Geco: 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 Geco, 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. Geco 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, Geco 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 Geco achieves the strongest confidentiality guarantee among existing systems and supports general contracts. Compared to three notable confidential blockchains, Geco achieved up to 7.14× higher effective throughput and 13% lower end-to-end latency on average.

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] process and store client data in plaintext, raising deep concerns about data confidentiality. Such concerns are especially problematic for applications involving highly sensitive information, such as the 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 has been proposed to achieve data confidentiality on smart contracts, and existing work can be summarized into two distinct approaches. The first is the access-control approach. It works by introducing new blockchain architectures to impose strict access controls on data 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 still processes and stores client data in plaintext, and is not designed for handling the sensitive client data leakage caused by malicious nodes that can access the data.

The second is the cryptographic approach, designed to address the data leakage caused by malicious nodes. This approach employs 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 potential malicious nodes. This approach adopts a *re-execution method* to generate non-interactive zero-knowledge proofs (NIZKPs) that prove the correctness of contracts' execution results (in ciphertext). The re-execution method involves decrypting the encrypted transaction input and result, then re-executing the smart contract using the decrypted input, and finally checking 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.

However, despite these great advancements, existing work of the cryptographic approach still faces two fundamental limitations. Firstly, existing work is incompatible with non-deterministic smart contracts, whose different executions may produce inconsistent results even with the same input and initial state [5]. Non-deterministic contracts are gaining popularity as developers can create contracts in general-purpose languages like Java and C++ and achieve high performance (e.g., multi-threading [39]). However, these contracts are incompatible with the NIZKP due to its re-execution method. This method implies that identical inputs will consistently yield the same results, rendering it unsuitable for accommodating the inherent non-determinism in these contracts.

Secondly, the performance of existing cryptographic approach is poor due to the inefficiency of the re-execution method. This method poses challenges in achieving efficient NIZKP generation and verification, especially when integrated with general cryptographic primitives like fully homomorphic encryption (FHE), which enables arbitrary arithmetic computations over ciphertexts. To illustrate, the combination of the BFV scheme [12, 21] (i.e., an FHE scheme) and an elliptic-curve based NIZKP system [16] takes tens of seconds for NIZKP generation or verification [43]. Even when using lightweight cryptographic primitives like PHE that restrict available arithmetic operations, the NIZKP operations remain cumbersome. For instance, generating a Groth16 [37] NIZKP using 2048-bit keys for the Paillier PHE encryption scheme [38] consumes more than 256 GB memory [44], making it an impractical demand for commodity desktops available today.

Overall, we believe the re-execution method of existing approaches in generating NIZKPs is the root cause of their inability to support non-deterministic general contracts and their poor end-to-end performance which is often a small fraction of typical blockchain applications (e.g., 1k txns/s []).

In this study, our key insight to tackle these limitations is that, instead of proving the correct execution of contracts using only the cryptographic primitives like NIZKPs with the re-execution method,

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

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

we can re-divide the responsibility of ensuring the correct execution of contracts between the blockchain and the cryptographic primitives. Specifically, we can integrate NIZKPs with the quorum-based trusted execution mechanism of the execute→order→validate (EOV) permissioned blockchains. The mechanism first independently executes transactions (*endorsing*) among multiple executor nodes in parallel. It then proves the correctness of executions by checking that quorum nodes have produced consistent results. The 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.

This insight leads to Geco[1], a confidentiality-preserving and high-performance permissioned blockchain framework that supports general blockchain applications. Geco 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 plaintext 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, Geco effectively preserves data confidentiality, while simultaneously guaranteeing the correctness of executions for general smart contracts.

However, Geco 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 con-

flicting 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 4. This challenge is further exacerbated in Geco 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.

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 sub-protocols: *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, Geco is capable of committing all merged conflicting transactions without any aborts.

We implemented Geco on the codebase of HLF [5], the most notable EOV permissioned blockchain framework. We integrated Geco with Lattigo [34], a highly efficient FHE library, and gnark [15], a popular NIZKP library. We evaluated Geco 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 Geco with HLF and ZeeStar [44], covering both the non-cryptography-based and cryptography-based baselines for data confidentiality. Our evaluation shows that:

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

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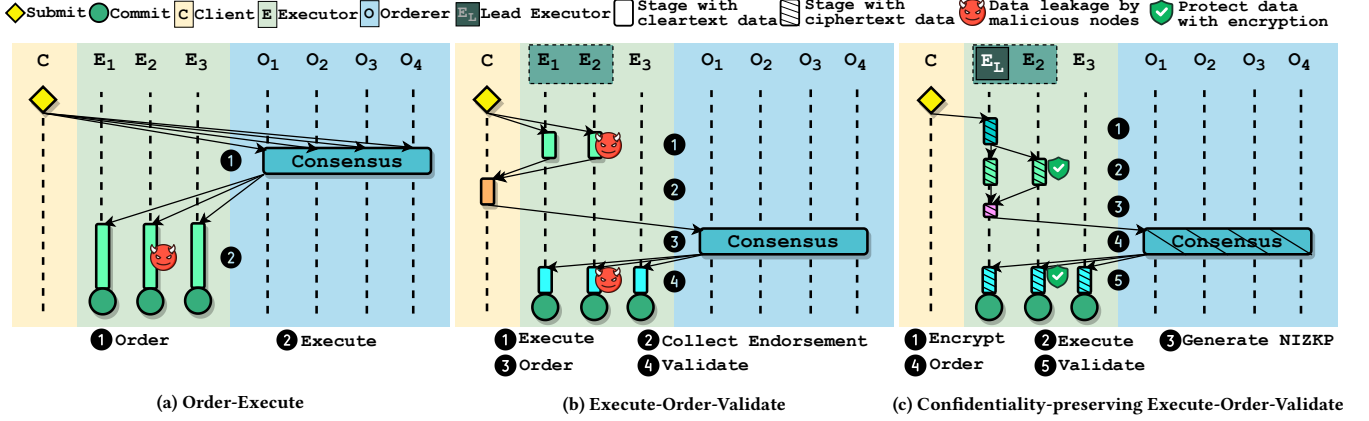[1]Geco stands for GEneral COnfidentiality-preserving blockchain framework

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

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 Geco as secure as existing cryptography-based confidentiality-preserving blockchains. Ctm enhances the effective throughput and reduces the average end-to-end latency of Geco by minimizing the conflicting aborts through the merging of transactions with data races. Overall, Geco can benefit blockchain applications that desire both data confidentiality and high performance, such as supply chain [20] and healthcare [32]. Geco can also attract broad traditional non-deterministic applications, developed with general-purpose programming languages like Golang and Java, to be deployed upon. Geco'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 Geco 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 Geco.

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 estab-

lish 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**). Geco extends EOV and proposes Ceov workflow (shown in Figure 1c) to leverage cryptographic primitives in order to preserve data confidentiality. Consequently, Geco 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 plaintext 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 plaintext *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, ei-

ther 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. Geco utilizes the BFV scheme [12, 21] (a FHE scheme) implementation of Lattigo [34], which is an optimized FHE library. This implementation enables Geco 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, Geco 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.
Access-control-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 plaintext, exposing a significant attack surface for corrupted participants seeking to steal confidential data.
Cryptography-based approach. Unlike the aforementioned solutions, many prior work use cryptographic primitives to protect confidentiality and enforce the correct execution 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 preserve confidentiality. However, two limitations impede its support for general smart contracts. Firstly, SmartFHE is also 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 capability 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.

3 OVERVIEW

3.1 System Model

Same as existing EOV permissioned blockchains, Geco contains three types of participants: *client*, *executor*, and *orderer*. The latter two are referred to as *nodes*. In Geco, participants are grouped into *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 Geco, 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 Geco, 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 libGeco (§5.1), a library that we developed to offer a range of FHE and NIZKP functionalities, which are essential for the correct functioning of Geco. libGeco is tailored for Geco smart contract execution and comes with pre-defined parameters for both cryptographic primitives. Therefore, smart contract developers can effectively incorporate smart contracts with FHE and NIZKP operations without requiring expertise in cryptography.

Each organization has one special executor, known as *lead executor*, as shown in Figure 2. In addition to the aforementioned tasks,
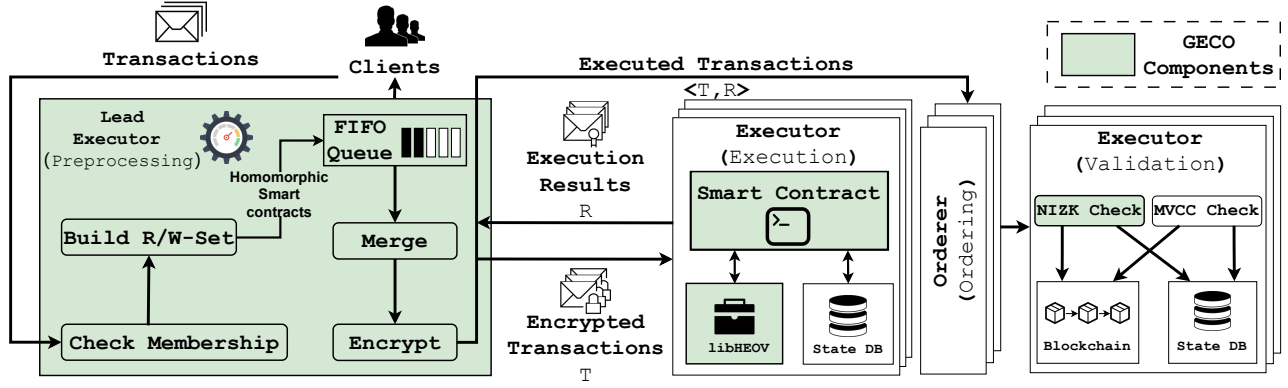
Figure 2: Geco's runtime workflow. Geco components are highlighted in green.

