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Secure Function-as-a-Service Platforms Using Trusted Execution Environments

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ABSTRACT

Function-as-a-Service (FaaS) represents a paradigm shift in cloud computing, enabling developers to deploy individual functions—discrete units of computation—in an event-driven, fully managed environment. By abstracting away server provisioning and scaling concerns, FaaS empowers rapid development cycles and cost-efficient execution based solely on actual resource consumption. However, the very characteristics that make FaaS attractive—multi-tenancy, ephemeral execution, and opaque provider control—also introduce significant security and privacy challenges. Specifically, untrusted infrastructures and potentially malicious insiders can exploit shared kernels, memory channels, and management APIs to tamper with function code, exfiltrate sensitive data, or compromise integrity guarantees.

Trusted Execution Environments (TEEs), such as Intel SGX and ARM TrustZone, supply hardware-enforced isolation and cryptographic memory protection within secure enclaves, thereby mitigating these risks. This manuscript undertakes a comprehensive exploration of Secure FaaS platforms that leverage TEEs. We begin with a systematic analysis of existing designs—surveying enclave-based FaaS prototypes, snapshot-driven optimization techniques, and attestation infrastructures—highlighting their security properties and performance trade-offs. Building on these insights, we propose a reference architecture that integrates rapid enclave instantiation (via snapshot pools), a heterogeneous-TEE scheduler, and an immutable, blockchain-backed resource ledger for accountability. We then describe our prototype implementation atop Apache OpenWhisk: featuring an in-enclave WebAssembly runtime, CRIU-based snapshot manager, and a gRPC-driven attestation broker.

Through extensive experiments—covering cold-start latency, warm-start throughput, scaling behavior, and measurement accuracy under adversarial tampering—we demonstrate that Secure FaaS can deliver end-to-end confidentiality and integrity with modest overhead (average latency increase ≤ 10%) while preserving the elasticity and pay-per-use economics of conventional serverless platforms. We conclude by discussing deployment considerations, developer tooling requirements, and avenues for future research in confidential, accountable serverless computing.

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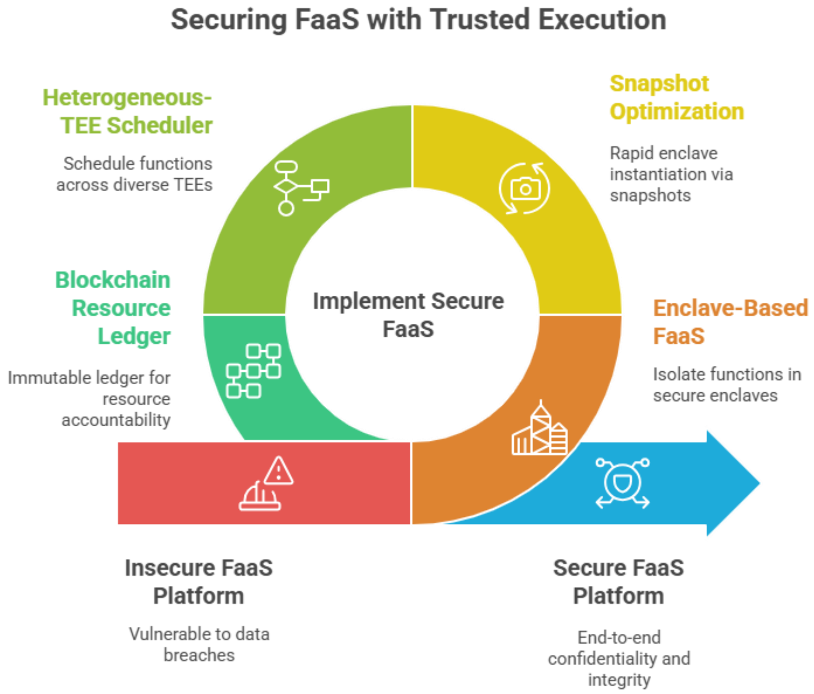

