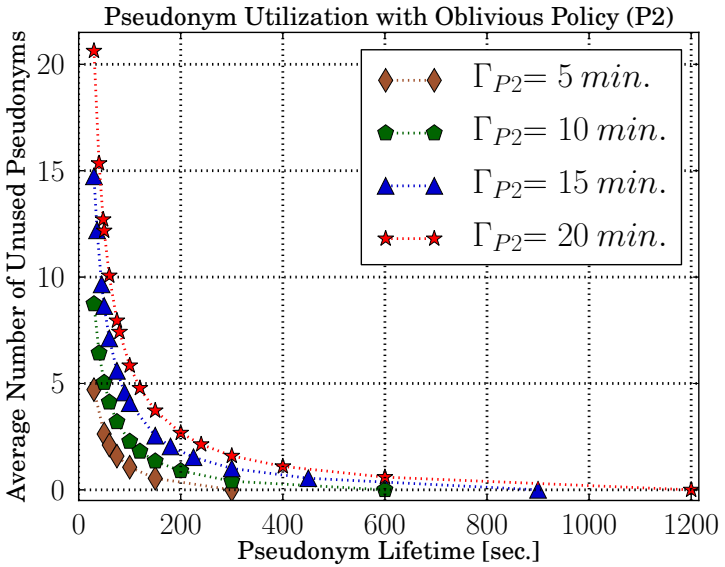
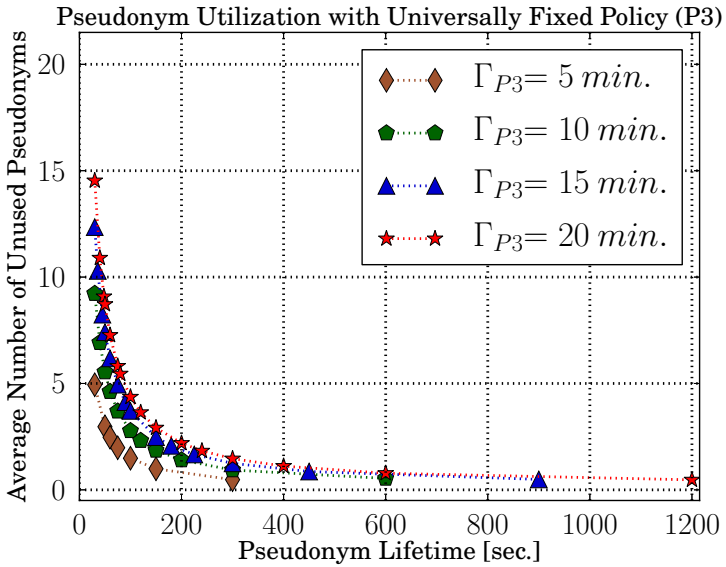


Figure: End-to-end latency comparison for different policies (Tapas Dataset)

