# 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 [50] 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 [49].

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 [11, 21] (i.e., an FHE scheme) and an elliptic-curve based NIZKP system [15] 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 conflicting transactions. Such transaction conflicts are prevalent in typical blockchain applications [42]. For example, in a conflict-heavy scenario where conflict ratio is 90%, HLF achieved only 24.5% of its peak throughput observed in a conflict-light scenario where the conflict ratio is 10%, as confirmed in Figure 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.

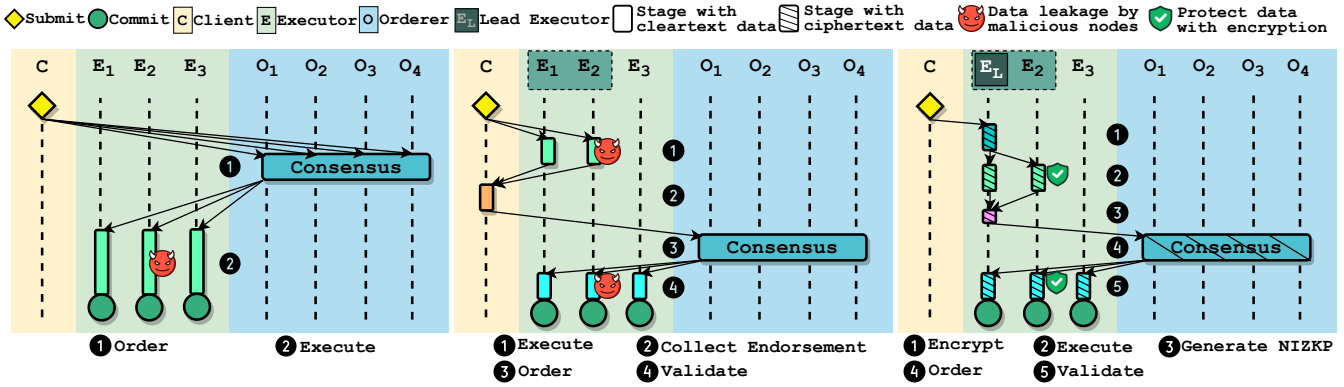
To tackle this challenge, we propose a Correlated Transaction Merging (Ctm) protocol. Ctm exploits the prevalent conflicting transactions in permissioned blockchain applications to reduce the number of invocations to cryptographic primitives. Ctm consists of two sub-protocols: *offline analysis* for 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 [14], 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 (§6.1). 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 (§6.2). Geco can achieve high effective throughput under attacks from malicious participants and conflicting transactions.
- Geco is general (§6.3). Geco tolerates non-deterministic smart contracts and supports cryptography primitives like FHE which allows arbitrary computations over encrypted data.

Our main contributions are Ceov, a new confidentiality-

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




(a) Order-Execute (b) Execute-Order-Validate (c) Confidentiality-preserving Execute-Order-Validate

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

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 [19] 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 mutually untrusted nodes. It can be summarized into two main categories: *permissionless* and *permissioned*. Permissionless blockchains (e.g., Bitcoin [35] and Ethereum [50]) are open to anyone, and their participants are mutually untrusted. In contrast, permissioned blockchains (e.g., HLF [5]) are maintained by a group of explicitly identified 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.

Typical 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 steps: Firstly, the orderer nodes establish a globally consistent transaction order (**O**); Subsequently, all executor nodes sequentially execute the transactions in the predetermined order (**E**). This workflow leads to significant performance issues and cannot tolerate non-deterministic transactions since each executor node independently executes all transactions.

In contrast, the EOV workflow (shown in Figure 1b) incorporates a **quorum-based trusted execution mechanism** to achieve high performance and to tolerate non-deterministic transactions.

This mechanism decouples the trust model of applications from the trust model of the blockchain. An application can define its own trust assumptions, which are conveyed through the endorsement policy and are independent of those of the blockchain's consensus protocol. Specifically, the application designates a group of executors for executing each transaction. The transaction's execution is deemed correct when a quorum of these executors produce consistent execution results for the transaction.

The EOV workflow has three phases. Initially, a group of executors called *endorsers* are selected to concurrently execute each transaction (**E**). Then, the client collects the executed results of each transaction from different endorsers to check their consistency; if the execution results are consistent, the execution is regarded as correct. The client sends the results to the orderers. Subsequently, the orderers determine the transaction order (**O**). Finally, each executor independently validates transaction results via multiversion concurrency control (MVCC) to prevent conflicting data access within a single block (**V**).

