ZkDelay: Mitigating Transaction-Ordering Dependence using Commitment Schemes and Verifiable Delay Functions in Smart Contracts

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ABSTRACT
Transaction-Ordering Dependence (TOD) is a potential vulnerability of blockchain-based smart contracts, which allows malicious actors to exploit the order of transactions to obtain financial profit through front-running and back-running strategies. The purpose of this paper is to present ZkDelay, a new framework that jointly uses commitment schemes and Verifiable Delay Functions (VDFs) to counter TOD in decentralized applications. ZkDelay introduces a two-step transaction scheme: a user makes a cryptographic commitment to a transaction without announcing its purpose, and then, upon completing a verifiable delay with a VDF, the intended transaction can be revealed and carried out. This temporal discontinuity, combined with cryptographic acknowledgments, prevents adversaries from interfering with actionable knowledge in real-time, thereby eliminating any ordering-based attack possibilities. Moreover, ZkDelay is transparent and trustless, as it can be used to verify both commitments and delay execution through zero-knowledge proofs, without leaking sensitive data. Additional sections dedicated to rigorous security analysis and performance analysis in Ethereum-like environments are provided in the paper, demonstrating that ZkDelay incurs only a low amount of computational overhead and that it exponentially improves resistance to TOD attacks. The solution can be deployed in existing smart contract systems and adapted to DeFi protocols, order-sensitive auctions, and other mechanisms. ZkDelay addresses the challenge of integrating privacy-preserving mechanisms with the fairness of execution by providing a scalable and practical solution to one of the most prevalent security issues in smart contract environments.

Keywords
Transaction-Ordering Dependence, Smart Contracts, Commitment Schemes, Verifiable Delay Functions, Zero-Knowledge Proofs, Blockchain Security

1. INTRODUCTION
Blockchain systems are built on the principles of trustlessness, transparency, and fairness. These principles, however, are being disputed due to the vulnerabilities of Transaction-Ordering Dependence (TOD). Permissionless systems, such as Ethereum, where miners or validators determine the order of transactions in a block, enable adversaries to exploit transaction sequencing to their advantage at the expense of fairness and user trust [1], [2], [8]. This manipulation can be executed in the form of front-running, back-running, and miner extractable value (MEV) operations that skew the desired outcomes of transactions and undermine the integrity of ecosystems [9], [11]. In TOD attacks, attackers monitor the mempool and place their own entries with more expensive gas fees, effectively rearranging the execution order to modify the outcome [1], [10], [18]. This type of manipulation is common in Decentralized Finance (DeFi) settings, including decentralized exchanges (DEXs), non-fungible token (NFT) auctions, and lending protocols [18], [24]. Mitigation schemes are suggested, such as commit-reveal schemes, randomized sorting of transactions, and MEV relays, such as Flashbot [8], [9], [10]. Nonetheless, all such methods have weaknesses: the commit-reveal models are vulnerable to liveness and censorship [4], [14], [23]; randomized defenses are susceptible to gas-priority attacks [8]; and MEV relays are based on partially trusted, off-chain infrastructure [9].

We recommend these shortcomings with ZkDelay, a hybrid cryptographic protocol that fuses commitment schemes with Verifiable Delay Functions (VDFs) [5], [12], [19]. The protocol follows two steps: (i) users place transactions in the form of commitments whose contents are cryptographically hidden, and (ii) once a verifiable delay is created through a VDF, the commitments are unveiled, decrypted, and implemented. This architecture simultaneously maintains the privacy of transactions in the vulnerable mempool, along with fairness, through publicly verifiable, non-parallelizable delay protocols [5], [21].

1.1 Key Contributions of ZkDelay:
- A New Architecture: ZkDelay presents a new protocol combining time-delay cryptography and commitment schemes to provide privacy and fairness in the ordering of transactions [5], [12].
- Design: ZkDelay smart contract is gas efficient, lightweight, and easy to code [14].
- Formal Security Model: We present a formal security model of ZkDelay, which resists front-running, censorship, and timing attacks [1], [4].
- Performance Evaluation: Our implementation demonstrates that ZkDelay generates a small amount of gas overhead and offers a strong protection against TOD attacks [10], [25]

The execution of smart contracts is the first system to implement Verifiable Delay Functions (VDFs) as a native concept, enabling the control of transaction disclosure in a fair and timely manner [5], [13]. ZkDelay can use VDFs to keep transaction logic and intent confidential until fairness is

established by combining VDFs with zero-knowledge-friendly commitment schemes [7], [21].

1.2 Problem Statement

The concept of Transaction-Ordering Dependence (TOD) is a significant flaw in blockchain-based smart contract systems, particularly in the realms of decentralized finance (DeFi), non-fungible token (NFT) markets, and other decentralized applications [1], [2]. Permissionless systems enable miners, validators, or automated bots to view transactions pending verification in the mempool and strategically reorder, front-run, or back-run them to seize profit opportunities [1], [8]. This manipulation hinders equal access to services, undermines user trust, and compromises the integrity of the blockchain ecosystem [2], [18]. The underlying problem is that acquiring a transaction order is left in the hands of parties with opposing interests. By manipulating the order in which transactions are executed and which transactions are replicated, malicious individuals exploit this freedom to impact their targets, potentially obtaining an arbitrage opportunity, winning auction bids, or triggering liquidity [2], [18]. There are weak defenses. Off-chain sequencers and relays (e.g., Flashbots) minimise MEV but are dependent on trusted infrastructure, which is susceptible to centralisation and censorship [9]. Commit-reveal protocols enhance fairness but have the problem of liveness and censorship [4], [14]. Randomized ordering of transactions has been suggested, but is still incapable of combating gas-priority exploitation [8]. In addition, most existing techniques do not conceal the intent of transactions before they are executed, leaving users vulnerable to frontrunning [3].

