Grace: A Confidentiality-Preserving and High-Performance Permissioned Blockchain Framework for General Smart Contracts

ABSTRACT

Data confidentiality among multiple parties is essential for safety-critical blockchain applications. A promising approach to achieving confidentiality is using cryptographic primitives like homomorphic encryption to encrypt client data, and enforcing the correct execution of smart contracts through non-interactive zero-knowledge proofs (NIZKPs). However, existing solutions still face significant limitations in supporting general smart contracts. Firstly, these solutions cannot tolerate non-deterministic contracts whose correct execution cannot be directly proven by NIZKPs. Secondly, many of these solutions adopt cryptographic primitives that restrict arithmetic operations, such as partial homomorphic encryption, which only allows either addition or multiplication over encrypted data.

We present Grace, a confidentiality-preserving and high-performance permissioned blockchain framework that supports non-deterministic smart contracts with cryptographic primitives allowing any arithmetic operations, such as the fully homomorphic encryption. Grace exploits the multi-party endorsement mechanism of execute-order-validate (EOV) blockchains to generate NIZKPs, which proves only that quorum parties produce consistent execution results, ensuring the correctness of contract execution and enabling support for non-deterministic contracts. Moreover, Grace detects and merges multiple conflicting transactions into a single one, minimizing the number of conflict aborts in EOV and cryptographic primitive invocations. Theoretical analysis and extensive evaluation on notable contracts demonstrate that Grace achieves the strongest confidentiality guarantee among existing systems and supports general contracts. Compared to three notable confidential blockchains, Grace achieved up to 7.14× higher effective throughput and 13% lower end-to-end latency on average.

CCS CONCEPTS

• **Networks → Network protocol design**; • **Security and privacy → Management and querying of encrypted data**; • **Computer systems organization → Dependable and fault-tolerant systems and networks**.

KEYWORDS

Blockchain, Data Confidentiality, Homomorphic Encryption, Non-Interactive Zero-Knowledge Proof

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1 INTRODUCTION

Blockchains are extensively deployed in both industry and academia. The main reason is their support for smart contracts that enable trusted execution over a tamper-resistant ledger shared among mutually untrusted participant nodes and clients. However, notable blockchains like Hyperledger Fabric (HLF) [5] and Ethereum [49] allow public access to on-chain data, raising deep concerns about data confidentiality. Such concerns are especially problematic for applications involving highly sensitive information, such as medical data [29], as they are subject to stringent privacy laws and regulations, such as the General Data Protection Regulation of the European Union [48].

Many previous work have been proposed to achieve data confidentiality on smart contracts, and these work can be summarized into two distinct approaches. The first is the non-cryptography-based approach. It works by introducing new blockchain architectures to impose strict access controls without resorting to cryptography primitives [3–5]. For example, HLF uses channels [6] and private data collections [23] to determine which participants are eligible to access certain data. However, this approach processes and stores client data in cleartext, making it highly vulnerable to sensitive client data leakage caused by malicious nodes with data access privileges.

The second is the cryptography-based approach, which is immune against data leakage attacks. This approach uses cryptographic primitives to encrypt client data for confidentiality and enforces the smart contract to directly execute on the encrypted data [31, 44–46], thereby preventing the exposure of sensitive data to malicious nodes. This approach adopts a *re-execution method* to generate non-interactive zero-knowledge proofs (NIZKPs) that prove the correctness of contract execution. The re-execution method starts by decrypting the encrypted transaction input and result, then re-executes the smart contract using the decrypted input, and finally checks the consistency between the decrypted and re-executed results. For example, ZeeStar [44] employs a partial homomorphic encryption (PHE) scheme to encrypt client data and uses the re-execution method to generate NIZKPs proving the execution correctness.

Unfortunately, existing solutions of the cryptography-based approach face two fundamental limitations. Firstly, these solutions are incompatible with non-deterministic smart contracts. This is because these solutions adopt the re-execution method, which is problematic for applying NIZKPs to non-deterministic smart contracts. On the one hand, NIZKPs assume that the same input will always produce the same result. On the other hand, non-deterministic smart contracts can yield different results when given the same inputs, making it challenging to generate a single proof for all possible results.

Secondly, the performance of these solutions are plagued by the inefficiency of the re-execution method. This method makes it challenging to attain efficient NIZKP generation and verification when integrated with general cryptographic primitives such as fully homomorphic encryption (FHE), which enables arbitrary arithmetic computations over ciphertexts. For example, the combination of the BFV scheme [12, 21] (i.e., an FHE scheme) and an elliptic-curve based NIZKP system [16] requires tens of seconds for both NIZKP generation and verification [43]. Even when utilizing lightweight cryptographic primitives like PHE that restrict available arithmetic operations, the NIZKP operations remains cumbersome. For instance, using 2048-bit keys to generate a Groth16 [37] NIZKP for the Paillier PHE encryption scheme [38] requires more than 256 GB of RAM [44], making it an impractical demand for commodity desktops available today.

In this study, our key insight to tackle these limitations is that we can obviate the need for the re-execution method by leveraging the *multi-party endorsement mechanism* of the execute→order→validate (EOV) permissioned blockchains. Prior to transaction ordering, this mechanism first conducts independent transaction execution (also known as *endorsing*) among multiple executor nodes. It then proves the execution correctness by checking that quorum nodes have produced consistent results. This mechanism eliminates the potential result inconsistency caused by non-determinism, enabling the support for non-deterministic smart contracts. Moreover, it decouples the proving logic of execution correctness from the smart contract logic itself, thereby significantly reducing the correctness proving overhead for smart contracts that involve expensive cryptographic primitives. These factors collectively contribute to high performance and support for general smart contracts.

This insight leads to GRACE[1], a confidentiality-preserving and high-performance permissioned blockchain framework that supports general blockchain applications. GRACE carries a novel Confidentiality-preserving Execute-Order-Validate (CEOV) workflow for provably correct execution of general smart contracts involving encrypted data, as shown in Figure 1c. CEOV executes transactions in three steps: firstly, a client sends a transaction with cleartext input to a trusted executor node, known as *lead executor*, which employs a designated cryptographic primitive (e.g., an FHE scheme) specified by the invoking contract to encrypt input data and relays the transaction to other executors; next, multiple executors independently and concurrently execute the transaction over the encrypted data; finally, the lead executor generates an NIZKP to prove that quorum results are consistent. By leveraging the CEOV workflow, GRACE effectively preserves data confidentiality, while simultaneously guaranteeing the correctness of executions for general smart contracts.

However, GRACE still faces a non-trivial performance challenge due to the transaction conflicting aborts caused by the concurrent execution of CEOV. In particular, when multiple transactions concurrently access the same key-value pair in the blockchain state database, and at least one of them modifies the value, only one transaction can successfully commit, leading to aborts of other conflicting transactions. Such transaction conflicts are prevalent in typical blockchain applications [42]. For example, in a conflict-heavy scenario where conflict ratio is 90%, HLF achieved only 24.5% of its peak throughput observed in a conflict-light scenario where the conflict ratio is 10%, as confirmed in Figure 3. This challenge is further exacerbated in GRACE due to the involvement of resource-intensive cryptographic primitives, which incur significant computation overhead. For example, Microsoft SEAL [41], a highly optimized FHE library, takes 2822 milliseconds to execute a single homomorphic multiplication [34]. In short, transaction conflicting aborts result in a substantial waste of computing resources on executor nodes, necessitating the need for an effective solution.

