F3B: A Low-Latency Commit-and-Reveal Architecture to Mitigate Blockchain Front-Running

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ABSTRACT
Front-running attacks, which benefit from advanced knowledge of pending transactions, have proliferated in the cryptocurrency space since the emergence of decentralized finance. Front-running causes devastating losses to honest participants—estimated at $280M each month—and endangers the fairness of the ecosystem. We present Flash Freezing Flash Boys (F3B), a blockchain architecture to address front-running attacks by relying on a commit-and-reveal scheme where the contents of transactions are encrypted and later revealed by a decentralized secret-management committee once the underlying consensus layer has committed the transaction. F3B mitigates front-running attacks because an adversary can no longer read the content of a transaction before commitment, thus preventing the adversary from benefiting from advance knowledge of pending transactions. We design F3B to be agnostic to the underlying consensus algorithm and compatible with legacy smart contracts by addressing front-running at the blockchain architecture level. Unlike existing commit-and-reveal approaches, F3B only requires writing data onto the underlying blockchain once, establishing a significant overhead reduction. An exploration of F3B shows that with a secret-management committee consisting of 8 and 128 members, F3B presents between 0.1 and 1.8 seconds of transaction-processing latency, respectively.

KEYWORDS
security & privacy, decentralized finance, front-running

1 INTRODUCTION
Front-running is the practice of benefiting from advanced knowledge of pending transactions by entering into a financial position [1, 4, 16]. While benefiting some entities involved, this practice puts others at a significant financial disadvantage, leading regulators to judge this behavior as illegal (and unethical) in traditional markets [16].

Once a significant problem for traditional (centralized) markets addressed via regulations, front-running has now become a significant problem for decentralized finance (DeFi), given blockchain transactions’ openness and pseudonymous nature and the difficulties involved with pursuing miscreants across numerous jurisdictions [12, 16, 30]. Since transactions are transparent before commitment, adversaries can take advantage of the contents of those pending transactions for their own financial gain by, for example, creating their own transactions and positioning them in a specific sequence with respect to the targeted transaction [2, 12, 16].

Front-running negatively impacts all honest DeFi actors, but automated market makers (AMM) are particularly vulnerable due to price slippage [2], i.e., the difference between expected and executed prices. An estimate shows that front-running attacks amount to $280 million in losses for DeFi actors each month [33]. In addition, front-running attacks threaten the underlying consensus layer’s security by incentivizing unnecessary forks [12, 14].

While there are existing approaches to address front-running attacks, they are either inefficient or restricted to a specific application or consensus algorithm. Namecoin, an early example of using a commit-and-reveal approach to mitigate front-running attacks, requires two rounds of communication to the underlying blockchain [21]. Submarine further improves the commit-and-reveal approach by hiding the addresses of smart contracts involved, but induces three rounds of communication to the underlying blockchain [21, 31], bringing significant latency overhead. Other solutions focus on specific applications, e.g., FairMM only applies to the market-maker-based exchange [10]. Other approaches apply only to a specific consensus algorithm [42, 45].

We present Flash Freezing Flash Boys (F3B), a new blockchain architecture with front-running protection that exhibits low transaction-processing latency overhead while remaining legacy compatible with both the underlying consensus algorithm and smart contract implementations. F3B addresses front-running by adopting a commit-and-reveal design that involves encrypting transactions and revealing them after they are committed by the consensus group, as presented in Figure 1. By encrypting transactions, adversaries no longer have foreknowledge of the contents of transactions, hindering their ability to launch successful front-running attacks. While adversaries may launch speculative front-running attacks, where the adversary guesses the contents of the transaction based on side-channel information, these attacks have a greater chance of failure and may prove to be unprofitable [2].

F3B builds on Calypso [25], an architecture that enables on-chain secrets by introducing a secret-management committee (SMC) that reveals these on-chain secrets when designated. In our setup, the on-chain secrets are the encrypted transactions and the designated reveal period occurs when the consensus group irreversibly commits the transaction on the blockchain. Once a transaction is revealed, the consensus nodes can proceed with verifying and executing a transaction. At this point, it is too late for malicious actors to launch a front-running attack since the consensus group has already irreversibly ordered the transaction on the blockchain.

To achieve practical front-running protection, the F3B architecture must address several challenges: a) preventing a single point of failure or compromise in the decryption process, b) mitigating spamming of inexecutable encrypted transactions onto the underlying blockchain, and c) limiting latency overhead. To withstand.

1The name Flash Boys comes from a popular book revealing this aggressive market-exploiting strategy on Wall Street in 2014 [30].
In an ideal world, front-running protection would consist of an immediate global ordering of each transaction as they are created to prevent attackers from changing their order. In reality, such global ordering is practically impossible, even if all participants were honest due to clock synchronization issues [13] and consistency problems if two transactions have the exact same time. By including malicious participants, timings can naturally easily be manipulated. A more practical solution is to encrypt transactions such that the consensus group has no knowledge about transactions when ordering them. This solution mitigates front-running attacks, as an attacker cannot benefit from pending transactions if they are encrypted.
2.4 Automated Market Maker

AMM is a decentralized exchange built on liquidity pools—pools of assets provided by the exchange—rather than conventional order books. AMM allows any user to trade between different assets using the liquidity pool as the counterpart.

Consider an AMM’s liquidity pool holding two assets, \( r_1 \) and \( r_2 \), whose balances are \( R_1 \) and \( R_2 \), respectively. When using the constant product model, the total amount of \( r_1 R_2 \) remains constant when carrying out a trade between these two assets. The rule indicates that the larger the input \( \Delta r_1 \) of trade, the smaller the exchange rate between \( r_2 \) and \( r_1 \). We can intuitively reason that large transactions with respect to the size of the liquidity pool cause significant price slippage indicated by the difference between expected and executed prices.

By launching a sandwich attack, \( i.e., \) an attack consisting of one front-run and one back-run transaction with respect to the targeted transaction, front-running actors can then profit from this price slippage effect \([2]\). Fundamentally, the front-run transaction reduces the exchange rate, while the back-run transaction benefits from the improved exchange rate caused by the execution of the victim’s transaction.