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 transactions 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. Geco orderers determine the order of transactions in blocks via a consensus protocol (e.g., PBFT [13]).

3.2 Threat model

Geco adopts the Byzantine failure model [9, 13], where orderers run a BFT consensus protocol that tolerates up to $\lfloor \frac{N-1}{3} \rfloor$ malicious orderers out of N orderers. Same as typical permissioned blockchains such as HLF, a participant trusts all participants within the same organization, but no participants from other organizations. We make standard assumptions on cryptographic primitives, including FHE and NIZKP.

3.3 Example Smart Contract

```
1  func Transfer(id src, id dst, euint val) {
2    if (!HasClientID(src) or !HasClientID(dst)) {Abort();}
3    if (src != GetClientID()) {Abort();}
4    euint srcBalance = GetState(src);
5    Require(srcBalance >= val);
6    euint dstBalance = GetState(dst);
7    PutState(src, Sub(srcBalance, val));
8    PutState(dst, Add(dstBalance, val));
9  }
```

Listing 1: An example contract for confidential token transfer. We denote a transaction (invoking the contract) that transfers one token from account A to B as $A \xrightarrow{1} B$.

Listing 1 is the pseudocode of a token transfer smart contract, which confidentially transfers *val* tokens from the sender client *src*, to the receiver client *dst*. Table 2 introduces the data types and functions utilized in Listing 1. Note that the Require function verifies a NIZKP that decrypts the encrypted data involved (i.e., srcBalance and val), and checks the validity of the predicate applied to the de-

Data type	Description
id	Represent a unique identifier for a participant client in Geco.
euint	Represent a single unsigned integer plaintext data, but stores different ciphertext data encrypted for different clients.

Function	Description
HasClientID	Check the existence of the given client id
GetClientID	Get the unique id associated with the sender client who submits the transaction.
Require	Require that the given predicate is true; otherwise, abort the transaction execution.
GetState	Read a state from the blockchain state database.
PutState	Write a state to the blockchain state database.
Add	Perform HE addition on the given input ciphertexts.
Sub	Perform HE subtraction on the given input ciphertexts.

Table 2: Data types and functions used in Listing 1.

crypted data. This NIZKP is generated by the lead executor during the preprocessing phase (§4.2) and is attached to the transaction. Intuitively, this smart contract achieves the following confidentiality guarantee: each client's balance is kept confidential and only accessible to the respective client, while the specific number of tokens being transferred remains known solely to the sender and the receiver.

3.4 Geco's Protocol Overview

The Geco contains two sub-protocols: (1) *offline contract analysis* and (2) *runtime transaction schedule*.

Offline contract analysis. (§4.1) Prior to deployment, the smart contract undergoes the offline analysis of Geco's Ctm protocol to determine whether it is *mergeable* (Definition 4.2). For example, the smart contract in Listing 1 is *additively mergeable*: multiple conflicting transactions that invoke this contract with identical src and dst ($tx_1 : A \xrightarrow{1} B$ and $tx_2 : A \xrightarrow{1} B$) can be merged into a single transaction ($tx_{1,2} : A \xrightarrow{2} B$) by adding their corresponding *val* parameters, while keeping src and dst unchanged.

Runtime transaction schedule. (§4.2) Geco incorporates a new Ceov workflow and the Ctm protocol to schedule transaction executions at runtime, as shown in Figure 2.

Phase 1: Preprocessing. The lead executor invokes the Ctm protocol to merge transactions: the lead executor collects transactions submitted by clients within the same organization (§3.2),

merges conflicting transactions whose parameters can be merged without changing their semantics, and leaves other transactions unchanged. Subsequently, the lead executor encrypts all transaction's plaintext inputs using the public keys (i.e., encryption keys) of corresponding organizations. Additionally, the lead executor also signs the encrypted transactions for auditability. The lead executor then selects a group of executors, known as endorsers in EOV [5], and dispatches the encrypted transactions to the endorsers for execution.

Phase 2: Execution. Upon receiving an encrypted transaction from a lead executor, the endorser invokes the smart contract specified by the transaction and produces a *read-write set* as the execution result. The endorser then signs the result and sends it back to the lead executor. After receiving execution results from all endorsers, the lead executors generate NIZKPs to prove that quorum executors (i.e., a majority of executors) have produced a consistent result for keys belonging to the same organization, thereby ensuring the correctness of execution. For instance, suppose the execution result of $tx_{1,2}$ by one endorser is $\{rset(A : 10, B : 10), wset(A : 8, B : 12)\}$, where A, B belong to different organizations org_1 and org_2, then org_1 provides proof that different endorsers produce consistent result $\{rset(A : 10), wset(A : 8)\}$ for key A. Similarly, org_2 provides proof that different endorsers produce consistent result $\{rset(B : 10), wset(B : 12)\}$ for key B. The NIZKPs from org_1 and org_2 are all submitted for ordering, collectively forming the correctness proof for $tx_{1,2}$. Note that a result is considered consistent iff one quorum executors have produced consistent read-write sets for all keys, regardless of whether those keys belong to the same organization or different organizations. In the above example, s

Phase 3: Ordering. GECO lead executors deliver the transactions with consistent results to the GECO orderers for transaction ordering. The orderers run a BFT protocol to achieve consensus on the order of transactions in blocks and disseminate the block to all executors for validation and commitment.

