F3B: A Low-Overhead Blockchain Architecture with Per-Transaction Front-Running Protection

Haoqian Zhang, Louis-Henri Merino, Mahsa Bastankhah, Vero Estrada-Galiñanes, and Bryan Ford

École polytechnique fédérale de Lausanne (EPFL) {haoqian.zhang,louis-henri.merino,mahsa.bastankhah,vero.estrada,bryan.ford}@epfl.ch

Abstract. Front-running attacks, which benefit from advanced knowledge of pending transactions, have proliferated in the blockchain space, since the emergence of decentralized finance. Front-running causes devastating losses to honest participants and continues to endanger the fairness of the ecosystem. We present Flash Freezing Flash Boys (F3B), a blockchain architecture that addresses front-running attacks by using threshold cryptography. In F3B, a user generates a symmetric key to encrypt their transaction, and once the underlying consensus layer has committed the transaction, a decentralized secret-management committee reveals this key. F3B mitigates front-running attacks because, before the consensus group commits it, an adversary can no longer read the content of a transaction, thus preventing the adversary from benefiting from advanced knowledge of pending transactions. Unlike other threshold-based approaches, where users encrypt their transactions with a key derived from a future block, F3B enables users to generate a unique key for each transaction. This feature ensures that all uncommitted transactions remain private, even if they are delayed. Furthermore, F3B addresses front-running at the execution layer; thus, our solution is agnostic to the underlying consensus algorithm and compatible with existing smart contracts. We evaluated F3B based on Ethereum, demonstrating a 0.05% transaction latency overhead with a secret-management committee of 128 members, thus indicating our solution is practical at a low cost.

1 Introduction

Front-running is the practice of benefiting from the advanced knowledge of pending transactions [19,7,1]. Although benefiting some entities involved, this practice puts others at a significant financial disadvantage, making this behavior illegal in traditional markets with established securities regulations [19].

However, the openness and pseudonymous nature of blockchain transactions and the difficulties of pursuing miscreants across numerous jurisdictions have made front-running attractive, particularly in decentralized finance (DeFi) [36,19,14]. Front-running actors in the blockchain space can read the contents of pending transactions and benefit from them by, e.g., creating their own transactions and positioning them according to the target transaction [4,14,19].

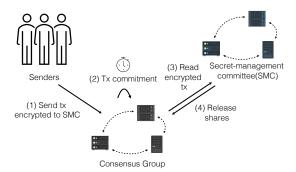


Fig. 1: F3B architecture. Senders publish encrypted transactions to the consensus group. Once the transactions are no longer pending, the secret-management committee releases the decryption shares.

Front-running negatively impacts honest DeFi actors and endangers the fairness of this multi-billion market [17]. One estimate suggests that front-running attacks amount to \$280 million in losses for DeFi actors each month [40]. Front-running also threatens the underlying consensus layer's security by incentivizing unnecessary forks [16,14].

Although there exist approaches to address front-running, they either exhibit high latency, are restricted to a specific environment, or raise security concerns. Namecoin, an early example of mitigating front-running attacks by having users send a commit and later a reveal transaction, requires two rounds of communication with the underlying blockchain [27]. Submarine further improves Namecoin's design by hiding the addresses of smart contracts involved, but it induces three rounds of communication to the underlying blockchain [37,27]. Other works have taken a different approach to mitigating front-running attacks by tailoring their solution to a specific application or consensus algorithm [12,50,58,5,2,3,38].

A promising approach is to use threshold encryption, where clients encrypt their transactions to prevent malicious actors from understanding those transactions, as presented in Fairblock [41] and Shutter [55,56]. However, these schemes require clients to choose a future block to derive the encryption key. Suppose a transaction failed to be committed in the client-chosen block due to, for example, a crypto storm [29] or a deliberate denial of service attack [19]. In this case, the transaction is undesirably revealed (see Section 3.3 for details).

We present Flash Freezing Flash Boys¹ (F3B), a novel blockchain architecture with front-running protection that has a low latency overhead and is compatible with existing consensus algorithms and smart contract implementations. Like Fairblock [41] and Shutter [55,56], F3B addresses front-running by adopting threshold encryption, but it accomplishes this on a per-transaction basis rather than a per-block basis. Instead of choosing an encryption key associated with a

¹ The name *Flash Boys* comes from a popular book revealing this aggressive market-exploiting strategy on Wall Street in 2014 [36].

future block, clients generate an encryption key for each transaction, thus ensuring that transactions remain private until they are committed to the blockchain.

As described in Figure 1, F3B's architecture consists of four steps: First, a client encrypts their transaction to a secret-management committee (SMC) and sends their encrypted transaction to the consensus group that operates the underlying blockchain. Next, the SMC waits for the consensus group to commit the transaction on-chain. Once committed, the SMC reads the encrypted transaction from the blockchain. Finally, the SMC provides the consensus group with the decryption key shares to proceed with their standard workflow, e.g., verifying and executing the transaction. At this point, malicious actors cannot launch a front-running attack because transactions are already irreversibly ordered on the blockchain. Although adversaries can launch speculative front-running attacks where, based on side-channel information, the adversary guesses the contents of the transaction, these attacks have a greater chance of failure and can prove unprofitable [4].

F3B addresses two key practical challenges: (a) mitigating spamming of inexecutable encrypted transactions onto the underlying blockchain, and (b) limiting latency overhead.

To mitigate spamming, we introduce a deposit-refund storage fee for storing encrypted transactions, along with the standard execution fee (e.g., gas in Ethereum). To limit the latency overhead, users need to write only data onto the underlying blockchain once.

We implemented a prototype of F3B with post-Merge² Ethereum [22] as the underlying blockchain and Dela [18] as the secret-management committee. Our analysis shows that, with a committee size of 128, the latency overhead is 0.05% for Ethereum; In comparison, Submarine, which achieves the same security guarantees as F3B, exhibits a 200% latency overhead, as it requires three rounds of communication with the underlying blockchain [37,10]. For part of our prototype, we modified Ethereum's execution layer by adding a new transaction type featuring encryption and delayed execution. By only modifying the execution layer, we can (1) provide compatibility with various consensus algorithms embedded in Ethereum's consensus layer, including Proof-of-Work (PoW), Proof-of-Authority (PoA) and the recently added, Proof-of-Stake (PoS) and (2) support existing smart contracts without any code modifications.