To provide long-term orders, Paradigm introduces the notion of a scheduled AMM, allowing a trade not to be executed immediately but in the future at a particular block height \([15]\). Smart contracts, however, then store these scheduled AMM inputs, making it easier for an adversary to launch sandwich attacks.

A natural approach to hinder adversaries’ exploitation of front-running is to blind transaction inputs, such as to ensure the adversary does not know the direction of the exchange: \( r_1 \) to \( r_2 \) or \( r_2 \) to \( r_1 \). Nevertheless, these actors can still launch a speculative sandwich attack using side-channels, such as determining the sender’s balance for \( r_1 \) and \( r_2 \) and examining past transaction history, with increased difficulty and cost but remains profitable \([2]\).

A further improvement is to encrypt the entire transaction, not only transaction inputs, effectively hiding the smart contract address involved and rendering the speculative attack even harder since an attacker needs to first infer the smart contract’s address.

3 STRAWMAN PROTOCOLS

In order to explore the challenges inherent in building a framework like F3B, we first examine a couple of promising but inadequate strawman approaches, simplified from state-of-art front-running techniques \([8, 31]\).

3.1 Strawman I: Sender Commit-and-Reveal

The first strawman has the sender create two transactions: a commit and a reveal transaction. The reveal transaction contains the sensitive inputs that could give an adversary the necessary information to launch a front-running attack while the commit transaction namely contains a commitment (\( e.g. \) hash) of the reveal transaction to prove the sender’s intent to transact at a specific time without giving the sender the ability to change the contents of the reveal transaction. The sender will proceed with propagating the commit transaction and wait until it is included inside a block by the consensus group before releasing the reveal transaction. Once the reveal transaction is propagated, the consensus group can proceed to verify and execute the transaction in the execution order that the commit transaction was committed on the blockchain.

This simple strawman mitigates front-running attacks since the execution order is determined by the commit transaction and the contents of the commit transaction do not expose the contents of the reveal transaction but this strawman presents some notable challenges: a) the sender must continuously monitor the blockchain to determine when to reveal her transaction, b) the sender may not be able to reveal her transaction due to a cryptokitties storm or blockchain DoS attacks \([16]\), c) this approach is subject to output bias as consensus nodes, or sender may deliberately choose not to reveal certain transactions after commitment \([2]\), and d) this approach has a significant latency overhead of over 100% given that the sender must now send two transactions instead of one.

3.2 Strawman II: The Trusted Custodian

A straightforward method to remove the sender from the equation after sending the first commit transaction is by employing a trusted custodian. This commit transaction would then consist of the necessary information for the trusted custodian to reveal the transaction after the consensus group has committed the transaction on the underlying blockchain.

This strawman also mitigates front-running attacks as the nodes cannot read the content of the transaction before ordering but significantly improves upon the challenges presented in the previous strawman. However, the trusted custodian presents a single point of failure: consensus nodes cannot decrypt and execute a transaction if the custodian crashes. In addition, the trusted custodian represents a single point of compromise where the trusted custodian may secretly act maliciously, such as colluding with front-running actors for their own share of the profit. Instead, by employing a decentralized custodian, we can mitigate the single point of failure and compromise issue and significantly make collusion more difficult.

4 SYSTEM OVERVIEW

This section presents F3B’s system goals, architecture, and models.

4.1 System Goals

Our system goals inspired by our strawman protocols (§3) are:

- **Front-running protection**: Preventing entities from launching front-running attacks.
- **Decentralization**: Mitigating a single point of failure or compromise.
- **Confidentiality**: Revealing a transaction only after the underlying consensus layer commits it.
- **Compatibility**: Remaining agnostic to the underlying consensus algorithm and smart contract implementation.
- **Low latency overhead**: Exhibiting low latency transaction-processing overhead.

4.2 Architecture Overview

F3B, shown in Figure 1, mitigates front-running attacks by working with a secret-management committee to manage the storage and release of on-chain secrets. Instead of propagating their transactions in cleartext, the sender now encrypts their transactions and
stores the corresponding secret keys with the secret-management committee. Once the transaction is committed, the secret-management committee releases the secret keys so that consensus nodes of the underlying blockchain can verify and execute transactions. Overall, the state machine replication of the underlying blockchain is achieved in two steps: the first is about ordering transactions, and the second is about the execution of transactions. As long as the majority of trustees in the secret-management committee is secure and honest and the key is revealed to the public when appropriate, each consensus node can always maintain the same state.

Notably, F3B encrypts the entire transaction, not just inputs, as other information such as the smart contract address may provide enough information to launch a probabilistic front-running attack, such as the Fomo3D attack [16] or a speculative attack [2].

### 4.3 System and Network Model

F3B’s architecture consists of three components: senders that publish (encrypted) transactions, the secret-management committee that manages and releases secrets, and the consensus group that maintains the underlying blockchain. While F3B supports various consensus algorithms, such as PoW like Ethereum and PBFT-style consensus algorithms like ByzCoin [24], F3B does require a forked instance of the underlying blockchain to allow the consensus group to commit encrypted transactions and process them after revealing their contents. In a permissioned blockchain, the secret-management committee and the consensus nodes can consist of the same set of servers. For clarity, however, we discuss them as separate entities. In addition, we interchangeably use the name “Alice” to represent a generic sender. We assume that the membership of the secret-management committee is static, but we discuss group membership reconfiguration in §7.

For the underlying network, we assume that all honest blockchain nodes and trustees of the secret-management committee are well connected, that their communication channels are synchronous, i.e., if an honest node or trustee broadcasts a message, and that all honest nodes and trustees receive the message within a known maximum delay [37].

### 4.4 Threat Model

We assume that the adversary is computationally bounded, that cryptographic primitives we use are secure, and that the Diffie-Hellman problem is hard. We further assume that all messages are digitally signed, and the consensus nodes and the secret-management committee only process correctly signed messages.