Geco's new Ceov workflow (Figure 1c) extends EOV's quorum-based trusted execution mechanism to preserve data confidentiality while supporting general non-deterministic contracts and cryptographic primitives (FHE and NIZKP), Geco inherits the advancements of EOV while tackling its limitations. On the one hand, Geco concurrently executes transactions to achieve high performance and tolerates general non-deterministic contracts. On the other hand, Geco tackles EOV's conflicting aborts caused by EOV's concurrent executions with a new Ctm protocol (§4.2).

### 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*; $\oplus$ is a binary operator taking two ciphertexts as input and produces a result ciphertext.

For instance, in an additive HE scheme, the $\oplus$ operator satisfies the following property:

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

HE schemes can be summarized into two main categories based on the supported operators: partial homomorphic encryption (PHE) and fully homomorphic encryption (FHE). PHE schemes are limited in their support to only one specific type of arithmetic operation, either addition or multiplication. In contrast, FHE schemes allow for arbitrary combinations of these operations. Although PHE schemes have relatively low computation overhead, they are limited in their computational capabilities. This restriction compromises the generality of smart contracts, as discussed in §1. FHE schemes typically demand higher computation overhead, but they are capable of preserving the generality of smart contracts. Furthermore, substantial improvements have been made to improve the performance of FHE schemes since the proposal of the first plausible FHE scheme [24], making FHE a promising and practical solution for supporting general smart contracts. Geco utilizes the BFV scheme [11, 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 $\phi$, 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) [10, 27, 51], which allows any arithmetic circuit $\phi$ and guarantees constant-cost proof verification in the size of $\phi$, making them suitable for blockchain applications [2, 7, 17, 37, 45]. Specifically, Geco employs the Groth16 [37] (a zkSNARKs construction) implementation of the gnark library [14] 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 (§3.3), a library that we developed to offer a range of NIZKP functionalities, which are

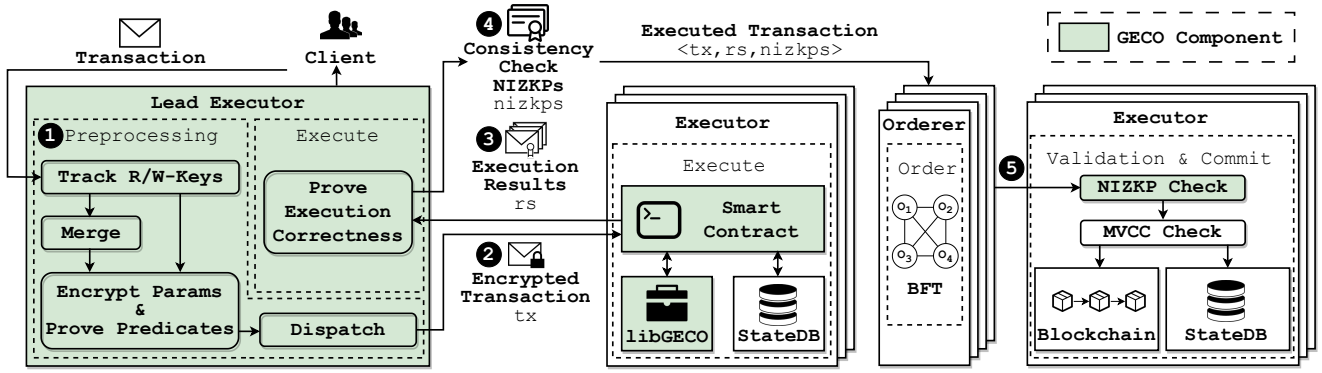



**Figure 2: Geco's runtime workflow. Geco components are highlighted in green.**

essential for the correct functioning of Geco.

Each organization has one special executor, known as *lead executor*, as shown in Figure 2. In addition to the aforementioned tasks, lead executors are assigned the following additional tasks:

- Detect multiple conflicting transactions and merge them into a single transaction.
- Encrypt transaction inputs with the cryptographic primitive specified by the invoking smart contract.
- Dispatch 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 [12]).

## 3.2 Threat model

Geco adopts the Byzantine failure model [8, 12], 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 libGeco

| API | Description |
|---|---|
| | Lead executor APIs |
| `Preprocess` | Preprocess the given transaction according to the runtime transaction schedule protocol (§4.2). |
| `ProveConsistency` | Generate *consistency check NIZKPs* to prove the consistency of the quorum results. |
| `VerifyConsistency` | Verify the given *consistency check NIZKPs* to ensure that the quorum results are consistent. |
| | Smart contract APIs |
| `Analyze` | Perform the offline analysis protocol (§4.1) on the given smart contract. |
| `Require` | Require that the given predicate for a contract is true; otherwise, abort the transaction execution. |

**Table 2: libGeco's APIs**

Geco provides a library named libGeco with five APIs (Table 2). The lead executor APIs assist lead executors in preprocessing transactions and ensuring the correctness of transaction execution. The smart contract APIs enable contract developers to analyze the mergeability (Definition 4.2) of the contract and enforce the validity of the given predicates involving encrypted data. Note that the `Require` API follows the idea of the *require* statement of ZeeStar [44]. We will further discuss how to integrate libGeco into Geco's protocol in §3.5 and §4.2.

