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 (HE) to encrypt user data, and enforcing the correct execution of contract logic (e.g., payment) through non-interactive zero-knowledge proofs (NIZKPs). However, existing solutions still face significant limitations in supporting general smart contracts: these solutions either cannot tolerate non-deterministic contracts whose correct execution cannot be proven by NIZKPs, or support cryptographic primitives with limited capabilities, such as partial HE, which allows only one type of arithmetic operation (either addition or multiplication) over encrypted data.

We present GRACE, a high-performance confidential permissioned blockchain framework that supports general non-deterministic smart contracts with any cryptographic primitives (e.g., fully HE). Inspired by the multi-party trusted execution mechanism of execute-order-validate (EOV) blockchains, we propose a Heightened EOV (HEOV) workflow that uses NIZKPs to prove only that quorum parties produce consistent execution results to ensure the correct execution of contracts, without involving the contract logic. Moreover, we design a novel Correlated Transaction Merging (CTM) protocol to detect and merge multiple conflicting transactions into a single one, minimizing the number of conflict aborts in EOV and cryptographic primitive invocations for high performance. 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 permissioned blockhains, GRACE achieved up to 7.14× higher effective throughput and 13% lower end-to-end latency on average.

1 Introduction

Modern blockchains such as Hyperledger Fabric (HLF) [5] are widely deployed in both industry and academia. A driving force is their support for smart contracts that enable trusted execution over a global tamper-resistant shared ledger. However, the paradigm of processing and storing blockchain data in cleartext raises deep concerns about data confidentiality. Such concerns are especially problematic for applications involving highly sensitive information, such as medical data [32], as they are subject to strict privacy laws and regulations, like the General Data Protection Regulation of Europe Union [54].

This problem has motivated prior works to achieve data confidentiality on smart contracts, and these works can be summarized into two categories. One approach is designing new blockchain architectures to impose strict data access control without resorting to cryptography technologies [3–5]. For example, HLF uses channels [6] and private data collection [25] to determine which parties are eligible to access certain transaction data. However, this approach still adheres to the convention of storing data in cleartext, making it highly vulnerable to corrupted nodes that can steal sensitive on-chain data.

An alternative approach to prevent sensitive data from being revealed by corrupted nodes is to use cryptographic primitives to protect confidentiality and enforce contract execution correctness [34, 49–51]. For example, ZeeStar [49] performs partial homomorphic encryption (PHE) computation off-the-chain and proves the execution correctness by generating NIZKPs that are submitted to the global ledger for third-party verification. As another example, smartFHE [47] enables clients to prove the well-formedness of their private inputs and allows miners to perform fully homomorphic encryption (FHE [53]) operations, supporting both addition and multiplication directly over ciphertext.

Unfortunately, existing solutions following the cryptography-based approach face a fundamental dilemma between supporting general smart contracts and achieving high performance. First, PHE schemes sacrifices smart contract generality as they do not support both on-ciphertext addition and multiplication operations. Second, FHE schemes are plagued by their high computation costs and long execution latency. A recent survey [18] shows that a simple proof-of-concept implementation of the ElGamal scheme [36] (i.e., a

PHE scheme) requires less than 20 microseconds to perform a homomorphic addition, while a highly optimized FHE library Microsoft SEAL [45] takes at least 500 milliseconds to finish the same arithmetic operation, resulting in a $25\times$ performance gap. Third, existing solutions do not support non-deterministic smart contracts as these solutions follow the same paradigm of proving the execution correctness through re-executing smart contracts; this paradigm, if encountering inconsistency between different independently executed results, would fail to prove the correctness of execution.

Our key insight to tackle the dilemma is that, we can leverage EOV's policy-based execution, which enables the blockchain nodes to efficiently verify the correctness of transaction executions, to obviate the necessity of verifying the correctness of executions using the NIZKP. With EOV's policy-based execution, each transaction is homomorphically executed on multiple executor nodes, and the correctness of the executions is validated by comparing the consistency of execution results from executor nodes. As a result, the system can seamlessly integrate with FHE schemes to support a wide array of general blockchain applications while still maintaining high performance.