The secret-management committee has n trustees, which f can fail or behave maliciously. We require $n \geq 2f + 1$ and set the secret-recovery threshold to $t = f + 1$. We assume that the underlying blockchain is secure: e.g., that at most $f''$ of $3f'' + 1$ consensus nodes fail or misbehave in a PBFT-style blockchain, or the adversary controls less than 50% computational power in a PoW blockchain like Bitcoin or Ethereum.

We assume that attackers do not launch speculative front-running attacks [2] but present a discussion on some mitigation strategies to reduce side channel leakage in §10.

### 4.5 Blockchain Layer Approach

We can categorize front-running mitigation approaches into two layers—the blockchain layer [8, 21, 31] and the application layer [10, 27, 34]. F3B is a systematic approach at the blockchain layer, exhibiting some fundamental trade-offs.

On the one hand, blockchain layer approaches a) offer protection to all smart contracts at once while an application layer approach would require protection individually [21, 31], b) have access to all transaction fields, ensuring that they can hide fields that are not accessible from the application layer (e.g., the smart contract address), and c) provide compatibility with existing smart contracts.

On the other hand, blockchain layer approaches a) cannot deal with front-running attacks that benefit from time-delayed transactions at the application layer (e.g., scheduled AMM) and b) require modification to the underlying blockchain (e.g., scheduled hard fork).

### 5 F3B PROTOCOL

We introduce the F3B’s protocol in this section, starting with preliminaries that offer necessary background knowledge and then presenting the full protocol that captures F3B’s detailed design.

#### 5.1 Preliminaries

This subsection outlines a few preliminary knowledge, such as the definition of transaction commitment and the cryptographic primitives used in F3B.

**Modeling the Underlying Blockchain.** To compare F3B’s impact, we model the underlying blockchain to involve a consensus protocol that commits transactions into a block linked to a previous block. We define the underlying’s block time as $t_b$ seconds, e.g., on average, Ethereum has a block time of 13 seconds [5]. For PBFT-style consensus algorithms, a transaction is committed once introduced into a block. For probabilistic consensus algorithms (e.g., PoW or PoS), a transaction is committed only after a certain number of
additional blocks have been added to the chain (also known as block confirmations²). We thus define that a transaction is committed after \( m \) block confirmations. Thereby, in our baseline, the transaction latency³ is \( mL_b \). For PBFT-style consensus, the required \( m \) is 1. Further, we assume that the underlying blockchain has a throughput of \( T_b \) tps.

**Shamir Secret Sharing.** A \((t, n)\)-threshold secret sharing scheme enables a dealer to share a secret \( s \) among \( n \) trustees such that any group of \( t \leq n \) or more trustees can reconstruct \( s \), but any group less than \( t \) trustees learn no information about \( s \). While a simple secret sharing scheme assumes an honest dealer, verifiable secret sharing (VSS) further improves VSS to allow a third party to check all shares [43]. Public verifiable secret sharing (PVSS) further improves VSS to a third party to check all shares [43].

**Distributed Key Generation (DKG).** DKG is a multi-party \((t, n)\) key-generation process to collectively generate a private-public key pair \((sk, pk)\) without relying on a single trusted dealer; each trustee \( i \) obtains a share \( sk_i \) of the secret key \( sk \) and collectively obtains a public key \( pk \) [18]. Any client can now use \( pk \) to encrypt a secret, and at least \( t \) trustees must cooperate to retrieve this secret [44].

### 5.2 Protocol Outline

#### 5.2.1 Setup

At each epoch, the secret-management committee runs a DKG protocol to generate a private key share \( s_{kmc}^t \) for each trustee and a collective public key \( p_{kmc} \). To offer chosen ciphertext attack protection and to verify the correctness of secret shares, we utilize the TDH2 cryptosystem containing NIZK proofs [44].

#### 5.2.2 Per-Transaction Protocol

We unpack the per-transaction protocol (Figure 2) as follows:

1. **Write Transaction:** Alice, as the sender, first generates a symmetric key \( k \) and encrypts it with \( p_{kmc} \), obtaining the resulting ciphertext \( c_k \). Next, Alice creates her transaction and symmetrically encrypts it using \( k \), denoted as \( enc_j(t_x) \). Finally, Alice sends \( (c_k, c_j) \) to the consensus group, who writes the pair onto the blockchain.

2. **Wait for confirmations:** The secret-management committee waits for Alice’s transaction \( (c_k, c_j) \) to be committed on the blockchain (after \( m \) block confirmations).

3. **Key Reconstruction:** Once committed, each secret-management committee trustee reads \( c_k \) from Alice’s transaction and releases their decrypted share of \( k \) along with a NIZK proof of correctness for the decryption process. Consensus nodes then verify the decrypted shares and use them to reconstruct \( k \) by Lagrange interpolation of shares when there are at least \( t \) valid shares. The consensus group finally symmetrically decrypts the transaction \( t_x = dec_k(c_k) \) using \( k \), allowing them to verify and execute \( t_x \). We denote the time for the entire key reconstruction step as \( L_r \).

### 5.3 Overhead Analysis

In the per-transaction protocol, (1) and (2) involve committing a transaction on the underlying blockchain and waiting until its committed, which takes \( mL_b \) time based on our baseline model (§5.1). Further, comparing our protocol with the baseline, (3) is an additional step, and we denote this overhead to be \( L_r \). The secret-management committee actor may cause bottlenecks with respect to the system’s throughput so we model the throughput of our proposed protocol as \( \min(T_b, T_{kmc}) \), assuming the secret-management committee’s throughput is \( T_{kmc} \).

Figure 3 demonstrates the conceptual difference in commitment and execution time between F3B and the baseline protocol. Since the secret-management committee releases the secret keys with a delay of \( m \) blocks, this introduces an execution delay of \( m \) blocks. However, for both PBFT-style consensus algorithms \( m = 1 \) and probabilistic consensus algorithms, the recipient should not accept a transaction until a transaction is committed for a variety of reasons, such as double-spending. This indicates that F3B on a commercial level is similar to the baseline protocol since it is the commitment time of a transaction that is of use to the recipient⁴.