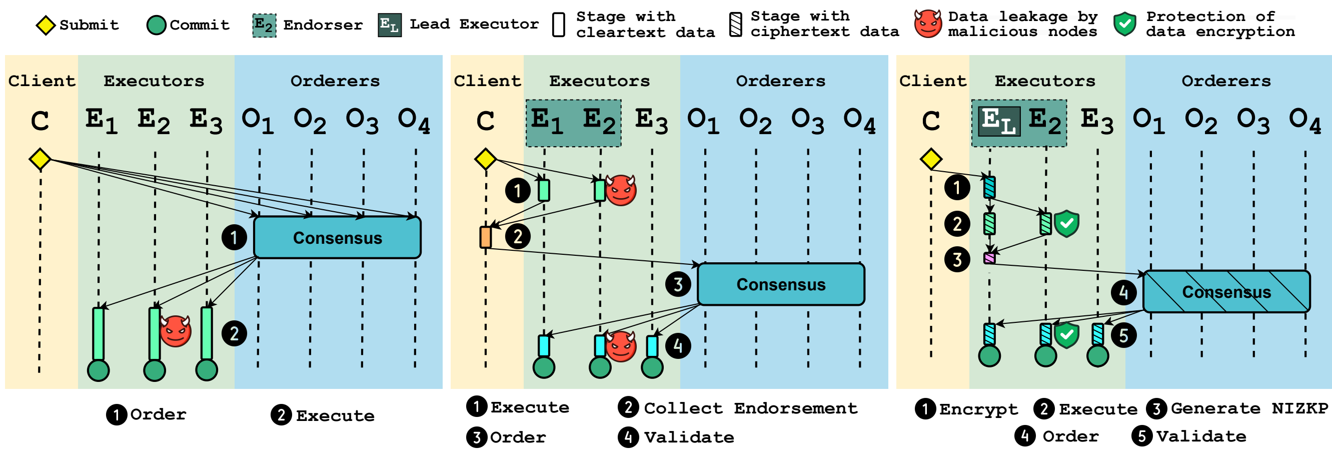
System	Data Encryption	Multiple Parties	General Contract	High Performance
✧ HLF [5]	✗	✓	✓	✓
✧ Qanaat [4]	✗	✓	✓	✓
✧ Caper [3]	✗	✓	✓	✓
♦ ZeeStar [44]	✓	✓	✗	✗
♦ SmartFHE [43]	✓	✓	✗	✗
♦ Zapper [46]	✓	✗	✗	✗
♦ FabZK [31]	✓	✗	✗	✗
♦ **GRACE**	✓	✓	✓	✓

Table 1: Comparison of GRACE and related confidentiality-preserving blockchain systems. "✧ / ♦" means that the system either takes the non-cryptography-based approach (✧) or the cryptography-based approach (♦).

To tackle this challenge, we propose a Correlated Transaction Merging (CTM) protocol. CTM exploits the prevalent conflicting transactions in permissioned blockchain applications to reduce the number of invocations to cryptographic primitives. CTM consists of two phases: *offline analysis* for smart contracts prior to deployment, and *online scheduling* for transactions during runtime. Before deployment, a smart contract undergoes CTM's offline analysis, which aims at determining whether multiple conflicting transactions invoking this contract can be merged into a single equivalent transaction. During runtime, CTM's online scheduling constructs a transaction dependency graph on a per-block basis for smart contracts whose conflicting transactions can be safely merged. This graph captures the read-write dependencies among all transactions within the block, enabling the detection of conflicting transactions and facilitating their merging into a single transaction. For instance, consider a scenario where two transactions both attempt to perform an addition operation on the same key (e.g., two $X + 1$ operations). In such cases, CTM merges these two addition transactions into a single transaction (e.g., one $X + 2$ operation). This reduces the number of cryptographic primitive invocations while preserving the semantics of the original transactions. Moreover, in contrast to existing EOV permissioned blockchains (e.g., HLF), which cause massive conflicting aborts, GRACE is capable of committing all merged conflicting transactions without any aborts.

We implemented GRACE on the codebase of HLF [5], the most notable EOV permissioned blockchain framework. We integrated

[1]GRACE stands for GeneRAl Confidentiality-prEserving blockchain



(a) Order-Execute

(b) Execute-Order-Validate

(c) Confidentiality-preserving Execute-Order-Validate

Figure 1: Our CEOV workflow (right side) and two other notable permissioned blockchain workflows.

GRACE with Lattigo [34], a highly efficient FHE library, and gnark [15], a popular NIZKP library. We evaluated GRACE using the SmallBank workload [28] (the de facto blockchain benchmark) under different conflict ratios, and ten diverse blockchain applications, including both deterministic and non-deterministic smart contracts. We compared GRACE with HLF and ZeeStar [44], covering both the non-cryptography-based and cryptography-based baselines for data confidentiality. Our evaluation shows that:

- GRACE is efficient (§7.1). GRACE achieved up to 7.14× higher effective throughput and 13% lower end-to-end latency than the ZeeStar (cryptography-based). Although GRACE witnessed a 32% drop in throughput compared to HLF (non-cryptography-based), HLF does not preserve confidentiality with malicious nodes.
- GRACE is secure (§7.2). GRACE can achieve high effective throughput under attacks from malicious participants and conflicting transactions.
- GRACE is general (§7.3). GRACE tolerates non-deterministic smart contracts and supports cryptography primitives like FHE which allows arbitrary computations over encrypted data.

Our main contributions are CEOV, a new confidentiality-preserving blockchain workflow tailored for general smart contracts, and CTM, a new concurrency control protocol for transactions involving encrypted data. CEOV addresses the challenge of ensuring the provably correct execution of non-deterministic contracts incorporating general cryptographic primitives (e.g., FHE), rendering GRACE as secure as existing cryptography-based confidentiality-preserving blockchains. CTM enhances the effective throughput and reduces the average end-to-end latency of GRACE by minimizing the conflicting aborts through the merging of transactions with data races. Overall, GRACE can benefit blockchain applications that desire both data confidentiality and high performance, such as supply chain [20] and healthcare [32]. GRACE can also attract broad traditional non-deterministic applications, developed with general-purpose programming languages like Golang and Java, to be deployed upon. GRACE's code is available at TODO

2 BACKGROUND

2.1 EOV Permissioned Blockchain

A blockchain is a distributed ledger that records transactions across multiple nodes. It can be summarized into two main categories: *permissionless* and *permissioned.* Permissionless blockchains (e.g., Bitcoin [35] and Ethereum [49]) are open to anyone, and their participants are mutually untrusted. In contrast, permissioned blockchains (e.g., HLF [5]) are maintained by a group of known organizations, and only grant access to explicitly authenticated participants which are trusted within their organizations. Thanks to explicit identity authentication, permissioned blockchains can utilize fast BFT consensus protocols like HotStuff [1] to tolerate malicious nodes. This enables GRACE to run multiple orderer nodes concurrently, forming a BFT ordering service that determines the transaction order within a few hundred milliseconds, demonstrating the performance advantage of GRACE.