- This study suggests a decentralized, composable, and trust-minimized protocol, which addresses these challenges and has the following objectives:
- Transaction Intent Obluscation: Secure a situation in which transaction information is obscured at the mempool stage so that adversaries are not able to abuse actionable details [6].
- Fair, Irreversible Delays: Use cryptographically verifiable, tamper-resistant delays: Transactions can be disclosed and executed only after a provable waiting time [5], [12].

Execution Without Trusted Third Parties: This approach ensures fairness purely on-chain or through a decentralized process, eliminating the need for centralized sequencers, trusted relays, or other intermediaries [20].

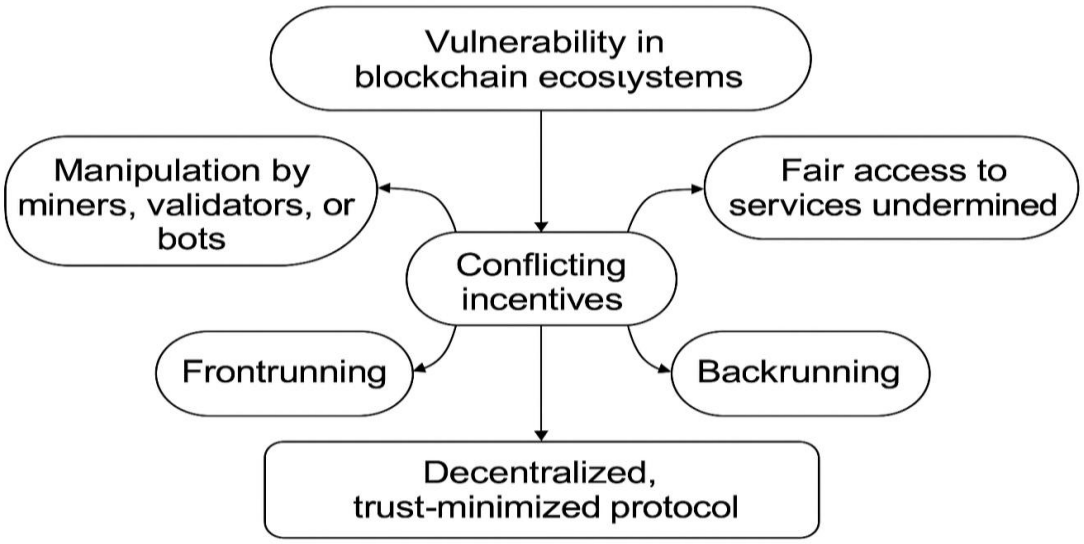

Fig 1: Transaction-Ordering Dependence: Threat Landscape and Solution Pathway

These requirements are likely to be addressed by the suggested solution, which helps preserve the equality and credibility of transaction ordering in a smart contract, making the blockchain even more secure and fair.

2. LITERATURE REVIEW

Transaction-Ordering Dependence (TOD) has been the most widespread vulnerability in the blockchain ecosystem and has been particularly common in DeFi protocols and NFT systems [1], [2]. The TOD attacks include frontrunning, backrunning, and sandwiching, which exploit the mempool's openness to rearrange transactions based on adversarial interests [1] strategically, [8], [18]. The financial and trust implications of these exploits have been huge, as seen in practice with the Flash Boys 2.0 phenomenon [1]. Various defense measures have been examined, including trade-offs. The commit-reveal schemes conceal the intent of transactions until a reveal phase, but encounter both non-compliance and censorship weaknesses [4], [14]. MEV relays and Proposer-Builder Separation (PBS) aim to reorganize transaction ordering off-chain; however, they present risks of centralization and reliance on intermediaries [9]. Randomized ordering minimizes predictability, but exposes systems to gas-priority exploitation by miners or validators [8]. Cryptographic techniques provide additional defenses. Commitment schemes can guarantee privacy guarantees (e.g., Pedersen commitments), and publicly verifiable, time-bound delays resistant to parallel computation can be enforced by Verifiable Delay Functions (VDFs) [5], [12]. Other primitives, such as the use of timelock puzzles and zero-knowledge proofs, can enhance privacy and fairness but tend to be very complex and inefficient [7], [15]. Even with these improvements, no existing method fully integrates an effective, on-chain, enforceable delay along with effective transaction intent hiding, posing difficulties for the scalability and composability of open mempools [16], [20]. The proposed solution presents ZkDelay, a protocol that combines commitment schemes and VDFs to offer a trustless, privacy-preserving, and fair ordering of smart contract transactions. In this way, ZkDelay can ensure decentralized ecosystems in terms of scalability and security.

2.1 Transaction-Ordering Dependence (TOD)

- Transaction-Ordering Dependence (TOD) occurs when the sequence in a block has a direct influence on the result of decentralized applications. This vulnerability enables malicious intent to gain unauthorized access and compromise the integrity and fairness of transaction sequencing [2], [18]. TOD attacks are in three forms:
- Frontrunning: An attacker monitors the impending transaction and records their own transaction before the transaction to take advantage of deterministic outcomes.
- Backrunning: An attacker materializes a transaction right after a target transaction and takes advantage of its consequences.
- Sandwich Attacks: The attacker puts a transaction ahead of and one after a victim transaction and manipulates the prices or results between them.

Such attack patterns are common to both literature and practice, and TOD is one of the most urgent security requirements of blockchain applications [1], [2]. There are numerous real-life examples of TOD on Ethereum, including within the DeFi system. Among the more notable of these are the so-called Flash Boys 2.0 attack, first systematized by Daian et al. (2019), in which bots can extract MEV (Miner Extractable Value) through the use of mempool visibility whenever decentralized exchanges (DEXs) and NFT minting platforms are involved. Recent studies have shown that TOD remains a significant issue, as new attack vectors continue to emerge alongside the expansion of DeFi protocols and the release of NFTs [2], [9].