### 5.4 Protocol

In this section, we present the in-depth F3B protocol. We define a cyclic group \( \mathbb{G} \) of prime order \( q \) with generators \( g \) and \( \bar{g} \) that are

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²For example, for Ethereum transactions, exchanges such as Kraken and Coinbase require 20 and 35 block confirmations before the funds are credited to users’ accounts [11, 26].

³For simplicity, we leave out the time for blockchain nodes to verify and execute transactions, and assume that a transaction propagates the network within one block time as to not contribute to transaction-processing latency.

⁴In F3B, transaction finalization is slower due to the key reconstruction and delayed execution after transaction commitment, but the overhead is insignificant compared with commitment time, as we discuss in §11.
known to all parties and define the following two hash functions: $H_1: \mathbb{G}^5 \times \{0, 1\}^1 \rightarrow \mathbb{G}$ and $H_2: \mathbb{G}^3 \rightarrow \mathbb{Z}_q$.

**Step 0: DKG Setup.** For a given epoch, the secret-management committee runs a DKG protocol to generate a shared public key $p_{skmc} = g^{skmc}$, and shares of the private key for each trustee denoted as $sk_i$. The corresponding private key $skmc$ can only be reconstructed by combining $t$ private key shares. All trustees also know the verification keys $H_i = g^{sk_i}$. We assume that $p_{skmc}$ and $H_i$ are written into the blockchain as metadata, e.g., in the first block denoting the start of this epoch. Given the rarity of this reconfiguration, we adopt the synchronous DKG protocol proposed by Gennaro et al. [18], using the underlying blockchain to emulate synchronous communication.

**Step 1: Write Transaction.** For the write transaction step, we use the encryption protocol presented by the TDH2 cryptosystem [44].

Alice and the consensus group execute the following protocol to write the $tx_w$ on the underlying blockchain. Alice then starts the protocol by performing the following steps to create the transaction $tx_w$:

1. Obtain the secret-management committee threshold collective public key $p_{skmc}$ from the underlying blockchain.
2. Generate a symmetric key $k$ and encrypt the transaction $tx$ using authenticated symmetric encryption as $c_k = enc_k (tx)$.
3. Embed $k$ as a point $k' \in \mathbb{G}$, and choose $r, s \in \mathbb{Z}_q$ at random.
4. Compute:

$$c = p_{skmc} k', u = g^r, w = g^s, \bar{w} = g^s, e = H_1 (c, u, \bar{w}, w, L), f = s + re,$$

where $L$ is the label of the underlying blockchain\(^5\).

5. Form the ciphertext $c_k = (c, L, u, \bar{w}, e, f)$ and construct the write transaction $tx_w = [c_k, tx_w]_{sig_{skA}}$ signed with Alice’s private key $sk_A$.
6. Send $tx_w$ to the consensus group.

Upon receiving the $tx_w$, the consensus group commits it onto the blockchain following its defined consensus rules.

**Step 2: Wait for confirmations.** Each trustee of the secret-management committee monitors the transaction $tx_w$, by determining which block the transaction is placed onto the blockchain and the number of blocks that have passed since then. Once the number of block confirmations is equal to $m$, indicating that the consensus group commits the transaction, each trustee may proceed with the following step.

**Step 3: Key Reconstruction.** For the key reconstruction step, each trustee of the secret-management committee must provide its decryption share along with a proof of correctness to the consensus group who then reconstructs the shares.

Each trustee $i$ performs the following steps to release its decryption share along with proof of correctness:

1. Extract $L$ from $c_k$ and verify that $L$ is consistent with the underlying blockchain’s metadata.

2. Verify the correctness of the ciphertext $c_k$ using the NIZK proof by checking:

$$e = H_1 (c, u, \bar{w}, w, \bar{w}, L),$$

where $w = g^f$ and $\bar{w} = g^r$.

3. If the $tx_w$ is valid, choose $s_i \in \mathbb{Z}_q$ at random and compute:

$$u_i = u^{sk_i}, \bar{u}_i = u^s, \bar{h}_i = g^{sn}, e_i = H_2 (u_i, \bar{u}_i, \bar{h}_i), f_i = s_i + sk_i e_i.$$

4. Create and sign the share: $share_i = [u_i, e_i, f_i]_{sig_{sk_i}}$ and send it to the consensus group.

In stage (2), the NIZK proof ensures that $\log_y u = \log_y \bar{u}$, guaranteeing that whoever generated the $tx_w$ knows the random value $r$. If one knows the value of $r$, then they are capable of decrypting the transaction; since it is impossible to generate $tx_w$ without knowing the plaintext transaction, this property prevents replay attacks mentioned in §9.2.

The following steps describe the operation of each node in the consensus group.

1. Upon receiving a share, each node in the consensus group verifies the share by checking:

$$e_i = H_2 ([u_i, \bar{u}_i, \bar{h}_i]),$$

where $\bar{u}_i = g^f, \bar{h}_i = g^{sn}$.

2. After receiving $t$ valid shares, the set of decryption shares is of the form:

$$\{(i, u_i) : i \in S\},$$

where $S \subset \{1, ..., n\}$ has a cardinality of $t$. Each node then executes the recovery algorithm, which does the Lagrange interpolation of the shares:

$$p_{skmc} = \prod_{i \in S} u_i^{\lambda_i},$$

where $\lambda_i$ is the $i^{th}$ Lagrange element.

3. Recover the encoded encryption key:

$$k' = c (p_{skmc})^{-1} = (p_{skmc} k') (p_{skmc})^{-1}.$$

4. Retrieve $k$ from $k'$ and decrypt the transaction $tx = dec_k (c_{tx})$.

5. Execute the transaction following the consensus group’s defined rules.

In stage (1), the NIZK proof ensures that $(u, h_i, u_i)$ is a Diffie-Hellman triple, i.e., that $u_i = u^{sk_i}$, guaranteeing the correctness of the share.