This insight leads to GRACE[1], the first high-performance confidentiality-preserving EOV permissioned blockchain framework that supports general blockchain applications. GRACE clients leverage FHE to encrypt sensitive user data, while executor nodes execute transactions on encrypted ciphertext. By synergizing the strengths of EOV and HE, GRACE ensures the correctness of transactions' executions by embracing EOV's policy-based executions, and preserves data confidentiality by preventing executors from accessing sensitive user data in plaintext.

The integration of the EOV workflow with FHE presents two unique challenges. The first challenge is tolerating non-deterministic transactions in EOV permissioned blockchains. For a non-deterministic transaction, different executors may produce inconsistent execution results, and EOV only commits transactions with consistent execution results. However, in GRACE, the executors cannot directly compare the FHE-encrypted execution results like existing EOV permissioned blockchains, due to the random noise that FHE inserts into the ciphertexts to defend against ciphertext attacks [24]. Consequently, the executors cannot determine whether a transaction is non-deterministic or not by checking the consistency of the transaction's execution results, as the ciphertexts of execution results are inconsistent even for a deterministic transaction.

The second challenge is the potentially disastrous performance degradation when integrating FHE with EOV, compared to plain text executions. First, FHE schemes incur a high computation overhead. Existing studies [53] have reported that FHE-encrypted transactions take 10^6x longer time to execute, which we confirmed in our evaluation (§7). Worse, the random noise that FHE inserts into ciphertext accumulates as the number of homomorphic computations increases. The ciphertext can be only decrypted when the noise is below a threshold, limiting the number of consecutive HE computations (e.g., multiplication) on the same ciphertext before decryption fails. This issue can be addressed by resetting the noise using relinearization, which can take tens of seconds even in efficient implementations [53].

This performance issue is further exacerbated by EOV's conflicting aborts. Due to EOV's concurrent transaction execution, when multiple concurrently executed transactions access the same key and at least one of them writes to the key (conflicting transactions), only one transaction can commit and other transactions will abort. Such conflicting transactions are prevalent in typical blockchain applications [46]. For example, HLF achieved only 24.5% of its conflict-free peak throughput in the stock trading application, as confirmed in Figure 3. These two factors are intertwined, as conflicting transactions result in a large number of HE-encrypted ciphertext computations on the same key, leading to frequent relinearizations.

To tackle the first challenge, GRACE clients generate NIZKP to prove the consistency of execution results of different executor nodes. Instead of generating heavyweight NIZKP to prove the correctness of the entire transaction execution process as existing studies [49], GRACE generates only lightweight NIZKP to prove the results' plaintext consistency without introducing prohibitive proof generation overhead. This enables GRACE to integrate FHE for supporting general blockchain applications with both addition and multiplication operations. Furthermore, the NIZKP safeguards against malicious participants falsifying the consistency of results, ensuring compatibility with BFT safety.

To tackle the second challenge, our basic idea is to exploit the conflicting transactions, which are ubiquitous in permissioned blockchain applications, to reduce the invocation number of homomorphic computations and relinearizations. We propose a new secure computing abstraction called correlated-merged homomorphic encryption for GRACE. This approach enhances the online schedule of transactions with an offline analysis of the transaction code. During the offline analysis, GRACE analyzes the smart contract and identifies whether multiple conflicting transactions invoking it can be merged into a single transaction. Based on the results of the offline analysis, GRACE's online schedule merges conflicting transactions and performs the necessary HE-encrypted ciphertext computations on the merged transactions. For example, when two transactions both add to the same key (e.g., two $X+1$ operations), GRACE combines the two adding transactions into a single add transaction on that key (e.g., one $X+2$ operation). This reduces the number of HE computations and relinearization required while preserving the semantics of the original transactions. Moreover, in contrast to existing permissioned blockchains with EOV consensus (e.g., HLF [5]), where conflicting transactions are resolved by committing only one and

[1] GRACE stands for GeneRAl Confidentiality-prEserving blockchain

invalidating the rest, GRACE can commit all conflicting transactions without any aborts.

