VeriEdge: Verifying and Enforcing Service Level Agreements for Pervasive Edge Computing

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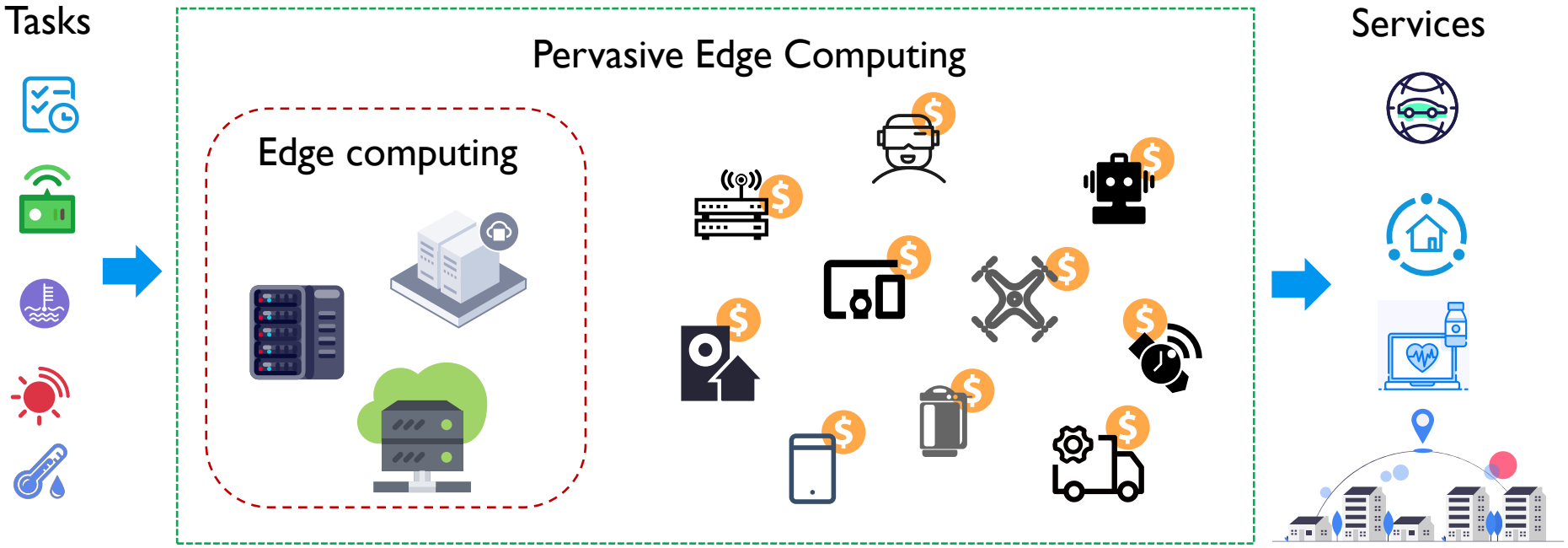
Outlines

- Background and Motivation
- Models and Problem Statement
- Solution Design
- Security Analysis
- Performance Evaluation
- Conclusions

Pervasive Edge Computing (PEC)

- Edge computing and **PEC**
  - Low latency
  - Network traffic reduction
  - **Edge devices can freely enter or exit the market**
  - **Device heterogeneity and dynamicity**