Phase 4: 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 previously committed transactions and updates the blockchain state database accordingly. Unlike existing EOV permissioned blockchains that abort conflicting transactions [5], GECO's CTM protocol enables the commitment of conflicting transactions tx_1 and tx_2 as a whole in $tx_{1,2}$.

In general, the highlights of GECO arise from achieving data confidentiality and high performance for general smart contracts. We illustrate our highlights in two aspects. Firstly, existing cryptography-based confidentiality-preserving blockchains face fundamental limitations in supporting general non-deterministic contracts or general cryptographic primitives like FHE (§1). GECO's CEOV workflow tackles these limitations by leveraging the quorum-based trusted execution of EOV permissioned blockchains to generate lightweight NIZKPs, which are agnostic to the specific logic of smart contracts and only serve to prove the consistency of quorum results, enabling the support for general non-deterministic smart contracts. This also enables GECO to encrypt user data using cryptographic primitives capable of performing arbitrary arithmetic computations over ciphertexts, such as FHE.

Secondly, in contrast to existing EOV permissioned blockchains which abort conflicting transactions [7, 44], the GECO's CEOV work-

flow incorporates the CTM protocol to merge multiple conflicting transactions into a single transaction, effectively eliminating the conflicting aborts and reducing the invocation number of cryptographic primitives 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
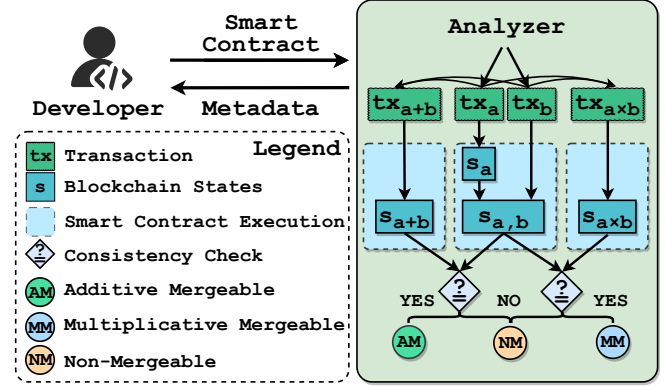
4.1 Offline Smart Contract Analysis

Figure 3: GECO's offline smart contract analysis protocol. tx_{a+b} and $tx_{a\times b}$ are formed by merging tx_a and tx_b through adding or multiplying their input parameters (§4.1). s_{a+b} and $s_{a\times b}$ are the states produced by executing tx_{a+b} and $tx_{a\times b}$. $s_{a,b}$ is the state produced by sequentially executing tx_a and tx_b.

Definition 4.1 (Smart contract parameter type). Smart contract input parameters can be classified into two types based on their roles within the transaction read-write set: *key* and *value*. The key parameters serve as keys in the key-value pairs of the read-write set, while the value parameters represent the corresponding values.

Definition 4.2 (Mergeable smart contract). A smart contract is *mergeable* iff, for conflicting transactions that share the same set of key parameters, these transactions can be merged into a single transaction without changing the execution results by using the same key parameters while generating new value parameters. Otherwise, the smart contract is *non-mergeable*.

Definition 4.3 (Additive mergeable smart contract). A smart contract is *additive mergeable* iff it is mergeable and can generate new value parameters by adding value parameters of the conflicting transactions.

Definition 4.4 (Multiplicative mergeable smart contract). A smart contract is *multiplicative mergeable* iff it is mergeable and can generate new value parameters by multiplying value parameters of the conflicting transactions.

The *offline smart contract analysis*, also known as *offline analysis*, is a fundamental sub-protocol of the CTM protocol. It is performed prior to smart contract deployment. As shown in Figure 3, the analyzer conducts the offline analysis on the code of the pro-

Function	Description
GetAllCFPs	Get all control flow paths of the given contract.
GenRandStateDB	Randomly generate a state database for the given contract and control flow path.
GenRandParams	Randomly generate transaction parameters for the given contract and control flow path.
GenTX	Generate a transaction based on the parameters provided by GenRandParams.
ExecTX	Execute a transaction over a state database and return the updated state database.
GetSize	Get the number of control flow paths.