Pseudonym Utilization, LuST Dataset for P2 & P3



P2: Oblivious Policy



P3: Universally Fixed Policy

The VPKI Servers under a DDoS Attack

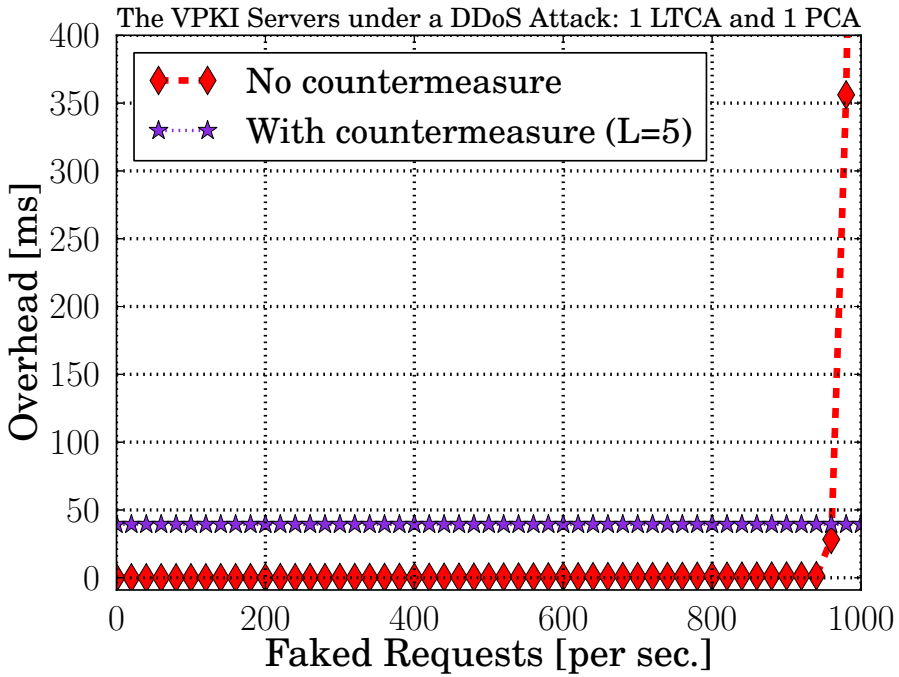
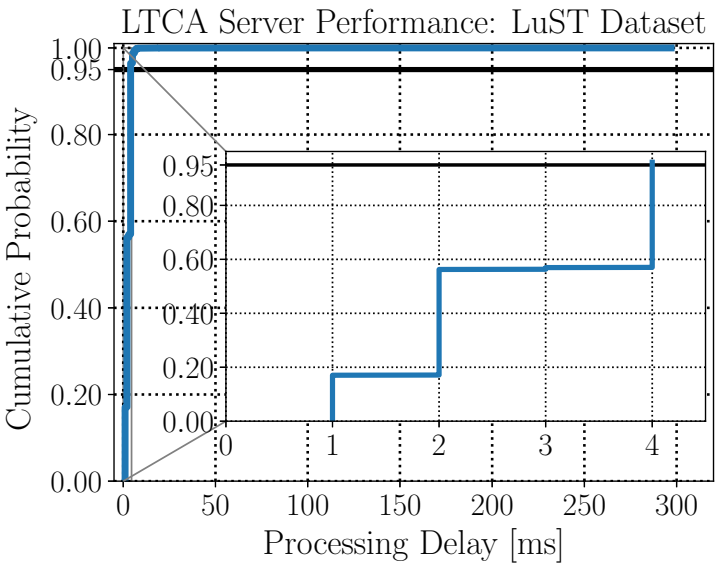
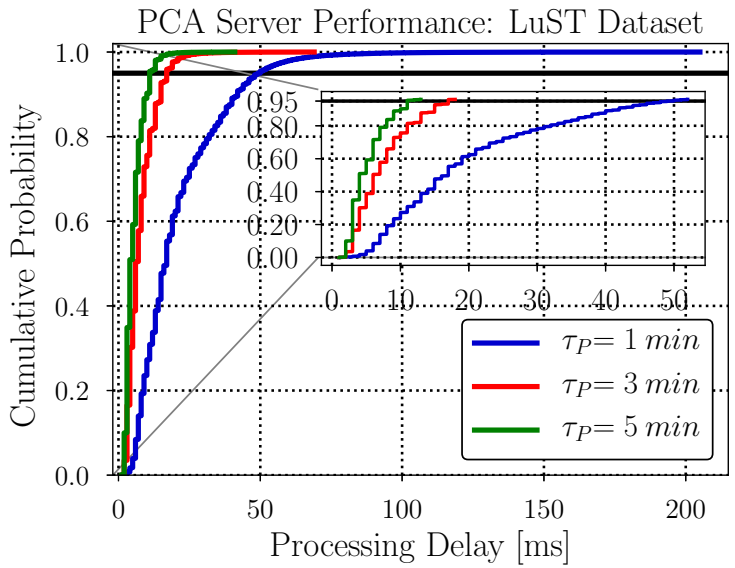


Figure: Overhead to obtain pseudonyms, LuST dataset with P1 (τ_P = 5 min.)