6 **ACHIEVING THE SYSTEM GOALS**

In this section, we present how F3B achieves the system goals set forth in §4.1.

**Front-running protection:** Preventing entities from launching front-running attacks.

We reason the protection offered by F3B from the definition of front-running: if an adversary cannot benefit from pending transactions, he cannot launch front-running attacks. In F3B, the sole entity that knows the content of a pending transaction is the sender, who is financially incentivized not to release its contents. The key is

\(^5\)This can be the hash of the genesis block.
released only when a transaction is committed; thus, by definition, the attacker has no chance to launch a front-running attack. However, we acknowledge that attackers may use metadata—such as the sender’s address and transaction size—of the encrypted transaction to launch speculative front-running attacks, as discussed in §4.4 and §10. We present a more comprehensive security analysis in §9.

**Decentralization:** Mitigating a single point of failure or compromise.

Due to the properties of DKG [18] and THD2 [44] cryptosystems, the secret-management committee can handle up to $t-1$ malicious trustees and up to $n-t$ offline trustees.

**Confidentiality:** Revealing a transaction only after the underlying consensus layer commits it.

Each transaction is encrypted with the sender’s generated symmetric key and this key is encrypted with the secret-management committee’s public key. Per our threat model, only $f$ trustees may behave maliciously, ensuring that the symmetric key cannot be revealed since $f+1$ trustees follow the protocol. We outline a more detailed security analysis in §9.

**Compatibility:** Remaining agnostic to the underlying consensus algorithm and smart contract implementation.

Since we are encrypting the entire transaction and require a modification at the blockchain layer to adapt F3B, F3B does not require modifications to existing smart contract implementations and support various consensus algorithm (PBFT-style, PoW, PoS).

**Low latency overhead:** Exhibiting low latency transaction-processing overhead.

Since F3B requires writing one transaction onto the underlying blockchain, as in the baseline protocol, this feature enables F3B to have a low latency overhead in comparison to front-running protection protocols which require multiple transactions. We present an evaluation of this latency overhead in §11.

7 DEPLOYMENT

This section discusses a few considerations when F3B is deployed on real-world blockchains.

**Settling on block confirmations:** To reliably provide front-running protection, we must select a reasonable $m$: the number of block confirmations. For a PBFT-style consensus, a transaction is irreversible once placed inside a block, and thus $m$ can safely be set to 1. However, for probabilistic consensus algorithms (e.g., PoW, PoS), choosing $m$ is more precarious. On the one hand, a larger $m$ suggests a better security level, rendering a successful front-running attack less likely. On the other hand, a larger $m$ indicates more time to commit a transaction, affecting the minimum baseline time until commitment and execution across the entire blockchain network.

Unlike blockchains without F3B protection, the public cannot observe transactions until the consensus group commits to them and the secret-management committee releases their corresponding keys. The exact formula for choosing $m$ is outside of the scope of this paper but we refer to Gervais et al.’s proposed framework to systematically analyze the security and performance of proof-of-work blockchain[19], which offers a reference for choosing $m$.

**Storing encrypted transactions and delayed execution:** Since all transactions are encrypted, the consensus group cannot verify and execute them until the secret-management committee releases their corresponding keys, which is only done after the consensus group commits a transaction on the underlying blockchain. This process indicates that the consensus group must store the transaction on the blockchain without any regard to its content. Unfortunately, this brings a notable challenge as attackers can then spam the blockchain by fabricating invalid transactions to flood the blockchain with, causing a backlog of pending transactions. Nonetheless, we present a mitigation technique in §8.1 involving a storage fee.

A hard fork on existing blockchain: The easiest way to deploy F3B is on a new blockchain. If an existing blockchain like Ethereum decides to deploy F3B, this would require a scheduled hard fork, given that all nodes need to adopt the new rules due to the different execution workflow.

**Reconfiguration of secret-management committee:** The membership of the secret-management committee needs to be reconfigured at some predefined interval (each epoch) to allow for new trustees and the removal of others. In addition, this helps to prevent a silent violation of our threat model—the assumption that $f+1$ trustees cannot collude—over a long period. Care must be taken when transitioning between two epochs so that pending transactions are unaffected by the transition. This could involve having the decommissioned secret-management committee operate into a new epoch until the remaining pending transactions are committed and revealed.

**Multiple secret-management committees:** The secret-management committee may inadvertently become the bottleneck of the underlying consensus protocol given its inability to achieve the same throughput. Yet, a secret-management committee is agnostic to the underlying blockchain layer, allowing for independently-operated secret-management committees. We thus suggest adopting a sharding strategy by allowing for numerous secret-management committees to operate in parallel, balancing pending transactions between them. Each secret-management committee needs to run the DKG protocol to set up its keys and store the public key $pk_{smc}$ and verification keys $h_i$ to the underlying blockchain as well as define its security parameters by choosing, for example, their committee size and $n$-bit security level.

One option would then be for secret-management committees to form at will and let users freely choose a secret-management committee over another according to their preferences or needs. This would naturally introduce a free market, where secret-management committees would compete with one another to provide quality service at low cost.

Another option is pooling all qualifying nodes and randomly sample them into multiple shards at the beginning of each epoch using bias-resistant, distributed randomness [46]. The aggregated sampling changes the threat model from an individual secret-management committee to all nodes. Under the assumption of a mildly adaptive adversary [23, 32] where an adversary can compromise a number of trustees with a time-delay, random sampling helps ensure that the compromise of any single secret-management committee is harder to accomplish. While this does introduce additional complexity for the setup of secret-management committees, this
overhead would not affect transaction-processing latency as it can be bootstrapped during the previous epoch.

Overall, we expect that, by adopting a sharding strategy, the throughput of F3B increases linearly with the number of trustees in secret-management committees.

Multiple blockchains: A secret-management committee can also provide threshold encryption services for multiple blockchains if it can monitor all the blockchains it supports and follow their set of rules (e.g., the blockchains can have different values for \( m \)). Recall that each blockchain is labeled with a distinct \( L \) (e.g., the genesis block’s hash), which allows the sender to designate which blockchain their encrypted transactions belongs to.