## 3.4 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 $A \xrightarrow{1} B$.**

| 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. |
| `GetState` | Read a state from the blockchain state database. |
| `PutState` | Write a state to the blockchain state database. |
| `Add` | Perform FHE addition on the given input ciphertexts. |
| `Sub` | Perform FHE subtraction on the given input ciphertexts. |

**Table 3: Data types and functions used in Listing 1.**

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 3 introduces the data types and functions used in Listing 1. Note that the FHE functions `Add` and `Sub` are implementation-independent; they can be implemented with any FHE scheme that supports addition and subtraction on encrypted data, such as the BFV scheme [11, 21]. In this contract, the `Require` API (introduced in Table 2) verifies a NIZKP that decrypts the encrypted data involved (i.e., `srcBalance` and `val`), and checks the validity of the predicate applied to the decrypted 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.

### 3.5 GECO's Protocol Overview

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

**Offline contract analysis (§4.1).** Prior to smart contract deployment, the developer invokes libGECO's `Analyze` API (Table 2) on the contract. The `Analyze` API performs the offline analysis of GECO's CTM protocol to determine whether the contract is *mergeable* (Definition 4.2). For example, the 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 libGECO's `Preprocess` API (Table 2) to preprocess the transactions submitted by clients. Firstly, the lead executor invokes the CTM protocol to merge transactions (❶ in Figure 2 [2]): 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 of the data type `euint` using the public keys (i.e., encryption keys) of corresponding organizations. Additionally, for smart contracts using libGECO's `Require` API introduced in Table 2, the lead executor generates NIZKPs to prove the given predicates. Lastly, the lead executor 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 (❷), the endorser executes the invoked smart contract and produces a *read-write set* as the execution result. The endorser then sends the result back to the lead executor.

After receiving execution results from all endorsers(❸), the lead executors invoke the `ProveConsistency` API (Table 2) to generate NIZKPs for proving that quorum executors (i.e., a majority of executors) have produced consistent results for keys belonging to the same organization, thereby ensuring the correctness of execution.

**Phase 3: Ordering**. The lead executors of different organizations deliver the transactions with the NIZKPs to the GECO orderers for transaction ordering (❹). 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(❺), the executor sequentially validates each transaction within the block in the predetermined order. During the validation process, the executor invokes libGECO's `VerifyConsistency` API (Table 2) for each transaction to check the consistency of the transaction's quorum results. 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 commits both conflicting transactions $tx_1$ and $tx_2$ as a whole in $tx_{1,2}$.

[2] unless otherwise specified, ❷ refers to annotations in Figure 2.

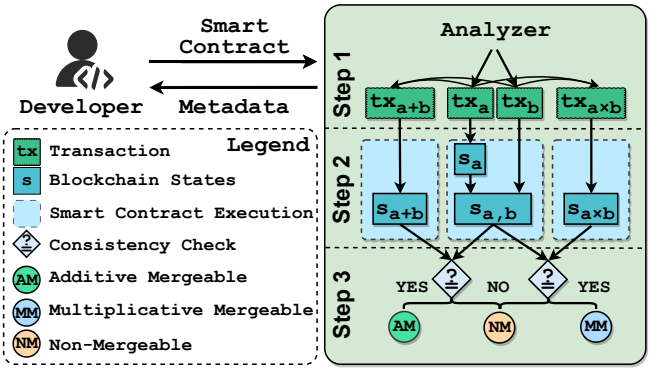



**Figure 3: GECO's offline smart contract analysis protocol. $tx_{a+b}$ and $tx_{a\times b}$ are formed by merging $tx_a$ and $tx_b$ through adding or multiplying their input parameters (§4.1). $s_{a+b}$ and $s_{a\times b}$ are the states produced by executing $tx_{a+b}$ and $tx_{a\times b}$. $s_{a,b}$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

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 workflow 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

**Definition 4.1** (Smart contract parameter type)**.** Smart contract input parameters are classified into two types: *key* and *value*. The key parameters specify the contract's accessed keys while the value parameters are used to derive the corresponding values.

| 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. |
| $n_{a+b}$ | The counter for tracking $s_{a,b} = s_{a+b}$. |
| $n_{a\times b}$ | The counter for tracking $s_{a,b} = s_{a\times b}$. |
| $k$ | Key parameters for the smart contract. |
| $v_a$, $v_b$ | Value parameters for the smart contract. |

**Table 4: Functions and variables for Algorithm 1.**

**Definition 4.2** (Mergeable smart contract)**.** A smart contract is *mergeable* iff, for any two conflicting transactions $tx_1$ and $tx_2$ that invoke the contract with identical key parameters, the transactions can be merged into a single transaction $tx_{1,2}$, whose key parameters are the same as $tx_1$ and $tx_2$, while the value parameters are the sums or products of the corresponding value parameters of $tx_1$ and $tx_2$.