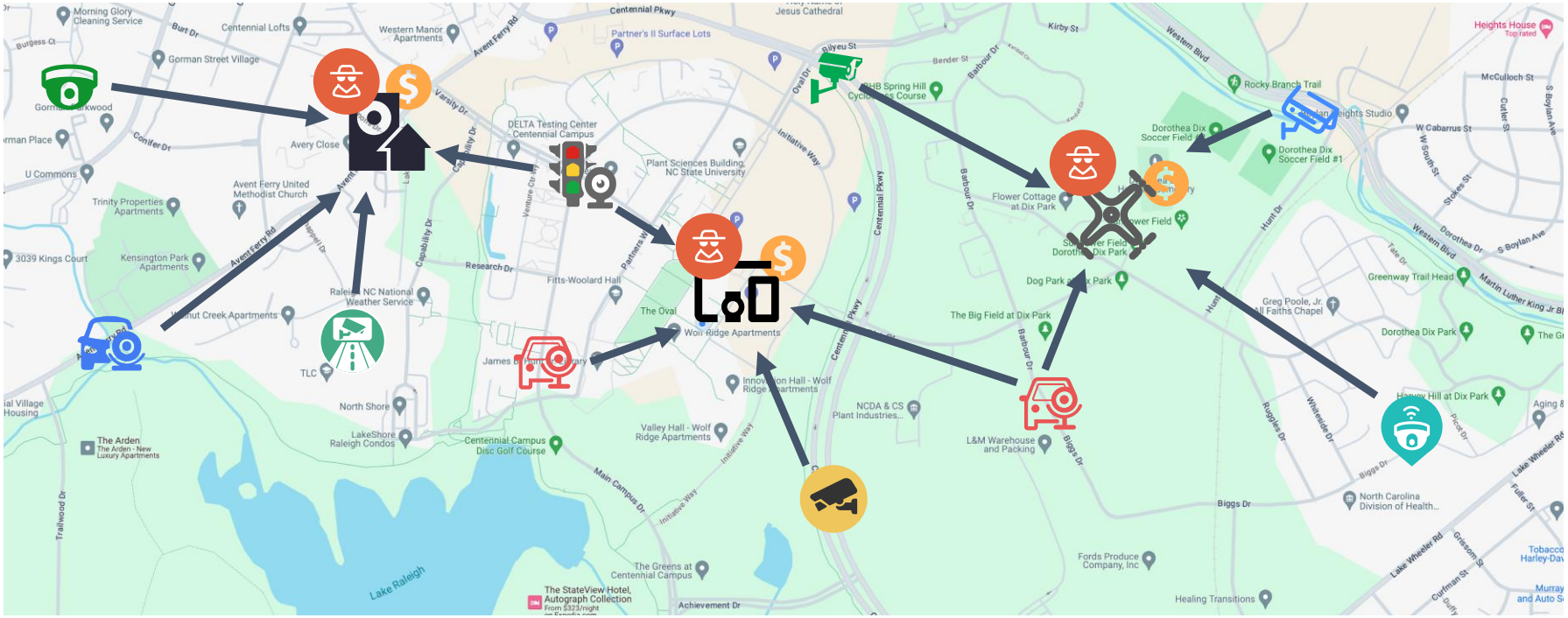


Service Level Agreements (SLAs)

- Mutual untrust between users and edge devices

SLA Compliance

A PEC device may not faithfully process the offloading video data while still trying to claim the service reward.



Monitoring SLA is imperative

Challenges in SLA Verification

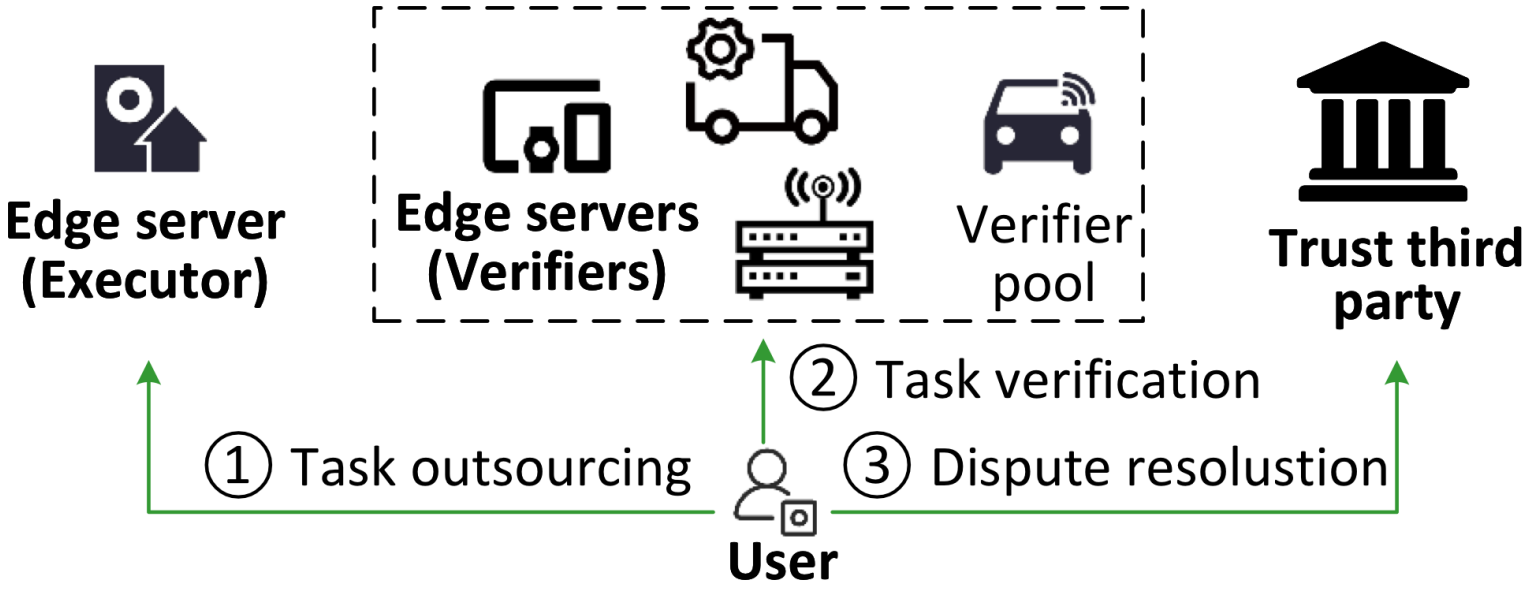
- Limited user resources hinder independent verification
  - Rely on external verifiers to assist.
- Verifiers can be untrusted as well
  - Verifiers are driven by financial interests.
- Fairly opportunities for verifier participation
  - For market stability, long-term viability, and preventing dominance or collusion by resource-intensive devices.