Performance Evaluation for Ticket and Pseudonym Acquisition



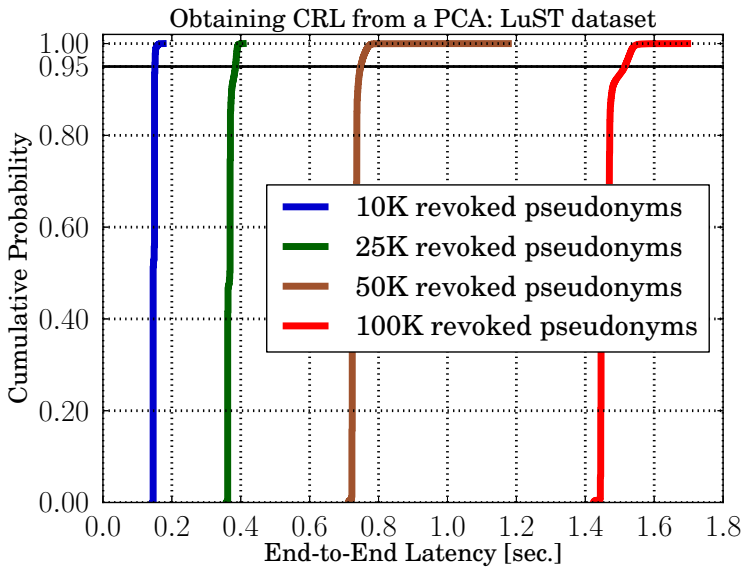
Obtaining a Certificate Revocation List (CRL)

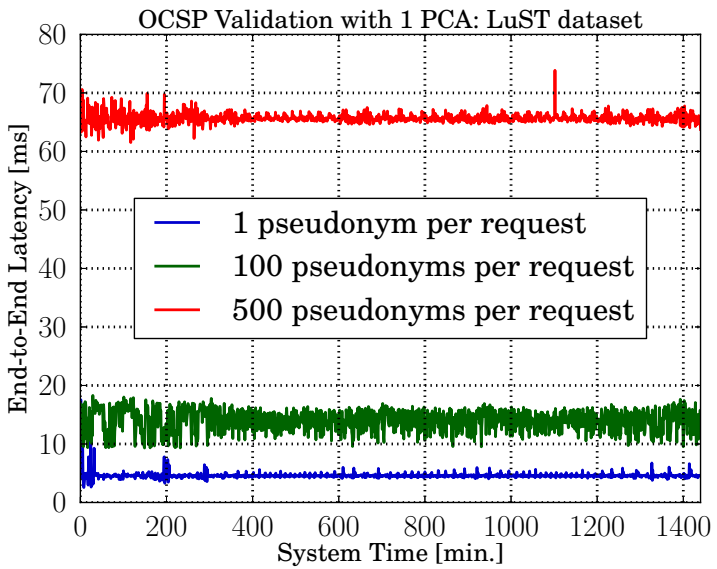


Online Certificate Status Protocol (OCSP) validation

- Ticket Acquisition: F_x(t=4ms)=0.95 or Pr{t$\leq$4ms}=0.95.
- Pseudonym Acquisition: F_x(t=52ms)=0.95 or Pr{t$\leq$52}=0.95.