A smart contract is *additive mergeable* iff it is mergeable and generates new value parameters by adding the corresponding value parameters of the conflicting transactions. A smart contract is *multiplicative mergeable* iff it is mergeable and generates new value parameters by multiplying the corresponding value parameters of the conflicting transactions. Otherwise, the contract is *non-mergeable*.

The *offline smart contract analysis*, also known as *offline analysis*, determines whether a smart contract is additive mergeable, multiplicative mergeable, or non-mergeable. libGeco's `Analyze` API implements the offline analysis protocol. As shown in Figure 3, Geco analyzes the smart contract in three steps using random interpretation [2], which generates different inputs and initial states to capture all possible control flow paths (see Algorithm 1 and Table 4). The offline analysis produces a *metadata* as its output, indicating the mergeability of the smart contract. During runtime, lead executors inspect the metadata and only carry out transaction merging on additive mergeable and multiplicative mergeable smart contracts.

**Analysis step 1: Preparation**. For a smart contract $C$, the Geco analyzer first determines whether each parameter is a key parameter or a value parameter. To accomplish this, the analyzer checks all calls to EOV's state modification APIs, such as `GetState(key)` and `PutState(key, value)` (see Table 3). A parameter is a key parameter if it is used as a key in any of the aforementioned APIs; otherwise, it is a value parameter.

Next, the analyzer randomly generates an initial blockchain state $S$, as well as two conflicting transactions $tx_a$ and $tx_b$ that share identical key parameters. In addition, the analyzer attempts to generate two "*merged*" transactions, namely $tx_{a+b}$ and $tx_{a\times b}$, based on $tx_a$ and $tx_b$. For $tx_{a+b}$, the analyzer generates new value parameters that are sums of the corresponding value parameters of $tx_a$ and $tx_b$, while leaving the key parameters unchanged. Similarly, for $tx_{a\times b}$, the analyzer generates new value parameters that are products of the corresponding value parameters of $tx_a$ and $tx_b$.

**Algorithm 1:** Offline analysis protocol (§4.1)

```
// Analyze API
n_{a+b} ← 0; n_{a×b} ← 0; paths ← GetAllCFPs(C);
foreach p in paths do
    // Step 1: Preparation
    s ← GenRandStateDB(C, p);
    k, v_a, v_b ← GenRandParams(C, p);
    tx_a ← GenTX(k, v_a); tx_b ← GenTX(k, v_b);
    tx_{a+b} ← GenTX(k, v_a + v_b);
    tx_{a×b} ← GenTX(k, v_a × v_b);
    // Step 2: Execution
    s_a ← ExecTX(tx_a, s); s_{a,b} ← ExecTX(tx_b, s_a);
    s_{a+b} ← ExecTX(tx_{a+b}, s); s_{a×b} ← ExecTX(tx_{a×b}, s);
    // Step 3: Consistency check
    if s_{a,b} = s_{a+b} then
        n_{a+b} ← n_{a+b} + 1;
    else if s_{a,b} = s_{a×b} then
        n_{a×b} ← n_{a×b} + 1;
if n_{a+b} = GetSize(paths) then
    return AdditiveMergeable
else if n_{a×b} = GetSize(paths) then
    return MultiplicativeMergeable
else
    return NonMergeable
```

**Analysis step 2: Random interpretation**. Geco performs three independent runs of execution for $C$ on the same initial state. In the first run, Geco executes $tx_a$ and produces $s_a$. Subsequently, Geco executes $tx_b$ on $s_a$, resulting in the final state $s_{a,b}$. 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 states. 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, $C$ is considered to be non-mergeable.

**Assumptions:** An analyzable contract must satisfy two requirements. For analysis step 1, the read-write set should be identified before execution, i.e., the read and write keys are explicitly identified in EOV's state modification APIs (e.g., `PutState()`). For analysis step 2, the contract should not contain recursive contract calls [2]. Geco can easily integrate more advanced analysis techniques to support contracts with fewer assumptions.

For non-analyzable contracts that do not satisfy these requirements, Geco conservatively regards these contracts as *non-mergeable*. Therefore, the non-analyzable contracts can at most degrade Geco's performance.