Variable	Description
C	The smart contract to be analyzed.
$s, s_a, s_{a,b}, s_{a+b}, s_{a\times b}$	States in blockchain database
$tx_a, tx_b, tx_{a+b}, tx_{a\times b}$	Transactions.
$paths$	The set of all control flow paths.
p	A control flow path.
n_{a+b}	The counter for tracking $s_{a,b} = s_{a+b}$.
$n_{a\times b}$	The counter for tracking $s_{a,b} = s_{a\times b}$.
k	Contract parameters annotated as "key".
v_a, v_b	Contract parameters annotated as "value".
o	Contract parameters without annotation.

Table 3: Functions and variables for Algorithm 1.

Algorithm 1: Offline Analysis protocol (§4.1)

1 $n_{a+b} \leftarrow 0$; $n_{a\times b} \leftarrow 0$; $paths \leftarrow$ GetAllCFPs(C);
2 **foreach** p in $paths$ **do**
     // Step 1: Preparation
3   $s \leftarrow$ GenRandStateDB(C, p);
4   $k, v_a, v_b, o \leftarrow$ GenRandParams(C, p);
5   $tx_a \leftarrow$ GenTX(k, v_a, o); $tx_b \leftarrow$ GenTX(k, v_b, o);
6   $tx_{a+b} \leftarrow$ GenTX($k, v_a + v_b, o$);
7   $tx_{a\times b} \leftarrow$ GenTX($k, v_a \times v_b, o$);
     // Step 2: Execution
8   $s_a \leftarrow$ ExecTX(tx_a, s); $s_{a,b} \leftarrow$ ExecTX(tx_b, s_a);
9   $s_{a+b} \leftarrow$ ExecTX(tx_{a+b}, s); $s_{a\times b} \leftarrow$ ExecTX($tx_{a\times b}, s$);
     // Step 3: Consistency check
10 **if** $s_{a,b} = s_{a+b}$ **then**
11   $n_{a+b} \leftarrow n_{a+b} + 1$;
12 **else if** $s_{a,b} = s_{a\times b}$ **then**
13   $n_{a\times b} \leftarrow n_{a\times b} + 1$;
14 **if** $n_{a+b} =$ GetSize($paths$) **then**
15 **return** AdditiveMergeable
16 **else if** $n_{a\times b} =$ GetSize($paths$) **then**
17 **return** MultiplicativeMergeable
18 **else**
19 **return** NonMergeable

---

vided smart contract. Under the hood, Geco analyzes the smart contract in three phases using random interpretation [2], which generates different inputs and initial states to capture all possible control flow paths. The offline analysis produces a *metadata* as its output, which indicates whether the contract is additive mergeable (Definition 4.3), multiplicative mergeable (Definition 4.4), or non-mergeable (Definition 4.2). During runtime, lead executors inspect the metadata and only carry out transaction merging on additive mergeable and multiplicative mergeable smart contracts. Algorithm 1 and Table 3 show the offline analysis protocol.

Analysis step 1: Preparation. For a given smart contract C, Geco randomly generates an initial state database S and two conflicting transaction inputs tx_a and tx_b. Furthermore, Geco also attempts to generate two "*merged*" transactions, namely tx_{a+b} and $tx_{a\times b}$, based on tx_a and tx_b. S emulates a real-world blockchain state database, comprising exclusively of valid key-value pairs written by C. Geco generates conflicting transactions by mandating them to modify the same set of blockchain states (i.e., key-value pairs). Specifically, smart contract developers provide annotations on input parameters to indicate which parameters serve as keys or values in the state database, and Geco utilizes these annotations to generate conflicting transactions. For tx_{a+b}, Geco applies addition to the parameters that are annotated as values in both tx_a and tx_b, while leaving the remaining parameters unchanged. Similarly, for $tx_{a\times b}$, Geco multiplies those parameters annotated as values.

Analysis step 2: Random interpretation. Geco performs three independent runs of execution for C on the same initial state database S. In the first run, Geco initially executes tx_a and produces s_a. Subsequently, Geco executes tx_b on s_a, resulting in the final state database $s_{a,b}$. In the second and third runs, Geco separately executes tx_{a+b} and $tx_{a\times b}$, producing s_{a+b} and $s_{a\times b}$, respectively.

Analysis step 3: Consistency check. Lastly, Geco conducts a consistency check among the three resulting state databases. If the equality $s_{a,b} = s_{a+b}$ holds for all control flow paths, the smart contract C is additive mergeable. Similarly, if $s_{a,b} = s_{a\times b}$, C is

multiplicative mergeable. Otherwise, if neither condition is met, C is considered to be non-mergeable.

4.2 Runtime Transaction Schedule

Geco's *runtime protocol* incorporates our Ceov workflow to process transactions in four phases, and enhances the workflow performance with a novel Ctm protocol.

Phase 1: Preprocessing. For each transaction from clients, the lead executor performs the following preprocessing tasks to invoke the Ctm protocol and encrypt the transaction.