8 INCENTIVE ANALYSIS

Each actor must be incentivized to operate and follow the protocol honestly. In this section, we address some of the key incentives in F3B to ensure protection against unsolicited transactions and prevent the release of shares prematurely.

8.1 Spamming protection

As transactions are encrypted, the consensus group cannot verify or execute transactions, opening up an availability attack that would otherwise not be present in an open system. A malicious adversary could spam the blockchain with inexecutable transactions (e.g., inadequate fees, malformed transactions), significantly hindering the throughput of honest transactions. To prevent such an attack, we introduce a storage fee alongside the traditional execution fee (e.g., Ethereum gas) that makes it costly for an attacker to operate this attack. The storage fee paid to miners covers the placement of the transaction on the blockchain and can either vary based on some parameter (e.g., size of the transaction) or be a flat fee. The execution fee is not calculated until after the secret-management committee reveals the transaction, given the lack of knowledge of the transaction’s contents.

8.2 The operational incentive for a SMC

Similar to how consensus nodes are incentivized to maintain the blockchain with block rewards and transaction fees, we need a similar incentive structure for the secret-management committees. In a permissioned blockchain system, becoming trustees of a secret-management committee could be an added responsibility to the consensus nodes and in exchange, receive storage fees as additional income. In a permissionless blockchain system, such as a PoW blockchain, the secret-management committee might differ from miners, indicating that a payment channel needs to be established between senders and the secret-management committee.

Now, how should a secret-management committee set the price? We believe free market forces will automatically solve this problem when multiple secret-management committees are competing with each other to provide cheap and quality service. On the one hand, if a secret-management committee sets the price too high, this will discourage users from using this secret-management committee. On the other hand, if a secret-management committee sets the price too low, the trustees may not be able to cover the cost of running a secret-management committee or handle the volume of incoming transactions. In general, we can expect a price equilibrium to be reached with some price fluctuations depending on the volume of transactions.

8.3 The incentive for not leaking the share

A corrupted secret-management committee might silently collaborate with the consensus group to front-run users’ transactions by releasing the shares prematurely. Since this behavior is difficult to detect—out of band collusion—we must provide an incentive structure that (significantly) rewards anyone that can prove misbehavior by a trustee or the entire secret-management committee to disincentivize such malicious activity. At the same time, we do not want anyone to accuse a secret-management committee or trustee did not actually misbehave.

To accomplish our objective, each trustee of each secret-management committee must stake some amount of cryptocurrency in a smart contract that handles disputes between a defendant (the entire secret-management committee or a particular trustee) and a plaintiff. To start a dispute, the plaintiff will invoke the smart contract with the correct decryption share for a currently pending transaction and their own stake. If the smart contract validates that this is a correct decryption share and that the dispute started before the transaction in question was revealed by the secret-management committee, then the defendant’s stake is forfeited and sent to the plaintiff.

At a protocol level, to prove a correct decryption share, the plaintiff submits \( \{ u_i, e_i, f_i \} \) such that \( e_i = H_2 \left( u_i, \hat{u}_i, \tilde{h}_i \right) \) where \( \hat{u}_i = \frac{u_i}{u_i^f} \) and \( \tilde{h}_i = \frac{u_i^f}{u_i^f \hat{h}_i} \). Deploying such a mechanism would require the smart contract to access the ciphertext of a transaction (e.g., \( u \) is necessary to verify the submitted share), suggesting a modification of the smart contract virtual machine.

9 SECURITY ANALYSIS

This section introduces the security analysis of F3B’s protocol.

9.1 Front-running protection

We reason, from our threat model, why an attacker can no longer launch front-running attacks with absolute certainty of a financial reward, even with the collaboration of at most \( f \) malicious trustees. As we assume that the attacker does not launch speculative attacks based on metadata of the encrypted transactions, the only way the attacker can front-run transactions is by using the plaintext content of the transaction. If the attacker cannot access the content of the transaction before it is committed on the underlying blockchain, the attacker cannot benefit from the pending transaction, thus preventing front-running attacks (by the definition of front-running). Since we assume that the symmetric encryption we use is secure, the attacker cannot decrypt the transaction based on its ciphertext. In addition, based on the properties of the TDH2 cryptosystem \[44\] and DKG \[18\] and our threat model, the attacker cannot obtain the private key nor reconstruct of the symmetric key. Recall that the attacker can only collude with at most \( f \) trustees and \( f + 1 \) are required to recover or gain information about the symmetric key.
9.2 Replay attack

We consider another scenario in which an adversary can copy a pending (encrypted) transaction and submit it as their own transaction to reveal the transaction’s contents before the victim’s transaction is committed. By revealing the contents of the copied transaction, the attacker can then trivially launch a front-running attack. However, we present why the adversary is unable to benefit from such a strategy.

In the first scenario, the adversary completely copies the ciphertext \( c_k \), the encrypted transaction \( tx_k \) from \( tx_w \), and makes their own write transaction \( tx_w' \) digitally signed with their signature. However, when sending the transaction on the underlying blockchain, the adversary’s \( tx_w' \) is decrypted no earlier than the victim’s transaction \( tx_w \).

In our second scenario, the adversary instead sends the transaction to a blockchain with smaller \( m \) block confirmations. Consider two blockchains \( b_1 \) and \( b_2 \) whose required number of confirmation blocks are \( m_1 \) and \( m_2 \) with \( m_1 > m_2 \). If the adversary changes the label \( L \) to \( L' \) for the blockchain \( b_2 \) instead of blockchain \( b_1 \), the secret-management committee will successfully decrypt the transaction.

However, we argue that forming a valid write transaction with \( L' \) by the adversary is hard. The adversary would need to generate an \( e' = H_1(c, u, w, \hat{w}, L') \), \( f = s + r' \), without knowing the random parameter \( r \) and \( s \). Suppose the adversary generates \( u = g^r \hat{u} = g^r \hat{u} \) with \( r \neq r' \) and \( w = g^s \hat{w} = g^s \hat{w} \) with \( s \neq s' \). To have \( tx_w' \) be valid, we must have \( g^{s'} = wu^{s'} \) and \( g^s = w\hat{u}^s \) which implies that \( (s - s') + e(r - r') = 0 \). Since \( r \neq r' \), the adversary only has a negligible chance of having \( tx_w' \) pass verification.