Permissioned blockchains can be further classified into two types according to their workflows: *order→execute* (OE) and *execute→order→validate* (EOV). As depicted in Figure 1a, the OE workflow involves two main steps: Firstly, the orderer nodes establish a globally consistent transaction order (**O**); Subsequently, all executor nodes sequentially execute the transactions in the predetermined order (**E**). This workflow leads to significant performance issue since all executor nodes are required to perform the same execution steps, limiting the scalability of throughput as the number of executor nodes increases. In contrast, the EOV workflow (shown in Figure 1b) reverses the relative order of transaction execution and ordering. Initially, a group of executors called *endorsers* are selected to concurrently execute transactions (**E**). Then, the client collects the executed results, known as *endorsement*, from endorsers to check their consistency; if the endorsements are consistent, the client sends the results to the orderers. Subsequently, the orderers determine the transaction order (**O**). Finally, each executor independently validates transaction results via multi-version concurrency control (MVCC) to prevent conflicting data access within a single block (**V**). GRACE extends EOV and proposes CEOV workflow (shown in Figure 1c) to leverage cryptographic primitives in order to preserve data confidentiality. Consequently, Grace inherits the benefits of EOV, including parallel execution and result consistency checks, which contribute to high performance and enable support for non-deterministic smart contracts.

2.2 Homomorphic Encryption

Homomorphic encryption (HE) is a family of encryption schemes that allow direct computation over encrypted data without decryption. A HE scheme consists of four algorithms: *KeyGen* generates key pairs necessary for other operations; *Enc(m, pk, r)* uses the public key *pk* to encrypt a cleartext message *m* into a ciphertext *c* along with randomness *r*; *Dec(c, sk)* uses the private key *sk* to decrypt ciphertext *c* back into the original cleartext *m*; ⊕ is a binary operator taking two ciphertexts as input and produces a result ciphertext. For instance, in an additive HE scheme, the ⊕ operator satisfies the following property:

$$Enc(m_1, pk, r_1) \oplus Enc(m_2, pk, r_2) = Enc(m_1 + m_2, pk, r_3)$$

HE schemes can be summarized into two main categories based on the supported operators: partial homomorphic encryption (PHE) and fully homomorphic encryption (FHE). PHE schemes are limited in their support to only one specific type of arithmetic operation, either addition or multiplication. In contrast, FHE schemes allow for arbitrary combinations of these operations. Although PHE schemes have relatively low computation overhead, they are limited in their computational capabilities. This restriction compromises the generality of smart contracts, as discussed in §1. FHE schemes typically demand higher computation overhead, but they are capable of preserving the generality of smart contracts. Furthermore, substantial improvements have been made to improve the performance of FHE schemes since the proposal of the first plausible FHE scheme [24], making FHE a promising and practical solution for supporting general smart contracts. Grace utilizes the BFV scheme [12, 21] (a FHE scheme) implementation of Lattigo [34], which is an optimized FHE library. This implementation enables Grace to perform FHE computations on 58-bit unsigned integers within tens of milliseconds, striking a balance between performance and smart contract generality.

2.3 Non-Interactive Zero-Knowledge Proofs

Non-interactive zero-knowledge proof (NIZKP) [22, 26] is a cryptographic primitive that enables a prover P to prove knowledge of a secret s to a verifier V without revealing s. Once P generates an NIZKP using a proving key, V can verify the proof using the corresponding verifying key without P being present. Formally, given a proof circuit ϕ, a private input s, and some public input x, prover P can generate an NIZKP to prove knowledge of s satisfying the predicate $\phi(s; x)$. One popular type of NIZKP is called zero-knowledge succinct non-interactive arguments of knowledge (zkSNARKs) [11, 27, 50], which allows any arithmetic circuit ϕ and guarantees constant-cost proof verification in the size of ϕ, making them suitable for blockchain applications [2, 7, 18, 37, 45]. Specifically, Grace employs the Groth16 [37] (a zkSNARKs construction) implementation of the gnark library [15] with advantages including constant proof size (several kilobytes) and short verification time (tens of milliseconds).

2.4 Related Work

We now discuss previous work on confidentiality-preserving blockchains, as illustrated in Table 1.

Non-Cryptograhpy-Based Approach. Several previous work attempt to achieve data confidentiality by adopting specialized blockchain architectures without utilizing cryptography technology. HLF [5] enforces access control to client data on the inter-contract and the intra-contract levels through two architectures, channels [6] and private data collection [23], respectively. Caper [3] requires each participant party to maintain only a partial view of the global ledger and prohibits them from owning copies of other parties' data. Qanaat [4] adopts a hierarchical data model consisting of a set of data collections that store transaction data and are accessible only to authenticated parties. However, these systems do not utilize cryptography primitives, but process and store all data in cleartext, exposing a significant attack surface for corrupted participants seeking to steal confidential data.

Cryptography-Based Approach. Unlike the aforementioned solutions, many previous work use cryptographic primitives to protect confidentiality and enforce the execution correctness of smart contracts.

ZeeStar [44] uses exponential ElGamal encryption [33], which is an additive PHE scheme, for encrypting transaction data. It claims to support on-ciphertext multiplication by repeatedly performing the addition operation. However, this extension is highly inefficient and only applicable to limited scenarios. Moreover, ZeeStar cannot tolerate non-deterministic smart contracts due to its reliance on the OE workflow, as discussed in §1. Consequently, these factors result in that ZeeStar does not support general smart contracts.

SmartFHE [43] is an Ethereum-based blockchain that uses FHE schemes to enable confidentiality-preserving contracts. However, two limitations seriously impede its support for general smart contracts. Firstly, SmartFHE, similar to ZeeStar, is unable to tolerate non-deterministic smart contracts since it relies on the OE workflow. Secondly, SmartFHE does not support smart contracts involving foreign values (i.e., ciphertexts encrypted by different parties), because this requires a multi-key variant of SmartFHE that is currently impractical according to the authors.

Zapper [46] uses an NIZK processor and an oblivious Merkle tree construction to provide confidentiality for both its users and the objects they interact with. However, Zapper faces the same limitations with SmartFHE: Zapper neither can tolerate non-deterministic smart contracts, nor support computation on foreign values. These significantly undermine the compatibility of Zapper with general smart contracts.

FabZK is a HLF-based blockchain that adopts a specialized tabular ledger data structure comprising $N + 3$ columns, with N representing the participating organizations. This structure is designed to obfuscate the transaction-related organizations. However, this data structure significantly restricts the compatible blockchain applications, compromising its ability to support general smart contracts. Additionally, as the number of organizations increases, the performance of FabZK is severely compromised since each transaction needs to update all columns in the ledger.