In this paper, our key contributions are as follows:

- 1. The design of a blockchain architecture with front-running protection that uses threshold encryption on a per-transaction basis, enabling confidentiality for all pending transactions, even if transactions are delayed.
- 2. A prototype that, on Ethereum's execution layer, demonstrates F3B's ability to be agnostic to (1) the underlying consensus algorithm and (2) to smart contract implementations while achieving low-latency overhead.
- 3. A systematic evaluation of F3B on post-Merge Ethereum by looking at transaction latency, throughput, and reconfiguration costs.

² The Merge refers to the merge executed on September 15th, 2022, to complete Ethereum's transition to proof-of-stake consensus.

2 Background

In this section, we present a brief background on blockchain and smart contracts, and we introduce front-running attacks and mitigation strategies.

2.1 Blockchain & Transaction Ordering

A blockchain is an immutable append-only ledger of ordered transactions [42]. However, transactions go through a series of stages before they are committed—irreversibly ordered—on the blockchain. After a sender creates a transaction, they need to propagate the transaction among the consensus nodes that then place the transaction in a pool of pending transactions, most commonly known as mempool. Notably, these transactions are not yet irreversibly ordered, thus opening up the possibility for front-running attacks. Furthermore, under certain probabilistic consensus algorithms, such as PoW or PoS, a transaction inserted onto the blockchain can still be reordered by inducing a fork of the underlying blockchain. Hence, to guarantee irreversible ordering for probabilistic consensus algorithms, a transaction must receive enough block confirmations—the number of blocks succeeding the block containing the transaction [42,32,13].

2.2 Smart Contract & Decentralized Exchange

A smart contract is an executable computer program modeled after a contract or an agreement that executes automatically [48]. A natural fit for smart contracts is on top of decentralized fault-tolerant consensus algorithms, such as PBFT-style algorithms, PoW, and PoS, to ensure their execution and integrity [61,42,30].

Although Bitcoin uses a form of smart contracts [42], it was not until Ethereum's introduction that the blockchain space realized Turing-complete smart contracts, the backbone necessary for creating complex decentralized exchanges. To interact with these complex smart contracts, users need to pay gas, a pseudo-currency that represents the execution cost by miners [20]. However, the expressiveness of smart contracts comes with significant risks, from inadvertent vulnerabilities to front-running. Front-running is exhibited by the lack of guarantees that the underlying blockchain provides regarding ordering.

2.3 Front-Running Attacks & Mitigation

The practice of front-running involves benefiting from advanced knowledge of pending transactions [19,7,1]. In itself, knowledge of pending transactions is harmless, but the ability to act on this information is where the true problem lies. In the context of blockchains, an adversary performs a front-running attack by influencing the order of transactions, provided that transactions in the mempool are entirely in the clear.

Cryptocurrencies suffer from mainly three types of front-running attacks [19]: displacement, insertion, and suppression. *Displacement* is the replacement of

a target transaction with a new transaction formulated by the front-running attacker. *Insertion* is the malicious introduction of a new transaction before a target transaction in the committed transaction ordering. *Suppression* is the long-term or indefinite delaying of a target transaction.

In an ideal world, front-running protection would consist of an *immediate* global ordering of each transaction, as clients broadcast their transactions to prevent attackers from changing their order. In reality, even if all participants were honest, such global ordering is practically impossible due to clock synchronization [15] and consistency problems (e.g., two transactions having the same time). Malicious participants can still carry out front-running attacks, because timings can easily be manipulated.

A more practical solution is to encrypt transactions so that the consensus group has no knowledge about the transactions when ordering them. This solution mitigates front-running attacks as an attacker is hindered from taking advantage of pending *encrypted* transactions.

3 Strawman Protocols

In order to explore the challenges inherent in building a framework, such as F3B, we first examine a couple of promising but inadequate strawman approaches, representative of state-of-the-art proposals [37,10,41,55] but simplified for expository purposes.

3.1 Strawman I: Sender Commit-and-Reveal

The first strawman design has the sender create two transactions: a *commit* and a *reveal* transaction. The commit transaction is simply a commitment (*e.g.*, hash) of the intended reveal transaction, which is simply the typical contents of a transaction that is normally vulnerable to front-running. The sender will propagate the commit transaction and then *wait* until its commitment by the consensus group, before releasing the reveal transaction. Once the reveal transaction is propagated, the consensus group proceeds to verify and to execute the transaction, in the execution order that the commit transaction was committed on the blockchain. Given the commitment in the former transaction, the sender is unable to change the contents of the reveal transaction.

This simple strawman protocol mitigates front-running attacks because the commit transaction determines the execution order and the contents of the commit transaction do not expose the contents of the reveal transaction. However, this strawman protocol presents some notable challenges: (a) the sender must remain online to continuously monitor the blockchain to know when to release their reveal transaction, (b) the reveal transaction might be delayed due to a congestion event like the cryptokitties storm [29] or a deliberate denial-of-service (DoS) attack like the Fomo3D incident [19]. (c) this approach is subject to output bias, as the consensus nodes or the sender can deliberately choose not to reveal certain transactions, after the commit transaction [4], and (d) this approach has

a significant latency overhead of over 100%, given that the sender must now send two non-overlapping transactions instead of the one standard transaction.

3.2 Strawman II: The Trusted Custodian

A straightforward method for removing the sender from the equation, after sending the commit transaction, is to employ a trusted custodian. After the consensus group commits the transaction onto the underlying blockchain, the trusted custodian reveals the transaction's contents.