Our main contribution is HEOV, a new confidentiality-preserving blockchain workflow tailored for general smart contracts, and CTM, a new concurrency control protocol for transactions involving encrypted data. HEOV addresses the challenge of ensuring the provably correct execution of non-deterministic contracts incorporating general cryptographic primitives (e.g., fully HE which supports both data addition and multiplication), rendering GRACE more secure than existing confidentiality-preserving permissioned 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 will benefit blockchain applications that desire both data confidentiality and high performance, such as supply chain [21] and healthcare [35]. 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

In the rest of this paper, §2 discusses GRACE's related work. §3 shows an overview of GRACE, §4 GRACE's protocols, §5 the analysis of correctness, liveness, and confidentiality, §6 the implementation details. §7 presents our evaluation, and §8 concludes.

2 Background And Related Work

System	Data Confidentiality	Ciphertext Computability	General Smart Contract
HLF [5]	✗	✗	✓
ZeeStar [49]	✓	✓	✗
Zapper [51]	✓	✗	✗
smartFHE [47]	✓	✓	✗
FabZK [34]	✓	✗	✗
GRACE	✓	✓	✓

Table 1: Compare GRACE with existing privacy-preserving blockchain systems.

In this section, we present a background overview of GRACE and review related works in the field of privacy-preserving blockchains, which are compared in Table 1.

2.1 Execute-Order-Validate Permissioned Blockchain

Permissioned [5, 17] and permissionless [27, 48] blockchains are maintained by multiple mutually untrusted organizations, but they differ significantly in their protocols. In permissioned blockchains, nodes are incentivized with cryptocurrency to follow the protocol, which requires specific proofs. For example, proof-of-work [38] involves high computation power, while proof-of-stake [26, 55] requires a large cryptocurrency holding. In contrast, permissioned blockchains employ a BFT consensus protocol among consensus nodes to tolerate malicious nodes instead of proof-of-work or stake. Permissioned blockchains, such as HLF and Cosmos, demonstrate better performance due to BFT protocols like PBFT [14] and HotStuff [1]. GRACE, inherited from HLF, can concurrently run multiple orderer nodes forming a BFT ordering service that can determine the order of transactions for each block within a few hundred milliseconds.

Permissioned blockchains can be further categorized into two sub-types based on their workflows: order→execute (OE) and execute→order→validate (EOV), as discussed in §1. GRACE adopts the EOV workflow for parallelism and applies the CTM protocol (i.e., pre-submission transaction merging) to minimize potential conflicting aborts, laying a solid foundation for the high performance of GRACE.

2.2 Homomorphic Encryption

Homomorphic encryption (HE) enables computation over encrypted data without revealing the plaintext. It is based on the concept of homomorphism, which is a structure-preserving map between algebraic structures. For instance, if $f : X \to Y$ is a map between two sets X and Y equipped with the same structure, and $\oplus$ is an operation of the structure (suppose $\oplus$ is a binary operation for simplicity), then f satisfies the property

$$f(a \oplus b) = f(a) \oplus f(b)$$

for every pair of elements a, b of X, and $a \oplus b$ of Y.

There are two major types of HE schemes: partially homomorphic encryption (PHE) and fully homomorphic encryption (FHE). PHE supports a specific operation (e.g., addition or multiplication), while FHE allows arbitrary combinations of computations. Despite simplicity, PHE is restricted by its limited computational capability and thus is not adopted by GRACE. For example, the Paillier cryptosystem [41, 42] only supports homomorphic addition. In contrast, FHE schemes (e.g., BFV [12, 22], BGV [13], and CKKS [15]) strike a balance between security and performance. GRACE employs the lattigo [37] library's BFV implementation, which can perform arithmetic computations on 58-bit unsigned integers within tens of milliseconds, achieving a good trade-off between security and performance.