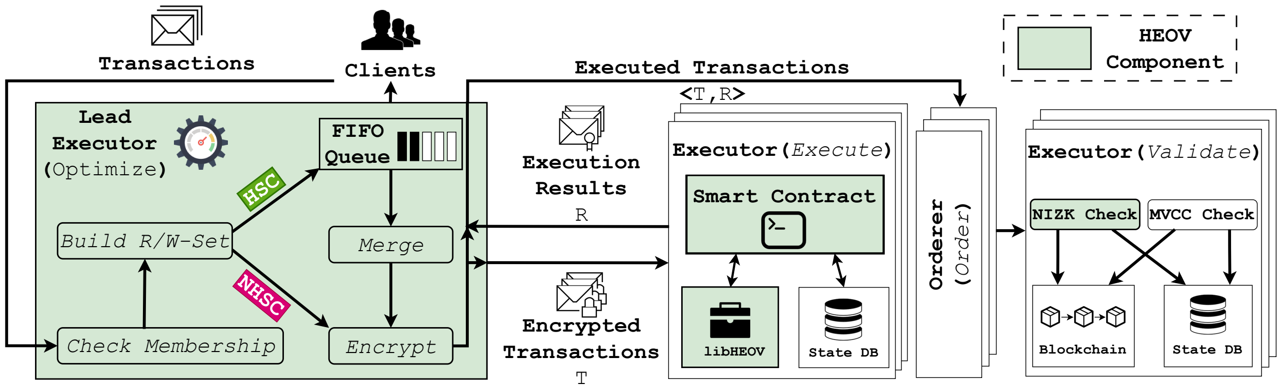


Figure 2: The GRACE Runtime Workflow. GRACE components are highlighted in green. An "HSC" transaction invokes a Homomorphic Smart Contract, while the "NHSC" one does not.

3 OVERVIEW

3.1 System Model

GRACE consists of three types of participants: *client*, *executor*, and *orderer*. The latter two are referred to as *nodes*. In GRACE, participants are grouped into distinct *organizations*. Each organization runs multiple executors and orderers, and possesses a set of clients. The roles and functionalities of each participant type are described as follows:
Clients. In GRACE, clients are the only participant type that can submit transactions to nodes for execution and commitment. Other participant types, namely executors and orderers, are not permitted to submit transactions.
Executors. In GRACE, all executors are responsible for three main tasks: executing transactions, validating results, and maintaining an up-to-date local copy of the blockchain state database. To support these tasks, executors leverages libGRACE (§6.1), a library that we developed to offer a range of FHE and NIZKP functionalities, which are essential for the correct functioning of GRACE. libGRACE is tailored for GRACE smart contract execution and comes with predefined parameters for both cryptographic primitives. Therefore, smart contract developers can effectively incorporate smart contracts with FHE and NIZKP operations without requiring expertise in cryptography.

To implement the CEOV workflow and the CTM protocol, GRACE establishes a special type of executor, known as *lead executor*, and elects exactly one lead executor for each organization, as shown in Figure 2. In addition to the aforementioned tasks, lead executors are assigned the following additional tasks:

- Detect multiple conflicting transactions and merge them into a single transaction.
- Encrypt transaction inputs with the cryptographic primitive specified by the invoking smart contract.
- Dispatch transaction to other executors and orderers for execution and ordering, respectively.
- Generate NIZKPs to prove the correctness of execution by checking the consistency of transaction results.

Orderers. GRACE orderers determine the order of transactions via a consensus protocol (e.g., BFT), and assemble the transactions into individual blocks. After assembling, orderers deliver these blocks to all executors, which will validate the transactions within each block in the predefined order and update their local copy of blockchain database accordingly for all valid transactions.

3.2 Threat model

GRACE adopts the Byzantine failure model [9, 13], where orderers run a BFT consensus protocol that tolerate up to f malicious orderers out of $3f + 1$ total orderers. Same as typical permissioned blockchains such as HLF, a participant trusts all participants within the same organization, but it does not trust participants belonging to another organizations. Any participant can be malicious, and malicious participants can collude. We make standard assumptions on cryptographic primitives, including FHE and NIZKP.

3.3 Runtime Workflow Overview

The runtime workflow of GRACE can be summarized into several steps, as shown in Figure 2. A more comprehensive discussion of the runtime workflow can be found in §4.2.
Phase 1: preprocessing. The lead executor collects transaction submitted by clients, merges conflicting transactions that can be merged without altering their semantics, and leaves other transactions unchanged.
Phase 2: encryption. The lead executor encrypts all transaction cleartext inputs using the public keys (i.e., encryption keys) of relevant organizations. Furthermore, the lead executor also signs the encrypted transactions with its identity for auditability.
Phase 3: dispatch. The lead executor selects a group of executors, know as endorsers, and dispatches the encrypted transactions to the endorsers for transaction execution.
Phase 4: execution. Upon receiving an encrypted transaction from a lead executor, the endorser invokes the designated smart contract specified by the transaction, generating a read-write set as the result. The endorser then signs the result and sends it back to the lead executor.
Phase 5: proof generation. Once all endorsers have executed the transaction and sent the results back to the lead executor, the lead executor generates a NIZKP to prove that the quorum endorsers (i.e., a majority of endorsers) produced a consistent result, thereby

ensuring the correctness of execution.

Phase 6: ordering. GRACE orderers run a BFT protocol to achieve consensus on the order of transactions received within a certain time interval. The orderers assemble the transactions into a block in the determined order and disseminate the block to all executors for validation and commit.

Phase 7: validation and commit. When receiving a block from the orderers, the executor sequentially validates each transaction within the block in the predetermined order. The executor commits only those transactions that do not conflict with the read-write set of previously committed transactions, and updates the blockchain state database accordingly.

In general, the highlights of GRACE runtime workflow arises from preserving data confidentiality and achieving high performance for general smart contracts. We illustrate these highlights in two dimensions. Firstly, the GRACE runtime workflow leverages the CEOV workflow, which (1) encrypts sensitive client data using cryptographic primitives capable of performing arithmetic computations over ciphertexts, such as FHE, and (2) generates lightweight NIZKPs, which are agnostic to the specific logic of smart contracts and only serve to prove the consistency of quorum results. These not only preserve the data confidentiality, but also ensure the correct execution of smart contracts with encrypted data. Moreover, CEOV enables the support for non-deterministic smart contracts as it also utilizes the multi-party endorsement mechanism. Secondly, in contrast to existing EOV permissioned blockchains that abort conflicting transactions, the GRACE runtime workflow incorporates the CTM protocol, which merges multiple conflicting transactions into one transaction, effectively eliminating the conflicting aborts of transactions without altering the original semantics. Therefore, CTM leads to a considerable reduction in average end-to-end latency and prevents the wastage of computational resources.

4 PROTOCOL DESCRIPTION

4.1 Offline Smart Contract Analysis

GRACE's offline analysis protocol determines if a smart contract is *homomorphic*, meaning multiple transactions modifying the same set of states can be merged without affecting the execution results. As shown in Figure **??**, before deployment, a smart contract analyzer conducts the analysis and generates metadata indicating if the contract is additive homomorphic (**AH**), multiplicative homomorphic (**MH**), or non-homomorphic (**NH**). This metadata is essential for permitting lead executors to perform transaction merging.

GRACE analyzes smart contracts with random interpretation [2], which generates different input and initial states to capture all possible control flow paths. As a first step, two random input sets I_1 and I_2, along with a random initial memory state M, are generated for the candidate smart contract SC. The memory state contains the SC outputs and all keys written by SC. Then, SC is interpreted in two different ways. First, GRACE executes SC twice consecutively: first with I_1, producing M_{I_1}, and then with I_2, producing the final state M_{I_1,I_2}. Simultaneously, GRACE begins with the same initial state M and executes SC once with $I_1 + I_2$, producing $M_{I_1+I_2}$. If $M_{I_1,I_2} = M_{I_1+I_2}$ for all control flow paths, SC is additive homomorphic. Similarly, if $M_{I_1,I_2} = M_{I_1 \times I_2}$, it is multiplicative homomorphic.