This strawman protocol mitigates front-running attacks, as the nodes cannot read, before ordering, the contents of the transaction. However, the trusted custodian presents a single point of failure: Consensus nodes cannot decrypt and execute a transaction if the custodian crashes. The trusted custodian also represents a single point of compromise, where the trusted custodian can secretly act maliciously, such as colluding with front-running actors. Instead, by employing a decentralized custodian, we can mitigate both the single point of failure and compromise issues, thus making collusion significantly more difficult.

3.3 Strawman III: Threshold Encryption with Block Key

The next natural step is to have a decentralized committee that generates a public key for each block, thus enabling a user to encrypt their transaction for a future block. The committee would then release the private key after the block commitment. Furthermore, the committee can use identity-based encryption [53] to enable users to derive a future block key based on the block's height.

This strawman protocol seems to mitigate front-running, as the transactions in a block are encrypted until they are committed in their intended block. However, if an encrypted transaction fails to be included in the specified block, its contents will be revealed shortly thereafter while remaining uncommitted, thus making it vulnerable to front-running. Blockchain networks have repeatedly observed such failures due to congestion, such as cryptokitties storm [29], or well-funded DoS attacks, such as the Fomo3D attack that flooded the Ethereum network with transactions for three minutes [19]. Such an approach can incentivize a consensus node to intentionally produce an empty block by aiming to reveal the pending transactions for that block. Therefore, we require a per-transaction rather than a "per-block" level of confidentiality, thus ensuring that a transaction is never revealed before it is committed on the blockchain.

4 System Overview

In this section, we present F3B's system goals, architecture, and models.

4.1 System Goals

Our system goals, inspired by our strawman protocols, are

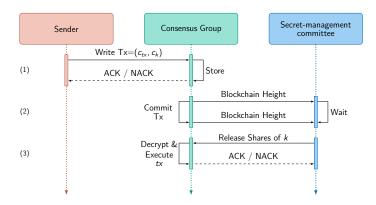


Fig. 2: F3B per-transaction protocol steps: (1) Send an encrypted transaction to the underlying blockchain, (2) Wait for the transaction commitment, (3) Release the key and executing the transaction

- Front-Running Protection: prevents entities from practicing front-running.
- **Decentralization:** mitigates a single point of failure or compromise.
- Confidentiality: reveals a transaction, only after the underlying consensus layer commits it.
- Compatibility: remains agnostic to the underlying consensus algorithm and to smart contract implementation.
- Low-Latency: exhibits 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 can now encrypt their transactions and store 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 the ordering of transactions, and the second is about the execution of transactions. As long as most trustees in the secret-management committee are secure and honest and the key is revealed to the public when appropriate, each consensus node can always maintain the same blockchain state.

Notably, F3B encrypts the entire transaction, not only inputs, as other information, such as the smart contract address, can provide enough information to launch a probabilistic front-running attack, such as the Fomo3D attack [19] or a speculative attack [4].

4.3 System and Network Model

F3B's architecture consists of three components: senders that publish (encrypted) transactions, the secret-management committee (SMC) that manages and releases secrets within an epoch, and the consensus group that maintains the underlying blockchain. Over a long epoch, an SMC can modify its membership and provide backward secrecy, without interrupting users' encryption by running a resharing protocol [60]. In practice, the secret-management committee and the consensus nodes can consist of the same servers but, for clarity in this paper, we discuss them as separate entities. For the underlying network, we assume that all honest blockchain nodes and trustees of the SMC are well connected and that their communication channels are synchronous, i.e., if an honest node or trustee broadcasts a message, then all honest nodes and trustees receive the message within a known maximum delay [44].

4.4 Threat Model

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

The secret management committee consists of n trustees, where 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., at most f' of 3f'+1 validators can fail or misbehave in a PBFT-style or PoS blockchain, or the adversary controls less than 50% computational power in a PoW blockchain.

We assume that attackers do not launch speculative front-running attacks [4], but we present a discussion on some mitigation strategies for reducing side-channel leakage in Appendix C.5.

5 F3B Protocol

In this section, we introduce F3B's protocol, starting with some preliminaries, followed by F3B's detailed design. Appendix A offers a more comprehensive description, and Appendix C introduces some optimizations.

5.1 Preliminaries

In this subsection, we introduce our preliminaries, including our baseline model for the underlying blockchain and the cryptographic primitives used in F3B.

Blockchain Model. To compare F3B's impact, we model the underlying blockchain to involve a consensus protocol that commits transactions into a block that is linked to a previous block. We define the underlying block's time as L_b seconds. In PoW and PoS-based blockchains, a transaction is committed only after a certain number of additional blocks have been added to the chain (also known as

block confirmations). Thus, we define that a transaction is committed after m block confirmations. Therefore, our baseline transaction latency is mL_h .

Shamir's 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 and no group less than t trustees learns any information about s. Whereas a simple secret sharing scheme assumes an honest dealer, verifiable secret sharing (VSS) enables the trustees to verify that the shares they receive are valid [23]. Public verifiable secret sharing (PVSS) further improves VSS to enable a third party to check all shares [51].

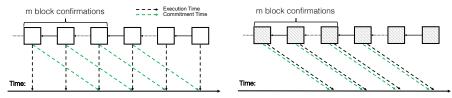
Distributed Key Generation (DKG). DKG is a multi-party (t, n) key-generation process for collectively generating a private-public key pair (sk, pk), without relying on a single trusted dealer; each trustee i obtains a share sk_i of the secret key sk, and collectively obtains a public key pk [25]. Any client can now use pk to encrypt a secret, and at least t trustees must cooperate to retrieve this secret [54].

5.2 Protocol Outline

Setup: Before an epoch, the secret-management committee runs a DKG protocol to generate a private key share sk_{smc}^i for each trustee and a collective public key pk_{smc} written onto the underlying blockchain. To offer chosen ciphertext-attack protection and to verify the correctness of secret shares, we utilize the TDH2 cryptosystem [54] containing NIZK proofs.