2.3 Non-Interactive Zero-Knowledge Proofs

Non-interactive zero-knowledge proof (NIZKP) [23, 29] 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 use an NIZKP to prove knowledge of s satisfying a predicate $\phi(s;x)$. One popular type of NIZKP is called zero-knowledge succinct non-interactive arguments of knowledge (zkSNARKs) [11,30,56], which allows any arithmetic circuit ϕ and guarantees constant-cost proof verification in the size of ϕ, making them suitable for blockchain applications [2,7,19,40,50].

GRACE employs the gnark library [16]'s Groth16 implementation, a zkSNARK construction known for its constant size of proof (several kilobytes) and short verifying time (tens of milliseconds), for two important reasons. Firstly, NIZKP is necessary for enabling conditional branching in the context of encrypted data. Since direct comparison between two ciphertexts is currently infeasible, traditional if-statements commonly used in programming languages is not applicable. NIZKP provides a solution to this problem. Secondly, NIZKP is essential to prove the correctness of transaction results generated by various executors, thereby preventing malicious clients from forging transaction results.

2.4 Related Works

Smart Contract Privacy. Privacy is crucial in smart contracts, and previous works have achieved varying levels of privacy.

SmartFHE [47] and ZeeStar [49] focus on *data privacy*, where only those with the decryption key, typically the data owner, can access the specific data. SmartFHE proposes a framework using FHE and NIZKP, while ZeeStar adopts ElGamal [36] as an additive homomorphic scheme and develops a Solidity-based domain-specific language and transpiler for private smart contracts.

Zapper [51] and FabZK [34] go beyond *data privacy* and also hide the data's identity, known as *key privacy*. Zapper achieves *key privacy* through a combination of an oblivious Merkle tree construction and an NIZK processor, but it sacrifices smart contract expressiveness. FabZK achieves *key privacy* by using zero-knowledge proof, verifiable Pedersen commitments, and a shared tabular structured ledger that stores only encrypted data and conceals the relevant members of transactions.

Smart Contract Generality. Previous works have achieved different levels of smart contract generality using different approaches, as compared in Table 1.

ZeeStar supports general-purpose Ethereum [55] smart contracts but has limited functionality. It only allows additive homomorphic encryption and partially implements multiplication for few limited scenarios. Additionally, it uses NIZKP to prove the correctness of offline HE computation, which requires significant proof generation time, as confirmed in its evaluation. These seriously undermine the applicability of ZeeStar. In contrast, GRACE addresses these two pain points by adopting FHE and light-weight NIZKP.

Zapper sacrifices smart contract generality by prohibiting control flow and computation on data belonging to multiple users. SmartFHE currently implements a single-key variant where all private inputs for a transaction must be owned by the same party, while the multi-key variant is currently impractical, leading to the same problem that hinders Zapper's generality. FabZK achieves stronger generality but faces scalability issues because every transaction causes an update of the values of all organizations, which puts heavy pressure on performance and even complicates the process of managing the number of FabZK organizations on-the-fly.

3 Overview

3.1 System Model

GRACE consists of three types of participants: clients, executors, and orderers. The latter two are often referred to as nodes because they act as "servers" in an GRACE network with which clients interact. An GRACE network is typically maintained by multiple organizations, each consisting of clients and nodes. Members of the same organization are mutually trusted, but those from various organizations do not trust each other.

Clients. Clients are end-users who submit transaction proposals to executors for execution and orderers for ordering. Additionally, clients are responsible for generating NIZKP to prove the consistency of transaction results.

Executors. All executors in GRACE are responsible for evaluating transactions and maintaining a local copy of the blockchain, similar to HLF. GRACE executors utilize libHEOV (§6.1), which offers a set of APIs that support NIZKP and HE operations to perform the execution of transactions with homomorphically encrypted data. libHEOV is tailored for EOV contract execution and comes with pre-defined parameters for HE; therefore, smart contract developers do not need to be cryptography experts to efficiently incorporate smart contracts with HE operations.