4.2 Runtime Transaction Execution and Commitment

The runtime transaction execution and commitment protocol specifies the rules for GRACE's transaction execution, as visualized in Figure 2.

Phase 0: Transaction submission. In the runtime protocol, the client first submits a transaction proposal to an executor within its organization. If the receiving leader is not a lead executor, it forwards the proposal to the designated lead executor. The submission process uses mutual TLS, which ensures the confidentiality of proposal arguments and requires both parties to authenticate themselves by presenting certificates to establish their identities.

Phase 1: Preprocessing. Upon receiving a transaction from a client, the lead executor undertakes a series of sequential preparation tasks: (Phase 2.1) constructing the read-write set, (Phase 2.2 and 2.3) merging homomorphic transactions, and (Phase 2.4) encrypting transaction arguments.

Phase 1.1: Read-write set construction. The read-write set of a transaction includes the read set and the write set, which encompass the states being read and written, respectively. Constructing a read-write set helps identify the owner of the value being written, which is necessary for selecting the appropriate public key to encrypt the value into ciphertext.

Phase 1.2: Conflicts detection. During Phase 1.2 and 1.3, lead executors handle transactions differently based on the homomorphic property of the smart contracts they invoke. This property is determined through the offline homomorphic smart contract analysis protocol mentioned in §4.1. For non-homomorphic smart contracts, the CTM protocol is not applicable, and proposals for these contracts undergo direct encryption as specified in Phase 1.4. For homomorphic smart contracts, proposals are temporarily stored in a FIFO queue, which collects all the proposals that will be packaged into the same block, thereby facilitating the potential merging of these proposals.

Phase 1.3: Correlated merging. The lead executor merges consecutive correlated proposals from the FIFO queue, specifically those that invoke the same homomorphic smart contract and have overlapping read-write sets. This merging process reduces the number of transaction proposals by merging certain proposals into newly merged ones. For example, consider two correlated $transfer$ transactions, T_1 and T_2, with shared relevant parties and inputs I_1 and I_2, respectively. After merging, a new transaction T_{1+2} is created, incorporating the combined input $I_1 + I_2$, effectively replacing T_1 and T_2.

Phase 2: Homomorphic encryption. Before submission, the arguments of each proposal undergo encryption using public keys corresponding to the identities listed in the write set. This encryption step is crucial because each argument may be utilized on different ciphertexts owned by clients from other organizations. For example, if *Sam* transfers M tokens to *Rachel*, the plaintext value M must be encrypted into two ciphertext, $Ct_{M,1}$ and $Ct_{M,2}$, using the public keys of *Sam*'s and *Rachel*'s organizations, respectively.

Phase 3: Dispatch. The lead executor signs and dispatches the proposal to other executors based on the endorsement policy. The client transaction ID and proposal signatures are retained as metadata, enabling clients to verify the correct execution of their proposals.

Phase 4: Encrypted Execution. An GRACE executor executes a smart contract and sends the execution response to the lead executor. Unlike HLF, GRACE smart contracts leverage the capabilities of libGRACE for HE and NIZKP operations. Additionally, GRACE smart contracts use NIZKP as an alternative to the *if* statements found in most programming languages. In GRACE, *if* statements are neither recommended nor allowed when ciphertext is involved in the condition expression because HE ciphertext does not support comparison operations such as <, >, or =, and executors are not authorized to access private keys, making it impossible to decrypt the ciphertext and compare the underlying plaintext. To address this, GRACE smart contracts generate NIZKP that validate the execution results and are stored on the blockchain for future reference.

Phase 5: Correctness NIZKP generation. Before submitting a transaction for ordering, the lead executor collects results from the executing executors. Each result comprises ciphertext and endorsement information (i.e., the acknowledgment of the transaction). The lead executor decrypts and compares the ciphertexts to ensure *plaintext consistency*. If a ciphertext belongs to another organization, the lead executor requests verification from that organization. Valid results require a quorum, typically a majority, of ciphertexts referencing the same plaintext. Only transactions with valid results are eligible for ordering. To ensure the integrity and prevent forgery of results, the lead executor generates an NIZKP to prove the plaintext consistency, which is also stored on the blockchain and is publicly verifiable. By employing this approach, the lead executor cannot create a fake result or tamper with the on-chain data, as the verification process ensures the accuracy and integrity of the results.

Phase 6: Transaction ordering. GRACE orderers run a BFT consensus protocol (e.g., BFT-SMaRT [10]) to reach a consensus on the order of transactions in one block. The block is then distributed to all executors for validation once finalized by orderers.

Phase 7: Validation and commit. Upon receiving a block from orderers, an executor sequentially validates each transaction, including verifying the consistency NIZKP associated with the transactions. If validation is successful, the executor applies the transaction result to its local world state database, ensuring accurate reflection of transaction changes. After validating and processing all transactions in the block, the block is permanently appended to the local blockchain. Since all executors take deterministic and consistent actions for the same block, all local copies of the blockchain maintain consistency, ensuring the overall consistency of GRACE.

Phase 8: Response. As a final step, the lead executor responds to the client who proposed the transaction. This response informs the client whether their transaction has been accepted or rejected.

4.3 Defense Against Malicious Participants

No-resubmission attack is a performance degradation attack that exploits the EOV workflow by maliciously skipping the transaction resubmission process. The attack is simple but detrimental because it wastes a significant amount of the computation power of executors, especially when smart contracts involve heavy HE computations. However, distinguishing no-resubmission attacks from legitimate actions can be challenging. A benign transaction can produce different results when executed by different executors, particularly for non-deterministic smart contracts. In such cases, the results of the current execution are discarded, and no-resubmission becomes a necessary action.

To mitigate the damages caused by no-resubmission attacks, GRACE adopts a per-executor counter-based approach. To be specific, each executor maintains a counter for each lead executor in the GRACE network, tracking the number of no-resubmission instances within a timeframe. If the count exceeds a configurable upper bound, the executor rejects transactions from that lead executor for a specified duration, mitigating the damages caused by no-resubmission attacks.

5 ANALYSIS

This section defines and analyzes the three guarantees of GRACE: safety, liveness, and confidentiality.

5.1 Correctness

Definition 1 (Safety). *For any two benign nodes $Node^1$ and $Node^2$, they hold the same world state with the n-th block as the latest block. The $(n+1)$-th blocks received by $Node^1$ and $Node^2$, denoted as $Block^1_{n+1}$ and $Block^2_{n+1}$ respectively, are consistent and deterministic.*

The correctness of smart contract execution in GRACE is ensured by satisfying ACID and BFT safety properties at the transaction and block levels, respectively.

GRACE guarantees ACID properties for transaction execution, which are the foundation of all reliable failure-tolerant transaction processing systems and are indispensable as concurrent transaction execution is possible and common in EOV workflow.