Our Solution: VeriEdge

- Commit-then-sample
  - Perform lightweight sampling and verification of intermediate computation results with non-repudiability.

- Crypto-based verifier selection and computation verification
  - Ensure verifiable fairness and a high probability for misbehavior detection.

VeriEdge Overview



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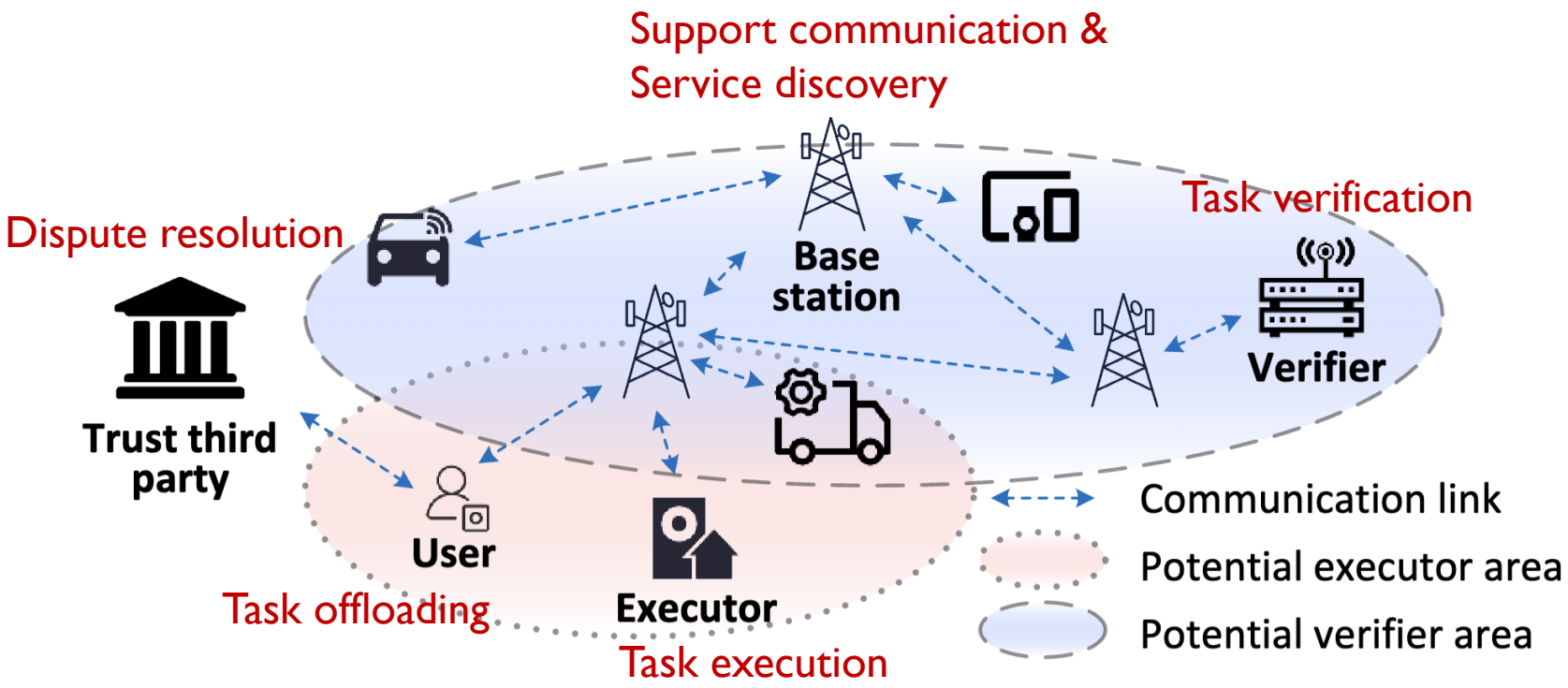
System Model