## 4.2 Runtime Transaction Schedule

Geco's *runtime protocol* (Algo 2) incorporates our new Ceov workflow to process transactions in four phases, and enhances the workflow performance with a Ctm protocol.

**Phase 1: Preprocessing**. Following our Ctm protocol, the lead executor invokes libGeco's `Preprocess` API (Table 2) to preprocess

| Function | Description |
|---|---|
| `GetRWKeys` | Get all read and write keys 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. |
| `SendForOrdering` | Send the transaction for ordering. |
| `CheckMVCC` | Perform a multi-version concurrency control check on the execution results. |
| `Commit` | Commit the given transaction. |
| `AppendBlock` | Append a block to the local copy of blockchain. |

| Variable | Description |
|---|---|
| $K$ | All read-write keys of transactions within a block. |
| $Q$ | The queue that buffers transactions during Phase 1. |
| $QSize$ | The maximum number of transactions in $Q$. |
| $txs_m$ | The set of mergeable transactions. |
| $txs_n$ | The set of non-mergeable transactions. |
| $txs_e$ | The set of encrypted transactions. |

**Table 5: Functions and variables for Algorithm 2.**

and encrypt the client transactions.

Phase 1.1: Tracking read-write keys. For each block, the lead executor buffers the transactions in a queue and keeps track of each transaction's read-write keys. For example, for a transaction ($tx : A \xrightarrow{1} B$) that invokes the smart contract in Listing 1, the lead executor tracks that the transaction has two read keys ($A$ and $B$) and two write keys ($A$ and $B$).

When the number of queuing transactions exceeds a specified size or a timeout occurs, the lead executor detects conflicting transactions according to the transactions' read-write keys. Based on the detection, the lead executor performs our Ctm protocol (Phase 1.2) to merge conflicting transactions with identical key parameters and encrypts all transactions using FHE (Phase 1.3).

Phase 1.2: Correlated transaction merging (Geco's Ctm protocol). For conflicting transactions with identical key parameters, the lead executor merges them by preserving their key parameters and generating new value parameters. In particular, the lead executor generates new value parameters by adding or multiplying the original value parameters of the mergeable transactions that invoke either an additive mergeable or multiplicative mergeable smart contract, respectively. For example, consider two transactions that invoke the additive mergeable smart contract in Listing 1: $tx_1 : A \xrightarrow{1} B$ and $tx_2 : A \xrightarrow{1} B$. The lead executor merges these transactions by preserving the key parameters $\{src = A, dst = B\}$, and adding the original value parameters to generate the new value parameter $\{val = 2\}$, resulting in the merged transaction $tx_{1,2} : A \xrightarrow{2} B$.

Phase 1.3: Encrypting transaction parameters and proving predicates. The lead executor encrypts the transaction input parameters that are of the data type `euint`, namely encrypted unsigned integers (Table 3). The lead executor analyzes the read-write keys associated with the `euint` parameters, then encrypts the parameter plaintexts using the encryption keys of the clients specified by the read-write keys. For example, for transaction $tx : A \xrightarrow{val} B$ (Listing 1), as `val` is computed together with `srcBalance` and `dstBalance`, the `euint` parameter `val` has two read-write keys $A$ and $B$, which belongs to $org_1$ and $org_2$ respectively. Therefore, the lead executor generates two ciphertexts for `val` by encrypting `val` using $org_1$ and $org_2$'s public keys, respectively.

**Algorithm 2:** Runtime protocol of the lead executor (§4.2)

```
// Phase 1: Preprocessing (Preprocess API).
K ← ∅; Q ← ∅;
Upon reception of Transaction tx from client; do
    K ← K ∪ GetRWKeys(tx);
    Q ← Q ∪ tx;
Upon |Q| ≥ QSize or timeout
    txs_m, txs_n ← DetectConflict(K, Q);
    txs_m ← Merge(txs_m);
    txs_e ← Encrypt(txs_m, K) ∪ Encrypt(txs_n, K);
    Dispatch(txs_e);
// Phase 2: Execution
Upon reception of Transaction tx from lead executor; do
    r ← Execute(tx);
    ReplyResult(tx, r);
// Phase 3: Ordering
Upon reception of all Results rs for Transaction tx; do
    nizkps ← ProveConsistency(rs);
    SendForOrdering(tx, rs, nizkps);
// Phase 4: Validation and commit
Upon reception of Block blk; do
    For tx, rs, nizkps in blk; do
        if VerifyConsistency(tx, rs, nizkps) ∧
          CheckMVCC(tx, rs) then
            Commit(tx, rs, nizkps);
    AppendBlock(blk);
```

The lead executor also generates NIZKPs for smart contracts that invoke the `Require` API (Table 2) to validate specific predicates. For example, the smart contract in Listing 1 requires that the encrypted `srcBalance` must be greater than `val` for a successful token transfer. Thus, the lead executor generates a NIZKP which first decrypts the encrypted data (`srcBalance`) and then proves whether the predicate holds (`srcBalance > val`). The NIZKPs are attached to the transactions for verifications by other participants.