- *Atomicity.* GRACE executes and commits (or aborts) each transaction as a whole.
- *Consistency.* GRACE only commits valid transactions with correct execution results (conform to the smart contract's logic) that satisfy the application-level endorsement policy 4.2. Specifically, the execution results of a transaction are considered valid as long as enough executors digitally sign the result.
- *Isolation.* GRACE inherits the isolation property from the EOV workflow. In other words, each GRACE transaction operates as if it is the only transaction executing, without interference or conflicts with other transactions.
- *Durability.* Same as existing EOV permissioned blockchains [5], GRACE inherits the durability guarantee from EOV's consensus protocol. Executors can retrieve the blockchain's transactions from their local copies of the blockchain.

GRACE achieves equivalent BFT safety as existing EOV blockchains [5] through the presence of two crucial properties:

- *Block consistency.* GRACE treats the consensus protocol as a blackbox, thereby enjoying the mature consistency (safety) guarantee of existing BFT consensus protocols [10] and their implementations. This ensures that all executors process and append the same set of blocks in an identical order determined by orderers.
- *State consistency.* Every executor follows the same deterministic protocol (§4.2) to validate each transaction in a given block. A transaction's result is committed to the state database *iff* all of its results produced by various executors are consistent and do not modify any key that has already been

modified by a previous transaction in the same block. In this way, all executors maintain a consistent state and a local copy of the blockchain after validation of a newly appended block.

5.2 Liveness

Definition 2 (Liveness). *Let C be a benign client and T be a well-formed transaction submitted by C and accepted by the lead executor LE. T will eventually be committed to GRACE, even in the event of a crash of C or a reboot of LE.*

Two liveness requirements must be met to commit T to GRACE successfully.

Firstly, the orderers must include T in a publicly agreed-upon clock to guarantee its proper ordering and inclusion in the blockchain. This requirement is satisfied as GRACE inherits the BFT liveness guarantee from its BFT protocol [10] running in EOV's ordering phase.

Secondly, T needs to be submitted to and executed by executors during the execution phase. This is addressed by the combined liveness guarantees of GRACE lead executor (LE) and the inherited EOV workflow. After T is accepted by LE, it is stored in a persistent FIFO queue that withstands crashes. In the event of a crash, T is not lost and will be finally dispatched to executors after LE reboots. The endorsement policy [5], which is an application-level agreement protocol among participating organizations in the EOV workflow, ensures that a sufficient number of benign organizations execute the transactions. This prevents a certain number of malicious executors from tampering with the correct result. For example, in a typical token transfer application with three organizations (*orgA*, *orgB*, *orgC*), the endorsement policy is *majority(orgA, orgB, orgC)*, which requires that every T must be endorsed by at least two of them and ensures that at most one organization can act maliciously.

5.3 Confidentiality

Definition 3 (Confidentiality). *Suppose C is a smart contract following the guideline of §6.2. With this setup, data owners can securely store and process the ciphertext CT without compromising the confidentiality of the corresponding plaintext PT. An active attacker A cannot deduce PT from CT (storage confidentiality). Moreover, even if A observes the execution of C and knows its type, A cannot infer specific details about the changes made to PT (computation confidentiality).*

GRACE is instantiated with two specific cryptographic primitives: (1) the BFV [12, 21] scheme, which achieves IND-CPA security based on the Decisional Ring Learning With Errors (D-RLWE) problem, and (2) Groth16 [26], which is a computationally sound and perfectly NIZKP system. When a probabilistic polynomial time attacker A corrupts a participating organization and observes all transactions, GRACE ensures *storage confidentiality*. This is achieved because A is computationally unable to distinguish the plaintext of a given ciphertext without the corresponding private key (decryption key), thanks to the IND-CPA security of the BFV scheme. Furthermore, throughout the transaction execution, transaction arguments are always concealed in ciphertext form. This ensures that any two transactions referring to the same set of keys are probabilistically indistinguishable. In other words, A cannot gain any information beyond the identities of relevant keys during transaction execution, thereby achieving *computation confidentiality*.

6 IMPLEMENTATION

We implement GRACE on the codebase of HLF v2.5 LTS [5]. The smart contract syntax of GRACE remains the same as HLF, but smart contracts need to be rewritten to use the libGRACE API for leveraging HE and NIZKP support, as discussed in §6.1.

6.1 libGRACE

libGRACE is a developer-friendly toolkit that minimizes the need for cryptography expertise and simplifies the use of HE and NIZKP functionalities. It harmonizes two mature libraries, lattigo [34] and gnark [15], which handle the arithmetic computations for HE and NIZKP operations, respectively.

Cryptography Arguments. libGRACE provides pre-defined cryptography arguments out-of-the-box (which will be discussed shortly) that balance security, speed, and memory consumption. libGRACE also offers high configurability, enabling developers to customize these arguments to achieve their desired trade-off between security and performance.

Homomorphic Encryption. libGRACE employs the BFV scheme [12, 21] as its FHE solution, ensuring 128-bit security in the default setting and supporting 58-bit unsigned integer arithmetic. HE multiplications in this setting take only tens of milliseconds on modern commodity servers [34]. Furthermore, the 58-bit unsigned integer is sufficient for many general applications without concerns about overflow.

Non-Interactive Zero-Knowledge Proof. libGRACE uses Groth16 [26] on the BN254 elliptic curve as its NIZKP solution. Like other systems relying on Groth16 zk-SNARKs [7, 44], our implementation requires a circuit-specific trusted setup, which can be performed using secure multi-party computation [8]. The overhead of the trusted setup process is considered trivial, as it is a one-shot procedure and therefore not included in the later evaluation section.

6.2 Rewrite Smart Contract With libGRACE

To enable HE and NIZKP support, developers need to manually rewrite a HLF smart contract according to the specifications stated below. Automated transpiling is not applicable here as it is challenging due to the potential ambiguity of smart contract semantics.

Use encrypted data type for private data. An encrypted variable is the ciphertext encrypted from its underlying plaintext. Throughout the execution of HE computation, the plaintext of it is never revealed without access to the relevant private key, ensuring the confidentiality of private data.

Use libGRACE functions to express HE and NIZKP operations. Replace standard addition and multiplication logic with the provided *Add* and *Mul* functions for HE computation. For NIZKP operations, use the $ProofGen$ and $ProofVerify$ functions to generate new proof instances and verify proofs with specific public input.

Use NIZKP instead of if-statements. Although most modern programming languages support if-statements or similar structures to control program flow based on conditional expressions, these statements cannot handle ciphertext directly due to the lack of support for direct comparison. As an alternative, GRACE employs NIZKP to simulate if-statements on the ciphertext. However, note that NIZKP cannot perfectly replace if-statements because, if a proof is verified as false, the program flow will exit without executing the remaining instructions.

7 EVALUATION

Testbed. We ran all experiments in a cluster with 20 machines, each equipped with a 2.60GHz E5-2690 CPU, 64GB memory, and a 40Gbps NIC. Each node and client was run in a separate docker container. A multi-host Docker Swarm network [17] orchestrated all participant containers. The average node-to-node RTT was about 0.2 ms.