Besides, a *lead executor* is elected for each organization to implement the CTM protocol, as shown in Figure 1. Lead executors are not different from other executors in transaction execution and blockchain maintenance, but they are assigned the following extra tasks.

- Receive transaction proposals from clients of its organization.
- Optimize transactions by merging multiple transactions targeting the same set of keys into a single transaction.
- Dispatch transaction proposals to other executors and orderers for execution and ordering, respectively.
- Pass transaction responses to clients.

Clients are not required to directly submit their transaction proposals to a lead executor as other executors will finally forward the proposals to it.

Orderers. Orderers in GRACE are the same as in HLF. Specif-

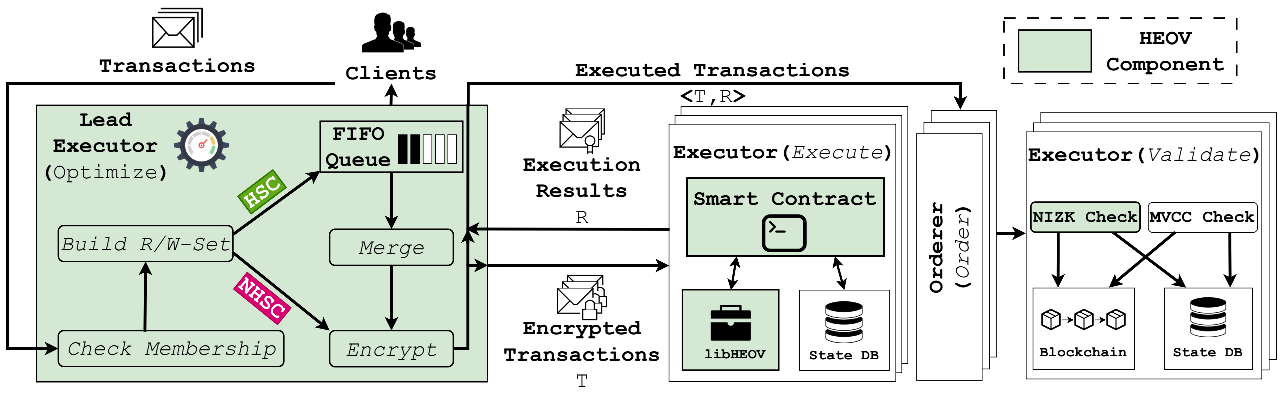


Figure 1: The GRACE Runtime Workflow. GRACE components are highlighted in green. An "HSC" transaction invokes a Homomorphic Smart Contract, while the "NHSC" one does not.

ically, they determine the order of transactions via some consensus protocol (e.g., BFT) and pack them into individual blocks, which are ultimately validated and recorded by relevant executors.

GRACE identifies all participants through a membership mechanism similar to HLF, where each participant is issued a pair of public/secret keys that encode their identity information. This mechanism enables access control to GRACE resources and, more importantly, makes all operations on GRACE auditable and traceable since any transaction is signed by a specific participant with the corresponding privilege.

3.2 Threat model

GRACE adopts the Byzantine failure model [9, 14], where malicious orderers run BFT consensus protocols that tolerate up to f malicious orderers out of $3f+1$ total orderers.

GRACE groups participants (i.e., clients, executor nodes, and orderer nodes) into organizations. Participants are mutually trusted only when they belong to the same organization. This implies that clients and nodes are mutually untrusted, as an organization only contains clients or nodes. Any clients or nodes can be malicious, in which case they are called attackers.