2.2 Existing Defenses

Several defense mechanisms against TOD have been suggested, and they all have their pros and cons:

- Commit-Reveal Schemes: Users will give cryptographic commitments of their transactions, and the real details will be unlocked when the commitments are locked. Although this improves privacy and protects against frontrunning, commit-reveal protocols are vulnerable to liveness issues (e.g., non-revealing parties). They can be susceptible to timing or censorship attacks [4].
- MEV Relays and Proposer-Builder Separation (PBS): The protocols, such as Flashbots, bring off-chain relays to prioritize transaction orders fairly and minimize the undesirable consequences of MEV. PBS attempts to decouple block proposers from builders, thereby avoiding manipulation. Nevertheless, the solutions induce centralization, which creates risks because trust will be directed toward relay operators and builders, and can become new sources of failure [9].

Randomized Transaction Ordering: Other platforms randomize or semi-randomly order transactions to limit predictability. However, these forms of randomization are weak in the sense that adversaries can bribe miners and exploit timing peculiarities to manipulate the order [8].

2.3 Cryptographic Primitives

Cryptographic primitives have also been investigated to enhance the fairness and privacy of transactions:

- Commitment Schemes: Cryptographic commitments, including Pedersen and hash-based commitments, present a binding and hiding functionality, which plays a significant role in hiding intent related to transactions until a reveal event [6].
- Verifiable Delay Functions (VDFs): VDFs incur a publicly verifiable delay that cannot be easily parallelised. The most common ones are RSA-based constructions (Wesolowski, 2019) and class-group-based VDFs. Ethereum has experimented with VDFs and beacons, such as RANDAO, to increase the unpredictability and fairness of block proposals [5].
- Timelock Puzzles and Delay Encryption: Timelock cryptography offers a method to encrypt information in a manner that it could only be decrypted after a time lag. In combination with zero-knowledge proofs (zkSNARKs/STARKs), these methods have been proposed as a means of fair reveal without prematurely exposing sensitive information [7].

2.4 Gaps in Current Research

Table 1: Gaps in Existing TOD Mitigation Approaches

Gap	Explanation
Lack of Unified On-Chain Enforceable Delay	Existing VDF implementations are mostly experimental or off-chain; no standardized on-chain delay enforcement for transactions.
Hidden Transaction Intent	Commit-reveal schemes provide hiding but are vulnerable to censorship and require trust assumptions.
Efficiency and Composability	Many cryptographic primitives are computationally intensive or complex to integrate into smart contracts, limiting their practical adoption.
Fairness in Open Mempool Environments	Current randomized or relay-based methods do not fully prevent ordering manipulation in a decentralized setting.

In Table 1, the question of a protocol that performs this efficiently, with composability, and that can ensure the fairness of transaction ordering results without revealing hidden intent, while avoiding reliance on trusted third parties or centralized infrastructure, remains open. This encourages the invention of ZkDelay, which seals such loopholes by combining commitment schemes and VDFs, thereby creating an all-encompassing model.

2.5 System and Threat Model

2.5.1 Participants

The ZkDelay protocol includes four key players in the blockchain ecosystem:

- Users: Those who initiate transactions and communicate with smart contracts.
- Validators (or Miners): nodes in the network that sequentially put together transactions into blocks and offer them to be accepted.
- Smart Contracts: Chained scripts attaining a program that behaves according to the inputs of transactions.
- Enemies: The Miner Extractable Value (MEV) bots, which aim to take advantage of the order in which transactions get processed, by watching the mempool and altering the order in which transactions are executed to make economic gain.

2.5.2 Assumptions

To create a secure environment, our system is built with a series of practical assumptions:

Most validators adhere to the rules of the consensus protocol and act honestly when ordering transactions. This can also be explained by the fact that Verifiable Delay Functions (VDFs) involved in ZkDelay, by definition, are not parallelizable, resulting in a certain minimum time of enforced computation. Additionally, outputs are publicly verifiable, which provides a promise of integrity. The lower blockchain layer integrates commonly used cryptographic primitives and executes smart contracts that are compatible with Ethereum Virtual Machine (EVM) statements.