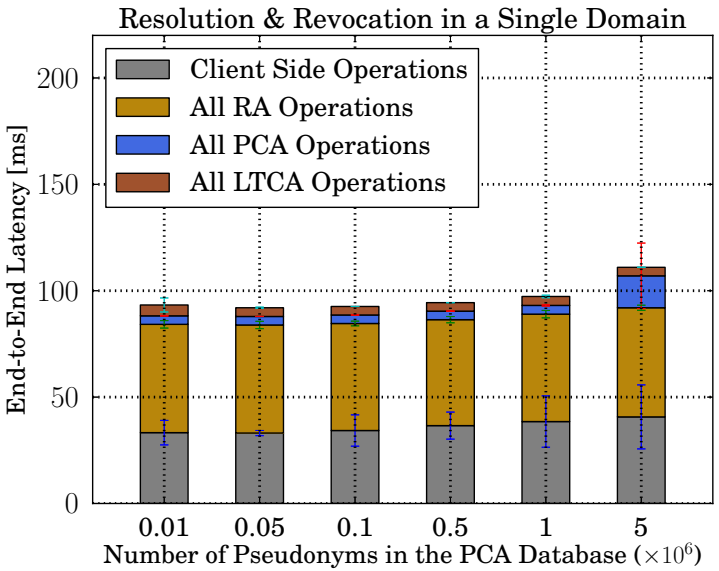
Performance Evaluation for Pseudonym Revocation (CRL or OCSP)



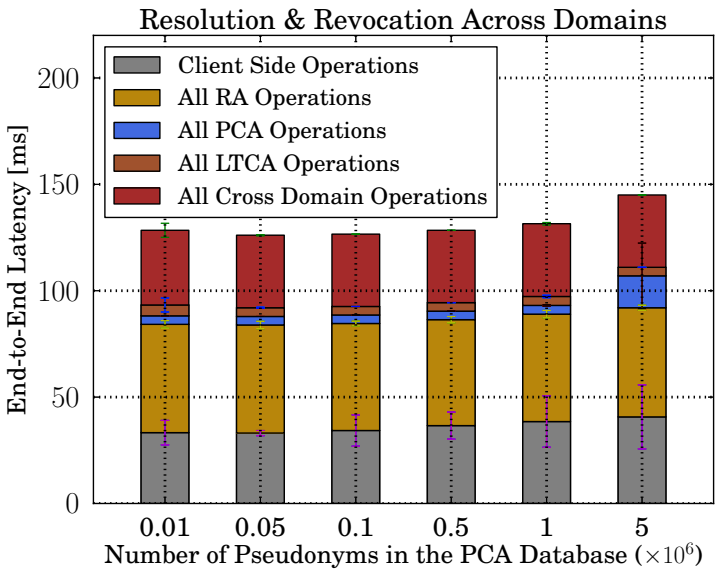


Obtaining a CRL OCSP validation

Entities Response Time to Resolve & Revoke a Pseudonym



Single Domain Operation



Across Domains Operation

- On average 100 ms to resolve & revoke a pseudonym

Comparison with Other Implementations

Table: Latency for issuing 100 pseudonyms (without communication delay)

	$Delay_{PCA}$	CPU_{PCA}
VeSPA [6]	817 ms	3.4 GHz
SEROSA [7]	650 ms	2.0 GHz
PUCA [8]	1000 ms	2.53 GHz
PRESERVE PKI (Fraunhofer SIT) [9]	$\approx$ 4000 ms	N/A
C2C-CC PKI (ESCRYPT) [3]	393 ms	N/A
SECMACE	260 ms	2.0 GHz

Outline

Summary of Contributions

1. Facilitating multi-domain operation
2. Offering increased user privacy protection
   - Honest-but-curious system entities
   - Eliminating pseudonym linking based on timing information
3. Eradication of Sybil-based misbehavior
4. Proposing multiple generally applicable pseudonym acquisition policies
5. Detailed analysis of security and privacy protocols
6. Extensive experimental evaluation
   - Efficiency, scalability, and robustness
   - Achieving significant performance improvement
   - Modest VMs can serve sizable areas or domain

Future Steps

VPKI enhancements

- Evaluation of the level of privacy, i.e., unlinkability, based on the timing information of the pseudonyms for each policy
- Evaluation of actual networking latency, e.g., OBU-RSU
- Rigorous analysis of the security and privacy protocols

Efficient distribution of revocation information

- *How to disseminate pseudonyms validity information without interfering with vehicles operations?*

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