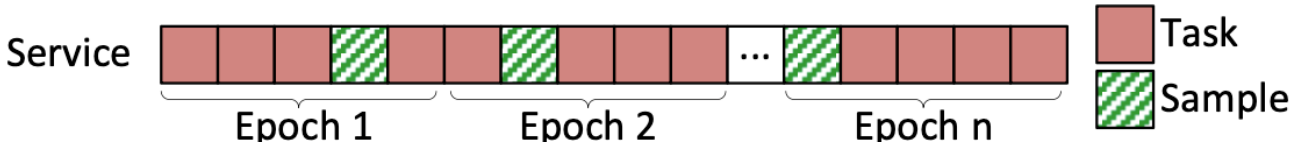
Threat Model and Security Goals

- Malicious executor
- Colluding executor and verifier
- Malicious users
- Trust Base station and TTP
- All parties communicate via authenticated secure channels

- ✓ SLA compliance
- ✓ Non-manipulable verification
- ✓ Dispute resolution

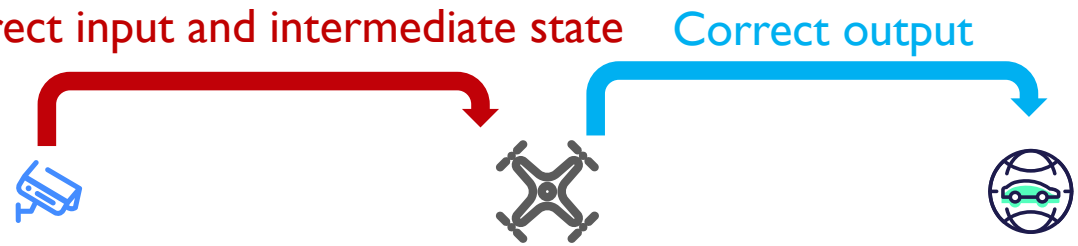
Problem Formulation

- Service Model



n epochs with epoch length $l_{\varrho_i} = 5$ tasks. Sampling rate $\eta_s = 0.2$.

- User's goal
  - To verify that each task is faithfully executed



Problem Formulation

- Goal: Define an edge outsourcing and verification framework ensures (Probabilistic) SLA compliance.

q-Algorithm

An executor/verifier executes the correct algorithm Φ_s and returns the correct result with probability q, and executes an arbitrary algorithm and returns potentially fake or malicious result with probability 1 - q.
An honest executor/verifier always executes a 1-algorithm.

(Probabilistic) SLA compliance

Given an executor using q-algorithm with q<1, for any pre-collusion ratio δ_s and sampling rate η_s, unterminated outsourcing indicates that user's SLA requirements are met with probability

$\Pr[\text{ executor is faithful }] > 1 - \epsilon(n)$,
where $\epsilon(n)$ is a negligible function in the number of epochs n, i.e., for all constants c, there exists an integer N such that for all $n > N$, $|\epsilon(n)| < \frac{1}{n^c}$.