Per-Transaction Protocol (Figure 2):

- 1. Write Transaction: A sender first generates a symmetric key k and encrypts it with pk_{smc} from the underlying blockchain, thus obtaining the resulting ciphertext c_k . Next, the sender creates their transaction and symmetrically encrypts it by using k, denoted as $c_{tx} = enc_k(tx)$. Finally, the sender sends (c_{tx}, c_k) to the consensus group who writes the pair onto the blockchain.
- 2. Wait for Confirmations: The secret-management committee waits for the sender's transaction (c_{tx}, c_k) to be committed on the blockchain (waiting m block confirmations).
- 3. Key Reconstruction: Once committed, each secret-management committee trustee reads c_k from the sender's transaction and releases their decrypted share of k, along with a NIZK proof of correctness for the decryption process. The consensus group then verifies the decrypted shares and uses them to reconstruct k by Lagrange interpolation of shares when there are at least t valid shares.
- 4. Decryption and Execution: The consensus group finally symmetrically decrypts the transaction $tx = dec_k(c_{tx})$ using k, thus enabling it to execute tx.



- (a) Execution and commitment time in Ethereum
- (b) Execution and commitment time in F3B

Fig. 3: In Ethereum, once they are inserted in the blockchain, the transactions are executed and committed after receiving m block confirmations. Whereas, in F3B, transactions are encrypted, and their executions are postponed after receiving m block confirmations when the secret-management committee releases the encryption keys. Both scenarios have a similar commitment time.

Resharing Protocol: To provide dynamic membership and backward secrecy over a long epoch, an SMC can periodically run a verifiable resharing protocol [60] to replace certain trustees or redistribute the trustees' private keys. Unlike DKG, resharing keeps the epoch's public key, thus preventing undesirable interruptions.

5.3 Overhead Analysis

In the per-transaction protocol, steps (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 (Section 5.1). Comparing our protocol with the baseline, (3) and (4) are additional steps, and we denote the time of those steps to be L_r .

Figure 3 demonstrates the conceptual difference in commitment and execution time between F3B and the baseline. As the secret-management committee releases the secret keys with a delay of m blocks, this introduces an execution delay of m blocks. However, in both cases, to prevent attacks such as double-spending, the recipient should not accept a transaction, until it is committed. Therefore on a commercial level, F3B is similar to the baseline because it exhibits the commitment time of a transaction that is of use to the recipient³.

6 Achieving the System Goals

In this section, we present how F3B achieves the system goals outlined in Section 4.1.

Front-Running Protection: prevents entities from practicing front-running. 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

³ In F3B, transaction finalization is slower due to the key reconstruction and delayed execution after transaction commitment. However, the overhead is negligible compared to commitment time, as discussed in Section 8.

transaction is the sender who is financially incentivized to *not* release its contents. The content is revealed only when its transaction is committed; thus, by definition, the attacker has no means to launch a front-running attack. However, we acknowledge that attackers can use side channels (*e.g.* metadata such as sender's address and transaction size) of the encrypted transaction to launch *speculative* front-running attacks, as discussed in Section 4.4 and Appendix C.5. We present a more comprehensive security analysis discussion in Appendix B.

Decentralization: mitigates a single point of failure or compromise.

Due to the properties of DKG [25] and THD2 [54] cryptosystems, the SMC can handle up to t-1 malicious trustees and up to n-t offline trustees.

Confidentiality: reveals a transaction, only after the underlying consensus layer commits it.

The sender encrypts each transaction with a newly generated symmetric key that is then encrypted under the secret-management committee's public key, thus requiring f+1 trustees to retrieve the symmetric key. Per our threat model, only f trustees can behave maliciously; this ensures that the symmetric key cannot be revealed. We outline a more detailed security analysis in Appendix B.

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

F3B requires modifying the execution layer to enable encrypted transactions. However, the consensus layer remains untouched, thus agnostic to the underlying consensus algorithms. Furthermore, F3B does not require to modify smart contract implementations, thus enabling existing smart contracts to benefit from front-running protection automatically.

Low-Latency: exhibits low-latency transaction-processing overhead.

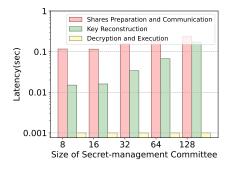
Similar to the baseline model, F3B requires clients to write only one transaction onto the underlying blockchain. This enables F3B to have a low-latency overhead compared to other front-running protection design that require multiple transactions for the same security guarantees. We present an evaluation of this latency overhead in Section 8.

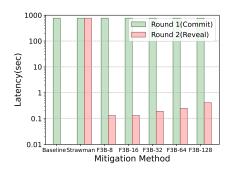
7 Incentive

F3B must incentivize actors to operate and follow the protocol honestly. In this section, we address the critical incentives that, in F3B, prevent spamming transactions and that deter collaboration among trustees from prematurely revealing transactions.

7.1 Spamming Protection

As the consensus group cannot execute encrypted transactions, an adversary could, at a low cost, spam the blockchain with non-executable transactions (e.g., inadequate fees, malformed transactions), thus delaying the commitment of honest transactions. To make such an attack costly, we introduce a storage deposit, alongside the traditional execution fee (e.g., gas in Ethereum) and adjustable





- (a) The latency result of each step in F3B by varying the number of secret-management committee trustees from 8 to 128 nodes.
- (b) A comparison of F3B's latency to that of the sender-only commit-and-reveal approach against a baseline modeled after the Ethereum protocol. The string "F3B-X" represents X trustees.

Fig. 4: Latency results of F3B on Ethereum achieving low overhead.

based on the transaction's size. This storage deposit could be partially refunded to the sender after the consensus nodes successfully executes the transaction, thus imposing a low cost on behaving users and a penalty on misbehaving ones.

7.2 Operational Incentive

We need a similar incentive structure for the secret-management committees; similar to the way consensus nodes are rewarded for following the blockchain protocol via an execution fee. Whereas SMCs could be rewarded using the execution fee, this fee does not prevent SMC trustees from colluding for their financial gain. For example, an SMC might silently collude with a consensus group by prematurely giving them the decryption shares. Given the difficulty of detecting out-of-band collusion, we need to discourage it from doing so by significantly rewarding anyone who can prove the existence of such collusion.