10 OPTIMIZATION DISCUSSION

This section discusses some possible directions to optimize the protocol. We leave the detailed analysis of those optimizations as future work.

*Not every node needs to do the reconstruction:* Under our proposed protocol, every consensus node needs to fetch the shares and run the Lagrange interpolation to reconstruct the key. Would it instead be possible for one of the consensus nodes to reconstruct the symmetric key \( k \) from the secret shares and propagate it to other consensus nodes with a succinct proof?

We thus propose a solution that requires additional storage overhead in exchange for faster verification: Instead of constructing their encrypted transaction as \( (c_k, c_{tx}, k) \), the sender additionally adds a hash of the symmetric key \( h_k = H(k) \) as the third entry, creating the following signed write transaction: \( tx_w = [c_k, c_{tx}, h_k]_{\text{sign}_{A,4}} \).

During key reconstruction, after recovering or receiving \( k \), consensus nodes only need to verify whether the hash of \( k \) is consistent with the one \( (h_k) \) published on the ledger. If it is consistent, consensus nodes can continue to decrypt the transaction and propagate the key \( k \) to others. If it is inconsistent, the provided key \( k \) is incorrect and discards it.

Reducing storage overhead: In the TDH2 cryptosystem, the label \( L \) is attached to the ciphertext during the encryption process, which includes the information that can be used by a secret-management committee to determine if the decryption is authorized [44]. While we cannot remove \( L \) since its used for protection against replay attacks §9.2, each party (miners, secret-management committee, sender) knows \( L \) implicitly and can insert \( L \) in their computation and verification steps, allowing Alice to exclude \( L \) from \( tx_w \).

*Metadata leakage:* In our architecture, adversaries can only observe encrypted transactions until they are committed, thus preventing the revelation of transaction contents to launch front-running attacks. Nevertheless, adversaries can rely on side channels such as transaction metadata to launch speculative attacks. Concretely, since the sender needs to pay the storage fee (§8.1) for publishing an encrypted transaction to the underlying blockchain, this leaks the sender’s address. Knowledge of the sender’s address can help in launching a front-running attack since an adversary may be able to predict the sender’s behavior based on history. In order to prevent this second-order front-running attack, an underlying blockchain needs to offer anonymous payment to users, such as Zerocash [40] or a mixing service [50]. Another side-channel leakage is the size of the encrypted transaction or the time the transaction is propagated. A possible remedy for mitigating metadata leakage is PURBs [36].

**Encryption based on block:** Under our F3B architecture, each transaction is encrypted with a key. However, this might not be necessary as transactions are committed and executed on a per-block basis; thus, transactions in the same block can be encrypted with the same key by leveraging identity-based encryption [7]. By adopting this batching approach, we expect that it can reduce the latency and increase throughput; we leave this approach’s actual performance and trade-offs as future work.

**Key Storage and Node Catchup:** In our protocol, if a new node wants to join the consensus group, it cannot execute the historical transactions to catch up unless it obtains all decryption keys. The secret-management committee or consensus group can store those keys independently from the blockchain, but this requires them to maintain an additional immutable ledger. Since consensus nodes already maintain one immutable storage medium, namely the underlying blockchain, the keys can be stored on this medium as metadata, and the blockchain rule can require storing valid keys to produce blocks.

However, this optimization brings about a timing issue, i.e., when should the blockchain require the consensus group to store keys in a block? From our protocol, the transaction is committed at block height \( n \) and revealed at block height \( n+m \), making the earliest block to write the key at block height \( n+m+1 \). With respect to the latest block height to write the key, there is much more flexibility and one needs to consider the balance between the delay tolerance for all consensus nodes to retrieve the key and the time that consensus nodes must retain the key. If we assume that the key reconstruction step takes up to \( \delta \) block times, the key should be written in or before the block \( n+m+\delta \).

While this setup would work well for a blockchain with fixed block time, care must be taken with respect to blockchains where block time is probabilistic since the key may not have been replicated to all consensus nodes at block height \( n+m+\delta \), inducing some artificial delay for new blocks.
We use ByzCoin [24], a PBFT-style consensus protocol as our un-
implemented a prototype of F3B in Go [20], built on Calypso [25]
and supported by Kyber [29], an advanced cryptographic library. We use ByzCoin [24], a PBFT-style consensus protocol as our under-
lying blockchain. We instantiate our cryptographic primitives
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11 EVALUATION

We implemented a prototype of F3B in Go [20], built on Calypso [25]
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11.1 Latency

In Figure 4, while varying the number of secret-management com-
mittee trustees from 8 to 128 nodes, we present the latency time a)
for setting up a DKG, b) for sending a transaction to the Byzcoid blockchain (Step 1), c) for reconstructing the key (Step 3). Recall
that DKG setup is a one-time operation per epoch that can be boot-
strapped during the previous epoch; thus, b) and c) represent the
true transaction-latency of our solution.

We consider the transaction’s overall latency in F3B to be ex-
pressed as $mL_b + L_r$ (§5.2). To evaluate F3B with Ethereum’s con-
sensus model, we adopt 13 seconds as the expected block time [5].
Since there is no standard number of confirmations before a block is
considered committed, we vary both the number of confirmations
and the size of the secret-management committee, as summarized
in Table 1. Our result shows that, for example, based on a committee
of size of 128 with 20 block confirmations, F3B brings a 0.68% latency
overhead.

Figure 5 presents the latency comparison between the baseline
protocol (§5.1), the F3B protocol—varying the size of the secret-
mangement committee stated after “F3B-”—and a sender-only commit-and-reveal protocol as presented in Strawman 1 (§3.1). Our
simulation adopts a fixed 13 seconds block time with 20 block
confirmations to commit a transaction consistent between different
comparisons; thus, any data written into the blockchain needs
13 + 2 = 260 seconds.