Baselines. To evaluate the performance of GRACE, we compared it with three notable confidentiality-preserving blockchain systems: HLF [5], ZeeStar [44], and GRACE (w/o. CTM). HLF adopts a non-cryptography approach to ensure data confidentiality and is one of the most popular blockchain frameworks in both industry and academia [25, 39, 40]. ZeeStar is a notable cryptography-based blockchain, which encrypts sensitive data by using exponential ElGamal encryption [33] (i.e., a PHE scheme) and generates Groth16 NIZKPs to prove correct contract execution. During our evaluation, we utilized the open-source implementations of HLF and ZeeStar. Additionally, We developed GRACE (w/o. CTM), which represents GRACE without the integration of the CTM protocol, in order to assess the performance gains achieved by incorporating the CTM protocol.

Workloads. We used two workloads to evaluate GRACE and the three baselines. The first workload was *SmallBank* [28], a widely adopted benchmark for blockchain system evaluation [39, 42]. It emulates the business logic of a banking scenario and provides various functionalities including token transfer. We employed SmallBank to evaluate the end-to-end performance in benign environments, where all participants adhere to the system protocol (§7.1), as well as in the presence of malicious participants (§7.2), where a portion of corrupted nodes disrupted the proper execution of blockchains. To fit the four tested blockchains, we adapted SmallBank into three functionally equivalent implementations: an unencrypted version for HLF, an additive HE-enabled version for ZeeStar, and a libGRACE-enabled version (§6) for GRACE and GRACE (w/o. CTM).

Our second workload comprised ten diverse smart contracts involving HE addition, multiplication, or both, as exemplified in Table 2. We implemented these contracts exclusively on GRACE and GRACE (w/o. CTM) with two objectives in mind. Firstly, they provide us with quantified outcomes on the performance improvement facilitated by the CTM protocol in diverse scenarios. Furthermore, they demonstrate that GRACE is capable of supporting general smart contracts in various industries, such as finance (⑦ `pay`) and management (⑨ `supply-chain`).

Metrics. We evaluated two metrics: *effective throughput*, which represents the average number of valid client transactions committed to the blockchain per second, excluding conflicting aborted transactions, and *commit latency* (also known as *end-to-end latency*), which measures the duration from client submission to transaction commitment. Additionally, we reported the 99th percentile commit latency and the cumulative distribution function (CDF) of the commit latency.

Evaluation methodology. We developed a distributed benchmark based on Tape [30], an efficient benchmark toolkit for HLF. The benchmark spawned 128 clients across multiple servers to prevent the benchmarking tool from becoming a bottleneck.

Each system was maintained by twenty executors and four orderers with the BFT-SMaRT [10] consensus protocol. The default block size was set to 100 transactions, a commonly used setting in relevant studies [40, 42]. To simulate real-world scenarios, we designated 1% of the accounts as *Hot Accounts*. The *Conflict Ratio* denoted the probability of each transaction accessing these hot accounts, with a default value of 50%. For each evaluation, we conducted ten runs and reported the average values of the metrics. Our evaluation focused on three primary questions.

§7.1 How efficient is GRACE compared to baselines?
§7.2 How robust is GRACE to malicious participants?
§7.3 How efficient is GRACE under diverse applications?

7.1 End-to-End Performance

We first conducted experiments in benign environments where the network was stable and all participants behaved correctly. We evaluated all systems under different conflict ratios of 10%, 50%, and 90%, respectively. Each experiment began with ten organizations, each consisting of 100 accounts identical and adequate initial account balances. Following that, we generated a series of *SendPayment* transactions in which a randomly selected account $Acct_1$ transferred a certain number of tokens to another randomly chosen account $Acct_2$. It should be noted that $Acct_1$ and $Acct_2$ may or may not belong to the same organization.

GRACE outperformed both ZeeStar and GRACE (w/o. CTM) in terms of effective throughput, achieving increases up to 7.14×. In Figure 3, GRACE achieved throughput values of 255 TPS, 307 TPS, and 343 TPS at conflict ratios of 10%, 50%, and 90%, respectively. In contrast, GRACE (w/o. CTM) only achieved 235 TPS, 95 TPS, and 55 TPS, demonstrating a significant performance gap between GRACE and GRACE (w/o. CTM), especially with higher conflict ratios. ZeeStar performed even worse, achieving only 213 TPS, 85 TPS, and 48 TPS.

The average end-to-end latency for GRACE is 2.7s, which is only 87% of the baseline ZeeStar (3.1s) and slightly higher than GRACE (w/o. CTM) (2.4s). The additional latency in GRACE is due to the pending time required for merging transactions, as introduced by the CTM protocol (§4.2). However, the latency overhead in GRACE was merely 10%, while the throughput gain could reach up to 5.2×. Even when using FHE, which incurs higher costs than the PHE solution of ZeeStar, GRACE demonstrated shorter average end-to-end latency compared to ZeeStar. This advantage is due to GRACE's lightweight NIZKP (§4.2), eliminating the need to prove the correctness of individual data updates in each transaction, a requirement in ZeeStar.

GRACE is particularly suitable for applications with conflicting transactions thanks to its CTM protocol (§4.2). Surprisingly, in Figure **??**, GRACE significantly outperformed HLF with 1.54x higher throughput at a 90% conflict ratio, despite the extra overhead from HE and NIZKP generation. In less conflicting scenarios, GRACE was not as performant as HLF, but it still achieved higher throughput than ZeeStar and GRACE (w/o. CTM) in all three settings, albeit at the cost of ensuring data confidentiality.

As shown in Figure 3, GRACE exhibited an increasing trend in throughput as the conflict ratio increased, performing even better in less conflicting scenarios. In contrast, ZeeStar, GRACE (w/o. CTM), and HLF suffered from a significant drop in throughput. This is

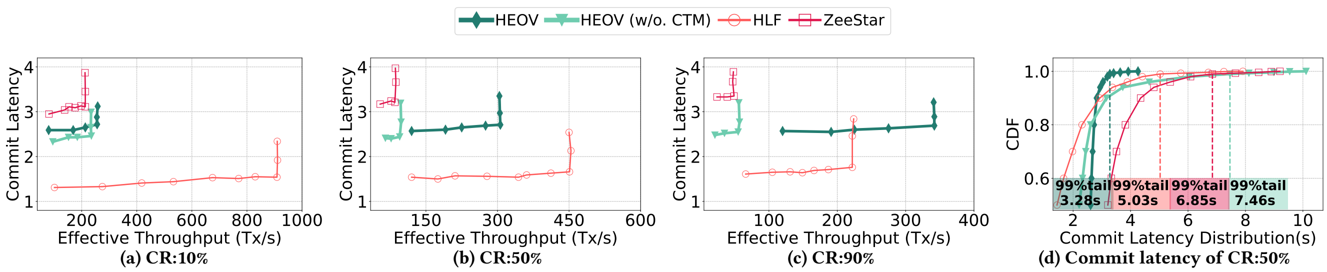


Figure 3: End-to-end performance of GRACE and HLF under applications with different conflict ratios.

No.	Name	⊕	⊗	Description
①	1d-convolution	✓	✓	Compute one-dimensional convolution on two vectors with different owners.
②	appraisal	✓		Appraise collectibles with confidential value estimates.
③	casino♠	✓	✓	A coin flip game with biased odds: 49% chance to win, 51% chance to lose, both 0.5× stake.
④	crowdfunding	✓		Raise funds from multiple owners for a single project.
⑤	election	✓		Determine the winner in a two-candidate election.
⑥	inner-product	✓		Compute the inner-product of two vectors with different owners.
⑦	pay	✓		Peer-to-peer currency payment.
⑧	rebate	✓	✓	Currency rebate for qualifying expenditures exceeding a threshold.
⑨	supply-chain	✓	✓	Inventory management.
⑩	taxing	✓	✓	Tax calculation and payment.