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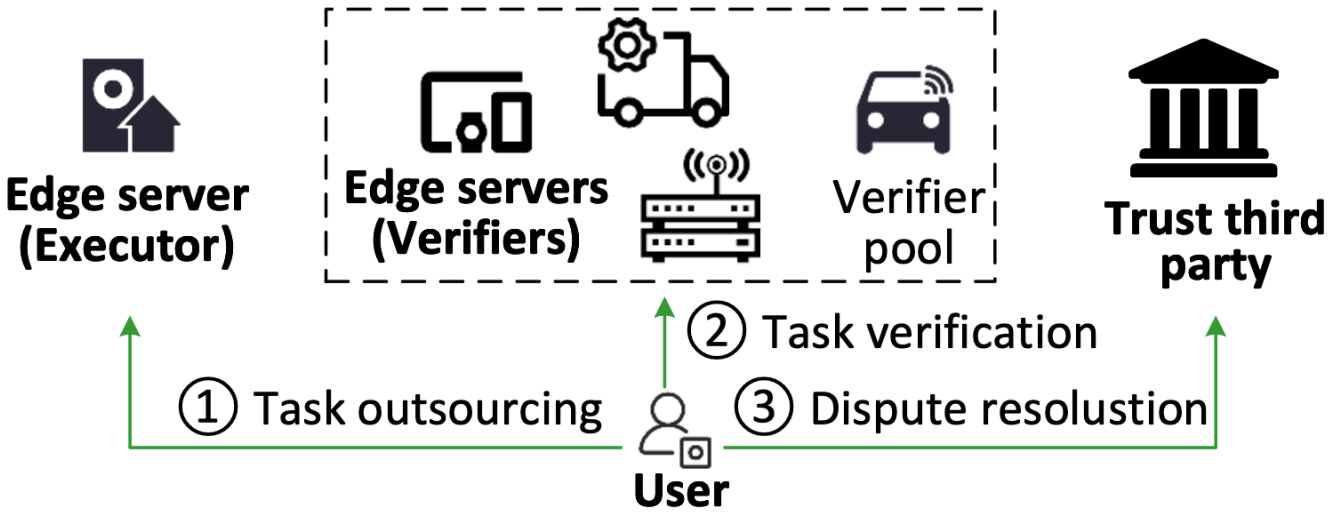
VeriEdge



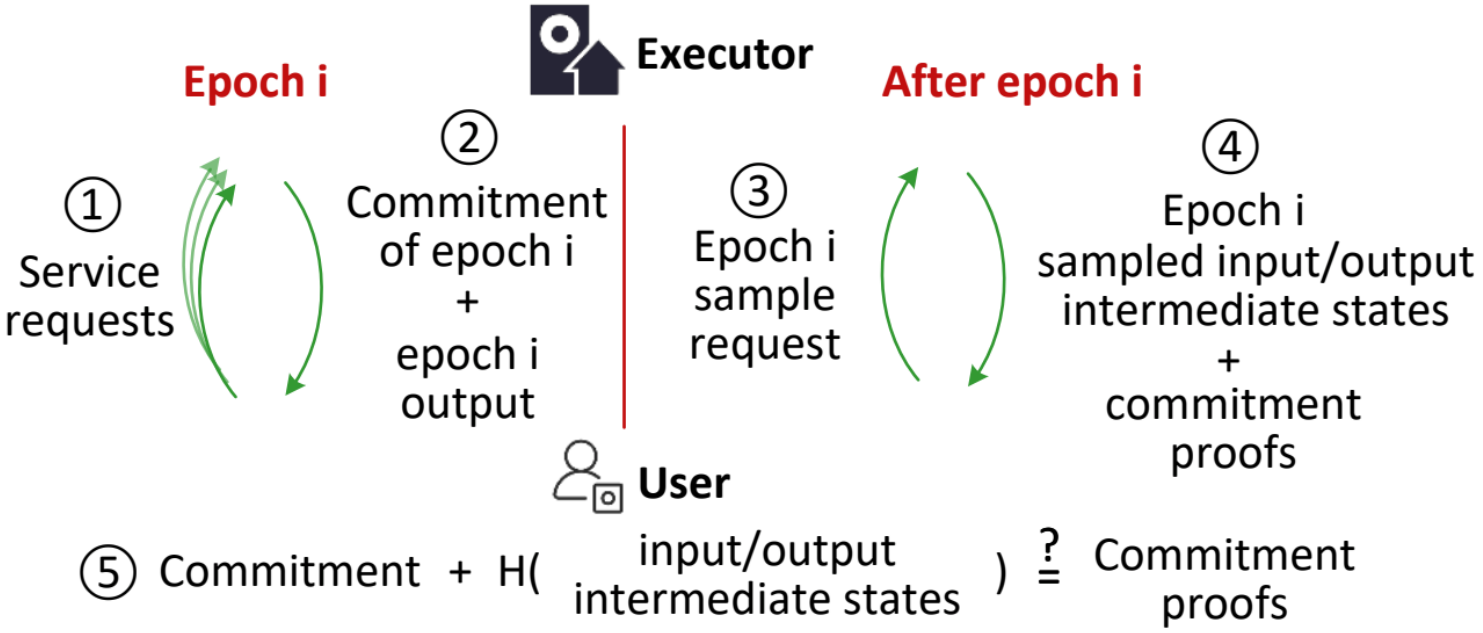
- Task Execution and Verifiable Sampling 1/3
- VRF-based Verifier Selection 2/3
- Dispute Resolution 3/3