Therefore, we propose an incentive structure, where we require each trustee in a secret-management committee to lock an amount c for collateral and, in exchange, they are rewarded proportionally to the staked amount ac for the services they provide. According to our threat model (Section 4.4), t trustees must collude with one another to reconstruct a transaction. Therefore, the value that t trustees would benefit from front-running must be smaller than (1+a)ct: the value that malicious trustees would lose by the slashing protocol mentioned in Appendix A.2. It follows that the amount of the collateral also determines the epoch length: a higher collateral requirement supports a longer epoch length.

8 Evaluation

We prototype F3B by using post-merge Ethereum [22] as the underlying blockchain and Dela [18] written in Go [26] as the secret-management committee for our evaluation⁴. Remaining consistent with Ethereum's security assumptions, one epoch length lasts 6.4 minutes and the trustees forming the secret-management committee from validators for a given epoch are randomly selected. We instantiate our cryptographic primitives by using the Edward25519 elliptic curve with 128-bit security supported by Kyber [35], an advanced cryptographic library. We ran experiments on a server with 32GB of memory and 40 (2.1GHz) CPU cores. We further discuss F3B integration with Ethereum in Appendix C.

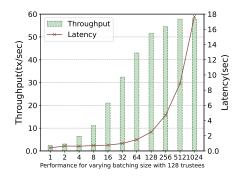
8.1 Latency

In Figure 4a, we present the latency of each F3B step after a transaction commitment while varying the number of SMC trustees from 8 to 128 nodes: (a) preparing and sending shares, (b) reconstructing the key, and (c) decrypting and executing the transaction. We can see that the latency for 8 trustees is 132ms, and an increase from 8 to 128 trustees presents 413ms in latency. The sum of these three steps represents F3B's added transaction latency, denoted as L_r . Recall that the overall transaction latency using F3B is $mL_b + L_r$ (Section 5.2). In post-Merge Ethereum, the block time is fixed to 12 seconds, i.e., $L_b = 12$ [8], and a block requires 64 block confirmations (two epochs) to be "finalized", i.e., m = 64 [21].

Figure 4b presents the latency comparison between the baseline protocol (Section 5.1), a sender-only commit-and-reveal protocol, as presented in Strawman 1 (Section 3.1), and F3B's protocol—varying the size of the secret-management committee stated after the string "F3B-". With the new PoS consensus, committing any data in Ethereum requires $mL_b = 64 * 12 = 768$ seconds. The baseline protocol's total latency is 768 seconds, as it requires only one write to the blockchain. Recall that in a sender-based commit-and-reveal approach (Strawman I), the sender must first commit a hash to the blockchain and then reveal the transaction, each step taking 768 seconds for a total of 1536 seconds. Those two steps cannot be overlapped as, before the sender can propagate the reveal transaction, the hash must be committed on 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 [37,10]

Compared with F3B, the reveal phase (key-reconstruction step) does not require the sender to write any data onto the blockchain. Therefore, we emphasize a significant difference between F3B and other application-based commit-and-reveal approaches, where F3B requires sending only one transaction to the underlying blockchain. Figure 4b shows that our design brings a low-latency overhead of 413ms, equivalent to 0.05% for Ethereum (relative to the 768 seconds commitment time), under an SMC size of 128.

⁴ We will release the code.



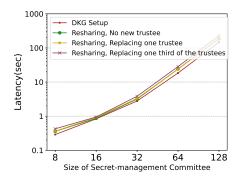


Fig. 5: Throughput of the key reconstruction for various batching sizes.

Fig. 6: The cost of DKG setup and three resharing scenarios.

8.2 Throughput

For throughput, we focus on Key Reconstruction (Step 3) as Write Transaction (Step 1) and Decryption and Execution (Step 4) are almost identical to sending and executing a transaction on the underlying blockchain, except for some negligible overhead due to the additional size of an encrypted transaction and one symmetric decryption of the encrypted transaction.

Figure 5 presents the throughput results of key reconstruction with a secret-management committee consisting of 128 trustees. If the keys are individually reconstructed, F3B provides limited throughput due to network transmission overhead incurred from sequential execution. Instead, we can batch keys by reconstructing them concurrently and presenting them in one network transmission. We present this batching effect in Figure 5 by varying the batching size to measure throughput and corresponding latency. By increasing the batching size from 1 to 1024, we can improve throughput from 2 txns/sec to 58 txns/sec. Increasing the batching size to 2048 or higher provides only marginal improvement. The increased throughput comes with a higher latency cost: With a batching size of 512, the key reconstruction step now takes 8.85 seconds to process; this latency is equivalent to a 1.15% latency overhead over Ethereum. Our results show that F3B provides sufficient throughput to support Ethereum (15 tx/sec [49]).

8.3 Reconfiguration

Figure 6 demonstrates the cost of reconfiguring a secret-management committee. Recall that DKG is a one-time setup operation per epoch, bootstrapped during the previous epoch. Our experiment shows that, with a committee size of 128 trustees, DKG takes about 150 seconds; this is about 40% of Ethereum's epoch time (384 seconds). We offer a further discussion about the transition between two epochs in Appendix C.1. To provide backward secrecy and dynamic membership, a secret-management committee can run a verifiable resharing protocol [60]

within an epoch and, by keeping the public key, without interrupting users' encryption. Figure 6 illustrates the cost of three scenarios: (a) resharing among the same committee, (b) replacing one trustee, and (c) replacing one-third of trustees. We can see that they all exhibit latency of the same magnitude.

9 Related Work

Namecoin is a decentralized name service and an early work on front-running protection using a commit-and-reveal design [27]. In Namecoin, a user first broadcasts a salted hash of their name and then, after commitment, broadcasts the actual name. Our first strawman protocol (Section 3.1) is based on Namecoin.

After Namecoin, Eskandari et al. [19] systematized front-running attacks on the blockchain by presenting three types of front-running attacks: displacement, insertion, and suppression. Daian et al. [14] also quantified front-running attacks from an economic point of view, determining that front-running attacks can also pose a security risk to the underlying consensus layer by incentivizing unnecessary forks driven by the miner extractable value (MEV).