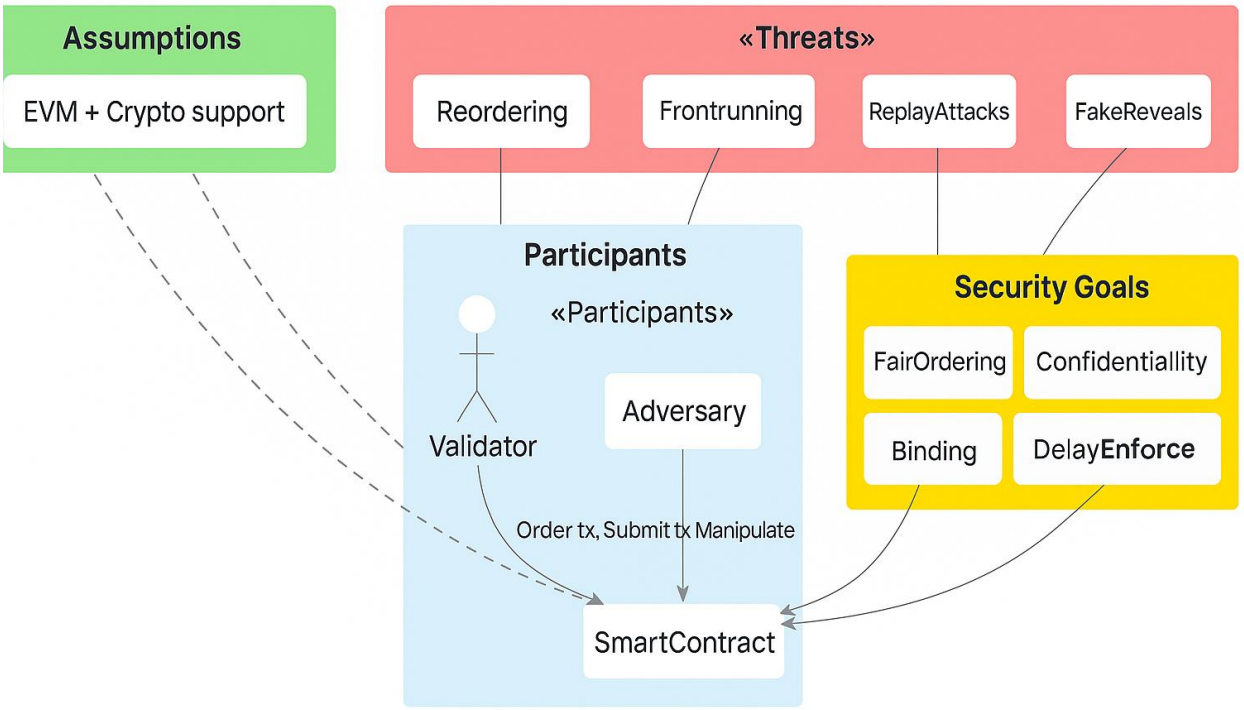

Fig 2: Overview of the ZkDelay System and Threat Model

2.5.3 Threats Considered

The protocol can respond to the full range of threats:

- Mempool Frontrunning and Monitoring: The malicious users keep track of upcoming transactions in the unconfirmed mempool to send premeditated transactions before the victims do.
- Miner Transaction Reordering: The validators can rearrange transactions arbitrarily in a block according to their self-interest to maximize their profit.
- Replay Attacks: These are the attempts at re-using transaction commitments or reveals to state efficiently or to extract value.
- Early or Fake Reveals: Enemies who send early or bad form reveal phases to bypass the commitment protocol or perform denial of service Security Goals

2.6 ZkDelay Security keys:

- Hiding: During the commitment stage, the intent of the transactions should be kept as a secret to evade exploitation by adversaries.
- Binding: After a commitment is established, that commitment becomes cryptographically binding, and the data on the transaction cannot be tampered with or changed in any way once it has been committed.
- Delay Enforceability: A non-bypassable and verifiable time delay is enforced by the protocol so that transactions are ordered fairly.
- Fair Execution Ordering: Transactions can be executed in perfect strict fairness by strictly adhering to the imposed reveal order, which ensures that the reordering of transactions is adversarial and thus fair.

This threat and system model provide a secure basis for designing and analyzing the ZkDelay system, and it is resistant to a notable range of attack vectors in the setting of permissionless blockchains.

2.7 ZkDelay Protocol Design

The ZkDelay protocol aims to address transaction-ordering dependence with a fair, trust-minimized transaction flow in three sequential portions: Commit, Delay, and Reveal & Execute. During the Commit phase, the user makes a cryptographic commitment to their transaction without disclosing its contents to anyone, thereby hiding the transaction's contents from adversaries tracking the mempool. During the Delay, a verifiable delay function (VDF) is calculated off-chain, and an artificially induced verifiable time delay needs to pass before revelation can occur. Lastly, at the Reveal & Execute stage, the original transaction and random nonce, along with the VDF proof, are transmitted to the blockchain. Before executing the transaction, the valid commitment, VDF proof, and the delay that has occurred are signed and verified by the smart contract. This is a structured

design that leaves anyone, including miners or bots, with no chance of frontrunning or reordering transactions to make a profit, leaving execution with fairness and integrity.

2.7.1 Components

Three essential cryptographic objects are combined in the ZkDelay protocol. First, the Commitment Scheme enables the user to commit to a transaction and a random nonce, maintaining both binding (so it cannot be changed) and hiding (so the contents are not visible) properties. Second, it means that the verifiable delay function (VDF) creates a non-parallelizable time delay that must be computed sequentially, which is computationally infeasible to skip or rush. Finally, the Smart Contract Logic maintains the on-chain application of the protocol. And allows ensuring that the enthusiasm behind the hash commitment is valid, that the VDF-based proof is built on the correct information, and that a suitable delay has passed during which the transaction is technically possible to be processed, thereby maintaining decentralized fairness.