Preliminaries

- Commitment
  - Com(x,r) → c: It takes a statement x and a random value r as input, and outputs a commitment c.
  - Verify(c,x,r) → {0,1}: It takes a commitment c, a statement x and a random value r as input, and outputs 1 if c = Com(x, r), and 0 otherwise.
  - ✓ Binding and Hiding

Task Execution and Verifiable Sampling 1/3

- Commitment and verification
  - Executor cannot know which tasks will be sampled before executing tasks.
  - Executor cannot return wrong intermediate states of a sampled task to mislead and evade verification.

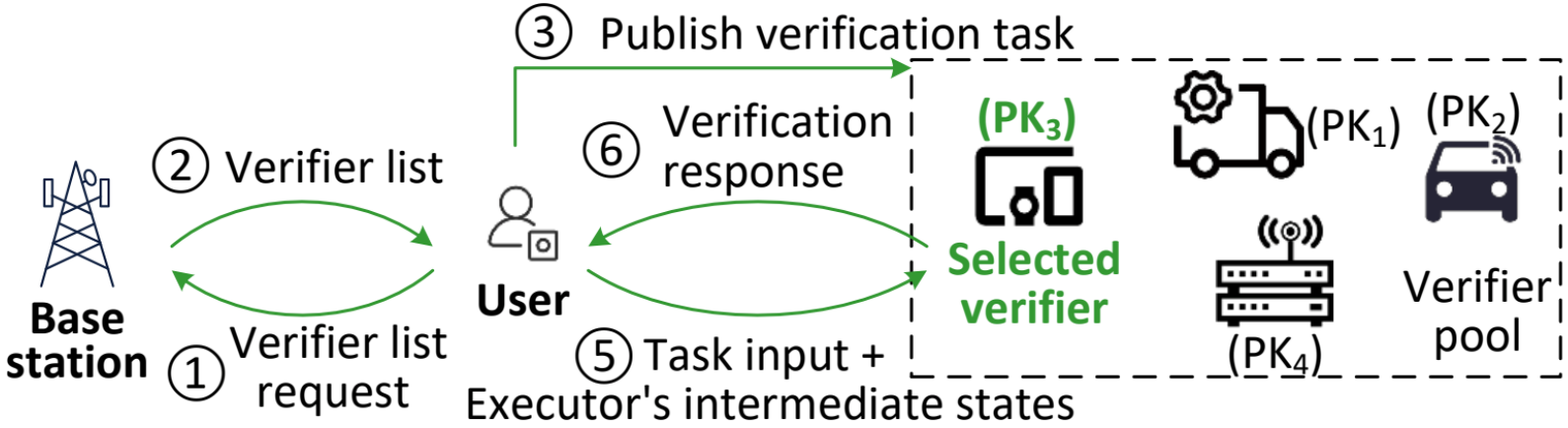


Preliminaries

- Verifiable Random Function (VRF)
  - VRFKeyGen(1^k)→(SK,PK)
    - It takes security param- eter k as input, and outputs a (SK,PK) key pair.
  - RFProve(SK,x)→(y,π)
    - It takes secret key SK and an input x, and generates an output y and its proof π.
  - VRFVerify(PK,x,y,π)→{0,1}
    - It takes the public key PK, input x, output y and proof π as input, and outputs 1 if (y,π)=VRFProve(SK,x) and 0 otherwise.
  - ✓ **Uniqueness, Provability, Pseudorandomness**