Phase 1.1: Read-write dependency graph construction. The lead executor constructs a read-write dependency graph for each block. Internally, the lead executor keeps track of all the keys that transactions read and write. After constructing the dependencies, the lead executor stores the transaction in a queue for following preprocessing tasks. For example, if a transaction tx invokes the smart contract in Listing 1 with input parameters $\{src = A, dst = B, val = 1\}$, the lead executor adds two read dependencies ($tx \xrightarrow{r} A$ and $tx \xrightarrow{r} B$) and two write dependencies ($tx \xrightarrow{w} A$ and $tx \xrightarrow{w} B$) to the graph.

Phase 1.2: Conflict detection. In the event of a block generation timeout or when the number of transactions in the queue exceeds a specified block size, the lead executor examines the dependency graph to identify transactions with identical key parameters. Conflicting transactions that meet this criterion are designated as mergeable by the lead executor, while the rest are considered non-mergeable.

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, tx_1 and tx_2, with shared relevant parties and inputs I_1 and

Function	Description
GetRWDeps	Get all read and write dependencies of a transaction.
DetectConflict	Detect and return the set of mergeable transactions and the set of non-mergeable transactions.
Merge	Merge the given set of mergeable transactions.
Encrypt	Encrypt the input parameters of the transactions.
Dispatch	Dispatch the given transactions to endorsers.
Execute	Execute the transaction and return the result.
ReplyResult	Send the execution results to the lead executor of the given transaction.
ProveConsistency	Generate NIZKPs to prove that quorum results are consistent.
VerifyConsistency	Verify the NIZKPs generated by ProveConsistency.
GetConsistentResult	Get the consistent result from a set of results.
SendForOrdering	Send the transaction for ordering.
IsValid	Check the validity of the transaction.
Commit	Commit the given transaction.

Variable	Description
Q	The queue that stores transactions during the preprocessing phase.
G	The read-write dependency graph.
blk	A block.
tx	A transaction.
txs_m	The set of mergeable transactions.
txs_n	The set of non-mergeable transactions.
txs_e	The set of all encrypted transactions.
r	An execution result.
rs	All execution results for a transaction.
$nizkps$	Non-interactive zero-knowledge proofs.

Table 4: Functions and variables for Algorithm 2.

Algorithm 2: Runtime protocol at lead executor (§4.2)

// Phase 1: Preprocessing
1 $G \leftarrow \varnothing; Q \leftarrow \varnothing;$
2 **Upon reception of** Transaction tx **from client; do**
3     $G \leftarrow G \cup \text{GetRWDeps}(tx);$
4     $Q \leftarrow Q \cup tx;$
5 **Upon** $|Q| \geq BlkSize$ **or** timeout
6     $txs_m, txs_n \leftarrow \text{DetectConflict}(G, Q);$
7     $txs_m \leftarrow \text{Merge}(txs_m);$
8     $txs_e \leftarrow \text{Encrypt}(txs_m, G) \cup \text{Encrypt}(txs_n, G);$
9     $\text{Dispatch}(txs_e);$
// Phase 2: Execution
10 **Upon reception of** Transaction tx **from lead executor; do**
11     $r \leftarrow \text{Execute}(tx);$
12     $\text{ReplyResult}(tx, r);$
13 **Upon reception of** all Results rs **for** Transaction tx; **do**
14     $nizkps \leftarrow \text{ProveConsistency}(rs);$
// Phase 3: Ordering
15   **if** $\text{VerifyConsistency}(nizkps)$ **then**
16         $r \leftarrow \text{GetConsistentResult}(rs);$
17         $\text{SendForOrdering}(tx, r, nizkps);$
// Phase 4: Validation and commit
18 **Upon reception of** Block blk; **do**
19   **For** $tx, r, nizkps$ **in** blk; **do**
20   **if** $\text{IsValid}(tx, r, nizkps)$ **then**
21             $\text{Commit}(tx, r, nizkps);$

I_2, respectively. After merging, a new transaction tx_{1+2} is created, incorporating the combined input $I_1 + I_2$, effectively replacing tx_1 and tx_2.

Phase 1.4: 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 1.5: 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 2: Execution. An Geco executor executes a smart contract and sends the execution response to the lead executor. Unlike HLF, Geco smart contracts leverage the capabilities of libGeco for HE and NIZKP operations. Additionally, Geco smart contracts use NIZKP as an alternative to the *if* statements found in most programming languages. In Geco, *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, Geco smart contracts generate NIZKP that validate the execution results and are stored on the blockchain for future reference.

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 3: Ordering. Geco 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 4: 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 Geco.

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, Geco adopts a per-executor counter-based approach. To be specific, each executor maintains a counter for each lead executor in the Geco 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 IMPLEMENTATION

We implement Geco on the codebase of HLF v2.5 LTS [5]. The smart contract syntax of Geco remains the same as HLF, but smart contracts need to be rewritten to use the libGeco API for leveraging HE and NIZKP support, as discussed in §5.1.

5.1 libGeco

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

Homomorphic encryption. libGeco 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. libGeco 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.