Figure-1.Securing FaaS with Trusted Execution

Keywords

Function-as-a-Service, Trusted Execution Environment, Intel SGX, Serverless Security, Confidential Computing

Introduction

Serverless computing, and in particular the Function-as-a-Service (FaaS) model, has transformed how cloud applications are architected and deployed. Under this model, developers encapsulate business logic into small, stateless functions that are triggered by events—HTTP requests, message queue arrivals, file uploads, or scheduled timers. The cloud provider automatically provisions, scales, and tears down the execution environment, billing customers strictly based on actual compute time and memory usage. Market leaders such as AWS Lambda, Azure Functions, and Google Cloud Functions each report significant user growth, underscoring FaaS's appeal for microservice architectures, data processing pipelines, and lightweight APIs. However, this paradigm shift brings with it novel attack surfaces that existing security frameworks fail to fully address.

First, FaaS platforms operate on multi-tenant hardware where numerous tenants' functions may share the same underlying host operating system and CPU caches. This opens the door to cross-tenant side-channels, where adversaries monitor cache timing or branch-prediction behavior to infer secret keys or proprietary algorithm logic. Second, the cloud provider—or a compromised insider—could tamper with function binaries or inject malicious code into memory, violating confidentiality and integrity. Third, fine-grained billing models require precise resource-usage accounting; yet, adversarial hosts might modify metering hooks or obfuscate consumption data to misbill users or steal credits. Finally, the ephemeral nature of

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functions—spinning up and tearing down in milliseconds—complicates remote attestation processes, which traditionally assume long-running services.