VRF-based Verifier Selection 2/3

- Dynamic verifier pool
  - Verifiable verifier selection
    - Selection process is fair and not manipulated

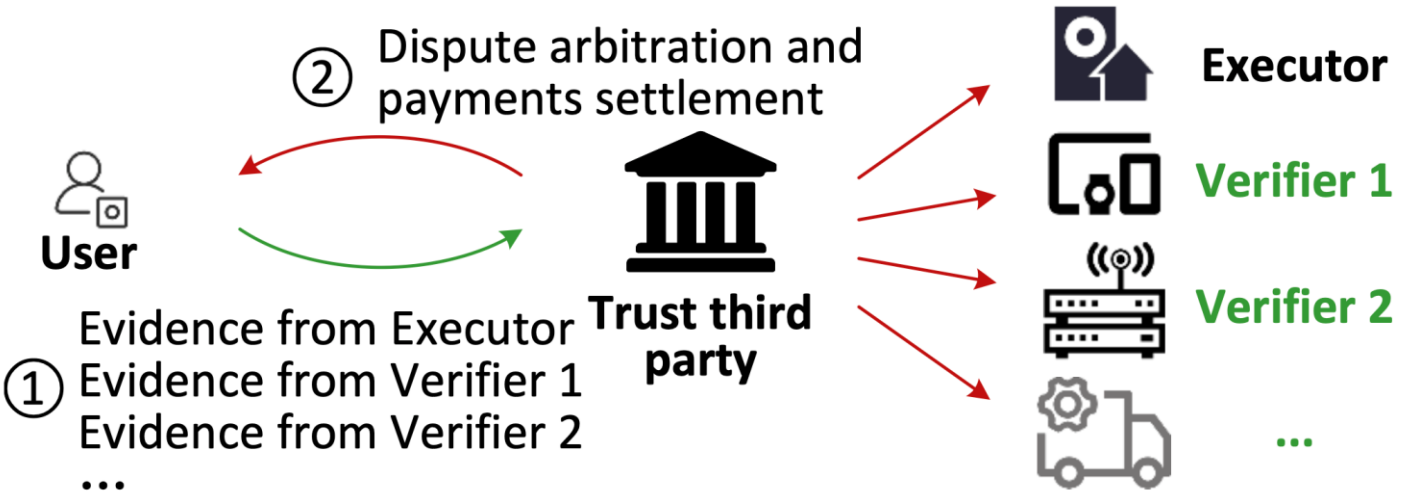


4 Verifiers generate verifiable random numbers

Public Key	PK_1	PK_2	**PK_3**	PK_4
Output	y_1	y_2	**y_3**	y_4
Proof	π_1	π_2	**π_3**	π_4

Dispute Resolution 3/3

- User can initiate a dispute to the TTP for arbitration
  - When results from the executor and (some of) the verifiers do not match



- epoch number for the dispute
- verifier list signed by base station
- proof list containing outputs
- proofs from all verifiers
- hash values of all samples' inputs
- random number

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Security Analysis

- Sound and correct execution

Theorem 1. *The probability of a malicious executor remaining undetected throughout n epochs, referred to as the* ***escape probability****, is* $\prod_{i=1}^{n} \left(q^{l_{\varrho_i} \cdot \eta_s} + (1 - q^{l_{\varrho_i} \cdot \eta_s}) \cdot \delta_s\right)$. □

- Non-manipulable dispute

Theorem 2. *Assume the SLA contract requires V verifiers for a majority vote. The probability that a malicious user can win the dispute for an arbitrary epoch is at most* $\delta_u^{\lfloor \frac{V}{2} \rfloor + 1}$. □