5.2 Rewrite Smart Contract With libGeco

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 libGeco 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, Geco 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.

6 ANALYSIS

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

6.1 Correctness

Definition 6.1 (Correctness). For any agreed block with a serial number s in the blockchain, given the same initial state for all nodes, once all transactions in all blocks with serial number $s' \leq s$ are committed, all benign executors will reach the same blockchain state (BFT safety). This state is equal to the state obtained by sequentially executing all transactions in blocks on the same initial state (ACID).

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

- *Block consistency*. Geco treats the consensus protocol as a black-box, 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.

Geco guarantees ACID properties for transaction execution.

- *Atomicity*. Geco executes and commits (or aborts) each transaction as a whole.
- *Consistency*. Geco only commits valid transactions with correct
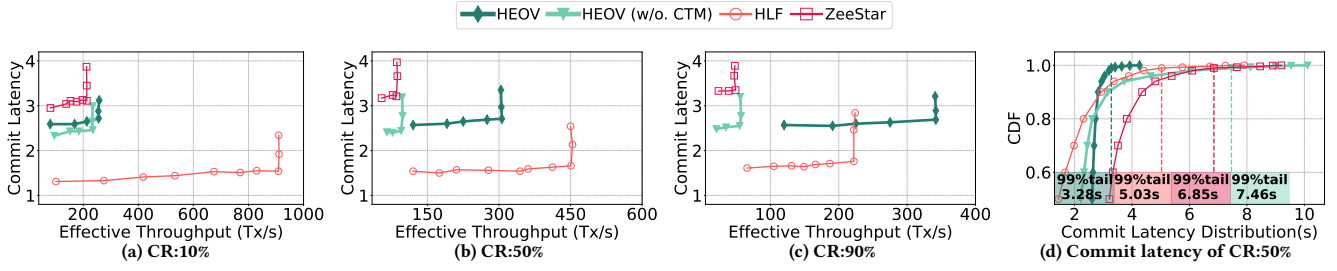
Figure 4: End-to-end performance of Geco and HLF under applications with different conflict ratios.

execution results (conform to the smart contract's logic) that satisfy EOV's application-level endorsement policy 4.2. Specifically, the execution results of a transaction are considered valid as long as enough executors sign on the result.

- *Isolation.* Geco inherits the isolation property from the EOV workflow. In other words, each Geco transaction operates as if it is the only transaction executing, without interference or conflicts with other transactions (**Phase 4**).
- *Durability.* Same as existing EOV permissioned blockchains [5], Geco inherits the durability guarantee from EOV's consensus protocol.

□

6.2 Liveness

Definition 6.2 (Liveness). Let C be a benign client and T be a valid (well-formed) transaction submitted by C. T will eventually be committed to Geco.

Proof. Two liveness requirements must be met to commit T to Geco successfully.

Secondly, T needs to be submitted to and executed by executors during the execution phase. This is addressed by the combined liveness guarantees of Geco 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.

Firstly, the orderers must include T in a block. This requirement is satisfied as Geco inherits the BFT liveness guarantee from its BFT protocol [10] running in EOV's ordering phase. □

6.3 Confidentiality

Definition 6.3 (Confidentiality). Suppose C is a smart contract following the guideline of §5.2. With this setup, data owners can securely store and process the ciphertext CT without compromising the confidentiality of the corresponding plaintext PT. An active at-

tacker 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*).

Proof. Geco 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, Geco 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*. □

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 or client ran 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 Geco, we compared it with three notable confidentiality-preserving blockchain systems: HLF [5], ZeeStar [44], and Geco (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 Geco (w/o. Ctm), which represents Geco 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 Geco and the three baselines. The first workload was *SmallBank* [28], a widely adopted benchmark for blockchain system evaluation [39, 42]. It em-

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	token-transfer	✓		Peer-to-peer token transfer.
⑧	rebate	✓	✓	Currency rebate for qualifying expenditures exceeding a threshold.
⑨	supply-chain	✓	✓	Inventory management.
⑩	taxing	✓	✓	Tax calculation and payment.

Table 5: 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.

ulates 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 libGeco-enabled version (§5) for Geco and Geco (w/o. Ctm).

Our second workload comprised ten diverse smart contracts involving HE addition, multiplication, or both, as exemplified in Table 5. We implemented these contracts exclusively on Geco and Geco (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 Geco 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 Geco compared to baselines?

§7.2 How robust is Geco to malicious participants?

§7.3 How efficient is Geco 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 *Send-Payment* 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.