3.3 Workflow Overview

The runtime workflow of GRACE can be summarized into several steps, as shown in Figure 1. A more comprehensive discussion of the runtime workflow can be found in §4.2.
Step 1: Correlated merging. The lead executor collects transaction proposals, merges consecutive *mergeable* proposals, and leaves non-mergeable proposals as is.
Step 2: encryption. The lead executor encrypts the merged proposals using relevant organizations' public keys and signs each transaction with its certificate.
Step 3: dispatch. The lead executor dispatches the signed transactions to other executors, gathering clients' signatures and notifying clients of the transaction ID.
Step 4: execution. Executors invoke smart contracts, sign proposals, and send them back to the lead executor along with the result.
Step 5: proof generation. The lead executor generates an NIZKP to prove the plaintext consistency of results without re-running the smart contract.
Step 6: consensus. GRACE orderer nodes use a BFT protocol to reach a consensus on the order of transactions in a block.
Step 7: commit. Executors commit a transaction after receiving a valid block, ensuring no overlap in read-write set with previous valid transactions.

Overall, the highlight of the GRACE runtime workflow stems from achieving data privacy and high performance, which are ensured by several key elements. To guarantee the correctness of results, a lightweight NIZKP is generated. The workflow leverages the CTM protocol, which optimizes mergeable transactions, effectively reducing the occurrence of conflicting transactions and the need for HE operations. To maintain data confidentiality, lead executors are responsible for safeguarding the private keys of their respective organizations. Additionally, the libHEOV library plays a crucial role in facilitating HE computations and NIZKP operations. By combining these elements, the GRACE runtime workflow achieves both data privacy and high performance for permissioned blockchain smart contracts.

4 Protocol

4.1 Offline Homomorphic 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 2, before deploy-

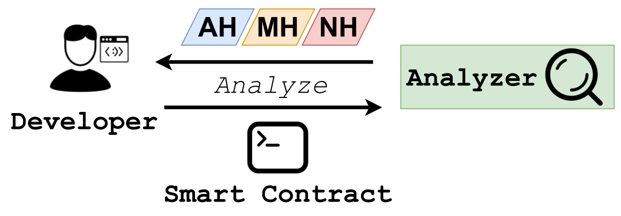


Figure 2: Offline Analysis Protocol. "AH", "MH", and "NH" means additive, multiplicative, and non-homomorphic, respectively.

ment, 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 1.

Phase 1: 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 2: Pre-execution preparation. 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 2.1: 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 2.2: Transaction diversion. During Phase 2.2 and 2.3, 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 2.4. 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 2.3: 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 2.4: 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: 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 libHEOV 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: 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. 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 No-Resubmission Attack

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: correctness, liveness, and confidentiality.

5.1 Correctness

Definition 1 (Correctness). *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, 22] scheme, which achieves IND-CPA security based on the Decisional Ring Learning With Errors (D-RLWE) problem, and (2) Groth16 [29], 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 v2.2 [5]. The smart contract syntax of GRACE remains the same as HLF, but smart contracts need to be rewritten to use the libHEOV API for leveraging HE and NIZKP support, as discussed in §6.1.

6.1 libHEOV

libHEOV 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 [37] and gnark [16], which handle the arithmetic computations for HE and NIZKP operations, respectively.

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

Homomorphic Encryption. libHEOV employs the BFV scheme [12, 22] 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 [37]. Furthermore, the 58-bit unsigned integer is sufficient for many general applications without concerns about overflow.

Non-Interactive Zero-Knowledge Proof. libHEOV uses Groth16 [29] on the BN254 elliptic curve as its NIZKP solution. Like other systems relying on Groth16 zk-SNARKs [7, 49], 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 libHEOV

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 libHEOV 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

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 orchestrated all participant containers. The average node-to-node RTT was about 0.2 ms.

Baselines. We compared GRACE with ZeeStar (EOV), GRACE (w/o. correlated-merging), and HLF [5]. ZeeStar is an OE-based blockchain on the Ethereum platform, differing from the systems in our evaluation. For a fair comparison, we implemented ZeeStar (EOV) on the codebase of HLF and used it as a baseline instead of directly benchmarking ZeeStar [49]. ZeeStar (EOV) uses the exponential ElGamal encryption [36] as its additive homomorphic encryption solution and Groth16 as its NIZKP solution. We also developed GRACE (w/o. correlated-merging) representing GRACE without the CTM protocol. Additionally, we evaluated HLF as it is the most popular permissioned blockchain framework in industry and academia [28, 43, 44].