As for the baseline protocol, sending a transaction only needs to
write data to the blockchain once. Hence, the total latency for base-
line is 260 seconds. Recall that in a sender-only commit-and-reveal
approach, the sender needs first to commit a hash to the blockchain
and then reveal the transaction, in which each step takes 260 sec-
onds. Those two steps cannot be parallelized since the hash must be
committed on the blockchain before sending the reveal transaction.
Otherwise, an adversary can read the reveal transaction and create
a fork of the blockchain, thwarting any front-running protection.
In practice, the protocol needs to offer enough buffer time to allow
the reveal transaction to be included in the blockchain, inducing
additional latency. This buffer time needs to be conservative in case
a cryptokitties storm or blockchain DoS attacks were to happen.
The Fomo3D attack blocked the Ethereum blockchain for about
three minutes [16], suggesting a reference for choosing the buffer
time. Hence, 260 + 2 = 262 seconds is the lower bound of this ap-
proach. Further, this approach also suffers the leakage of the smart
contract address when submitting the commit transaction to the
blockchain. Submarine is a more advanced approach that hides the
smart contract address, but it requires the sender to send three
different transactions to the blockchain, suffering a 200% latency
overhead compared to the baseline [8, 31].

Compared with F3B, the reveal phase (Key Reconstruction step)
does not require writing any data onto the blockchain. We, there-
fore, emphasize a significant difference between F3B and other
commit-and-reveal approaches where F3B only requires sending
one transaction to the underlying blockchain. This advantage brings
a low latency overhead for Ethereum.

11.2 Throughput

With respect to throughput, we only focus on Key Reconstruction
(Step 3) as Write Transaction (Step 1) is identical to sending a trans-
action to the underlying blockchain, except for some negligible
overhead due to the additional size of an encrypted transaction.

Figure 6 presents the throughput result of key reconstruction
with a secret-management committee consisting of 128 trustees. If the keys are individually reconstructed, F3B can only provide
limited throughput due to the network transmission overhead on a
per-transaction basis and non-parallel execution. Instead, we can
batch the keys, reconstruct them concurrently and present them
in one network transmission. We present this batching effect in
Figure 6, varying the batching sizes to measure the throughput
and the corresponding latency. Increasing the batching size to 128,
can improve throughput to 13.2 txns/sec from 0.56 txns/sec. Our
result shows that the marginal improvement is negligible when
further increasing the batching size to 256 or 512. The increased

![Figure 4: Overhead of F3B for varying sizes of the secret-
management committee.](image)

![Table 1: Latency Overhead for Ethereum Blockchain](image)
Performance for varying batching size with 128 nodes

12 RELATED WORK

Namecoin, a decentralized name service, is an early example of using a commit-and-reveal approach to mitigate front-running attacks [21]. In Namecoin, a user first sends a salted hash to the blockchain and, after a certain number of blocks, broadcasts the actual name when it is too late for an attacker to front-run the user, similar to our Strawman I protocol (§3).

Later, Eskandari et al. [16] first systematized front-running attacks on the blockchain by presenting three types of front-running attacks: displacement, insertion, and suppression. Daian et al. [12] first quantified front-running attacks from an economic point of view, determining that front-running attacks can pose a security problem of the underlying consensus layer by incentivizing unnecessary forks driven by the miner extractable value (MEV).

Previous works [34, 42] explore the idea of applying threshold encryption at the blockchain layer to mitigate front-running attacks. Schmid [42] proposed a secure causal atomic broadcast protocol with threshold encryption to prevent front-running attacks but did not provide a solution for integrating with a PoW blockchain nor scale to a large number of trustees. A commercial crypto project CodeChain [34] proposed to reveal transactions by their trustees using the Shamir secret sharing scheme but did not offer implementation or experiment details. Submarine, an application layer front-running protection approach, uses a commit-and-reveal strategy to enable hiding the smart contract address, but it requires three rounds of communication to the underlying blockchain, inducing a high latency overhead [8, 31]. To our knowledge, our work is the first solution to achieve legacy compatibility with both the consensus algorithm and smart contract implementation while achieving low latency overhead.

Other research adopts different approaches to mitigate front-running. A series of recent studies focus on fair ordering [22, 27, 28], but it alone cannot prevent a rushing adversary [2]. Wendy explores the possibilities of combining fair ordering with commit-and-reveal [28] but does not present quantitative overhead analysis. Furthermore, F3B hides the content of all transactions before commitment, unlike Wendy which only guarantees the fairness of transactions with the same label. Although our approach has a higher latency overhead than Wendy, we believe it is necessary as the label can provide useful information for adversaries to launch a front-running attack, such as the Fomo3D attack [16].

Some research adopts time-lock puzzles [39] to blind transactions. Injective protocol [9] deploys a verifiable delay function [6] as proof-of-elapsed-time to prevent front-running attacks. However, it is still an open challenge to link the time-lock puzzle parameters to the actual real-world delay [2].

Tesseract, proposed by Bentov et al., is an exchange preventing front-running attacks by leveraging a trusted execution environment [3]. However, this approach brings an unreliable centralized component subject to a single point of failure and compromise [38, 48].

Calypso is a framework that enables on-chain secrets by adopting threshold encryption governed by a secret-management committee [25]. Calypso allows ciphertexts to be stored on the blockchain and collectively decrypted by trustees according to a pre-defined policy. F3B builds on Calypso to mitigate front-running attacks.

13 CONCLUSION

This paper introduces F3B, a blockchain architecture that addresses front-running attacks by encrypting pending transactions with threshold encryption. We performed an exploration demonstrating that F3B can protect the Ethereum blockchain with a low latency overhead.
overhead. While acknowledging that widespread deployment of F3B is challenging given the need for modifications to the blockchain workflow, F3B provides substantial benefits: the blockchain, by default, would now contain standard front-running protection for all applications at once without requiring any modifications to smart contracts themselves.

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