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Evaluation Settings

- Settings
  - Object tracking service
    - Real-time multi-object, segmentation and pose tracking with Yolov8
    - KITTI dataset
  - Platform
    - Phone, Raspberry Pi, Laptop, Desktop
  - Parameters
    - 100 epochs, each with100 tasks
    - Verifier pool 30 verifiers, pre-defined verifier number 2
    - Sampling rate 0.01
  - Baseline
    - Full replay without sampling

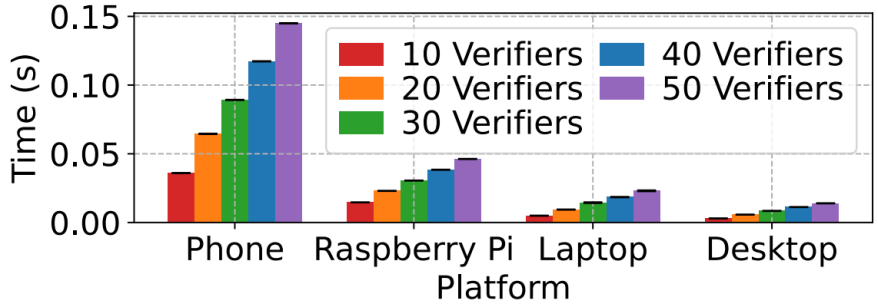
Communication and Computation Overhead

Description	Communication Cost (bytes)*			Execution Time (ms)		
	Message	VeriEdge	Baseline	Step	VeriEdge	Baseline
Obtaining inputs for verification (verifiable sampling in VeriEdge)	User → executor task request	86759200	86759200	Executor Merkle tree construction	0.33	0.34
	Executor → user Merkle tree root	113	113	User got results from executor	2778.76	3719.26
	Executor → user results	72	72	Executor generated proof	**28.45**	30.81
	User → executor sample request	515	-	User got proof response from executor	**30.29**	34.48
	User got proof from executor	**1789**	70124	User validated proofs from executor	**1.07**	79.56
VRF-based verifier selection	User → BS verifier list request	330	330	User got BS verifier list	61.82	90.27
	BS → user verifier list response	832	832			
	User → first verifier task request	**2612023**	86703281	Verifier key generation	124.27	96.21
				User found first verifier	30.56	30.56
	First verifier → user response	**552**	14160	User got results from first verifier	**643.78**	19762.93
				User checked correctness	**0.07**	221.44
Dispute resolution	User → second verifier request	**2612023**	86703281	User got results from second verifier	**642.77**	22205.78
	Second verifier → user response	**552**	14160			
	User → TTP dispute request	**56700**	104865	User got the dispute result from TTP	20.04	108.86
	TTP → user dispute response	16	17			

- Compared to raw application without verification
  - ↑ communication cost by 0.0028%
  - ↑ execution time by 1.14%
- Compared to Baseline
  - ↓ communication cost
  - ↓ execution time

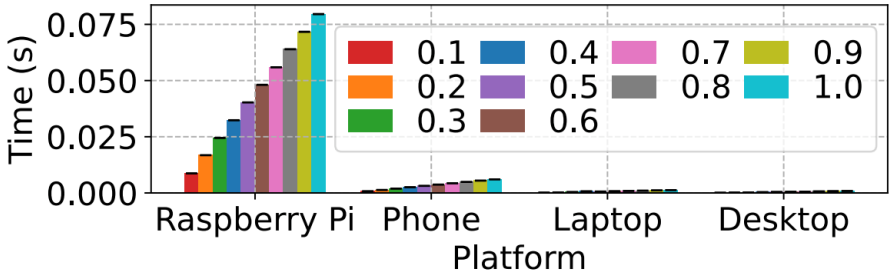
User End Computation Overhead

VeriEdge is lightweight, practical, and efficient.



VRF-based verifier selection time.

Verifier Selection <150ms



Merkle tree commitment checking time with different sampling rates.

Commitment checking time <80ms

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Conclusions

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  - A framework for SLA verification and enforcement in dynamic PEC environments with untrusted edge devices
- Commit-then-sample
  - Perform lightweight sampling and verification of intermediate computation results with non-repudiability.
- VRF based verifier selection and computation verification
  - Ensures verifiable fairness and a high probability for misbehavior detection
- Stateful object tracking application evaluation
  - Efficiency and scalability

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The information reported here does not reflect the position or the policy of the federal government.

Thank you very much!

Q&A?