Phase 1.4: Dispatch. The lead executor disseminates transactions to the involved organizations' executors (we name these executors "endorsers") for execution. For instance, the above $tx$ is submitted to executors in $org_1$ and $org_2$ for executions.

**Phase 2: Execution**. The executors execute each transaction in two steps: (1) the endorsers produce execution results, and (2) the lead executor checks the correctness of executions.

Phase 2.1: Producing execution result. Upon receiving a transaction from a lead executor, the endorser invokes the smart contract specified by the transaction. The execution produces a read-write set as the execution result, which records the blockchain states that the transaction reads from and writes to the blockchain state database. Next, the endorser signs the result and replies it to the lead executor for checking the correctness of executions.

Phase 2.2: Checking the correctness of executions. After collecting a transaction's results from endorsers of all involved organiza-

tions, the lead executor ensures correct executions by proving that quorum executors have produced consistent read-write sets. However, the read-write sets contain HE ciphertext data that cannot be directly compared without decryption as they involve random noise for security reasons [48]. To address this issue, the lead executor invokes libGECO's `ProveConsistency` API (Table 2) to generate a *consistency check NIZKP* that first decrypts the ciphertext data belonging to clients within the same organization, and then checks the consistency of the decrypted data. In the case where the read-write sets contain ciphertext data of multiple organizations, the lead executors of those organizations all follow the same procedure for proving the result consistency.

For instance, consider a transaction $tx$ that modifies three keys $A$, $B$ and $C$, belonging to different organizations, namely $org_1$, $org_2$ and $org_3$. To prove the consistency of $tx$'s execution results from different endorsers, $org_1$ provides a consistency check NIZKP that different endorsers produce consistent result for key $A$. Similarly, $org_2$ provides a NIZKP that different endorsers produce consistent result for key $B$. NIZKPs from $org_1$, $org_2$, and $org_3$ are all submitted for ordering, collectively forming the correctness proof of $tx$.

Note that a transaction's result is considered consistent iff the same quorum of executors produces consistent read-write set results for all keys. If the endorsers of $org_1$ and $org_2$ produce consistent results for key $A$, while the endorsers of $org_2$ and $org_3$ produce consistent results for key $B$, it indicates that the consistent results for different keys are produced by different quorums of endorsers. Consequently, we cannot affirm the consistency of $tx$'s execution results. The results of $tx$ are deemed consistent only when the same quorum of endorsers (e.g., $org_1$ and $org_2$) produce consistent results for all keys $A$, $B$ and $C$, in $tx$'s read-write set results.

**Phase 3: Ordering**. GECO orderers run a BFT consensus protocol (e.g., BFT-SMaRT [9]) to reach a consensus on the transaction order within a block. After a block is agreed upon by all orderers, they distribute it to all executors for validation and commit.

**Phase 4: Validation and commit**. The executor sequentially validates each transaction upon receiving a block from the orderers. This validation process involves two steps: (1) invoking libGECO's `VerifyConsistency` API (Table 2) to verify the consistency NIZKPs associated with the transactions, and (2) performing a multi-version concurrency check on the execution results. For each valid transaction, the executor commits the result to the blockchain state database. For invalid transactions, the executor does not commit their results (i.e., transaction abort). Once the executor has applied the above procedure to all transactions, it permanently appends the block to its local copy of the blockchain.

## 4.3 Defend Against Malicious Participants

The above protocol ensures data confidentiality even in the presence of malicious participants. Specifically, each GECO participant can access the cleartext data of only clients within the same organization, as participants in the same organizations are mutually trusted (§3.2). For clients in other organizations, the participant can only access the ciphertext data.

Although malicious participants are unable to compromise GECO's confidentiality, they may still significantly degrade the system's performance. In Phase 2.2, a lead executor may fail (e.g., network failures) or maliciously omit the submissions of the consistency check NIZKPs for specific transactions submitted by other organizations, causing these transactions to be always aborted in Phase 4. The attack is detrimental in GECO because it causes a substantial waste of computation resources on multiple executors, especially when smart contracts involve resource-intensive FHE computations (§1).

To tackle the above NIZKP omission attacks caused by malicious lead executors, GECO mandates the lead executors to submit the *consistency check NIZKPs* for all involved transactions, even if the transaction's execution results from different executors are inconsistent. To reduce false positives caused by network failures, GECO executors track the number of NIZKP omissions for different lead executors. A lead executor is deemed malicious only when the number of omissions caused by the lead executor exceeds a configurable upper bound (by default, ten omissions). GECO executors proactively reject transactions that involve organizations of the malicious lead executors in Phase 1 for a long duration (by default, 1000 blocks, after which the omission number for a lead executor is reset to zero), preventing the potential wastage of computation resources.