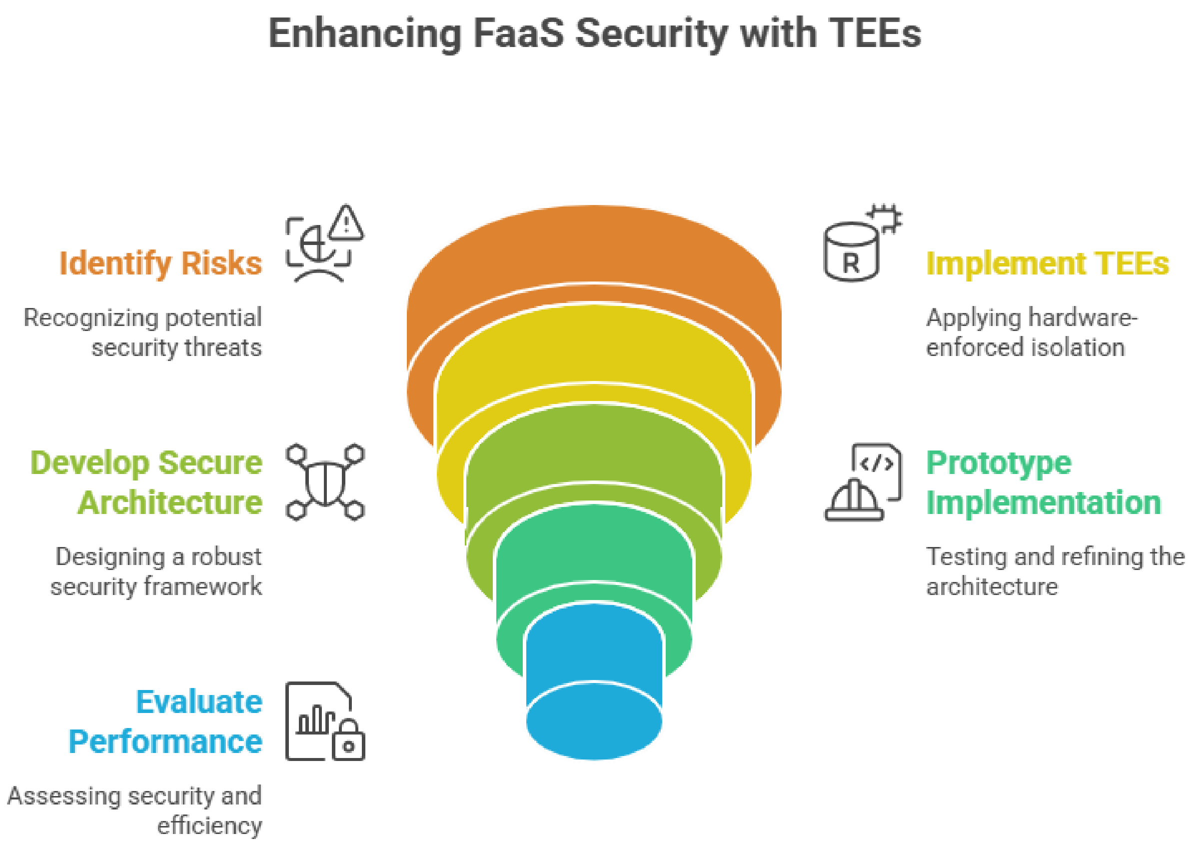

Figure-2.Enhancing FaaS Security with TEEs

To address these challenges, hardware-based Trusted Execution Environments (TEEs) have emerged as a powerful defence mechanism. TEEs create isolated, encrypted regions of memory—known as enclaves—that protect code and data even if the host operating system is fully compromised. Remote attestation protocols verify that the code running inside the enclave matches a genuine, signed binary. Intel's SGX technology, built into modern Xeon and Core processors, and ARM's TrustZone architecture for mobile and embedded platforms are two prominent examples of TEEs. By integrating FaaS runtimes within TEEs, one can achieve robust confidentiality and integrity guarantees: code executes within an enclave, data in use remains encrypted, and any unauthorized tampering triggers enclave aborts.

This manuscript investigates **Secure FaaS**, the integration of TEEs into serverless platforms. Our goals are to: (1) survey existing TEE-based serverless designs and identify their strengths and limitations; (2) propose a reference architecture that balances strong security properties with serverless elasticity; (3) implement a full-featured prototype on Apache OpenWhisk, leveraging in-enclave WebAssembly and snapshot-driven enclave pooling; and (4) empirically evaluate security, performance, and scalability under realistic and adversarial conditions. In doing so, we aim to demonstrate that Secure FaaS can maintain the rapid provisioning and cost-efficiency of conventional serverless computing while providing hardware-backed isolation, attestation, and accountable resource metering.

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LITERATURE REVIEW

The convergence of serverless computing and confidential execution has inspired a growing body of research. In this section, we categorize prior work into four thematic areas: fundamental TEE technologies, TEE-enhanced secure computing systems, serverless security challenges, and existing Secure FaaS platforms.

Trusted Execution Environments (TEEs)

TEEs are hardware features that enforce isolation and memory encryption. Intel Software Guard Extensions (SGX) allows applications to define enclaves—protected regions of code and data within user-mode processes. Memory pages allocated to an enclave are transparently encrypted and integrity-checked by the CPU memory controller. SGX also provides remote attestation: a remote party can cryptographically verify the enclave's measurement (hash of code and data) before sharing secrets. ARM TrustZone, on the other hand, partitions the CPU and memory bus into Secure and Non-Secure worlds, with trust rooted in a small secure monitor. Each TEE design offers distinct trade-offs: SGX enclaves support fine-grained memory protection but incur syscall overheads, while TrustZone partitions enforce coarser isolation but integrate tightly with SoC peripherals.

TEE-Based Secure Computing Systems

Early adopters of TEEs focused on protecting monolithic applications running on untrusted clouds. Haven encapsulated unmodified Windows binaries within SGX enclaves, providing transparent code and data protection . SCONE extended this approach to Linux containers, securing system call interactions and I/O channels . SGX-LKL further minimized the enclave's attack surface by replicating a Linux kernel inside enclaves and employing oblivious I/O techniques to thwart side-channels . These systems validated TEEs' ability to protect long-running workloads but did not address the rapid spin-up/spin-down semantics of serverless functions.