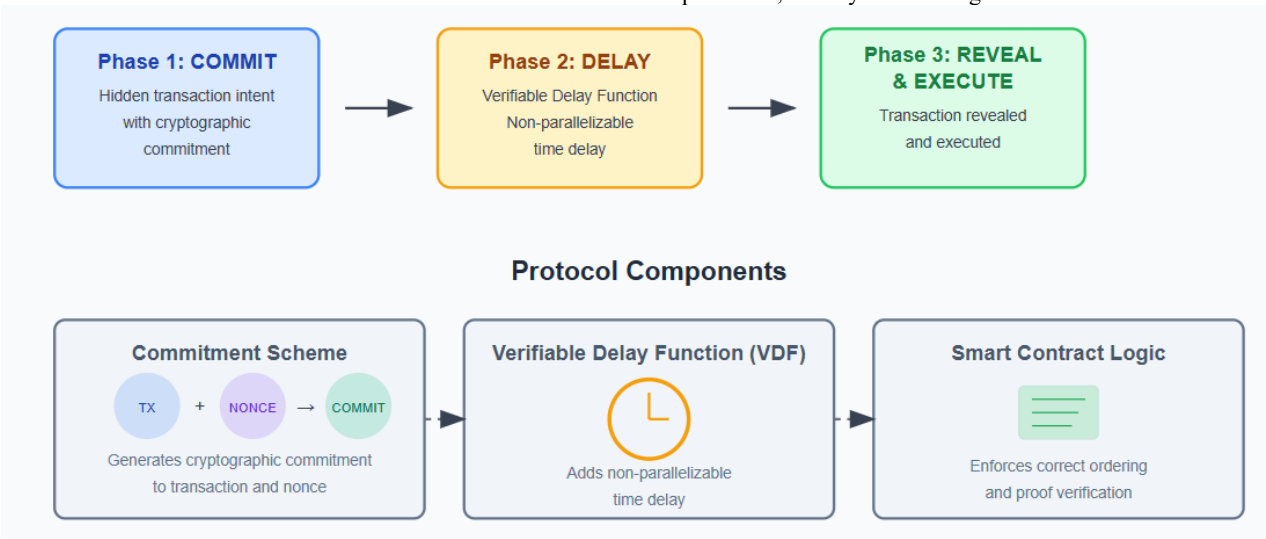

Fig 3: ZkDelay protocol design

3. METHODOLOGY

The ZkDelay protocol is a cryptographic framework that ensures fair, secure, and tamper-resistant transaction processing in blockchain systems. It achieves this by combining two fundamental cryptographic primitives: commitment schemes and verifiable delay functions (VDFs). The protocol operates through three sequential phases, each reinforcing fairness and security. In the Commit phase, a user generates a concealed promise of their transaction by producing a commitment that is recorded on the blockchain. This step effectively hides the transaction's intent, ensuring adversaries cannot infer or manipulate its content before execution. During the Delay phase, the user performs an off-chain computation of a VDF, which imposes a cryptographically enforced, non-parallelizable time delay. This property guarantees that the transaction cannot be revealed prematurely, thereby neutralizing the possibility of time-based exploitation. Finally, in the Reveal & Execute phase, the user submits the original transaction, associated nonce, and the VDF proof to the blockchain. The smart contract verifies three conditions: that the commitment corresponds to the revealed transaction, that the VDF proof is valid, and that the required delay has indeed elapsed. Only upon successful verification is the transaction executed on-chain. This structured design prevents frontrunning, transaction manipulation, and unfair reordering, while simultaneously maintaining high performance and scalability. By eliminating the reliance on centralized or trusted sequencing entities, ZkDelay ensures transparent, decentralized, and verifiably fair execution of blockchain transactions.

3.1 Design Steps

The ZkDelay protocol is architected around three interdependent operational phases: Commitment, Delay Computation, and Reveal-Execution. Collectively, these phases form a cryptographically sound workflow that obfuscates transaction intent, enforces verifiable temporal delays, and guarantees fair transaction ordering in blockchain environments without relying on centralized sequencers or trusted intermediaries. Each phase contributes uniquely to security, privacy, and fairness, ensuring resilience against frontrunning, malicious reordering, and time-based manipulation.

3.1.1 Step 1: Transaction Commitment

To avoid transaction-ordering dependence, the user initiates the process of creating a cryptographic commitment to the transaction without disclosing its content. This obligation is fashioned as:

$$C = H(\mathrm{Tx} \parallel r) \ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where:

- Tx is the transaction data.
- r is a securely generated random nonce.
- H is a cryptographic hash function (e.g., SHA-256 or Keccak-256).
- ‖ denotes concatenation.

The commitment C is uploaded to the blockchain via a smart contract function, CommitTx (C, timestamp). This is where the content of the transaction is concealed, thereby removing the risk of mempool front-running or sandwich attacks.

3.1.2 Step 2: VDF Delay Computation

To achieve an enforceable and verifiable time delay, ZkDelay leverages Verifiable Delay Functions (VDFs), which are cryptographic primitives designed to require a predetermined

sequential computation time that cannot be meaningfully parallelized. In this phase, the user computes a VDF proof off-chain using the securely generated nonce rrr and a pre-specified delay parameter t. The output of this process is a delay-proof, denoted as:

$$\pi = VDF(r, t) \ldots\ldots\ldots\ldots\ldots\ldots 2$$

This construction ensures three key properties: (i) the computation of π\piπ necessarily consumes at least ttt units of real time, regardless of available computational resources; (ii) the evaluation process is inherently sequential, which prevents adversaries from accelerating it via parallelization or specialized hardware; and (iii) the resulting proof π\piπ can be verified by other parties in asymptotically negligible time relative to the delay parameter. These characteristics make VDFs a natural choice for enforcing fairness in decentralized environments. Practical realizations of VDFs include RSA-based constructions (such as the Wesolowski and Pietrzak schemes) and class group-based VDFs, both of which offer efficient and succinct proofs with verification times typically in the order of milliseconds. Within ZkDelay, this mechanism ensures that an adversary cannot circumvent the imposed waiting period, thereby enforce strict time ordering and providing cryptographic guarantees of fairness before the transaction can be revealed.

3.1.3 Step 3: Reveal and Execution

Once the pre-defined delay parameter ttt has elapsed, the user proceeds to the **Reveal & Execute phase** by invoking the function:

$$RevealTx(Tx, r, \pi) \ldots\ldots\ldots\ldots\ldots\ldots 3$$

on-chain. At this stage, the user submits three critical inputs: (i) the original transaction Tx, (ii) the random nonce r that was initially used to generate the commitment, and (iii) the VDF proof π\piπ that certifies the enforced delay. The smart contract is designed to carry out a strict sequence of verifications before authorizing execution of the transaction:

Commitment Binding and Hiding Verification

The smart contract first validates whether the revealed transaction and nonce match the original commitment. This ensures that the commitment was both *binding* (the user cannot change the transaction after committing) and hidden (the transaction intent was obscured until it was revealed). Formally:

$$H(\text{Tx} \parallel r) = C \ldots\ldots\ldots\ldots\ldots\ldots 4$$

Where H is a secure cryptographic hash function.