# 5 ANALYSIS

This section defines and analyzes the three guarantees of GECO: correctness, liveness, and confidentiality.

## 5.1 Correctness

**Definition 5.1** (Correctness)**.** For any agreed block with a serial number $s$, assuming that all executors start with the same initial blockchain state, once all valid transactions in blocks with serial numbers $s' \leq s$ are committed, all benign executors will converge to the same state (BFT safety). This resulting state is equivalent to the state obtained by sequentially executing all valid transactions on the same initial state (ACID).

PROOF. GECO achieves equivalent BFT safety to existing EOV blockchains [5] through two properties of consistency:

- *Block consistency.* GECO treats the consensus protocol as a blackbox, as illustrated in Phase 3 of the runtime protocol (§4.2). Therefore, GECO inherits the mature consistency (safety) guarantee of existing BFT consensus protocols [9] and their implementations. This ensures that all benign executors process and append the same blocks in an identical order determined by the orderers.
- *State consistency.* Every benign executor follows the same deterministic protocol to validate and commit transactions in a given block, as demonstrated in Phase 4 of the runtime protocol (§4.2). A transaction's result is committed to the state database *iff* a quorum of the transaction results are consistent and do not modify any key that has already been modified by a previous transaction within the same block. This ensures that all benign executors maintain a consistent state and a consistent local copy of the blockchain after validating and committing a newly agreed block.

GECO guarantees the ACID properties for transaction execution by inheriting them from the EOV workflow.

- *Atomicity.* GECO commits or aborts each transaction as an indivisible unit.
- *Consistency.* GECO exclusively commits valid and consistent trans-

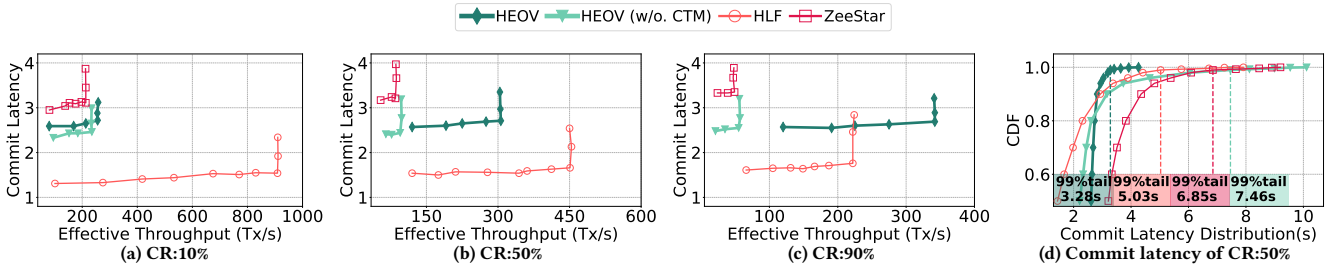



**Figure 4: End-to-end performance of Geco and HLF under applications with different conflict ratios.**

action results in a sequential order determined by the orderers. This leads to a consistent resulting state across benign executors given an identical initial state.

- *Isolation.* Each Geco transaction operates as if it is the only transaction executing, without interference or conflicts with other transactions.
- *Durability.* Once a Geco transaction is committed, its changes to the blockchain state become permanent and cannot be reversed.

□

## 5.2 Liveness

**Definition 5.2** (Liveness)**.** For any valid transaction $tx$ created by a benign client, $tx$ will eventually be committed to Geco.

Proof. Geco's liveness guarantee is achieved by inheriting the BFT liveness guarantee from existing EOV permissioned blockchains [5]. Firstly, the lead executor preprocesses $tx$ and buffers $tx$ in a crash-tolerant queue to ensure that $tx$ is eventually dispatched to endorsers for execution, as demonstrated in Phase 1 of the runtime protocol (§4.2). Secondly, $tx$ is executed by multiple mutually untrusted endorsers, which prevent malicious endorsers from tampering the correct transaction execution. Lastly, the orderers finalize $tx$ into a block (§4.2), which will eventually be committed to the blockchain by all executors. □

## 5.3 Confidentiality

**Definition 5.3** (Confidentiality)**.** For any transaction involving ciphertext data $ct$ belonging to a client of organization $org_1$ and associated with the corresponding plaintext data $pt$, it is guaranteed that any attacker from a different organization $org_2$ is unable to correctly decrypt $ct$ to obtain $pt$.