Table 2: Example contracts used in the second workload. ⊕ and ⊗ indicate whether a contract uses HE addition or multiplication, respectively. ♠ indicates that a contract is non-deterministic.

System	Average Latency (s)					99% tail latency (s)
	P	E	O	V	E2E	
GRACE	0.75	0.85	0.89	0.23	2.72	3.28
GRACE (w/o. CTM)	0.47	0.87	0.88	0.24	2.46	7.46
ZeeStar	n/a	n/a	n/a	n/a	3.11	6.85
HLF	0.03	0.41	0.91	0.19	1.54	5.03

Table 3: Latency of systems under test in Figure 3b and 3d. The "P" phase represents the preparation period before execution.

because GRACE's CTM protocol effectively reduces a substantial portion of conflicts, resulting in fewer cryptographic operations and conflicting aborts. Unlike the other systems, GRACE efficiently handles conflicts, allowing for sustained high throughput.

Figure 3d shows that GRACE's average latency (2.7s) was higher than that of HLF (1.6s), due to the extra overhead introduced by the HE and NIZKP operations. However, the increase in latency is fully justified by GRACE's confidentiality guarantee for general smart contracts. Furthermore, it is noteworthy that GRACE achieved a shorter 99%-tail latency compared to HLF, and all transaction latencies were concentrated within a narrow range. This indicates that the CTM protocol employed by GRACE generally reduces the need for transaction re-submission.

Table 3 provides a more detailed insight into the latency for each phase: preparation (**P**), execution (**E**), ordering (**O**), and validation (**V**). GRACE incurred extra overhead primarily in the preparation and execution phases due to encryption, merging, expensive operations like HE evaluation, NIZKP generation, and verification. The validation phase also experienced a slight latency increase due to NIZKP verification. The ordering phase, on the other hand, remains unaffected as expected. These results highlight the trade-off between the confidentiality guarantee provided by GRACE and the extra overhead from FHE and NIZKP operations.

Overall, GRACE offers a compelling combination of high performance and strong security guarantees, making it well-suited for applications that prioritize data confidentiality and involve conflicting transactions.

7.2 Robustness to Malicious Participants

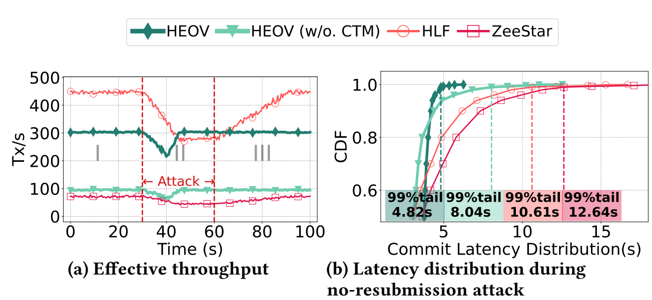


Figure 4: Performance under malicious participants.

We conducted no-resubmission attacks on four systems (Figure 4) involving four benign organizations (O_B) and one malicious organization (O_M). A victim organization O_V was selected from O_B. O_M created transactions involving O_V and intentionally did not resubmit them in order to attack O_V. The experiments were divided into three consecutive periods: *Period I: pre-attack*, *Period II: attack*, and *Period III: post-attack*. Metrics are shown in Figure 4.

Figure 4a shows that initially, all four systems experienced varying levels of performance degradation during the no-resubmission attack. However, GRACE and GRACE (w/o. CTM)'s throughput quickly resumed to the *Period I* level, while ZeeStar and HLF remained at a low level. This showcases the effectiveness of the countermeasure, where executors of benign organizations block malicious lead executors, preventing monopolization and ensuring fair access.

In Figure 4b, both GRACE and GRACE (w/o. CTM) exhibited much better average latency than ZeeStar and HLF during the no-resubmission attack. They efficiently detected and rejected malicious attackers, preserving computation power for benign clients and mitigating latency impact.

Overall, the results in Figure 4 emphasize that GRACE is particularly suitable for confidentiality-sensitive applications involving malicious participants. It incorporates countermeasures against no-resubmission attacks, ensuring fair access, and reducing latency.

7.3 Performance under Diverse Applications

The *SmallBank* workload represents real-world applications like token transfers, focusing on homomorphic addition rather than multiplication. To fully benchmark the performance improvement brought by CTM on both addition and multiplication, we developed the second workload introduced in §7, and conducted three experiments to evaluate the performance of GRACE and GRACE (w/o. CTM): (1) (**Add**) all transactions only invoked SC_A; (2) (**Mul**) all transactions only invoked SC_M; and (3) (**Add-Mul**) 50% of transactions invoked SC_A, while the other 50% invoked SC_M.

Results in Figure **??** show that GRACE's CTM protocol supports both addition and multiplication operations, making it ideal for applications that require one or both of these types of operations, such as cryptocurrency [19] and finance [47]. Figure **??** also demonstrates that GRACE significantly outperformed GRACE (w/o. CTM) in all three experiments, with throughput enhancements of 3.2x, 5.4x, and 7.8x for addition-only, multiplication-only, and hybrid applications, respectively. These results highlight the effectiveness of GRACE's CTM protocol, particularly when both addition and multiplication are involved. Additionally, the results suggest that the CTM protocol excels when multiplication is the major HE computation of the business logic.

In summary, GRACE's CTM protocol has delivered substantial performance advantages to GRACE without altering the transaction semantics. This breakthrough enables GRACE to safeguard the confidentiality of sensitive client data with cryptographic guarantees while maintaining high performance.

7.4 Lessons Learned

GRACE has two limitations. First, GRACE is designed specifically for blockchain applications involving conflicting transactions, such as token transfers [19]. It employs the CTM protocol that effectively reduces the rate of conflicting aborts and minimizes the computational overhead of expensive HE operations. However, for conflict-free applications, GRACE performs similarly to the baseline. Note that conflicts are common in typical real-world blockchain applications, and achieving conflict-free applications would require significant modifications to the application logic, such as rewriting the smart contract using CRDT [36]. This may not be feasible for widely used blockchain applications, such as financial trading [36].

Second, the current implementation of GRACE only supports HE computations on bounded unsigned integers due to its adoption of the BFV scheme [12, 21]. However, incorporating more capable FHE schemes like CKKS [14]) would enable GRACE to easily support HE computations on floating-point numbers. This would broaden the range of applications that GRACE can accommodate, enhance its flexibility, and improve its usability for real-world blockchain applications.

8 CONCLUSION

We present GRACE, the first high-performance confidential permissioned blockchain. GRACE integrates fully homomorphic encryption with a novel CTM protocol to significantly lower the cost of ensuring data confidentiality. GRACE also tailors non-interactive zero-knowledge proofs by leveraging the endorsement mechanism of permissioned blockchains, resulting in lightweight transaction result verification. Extensive evaluation demonstrates that GRACE achieves superior performance compared to baselines while maintaining data confidentiality, making it perfect for privacy-sensitive blockchain applications that require both high throughput and low latency.

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