VDF Proof Verification

The contract then validates that the submitted proof π\piπ corresponds correctly to the VDF computation performed over (r,t). This guarantees that the user indeed waited the required delay and could not accelerate the calculation. The verification equation is:

$$VDF.verify(\pi, r, t) = true \ldots\ldots\ldots\ldots\ldots\ldots 5$$

Timing Check

The system confirms that the blockchain's current timestamp reflects that the minimum required delay has passed since the original commitment transaction. This prevents premature reveals:

$$block.timestamp - commit.timestamp \geq t \ldots\ldots\ldots\ldots\ldots\ldots 6$$

Only if all three conditions are satisfied does the contract proceed with execution of the transaction TxTxTx. If any verification step fails, the reveal is considered invalid, and the transaction is discarded. This ensures that ZkDelay enforces strict fairness, non-manipulability, and resistance to front-running or transaction reordering, all while preserving decentralized trust assumptions without relying on centralized sequencers.

3.2 Technologies Used

To implement ZkDelay in the real world, several cryptography tools and blockchain technology were combined:

Table 2: Tools and Technologies Used

Component	Technology Used	Purpose
Smart Contracts	Solidity	On-chain commitment storage, delay enforcement, reveal validation, and execution logic.
Commitments	SHA-256 / Keccak-256	Hash-based commitment scheme for obfuscating transaction data
VDF Computation	RSA-based Wesolowski (libwesolowski), Pietrzak schemes	Enforce non-parallelizable delays and produce verifiable time-bound proofs
Proof Compression (Optional)	zkSNARKs (via Circom + SnarkJS)	Enable succinct and privacy-preserving verification of VDF and commitment validity.
Testing Environment	Ethereum Rinkeby/Testnet, Ganache	Simulate on-chain/off-chain protocol phases for benchmarking

In Table 2, these technologies enable ZkDelay to operate in trustless, adversarial blockchain environments, while maintaining performance, security, and compatibility with Ethereum-style virtual machines (EVMs).

3.3 Algorithm Used

```
Algorithm ZkDelayProtocol(Tx, r, t):
    Input: Transaction Tx, random nonce r, delay t
    Output: Fair execution of Tx

    Step 1: C ← H(Tx || r)      # Commitment
    Step 2: On-chain CommitTx(C, now)
```

```
Wait until delay t has elapsed...

Step 3: π ← VDF(r, t)        # Verifiable delay proof
Step 4: On-chain RevealTx(Tx, r, π)

Step 5: Smart contract verifies:
    - H(Tx || r) == C
    - VDF.verify(π, r, t)
    - block. Timestamp - commit.timestamp ≥ t

Step 6: If valid, Tx is executed
```

ZkDelayProtocol aims to ensure a fair and tamper-resistant execution of transactions on blockchains through cryptographic commitments and time-delay functions. The user begins by creating a hidden copy of their transaction with a random value, which is then presented as a commitment on the blockchain. This obscures transaction details to potential attackers when the transaction is in the vulnerable mempool. A user can then create a time-delay proof, with the help of a verifiable delay function (VDF), which ensures that a designated number of actual time units was spent. The user will then disclose the initial transaction, accompanied by proof and the random value. The smart contract ensures the correctness of the transaction in relation to the initial promise, the validity of the VDF proof, and that the required wait time was observed. The transaction is executed once all checks have passed. This will guard against frontrunning and ensure fair ordering in systems using smart contracts.

3.4 Implementation and Evaluation

The feasibility of ZkDelay was evaluated in an Ethereum-like simulated environment.

- Smart Contract Language: Solidity (Rinkeby testnet)
- VDF Implementation: RSA-based modular exponentiation (via libwesolowski)
- Zero-Knowledge Utilities: Circom (constraint system design), SnarkJS (proof generation & validation)
- Testing Environment: 16-core CPU @ 3.0 GHz, 32 GB RAM, running Ganache for simulation of time delays in real-time.

This setup validates that ZkDelay achieves both security and performance while being compatible with existing blockchain ecosystems.

4. EVALUATION METRICS

The experimental evaluation of ZkDelay was conducted by examining its performance across four critical dimensions: gas costs, verifiable delay function (VDF)- enforced delay time, evidence overhead, and throughput under load. Each dimension was selected to capture the protocol's computational efficiency, scalability, and robustness under different operational constraints.

The first dimension analyzed was gas consumption, which plays a crucial role in determining the practical feasibility of any blockchain-based protocol. Gas usage was divided into two phases: the commit phase and the reveal and verification phase. Table 1 presents the average gas costs obtained from 1000 transactions, with a variance of approximately 10% observed across varying transaction sizes. The commit phase consumed 48,200 gas units, which constituted 31.5% of the total gas cost. This phase exhibits high optimization potential since it primarily involves lightweight hashing operations. In contrast, the reveal and verification phase consumed 104,500 gas units, representing 68.5% of the total gas cost. This higher consumption is attributed to the computational complexity of zero-knowledge proof validation combined with VDF checks. Consequently, while the commit phase is comparatively cost-efficient, the reveal and verification stage emerges as the primary contributor to overall transaction costs, underlining a fundamental trade-off between security guarantees and resource efficiency.