Proof. Geco's confidentiality guarantee is based on two inherent confidentiality guarantees separately provided by NIZKPs and the encryption scheme employed. Firstly, the private inputs for generating NIZKPs are probablistically impossible to be revealed by verifiers [26]. This aids Geco in ensuring the confidentiality of private inputs such as decryption keys, as illustrated in libGeco's `ProveConsistency` and `Require` APIs (Table 2). Secondly, the encryption scheme employed by Geco (e.g., the BFV scheme [11, 21]) achieves the indistinguishability under chosen-plaintext attack (IND-CPA) security, meaning that any attacker is computationally infeasible to distinguish the plaintext of a given ciphertext without the corresponding decryption key (private key). Specifically, it is impossible for an attacker from a different organization $org_2$ to access the plaintext data corresponding to ciphertext data belonging to $org_1$'s clients. This is because $org_1$ keeps its decryption key confidential, and the IND-CPA security makes it computationally infeasible for the attacker to gain any information about the ciphertext without knowledge of the decryption key. □

# 6 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 [16] orchestrated all participant containers. The average node-to-node RTT was about 0.2 ms.

**Geco implementation**. We built Geco on top of Hyperledger Fabric v2.5 [20]. Geco uses the implementation of the BFV scheme [11, 21] provided by the Lattigo library [34]. With the pre-configured cryptographic parameters, Geco supports FHE arithmetic computation over 58-bit unsigned integers, which satisfy the requirements of notable smart contracts listed in Table 6. Geco uses the implementation of the Groth16 NIZKP system [26] on the BN254 elliptic curve provided by the gnark library [14]. Same as existing systems [7, 44] that also use Groth16, our implementation requires a circuit-specific trusted setup to generate the verification key for each NIZKP circuit. This trusted setup is a one-time procedure with negligible overhead, and hence it is not discussed in our evaluation.

**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 emulates the business logic of a banking scenario and provides various functionalities including token transfer. We employed SmallBank

| 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 6: 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.**

to evaluate the end-to-end performance in benign environments, where all participants adhere to the system protocol (§6.1), as well as in the presence of malicious participants (§6.2), 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 (§**??**) 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 6. 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 [9] 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.

§6.1 How efficient is Geco compared to baselines?
§6.2 How robust is Geco to malicious participants?
§6.3 How efficient is Geco under diverse applications?

## 6.1 End-to-End Performance

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

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 in less conflicting scenarios. In contrast, ZeeStar, Geco (w/o. Ctm), and HLF suffered from a significant drop in throughput. This is be-

| System | Average Latency (s) | | | | | 99% tail |
|---|---|---|---|---|---|---|
| | P | E | O | V | E2E | latency (s) |
| 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 7: Latency of systems under test in Figure 4b and 4d. The "P" phase represents the preparation period before execution.**

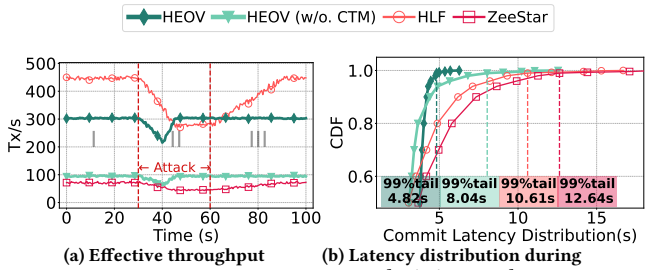
cause Geco's Ctm protocol effectively reduces a substantial portion of conflicts, resulting in fewer cryptographic operations and conflicting aborts. Unlike the other systems, Geco efficiently handles conflicts, allowing for sustained high throughput.

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 7 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.

## 6.2 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 (Figure 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.

## 6.3 Performance under Diverse Applications

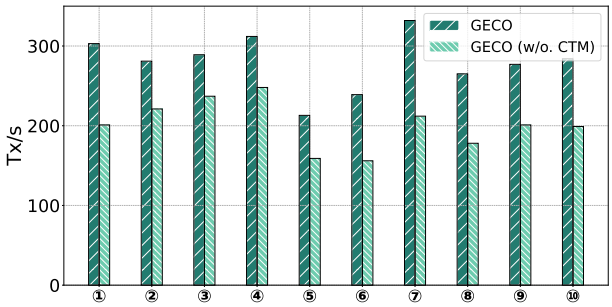



**Figure 6: Average throughputs under diverse applications discussed in Table 6.**

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 §6, 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 [18] 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 ex-

cels 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.

## 6.4 Lessons Learned

Geco has two limitations. First, Geco is designed specifically for blockchain applications involving conflicting transactions, such as token transfers [18]. 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 [11, 21]. However, incorporating more capable FHE schemes like CKKS [13]) 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.

# 7 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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