Workloads. We evaluated four blockchains (GRACE, ZeeStar (EOV), GRACE (w/o. correlated-merging), and HLF) using two workloads.

The first workload was *SmallBank* [31], a widely used benchmark [43, 46] for evaluating blockchain systems that simulates bank business logic. The SmallBank workload was used to measure end-to-end performance (§7.1) and performance under no-resubmission attacks (§7.2). Due to the disparity in capabilities, we created three semantically equivalent implementations of SmallBank for each blockchain platform: an unencrypted version for HLF, an implementation using additive homomorphic encryption for ZeeStar (EOV), and an implementation using FHE with the libHEOV APIs (§6.1) for GRACE and GRACE (w/o. correlated-merging). Each experiment started with ten organizations, each with 100 accounts initialized with the same balance. Subsequently, we generated a set of *transfer* transactions, where a randomly selected account $Acct_1$ transferred a specific number of tokens to another randomly chosen account $Acct_2$. Note that $Acct_1$ and $Acct_2$ may or may not belong to the same organization.

Our second workload is a microbenchmark designed to showcase the performance improvement introduced by the CTM protocol. It comprises two smart contracts, SC_A and SC_M, which execute homomorphic additive and multiplicative transactions, respectively. The ratio between these two transaction types is configurable to simulate various scenarios. We assessed this workload exclusively on GRACE and GRACE (w/o. correlated-merging) (§7.3), as HLF does not support on-ciphertext computation and ZeeStar (EOV) does not utilize the CTM protocol, therefore not applicable to this evaluation.

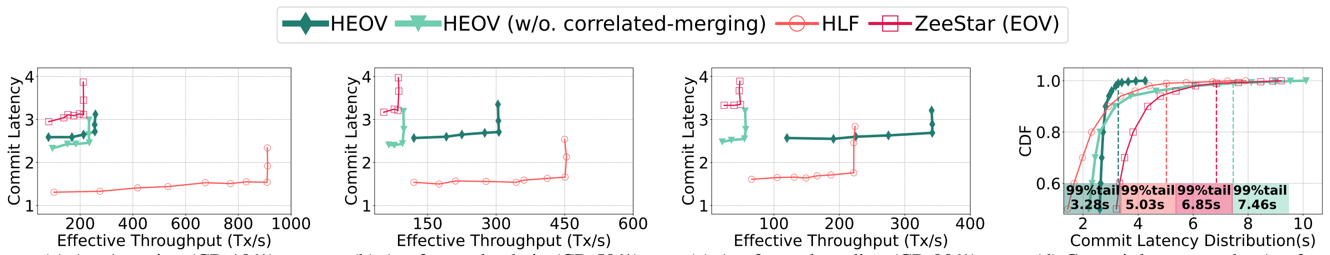
Metrics. We evaluated two metrics: *effective throughput*, which represents the average number of valid client transactions committed to the blockchain per second, excluding conflicting aborted transactions, and *commit latency* (also known as *end-to-end latency*), which measures the duration from client submission to transaction commitment. Note that if a transaction fails to commit, GRACE's lead executor will automatically resubmit the transaction until it is eventually committed. Additionally, we reported the 99th percentile commit latency and the cumulative distribution function (CDF) of the transactions' commit latency.

Evaluation methodology. We developed a distributed benchmark using Tape [33], an efficient benchmark tool for HLF. The benchmark spawned 128 clients across multiple servers to prevent the benchmarking tool from becoming a bottleneck.

Each system was configured with ten executors and four orderers, utilizing BFT-SMaRT [10] as the consensus protocol. The default block size was set to 100 transactions, a commonly used setting in relevant studies [44, 46]. To mimic real-world scenarios, we designated 1% of the accounts as *Hot Accounts*, and the *Conflict Ratio* represented the probability of each transaction accessing these hot accounts, with a default value of 50%. For each evaluation, we performed ten runs and reported the average values for each metric. Our evaluation focused on three primary questions.