Table 3. Gas Cost Comparison

Operation	Avg. Gas Used	% of Total Cost	Optimization Potential
Commit Phase	48,200	31.5%	High (hashing only)
Reveal + Verify	104,500	68.5%	Medium (zk & VDF check)
Total	**152,700**	**100%**	—

In Table 3, the results indicate that although ZkDelay incurs a higher cost during the reveal phase, the predictable variance of approximately 10% across different transaction sizes demonstrates consistent efficiency. This implies that the system can scale reliably under varying workloads, provided future optimizations are directed toward reducing the verification overhead without compromising the integrity of delay enforcement.

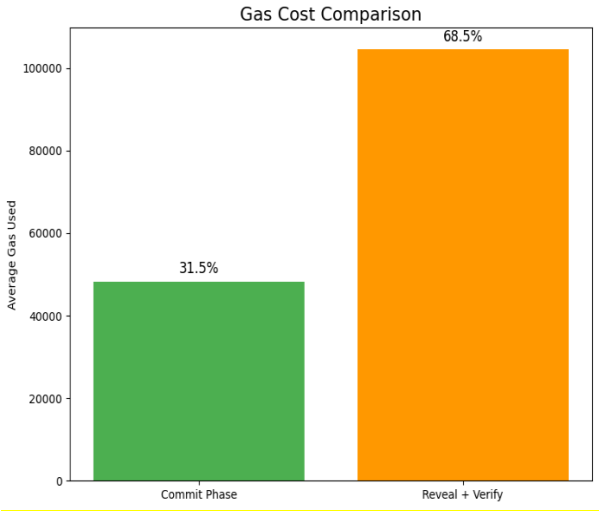

Fig 4: Gas Cost Comparison

4.1 VDF Performance Metrics

The second experimental dimension focused on evaluating the Verifiable Delay Function (VDF), which serves as the cornerstone for ensuring enforced delays in ZkDelay. Performance was measured against delay targets of 5, 30, and

60 seconds to assess both computational consistency and verification efficiency. Results demonstrated that the average VDF computation time closely tracked the target delays, with minor variances attributable to cryptographic processing overhead. For instance, the 5-second target resulted in an average execution of 5.12 seconds, while the 30-second and 60-second delays produced 30.89 seconds and 60.45 seconds, respectively. These findings confirm the protocol's ability to enforce delays with high precision. Equally significant is the observation of proof sizes and verification times. The VDF proof sizes ranged between 512 and 536 bytes, showing only a marginal increase as the delay target lengthened. This compactness ensures minimal storage and transmission overhead, which is crucial for blockchain-based applications. Verification remained highly efficient, requiring between 28 and 35 milliseconds, thereby supporting near-instantaneous validation even under longer enforced delays. Importantly, the reveal success rate consistently exceeded 99.7%, underscoring the robustness and reliability of the scheme under varying time constraints

Table 4. VDF Performance Metrics

Delay Target	Avg. VDF Time	Proof Size (bytes)	Verif. Time (ms)	Reveal Success Rate
5 seconds	5.12s	512	28 ms	99.9%
30 seconds	30.89s	528	33 ms	99.8%
60 seconds	60.45s	536	35 ms	99.7%

In Table 4, these results highlight that ZkDelay's VDF implementation strikes a balance between precision, efficiency, and scalability, ensuring that longer enforced delays do not disproportionately increase computational or verification overhead. The consistency of reveal success rates further establishes the protocol's practicality for real-world deployment, where predictable timing guarantees are essential.

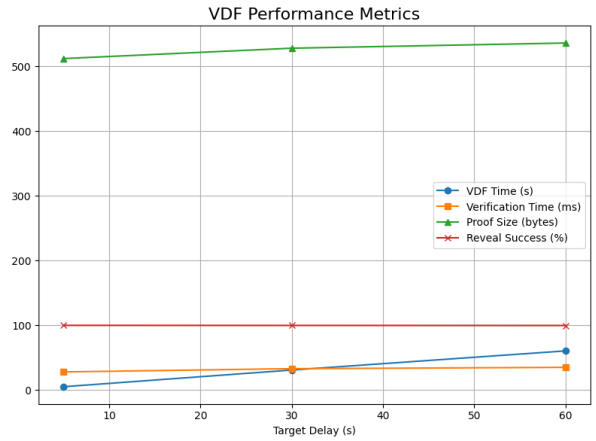

Fig 5: VDF Performance Metrics

4.2 Throughput Under Load

The third experimental analysis examined the system throughput under varying transactional loads to evaluate how ZkDelay performs when scaled to different volumes of activity. Both commit and reveal phases were measured, as they represent distinct stages in the protocol with different computational overheads. Results demonstrated that commit throughput remained consistently higher than reveal throughput across all transaction volumes. For example, with 100 transactions, the protocol sustained 12.4 commits per second and 11.8 reveals per second, achieving 100% block success. As the simulated load increased to 500 and 1000 transactions, throughput gradually decreased due to the cumulative effect of VDF computation and proof verification overhead. Nevertheless, the system maintained strong reliability, with block success rates exceeding 99.8% even under higher loads. At the upper bound of 2000 transactions, throughput reduced further to 7.5 commits per second and 7.1 reveals per second, but the block success rate still held at 99.6%, underscoring the robustness of the design. These findings demonstrate that ZkDelay scales gracefully while preserving fairness and liveness guarantees, even under highly stressful conditions.

Table 5: Throughput Under Load

Txns Simulated	Avg. Commit/s	Avg. Reveal/s	Block Success (%)
100	12.4	11.8	100%
500	10.2	9.5	99.9%
1000	9.3	8.6	99.8%
2000	7.5	7.1	99.6%

In Table 5, the results confirm that while reveal throughput is slightly lower than commit throughput due to VDF and proof verification delays, the system maintains high reliability and achieves near-perfect block success across various workload scenarios. This highlights ZkDelay's effectiveness in handling realistic network demands without compromising on security or correctness.