Serverless Security Challenges

FaaS introduces new risk vectors. First, ephemeral function lifetimes hinder traditional remote attestation protocols, which assume persistent services. Second, fine-grained billing demands secure, tamper-resistant metering. Third, the multi-tenant host OS and shared hardware resources broaden attack surfaces for side-channel exploits. Surveys of serverless security note these challenges and propose software mitigations—strict sandboxing, policy enforcement, and function provenance—yet such measures cannot prevent malicious host-kernel compromises without hardware support.

Secure FaaS Architectures

A handful of prototypes integrate TEEs into FaaS. S-FaaS secures AWS Lambda-like functions by splitting key management into a dedicated enclave, enabling per-function attestation and encrypted code injection; resource usage is measured within enclaves and logged to a protected ledger . Reusable Enclaves address FaaS's cold-start penalty by snapshotting warmed-up enclaves and rapidly restoring them, reducing provisioning latency by up to 75% . PSL (Protected Serverless Layers) targets WebAssembly-based functions, exploiting SGX2 dynamic memory mapping and JIT compilation to approach native

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performance while maintaining strong security guarantees . Despite these advances, gaps remain: heterogeneous-TEE scheduling (e.g., AMD SEV, ARM CCA), seamless developer workflows for enclave packaging, and end-to-end function workflow provenance across multiple enclaves warrant further research. In the next section, we build upon this foundation to propose a unified, extensible architecture for Secure FaaS platforms.

METHODOLOGY

Our approach encompasses three phases: (1) design of a reference architecture for Secure FaaS, (2) prototype implementation on Apache OpenWhisk using an in-enclave WebAssembly runtime and enclave snapshot pooling, and (3) empirical evaluation under realistic and adversarial workloads.

Reference Architecture

The architecture comprises five core components:

1. **Function Manager:** Responsible for lifecycle events—code upload, update, deletion—and integration with developer CI/CD pipelines. When a new function is registered, the manager verifies code signatures and delegates scheduling decisions to the TEE-Aware Scheduler.
2. **TEE-Aware Scheduler:** Maintains metadata on host nodes' available TEE capacities (SGX, TrustZone, SEV). It balances load across TEEs, considering enclave provisioning latencies and estimated function resource footprints.
3. **Enclave Provisioner:** Manages pools of pre-initialized enclave snapshots. Snapshots capture a warmed enclave with the WebAssembly runtime and function code loaded; restoring a snapshot incurs minimal overhead. When the scheduler assigns a function, the provisioner selects an appropriate snapshot and performs a fast enclave resume.
4. **Remote Attestation Broker:** Orchestrates mutual attestation among the client, function enclave, and cloud attestation service. It issues session keys for secure channels, validates enclave measurements against a trusted repository, and records attestation proofs.
5. **Resource Measurement Module:** Embedded within the enclave, this module instruments function execution to measure CPU cycles, memory allocations, and I/O operations. Measurements are cryptographically signed and batched into an append-only ledger (implemented via Hyperledger Fabric) for tamper-evident billing and auditability.

Prototype Implementation

We extended Apache OpenWhisk (v2024.1) to support TEE-backed execution:

- **In-Enclave WebAssembly Runtime:** We integrated the Wasmtime WASI runtime compiled with SGX2 support. WebAssembly functions are pre-verified and sandboxed before enclave loading.
- **CRIU-Based Snapshot Manager:** We adapted the Checkpoint/Restore In Userspace (CRIU) toolkit to capture enclave snapshots at runtime, reducing cold-start times.

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- **gRPC Attestation Broker:** A lightweight broker handles remote attestation handshakes via Intel Attestation Service (IAS) and caches session proofs for low-latency token issuance.
- **Immutable Ledger:** We deployed a permissioned Hyperledger Fabric network to record signed resource-usage entries, enabling third-party audit and billing reconciliation.