Many previous works explore the idea of applying threshold cryptography on blockchain. Virtual ASICs use threshold encryption to implement an all-ornothing broadcast in the blockchain layer [24]. Calypso enables on-chain secrets that trustees then decrypt according to a pre-defined policy [31]. Sikka [57], Ferveo (Anoma) [5], Schmid [50], Dahlia [38], and Helix [3] apply threshold encryption to mitigate front-running but only present discussions with specific consensus algorithms. Fairblock [41] and Shutter [55,56] enable encrypted transactions on a per-block basis, but if an encrypted transaction fails to be included in the sender-chosen block, then the transaction would be revealed; our Strawman III design (Section 3.3) is based on their approach. F3B uses a similar approach but adopts per-transaction encryption, thus protecting all uncommitted transactions, even if the transactions are delayed.

Other works adopt different approaches to mitigate front-running. A series of recent studies focus on fair ordering [28,33,34], but they cannot prevent an adversary with a rapid network connection [4]. Wendy explores the possibility of combining fair ordering with commit-and-reveal [34] but is in need of quantitative overhead analysis. Submarine is an application-layer front-running protection approach that extends a commit-and-reveal design to prevent leakage of the smart contract address. However, it presents a high latency overhead by requiring senders to have three rounds of communication with the underlying blockchain [37,10].

Some works adopt time-lock puzzles [46] to blind transactions. For example, the injective protocol [11] uses a verifiable delay function [9] to achieve a proof-of-elapsed-time. However, an open challenge remains to link the time-lock puzzle parameters to an actual real-world delay [4].

Finally, works such as MEV-SGX [39], Tesseract [6], Secret Network [52], and Fairy [58] use a trusted execution environment [62] to mitigate front-running.

Nevertheless, these approaches use a centralized component that is then subject to a single point of failure or compromise [45,59].

10 Conclusion

In this paper, we have introduced F3B, a novel blockchain architecture that addresses front-running attacks by using threshold encryption on a per-transaction basis. Our evaluation of F3B demonstrates that F3B is agnostic to consensus algorithms and to existing smart-contract implementations. We have also shown that F3B meets the necessary throughput while presenting a low-latency overhead, thus fitting with Ethereum. Given that the deployment of F3B would require modifications to a blockchain's execution layer, F3B, in return, would also provide a substantial benefit: the F3B-deployed blockchain would now, by default, contain standard front-running protection for all applications at once without requiring any modifications to smart contracts themselves.

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References

- Nasdaq: Front running. https://www.nasdaq.com/glossary/f/front-running (2018), accessed: 2022-04-17
- Ankalkoti, P., Santhosh, S.: A relative study on bitcoin mining. Imperial Journal of Interdisciplinary Research (IJIR) 3(5), 1757–1761 (2017)
- Asayag, A., Cohen, G., Grayevsky, I., Leshkowitz, M., Rottenstreich, O., Tamari, R., Yakira, D.: Helix: A scalable and fair consensus algorithm resistant to ordering manipulation. Cryptology ePrint Archive (2018)
- 4. Baum, C., Chiang, J.H.y., David, B., Frederiksen, T.K., Gentile, L.: Sok: Mitigation of front-running in decentralized finance. Cryptology ePrint Archive (2021)
- Bebel, J., Ojha, D.: Ferveo: Threshold decryption for mempool privacy in bft networks. Cryptology ePrint Archive (2022)
- Bentov, I., Ji, Y., Zhang, F., Breidenbach, L., Daian, P., Juels, A.: Tesseract: Real-time cryptocurrency exchange using trusted hardware. In: Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security. pp. 1521–1538 (2019)
- 7. Bernhardt, D., Taub, B.: Front-running dynamics. Journal of Economic Theory 138(1), 288–296 (2008)
- 8. Blocks (2022), https://ethereum.org/en/developers/docs/blocks, accessed: 2022-10-03

- 9. Boneh, D., Bonneau, J., Bünz, B., Fisch, B.: Verifiable delay functions. In: Annual international cryptology conference. pp. 757–788. Springer (2018)
- Breidenbach, L., Daian, P., Tramèr, F., Juels, A.: Enter the hydra: Towards principled bug bounties and {Exploit-Resistant} smart contracts. In: 27th USENIX Security Symposium (USENIX Security 18). pp. 1335–1352 (2018)
- 11. Chen, E., Chon, A.: Injective protocol: A collision resistant decentralized exchange protocol [White paper] (2018), https://coinpare.io/whitepaper/injective-protocol.pdf
- 12. Ciampi, M., Ishaq, M., Magdon-Ismail, M., Ostrovsky, R., Zikas, V.: Fairmm: A fast and frontrunning-resistant crypto market-maker. Cryptology ePrint Archive (2021)
- Coinbase: Coinbase confirmations (2022(?)), https://help.coinbase.com/ en/coinbase/getting-started/crypto-education/glossary/confirmations, accessed: 2022-03-03
- Daian, P., Goldfeder, S., Kell, T., Li, Y., Zhao, X., Bentov, I., Breidenbach, L., Juels, A.: Flash boys 2.0: Frontrunning in decentralized exchanges, miner extractable value, and consensus instability. In: 2020 IEEE Symposium on Security and Privacy (SP). pp. 910–927. IEEE (2020)
- Dalwadi, N.N., Padole, C.M.: Comparative study of clock synchronization algorithms in distributed systems. Advances in Computational Sciences and Technology 10(6), 1941–1952 (2017)
- 16. dapp.org: Uniswap v2 audit report (2020), https://dapp.org.uk/reports/uniswapv2.html, accessed: 2022-01-22
- 17. Defi pulse, https://www.defipulse.com/?time=All
- 18. Dedis ledger architecture, https://github.com/dedis/dela
- 19. Eskandari, S., Moosavi, M., Clark, J.: Sok: Transparent dishonesty: front-running attacks on blockchain (2019)
- 20. Gas and fees (2022), https://ethereum.org/en/developers/docs/gas/, accessed: 2022-10-03
- 21. Gasper (2022), https://ethereum.org/en/developers/docs/consensus-mechanisms/pos/gasper/, accessed: 2022-10-03
- 22. The merge (2022), https://ethereum.org/en/upgrades/merge/, accessed: 2022-10-03
- 23. Feldman, P.: A practical scheme for non-interactive verifiable secret sharing. In: 28th Annual Symposium on Foundations of Computer Science (sfcs 1987). pp. 427–438. IEEE (1987)
- 24. Ganesh, C., Orlandi, C., Tschudi, D., Zohar, A.: Virtual asics: generalized proof-of-stake mining in cryptocurrencies. In: Data Privacy Management, Cryptocurrencies and Blockchain Technology, pp. 173–191. Springer (2021)
- 25. Gennaro, R., Jarecki, S., Krawczyk, H., Rabin, T.: Secure distributed key generation for discrete-log based cryptosystems. In: International Conference on the Theory and Applications of Cryptographic Techniques. pp. 295–310. Springer (1999)
- 26. Go: The go programming language (2009), https://go.dev
- 27. Kalodner, H.A., Carlsten, M., Ellenbogen, P., Bonneau, J., Narayanan, A.: An empirical study of namecoin and lessons for decentralized namespace design. In: WEIS. Citeseer (2015)
- 28. Kelkar, M., Deb, S., Kannan, S.: Order-fair consensus in the permissionless setting. Cryptology ePrint Archive (2021)
- 29. Kharif, O.: Cryptokitties mania overwhelms ethereum network's processing (2017), https://www.bloomberg.com/news/articles/2017-12-04/cryptokitties-quickly-becomes-most-widely-used-ethereum-app