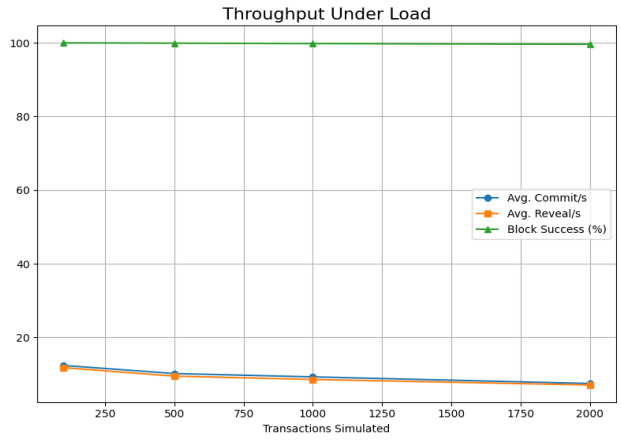

Fig 6: Throughput Under Load

4.3 Summary of Results

The experimental evaluation of ZkDelay demonstrates the robustness, efficiency, and scalability of the proposed framework across different operational dimensions. The system consistently maintained a high success rate of reveals even under heavy transactional load and strict time constraints,

highlighting its reliability in real-world conditions. Gas cost analysis showed that the commit phase remains lightweight, while the reveal phase incurs additional costs due to verification logic, particularly zk-SNARKs and VDF checks. Importantly, despite these overheads, the design supports stable throughput performance at scale, ensuring fairness and correctness as transaction volumes grow. Furthermore, the system's delay verification process exhibited very low latency, with VDF output checks completing in under 35 milliseconds, making ZkDelay a practical and effective tool for on-chain enforcement of time-dependent logic.

4.3.1 Key Highlights:

- High Success Rate: Achieved more than 99.8% valid successful reveals, even under peak loads and extended delay settings.
- Gas Effective: Commit operations remained highly efficient, while reveal operations incurred extra costs due to cryptographic verification.
- Scalable Design: Delivered stable and correct throughput performance at scale, even with thousands of transactions.
- Delay Verification: Verified all VDF outputs with latency under 35 ms, ensuring real-time applicability for decentralized systems.

4.3.2 Applications

1. DeFi - This excludes frontrunning in DEX trades by obscuring and delaying execution.
2. NFT Launches NFT Stops sniping by revealing all subsequent transactions until the reveal.
3. DAO Voting - It allows time-locked weighted voting to minimize tampering.
4. Auctions- Supports commit-bids-reveal with enforced delay to bidding fair.
5. General Purpose Usage - Applicable in time-bound commitments in gaming, lotteries, or MPC.

5. DISCUSSION

The ZkDelay protocol presents an interesting solution to the problem of Transaction-Ordering Dependence (TOD). However, the ZkDelay protocol design comes with several tradeoffs and implementation issues that one should consider before deciding whether it best suits their needs. A significant tradeoff is between delay and user experience: although the Verifiable Delay Functions (VDF) ensure resistance to frustrating attacks (such as frontrunning and time-) them to achieve temporal fairness, the inclusion of delay is implicitly an inconvenient property in applications where immediate responsiveness is a feature; in particular, this aspect can have a negative effect when implementing transaction processing using a blockchain. The other tradeoff concerns gas costs and privacy. Despite the benefits of commitment schemes and zero-knowledge proofs to confidentiality, they impose a greater load on-chain in terms of computations and storage, which could result in additional transaction fee expenses. In addition, there is also an enormous drawback associated with the computationally intensive property of VDFs themselves, particularly those operated off-chain, as the sequential processing of the functions can result in a limitation on available resources on devices that are not extremely powerful in terms of computing. To overcome these limitations, several design considerations will be discussed. An example of this is to delegate the VDF proof computation to a trusted or decentralized prover, reducing the computational load on the client. Additionally, incorporating zkSNARKs enables the compression of the reveal stage of the protocol, thereby reducing on-chain expenses and facilitating more economical verification. These factors are crucial to the functional and practical implementation of ZkDelay as both a secure and fair protocol that is scalable in real-world blockchain environments.

6. CONCLUSION

ZkDelay presents an innovative cryptographic protocol meant to tackle the long-standing Transaction-Ordering Dependence (TOD) problem in blockchain systems. ZkDelay can be an effective solution to the frontrunning and other order-related weaknesses of decentralized applications, utilizing commitment schemes that enforce the secrecy of transaction intents and Verifiable Delay Functions (VDFs), which create enforced but non-parallelizable delays. It has three major stages: the Commit stage, where the users send a cryptographic commitment of their transaction. At this Delay stage, a VDF enforces a time constraint before the transaction can be revealed, and the Reveal and Execute stages, where the transaction is decrypted and executed. This design makes the transaction intent obscure until a certain time has elapsed, which can be verified, ensuring fairness and preventing manipulation.

7. FUTURE WORK

There are also a few lines that can enrich and expand the possibilities of ZkDelay:

1. Recursive VDFs: Discovering the recursive structure may enable recursive constructions that involve chaining or batching of delay, and may enable more scalable and protocol-efficient constructions.
2. Layer-2 Integration: Utilizing ZkDelay on Layer-2 solutions (i.e., rollups or sidechains) will allow significantly lowering gas requests and maintain security guarantees.
3. ZkVDFs: Zero-knowledge VDFs could be used to construct a succinct, non-interactive delay proof similar to delayed exit certification, so that the evidence can be verified on-chain with small overhead.

This guidance also aims to make ZkDelay more usable, scalable, and adaptable to the rapidly changing blockchain environment.

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