Geco outperformed both ZeeStar and Geco (w/o. Ctm) in terms of effective throughput, achieving increases up to 7.14×. In Figure 4, Geco achieved throughput values of 255 TPS, 307 TPS, and 343 TPS at conflict ratios of 10%, 50%, and 90%, respectively. In contrast, Geco (w/o. Ctm) only achieved 235 TPS, 95 TPS, and 55 TPS, demonstrating a significant performance gap between Geco and Geco (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 Geco is 2.7s, which is only 87% of the baseline ZeeStar (3.1s) and slightly higher than Geco (w/o. Ctm) (2.4s). The additional latency in Geco is due to the pending time required for merging transactions, as introduced by the Ctm protocol (§4.2). However, the latency overhead in Geco 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, Geco demonstrated shorter average end-to-end latency compared to ZeeStar. This advantage is due to Geco's lightweight NIZKP (§4.2), eliminating the need to prove the correctness of individual data updates in each transaction, a requirement in ZeeStar.

Geco is particularly suitable for applications with conflicting transactions thanks to its Ctm protocol (§4.2). Surprisingly, in Figure 6, Geco 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, Geco was not as performant as HLF, but it still achieved higher throughput than ZeeStar and Geco (w/o. Ctm) in all three settings, albeit at the cost of ensuring data confidentiality.

As shown in Figure 4, Geco exhibited an increasing trend in throughput as the conflict ratio increased, performing even better

System	Average Latency (s)					99% tail latency (s)
	P	E	O	V	E2E	
GECO	0.75	0.85	0.89	0.23	2.72	3.28
GECO (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 6: Latency of systems under test in Figure 4b and 4d. The "P" phase represents the preparation period before execution.

in less conflicting scenarios. In contrast, ZeeStar, GECO (w/o. CTM), and HLF suffered from a significant drop in throughput. This is because GECO's CTM protocol effectively reduces a substantial portion of conflicts, resulting in fewer cryptographic operations and conflicting aborts. Unlike the other systems, GECO efficiently handles conflicts, allowing for sustained high throughput.

Figure 4d shows that GECO'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 GECO's confidentiality guarantee for general smart contracts. Furthermore, it is noteworthy that GECO 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 GECO generally reduces the need for transaction re-submission.

Table 6 provides a more detailed insight into the latency for each phase: preparation (**P**), execution (**E**), ordering (**O**), and validation (**V**). GECO 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 GECO and the extra overhead from FHE and NIZKP operations.

Overall, GECO 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

(a) Effective throughput

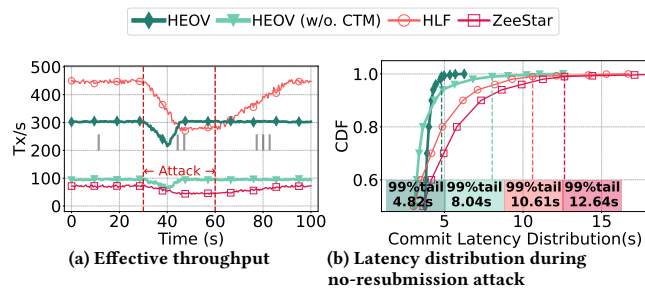**(b) Latency distribution during no-resubmission attack**

Figure 5: Performance under malicious participants.

We conducted no-resubmission attacks on four systems (Fig-

ure 5) 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 5.

Figure 5a shows that initially, all four systems experienced varying levels of performance degradation during the no-resubmission attack. However, GECO and GECO (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 5b, both GECO and GECO (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 5 emphasize that GECO is particularly suitable for confidentiality-sensitive applications involving malicious participants. It incorporates countermeasures against no-resubmission attacks, ensuring fair access, and reducing latency.

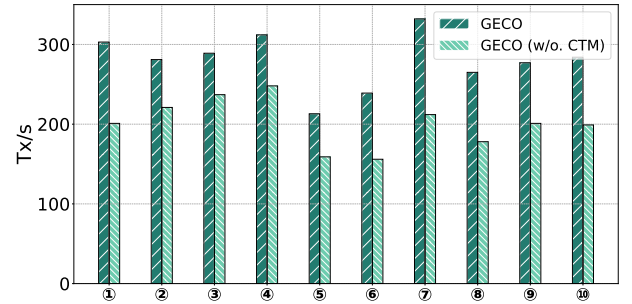## 7.3 Performance under Diverse Applications

Figure 6: Average throughputs under diverse applications discussed in Table 5.

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 GECO and GECO (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 6 show that GECO'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 6 also demonstrates that GECO significantly outperformed GECO (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 GECO'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, GECO's CTM protocol has delivered substantial performance advantages to GECO without altering the transaction semantics. This breakthrough enables GECO to safeguard the confidentiality of sensitive client data with cryptographic guarantees while maintaining high performance.

7.4 Lessons Learned

GECO has two limitations. First, GECO 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, GECO 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 GECO 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 GECO to easily support HE computations on floating-point numbers. This would broaden the range of applications that GECO can accommodate, enhance its flexibility, and improve its usability for real-world blockchain applications.

8 CONCLUSION

We present GECO, the first high-performance confidential permissioned blockchain. GECO integrates fully homomorphic encryption with a novel CTM protocol to significantly lower the cost of ensuring data confidentiality. GECO 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 GECO 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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