- 30. Kogias, E.K., Jovanovic, P., Gailly, N., Khoffi, I., Gasser, L., Ford, B.: Enhancing bitcoin security and performance with strong consistency via collective signing. In: 25th usenix security symposium (usenix security 16). pp. 279–296 (2016)
- 31. Kokoris-Kogias, E., Alp, E.C., Gasser, L., Jovanovic, P., Syta, E., Ford, B.: Calypso: Private data management for decentralized ledgers. Cryptology ePrint Archive (2018)
- 32. Kraken: Cryptocurrency deposit processing times (2022(?)), https://support.kraken.com/hc/en-us/articles/203325283-, accessed: 2022-03-03
- 33. Kursawe, K.: Wendy, the good little fairness widget: Achieving order fairness for blockchains. In: Proceedings of the 2nd ACM Conference on Advances in Financial Technologies. pp. 25–36 (2020)
- 34. Kursawe, K.: Wendy grows up: More order fairness. In: International Conference on Financial Cryptography and Data Security. pp. 191–196. Springer (2021)
- 35. https://github.com/dedis/kyberThe Kyber Cryptography Library (2010 2022)
- 36. Lewis, M.: Flash boys: a Wall Street revolt. WW Norton & Company (2014)
- 37. LibSubmarine: Defeat front-running on ethereum (2017(?)), https://libsubmarine.org, accessed: 2022-01-24
- 38. Malkhi, D., Szalachowski, P.: Maximal extractable value (mev) protection on a dag. arXiv preprint arXiv:2208.00940 (2022)
- Mev-sgx: A sealed bid mev auction design (2021), https://ethresear.ch/t/mev-sgx-a-sealed-bid-mev-auction-design/9677
- 40. Mikalauskas, E.: 280 million stolen per month from crypto transactions (2021), https://cybernews.com/crypto/ flash-boys-2-0-front-runners-draining-280-million-per-month-from-crypto-transactions, accessed: 2022-02-16
- 41. Momeni, P.: Fairblock: Preventing blockchain front-running with minimal overheads. Master's thesis, University of Waterloo (2022)
- Nakamoto, S.: Bitcoin: A peer-to-peer electronic cash system. Decentralized Business Review p. 21260 (2008)
- 43. Nikitin, K., Barman, L., Lueks, W., Underwood, M., Hubaux, J.P., Ford, B.: Reducing metadata leakage from encrypted files and communication with purbs. Proceedings on Privacy Enhancing Technologies **2019**(4), 6–33 (2019)
- 44. Pass, R., Seeman, L., Shelat, A.: Analysis of the blockchain protocol in asynchronous networks. In: Annual International Conference on the Theory and Applications of Cryptographic Techniques. pp. 643–673. Springer (2017)
- Ragab, H., Milburn, A., Razavi, K., Bos, H., Giuffrida, C.: Crosstalk: Speculative data leaks across cores are real. In: 2021 IEEE Symposium on Security and Privacy (SP). pp. 1852–1867. IEEE (2021)
- 46. Rivest, R.L., Shamir, A., Wagner, D.A.: Time-lock puzzles and timed-release crypto (1996)
- 47. Sasson, E.B., Chiesa, A., Garman, C., Green, M., Miers, I., Tromer, E., Virza, M.: Zerocash: Decentralized anonymous payments from bitcoin. In: 2014 IEEE symposium on security and privacy. pp. 459–474. IEEE (2014)
- 48. Savelyev, A.: Contract law 2.0: 'smart' contracts as the beginning of the end of classic contract law. Information & communications technology law **26**(2), 116–134 (2017)
- 49. Schäffer, M., Angelo, M.d., Salzer, G.: Performance and scalability of private ethereum blockchains. In: International Conference on Business Process Management. Springer (2019)