§7.1 How efficient is GRACE in a benign environment?

§7.2 How robust is GRACE against no-resubmission attacks?



(a) App1: voting (CR:10%) (b) App2: supply chain (CR:50%) (c) App3: stock trading (CR:90%) (d) Commit latency under App2

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

§7.3 How efficient is GRACE across 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. All systems are evaluated with different conflict ratios of 10%, 50%, and 90%, respectively.

GRACE outperformed both ZeeStar (EOV) and GRACE (w/o. correlated-merging) 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. correlated-merging) only achieved 235 TPS, 95 TPS, and 55 TPS, demonstrating a significant performance gap between GRACE and GRACE (w/o. correlated-merging), especially with higher conflict ratios. ZeeStar (EOV) 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 (EOV) (3.1s) and slightly higher than GRACE (w/o. correlated-merging) (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 (EOV), GRACE demonstrated shorter average end-to-end latency compared to ZeeStar (EOV). 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 (EOV).

GRACE is particularly suitable for applications with conflicting transactions thanks to its CTM protocol (§4.2). Surprisingly, in Figure 5, 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 (EOV) and GRACE (w/o. correlated-merging) in all three settings, albeit at the cost of ensuring data confidentiality.

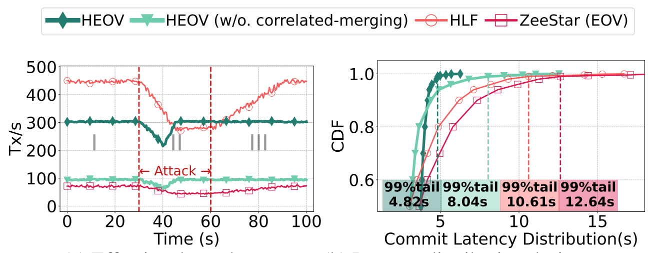
System	**Average Latency (s)**					**99% tail**
	P	E	O	V	E2E	**latency (s)**
GRACE	0.75	0.85	0.89	0.23	2.72	3.28
GRACE (w/o. correlated-merging)	0.47	0.87	0.88	0.24	2.46	7.46
ZeeStar (EOV)	0.26	1.66	0.87	0.32	3.11	6.85
HLF	0.03	0.41	0.91	0.19	1.54	5.03

Table 2: Latency of systems under test in Figure 3b and 3d. The "P" phase represents the preparation period before execution.

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 (EOV), GRACE (w/o. correlated-merging), and HLF suffered from a significant drop in throughput. This is 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 2 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.



(a) Effective throughput (b) Latency distribution during no-resubmission attack

Figure 4: Performance under no-resubmission attack

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

7.2 Robustness to No-Resubmission Attacks

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. correlated-merging)'s throughput quickly resumed to the *Period I* level, while ZeeStar (EOV) 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. correlated-merging) exhibited much better average latency than ZeeStar (EOV) 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 privacy-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. correlated-merging): (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 5 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 [20] and finance [52]. Figure 5 also demonstrates that GRACE significantly outperformed GRACE (w/o. correlated-merging) 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 privacy of sensitive user 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 [20]. 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 [39]. This may not be feasible for widely used blockchain applications, such as financial trading [39].

Second, the current implementation of GRACE only supports HE computations on bounded unsigned integers due to its adoption of the BFV scheme [12, 22]. However, incorporating more capable FHE schemes like CKKS [15]) 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

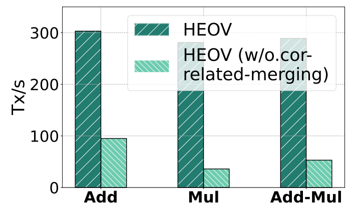


Figure 5: GRACE's optimization improvement under different combinations of HE computation.

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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