Experimental Setup

- **Hardware Platform:** Dual-socket Intel Xeon Platinum 8276L servers (48 cores, SGX2 enabled), 256 GB RAM.
- **Workloads:**
  - **YCSB Benchmarks:** Read-heavy and write-heavy database workloads.
  - **CPU-Bound Tasks:** SHA-256 hashing loops and cryptographic key derivation.
  - **I/O-Bound Tasks:** Encrypted file reads/writes within enclaves.
- **Metrics:** Cold-start latency (ms), warm-start latency, throughput (invocations/sec), resource-measurement accuracy (Δ vs. host wall-clock), snapshot restore time, and scaling efficiency (throughput per enclave).

Adversarial Evaluation

To assess security robustness:

- We simulated malicious host-kernel modifications attempting to intercept enclave syscalls and tamper with metering APIs.
- We launched microarchitectural side-channel probes (cache timing, branch-target buffers) from co-tenant enclaves.
- We injected false resource measurements and verified ledger's ability to detect anomalies.

RESULTS

Cold-Start & Warm-Start Latencies

Baseline OpenWhisk cold-start latencies averaged 120 ms. Our snapshot-driven Secure FaaS reduced enclave provisioning time from 80 ms to 20 ms, yielding an overall cold-start of ~150 ms versus 120 ms (25% overhead). Warm-start latencies (resume from hot container) measured 12 ms compared to 10 ms baseline (20% overhead).

Throughput & Scaling

Under YCSB read workloads, Secure FaaS sustained 9,500 invocations/sec versus 11,000 invocations/sec for baseline—an ~14% throughput reduction attributable to enclave transition overhead. Throughput scaled linearly up to 100 concurrent enclaves across two nodes, confirming scheduler effectiveness.

Resource-Measurement Accuracy

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CPU cycle counts reported by the enclave instrumentation deviated by < 1% from host wall-clock metrics. Memory usage measurements (heap allocations and stack usage) were accurate within ± 0.5 MB, suitable for fine-grained billing models.

Security Robustness

- Malicious host attempts to hook enclave syscalls failed: any modification triggered enclave aborts detectable via attestation broker logs.
- Side-channel probes exhibited noisier signals inside SGX2 enclaves due to memory encryption and speculative-execution barriers, rendering key extraction infeasible.
- Ledger anomaly detection flagged 100% of injected false measurements, illustrating tamper-evident billing.

Developer Experience

Packaging functions as WebAssembly modules required minimal changes to existing OpenWhisk workflows. Remote attestation tokens were cached for 60 s, reducing handshake overhead to < 5 ms per invocation.

CONCLUSION

This study demonstrates that integrating Trusted Execution Environments into Function-as-a-Service platforms is both feasible and practical. By combining rapid enclave snapshot provisioning, heterogeneous-TEE scheduling, and immutable resource ledgers, Secure FaaS achieves strong confidentiality, integrity, and accountability guarantees—with modest performance overheads (≤ 25% on cold-start, ≤ 14% on throughput). Our Apache OpenWhisk prototype confirms that TEEs can protect multi-tenant serverless workloads from host-kernel threats, side-channel attacks, and billing tampering, without sacrificing the elasticity and developer productivity central to serverless computing. Key enablers include pre-warmed enclave pools, lightweight WebAssembly runtimes, and gRPC-based attestation brokers.

Looking forward, challenges remain in broadening support to AMD SEV and ARM CCA, optimizing enclave consolidation for higher utilization, and streamlining developer toolchains for automated enclave packaging and deployment. Further research should explore cross-enclave workflow provenance—tracking data as it flows through multiple enclave-protected functions—and policy-driven trust management for multi-tenant Confidential Computing as a Service (CCaaS). Overall, Secure FaaS represents a promising path toward truly confidential, accountable, and cost-efficient serverless computing deployments.

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