- 50. Schmid, N.: Secure causal atomic broadcast (2021), https://crypto.unibe.ch/archive/theses/2021.bsc.noah.schmid.pdf
- 51. Schoenmakers, B.: A simple publicly verifiable secret sharing scheme and its application to electronic voting. In: Annual International Cryptology Conference. pp. 148–164. Springer (1999)
- 52. Secret markets: Front running prevention for automated market makers (2020), https://scrt.network/blog/secret-markets-front-running-prevention
- 53. Shamir, A.: Identity-based cryptosystems and signature schemes. In: Workshop on the theory and application of cryptographic techniques. pp. 47–53. Springer (1984)
- 54. Shoup, V., Gennaro, R.: Securing threshold cryptosystems against chosen ciphertext attack. In: International Conference on the Theory and Applications of Cryptographic Techniques. pp. 1–16. Springer (1998)
- 55. Combating front-running and malicious mev using threshold cryptography, https://blog.shutter.network
- 56. Shutterized beacon chain, https://ethresear.ch/t/shutterized-beacon-chain/12249
- 57. https://sikka.tech
- 58. Stathakopoulou, C., Rüsch, S., Brandenburger, M., Vukolić, M.: Adding fairness to order: Preventing front-running attacks in bft protocols using tees. In: 2021 40th International Symposium on Reliable Distributed Systems (SRDS). pp. 34–45. IEEE (2021)
- Van Bulck, J., Minkin, M., Weisse, O., Genkin, D., Kasikci, B., Piessens, F., Silberstein, M., Wenisch, T.F., Yarom, Y., Strackx, R.: Foreshadow: Extracting the keys to the intel {SGX} kingdom with transient {Out-of-Order} execution. In: 27th USENIX Security Symposium (USENIX Security 18). pp. 991–1008 (2018)
- Wong, T.M., Wang, C., Wing, J.M.: Verifiable secret redistribution for archive systems. In: First International IEEE Security in Storage Workshop, 2002. Proceedings. pp. 94–105. IEEE (2002)
- Wood, G., et al.: Ethereum: A secure decentralised generalised transaction ledger.
 Ethereum project yellow paper 151(2014), 1–32 (2014)
- 62. Xing, B.C., Shanahan, M., Leslie-Hurd, R.: Intel® software guard extensions (intel® SGX) software support for dynamic memory allocation inside an enclave. Proceedings of the Hardware and Architectural Support for Security and Privacy 2016 pp. 1–9 (2016)
- 63. Ziegeldorf, J.H., Matzutt, R., Henze, M., Grossmann, F., Wehrle, K.: Secure and anonymous decentralized bitcoin mixing. Future Generation Computer Systems 80, 448–466 (2018)

A Protocol

A.1 Full F3B Protocol

We define a cyclic group \mathbb{G} of prime order q with generators g and \bar{g} that are known to all parties, and we define the following two hash functions: $H_1: \mathbb{G}^5 \times \{0,1\}^l \to \mathbb{G}$ and $H_2: \mathbb{G}^3 \to \mathbb{Z}_q$.

Step 0: DKG Setup. Before initiating an epoch, the secret-management committee runs a DKG protocol to generate a shared public key $pk_{smc} = g^{sk_{smc}}$, and shares of the private key for each trustee are denoted as sk_i . The corresponding private key sk_{smc} can be reconstructed only by combining t private key shares. All trustees also know the verification keys $h_i = g^{sk_i}$. We assume that pk_{smc} and h_i are written into the blockchain as metadata, e.g., in the first block denoting the beginning of this epoch. We adopt the synchronous DKG protocol proposed by Gennaro et al. [25].

Step 1: Write Transaction. For the write transaction step, we use the encryption protocol presented by the TDH2 cryptosystem [54]

The sender and the consensus group execute the following protocol to write the tx_w on the underlying blockchain. The sender 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 pk_{smc} from the underlying blockchain.
- 2. Generate a symmetric key k and encrypt the transaction tx using authenticated symmetric encryption as $c_{tx} = \text{enc}_k(tx)$.
- 3. Embed k as a point $k' \in \mathbb{G}$, and choose $r, s \in \mathbb{Z}_q$ at random.
- 4. Compute:

$$c = pk_{smc}^r k', u = g^r, w = g^s, \bar{u} = \bar{g}^r, \bar{w} = \bar{g}^s,$$

 $e = H_1(c, u, \bar{u}, w, \bar{w}, L), f = s + re,$

where L is the label of the underlying blockchain⁵.

- 5. Finally, form the ciphertext $c_k = (c, L, u, \bar{u}, e, f)$ and construct the write transaction as $\operatorname{tx}_{\mathbf{w}} = [c_k, c_{\mathsf{tx}}]_{\operatorname{sig}_{\mathsf{sk}_A}}$ signed with the sender'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 (a) which block the transaction is placed onto the blockchain and (b) the number of blocks that have passed since then. Once the number of block confirmations is equal to m, which indicates that the consensus group commits the transaction, each trustee proceeds with the following step.

⁵ This can be the hash of the genesis block.

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 that 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:

$$e = \mathbf{H}_1 \left(c, u, \bar{u}, w, \bar{w}, L \right),\,$$

where $w=\frac{g^f}{u^e}$ and $\bar{w}=\frac{\bar{g}^f}{\bar{u}^e}$. 3. If the tx_w is valid, choose $s_i\in\mathbb{Z}_q$ at random and compute:

$$\begin{aligned} u_i &= u^{\mathrm{sk}_i}, \hat{u_i} = u^{s_i}, \hat{h_i} = g^{s_i}, \\ e_i &= \mathrm{H}_2\left(u_i, \hat{u_i}, \hat{h_i}\right), f_i = s_i + \mathrm{sk}_i e_i. \end{aligned}$$

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

In Item 2, the NIZK proof ensures that $\log_q u = \log_{\bar{q}} \bar{u}$, guaranteeing that whoever generated the tx_w knows the random value r. If the value of r is known, then the transaction can be decrypted; as it is impossible to generate tx_w without knowing the plaintext transaction, this property prevents replay attacks mentioned in Appendix B.2.

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

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

$$e_i = H_2\left(u_i, \hat{u_i}, \hat{h_i}\right),$$

where $\hat{u_i} = \frac{u^{f_i}}{u_i^{e_i}}$ and $\hat{h_i} = \frac{g^{f_i}}{\hat{h_i}^{e_i}}$. 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 that does the Lagrange interpolation of the shares:

$$pk_{smc}^r = \prod_{i \in S} u_i^{\lambda_i},$$

where λ_i is the i^{th} Lagrange element.

3. Recover the encoded encryption key:

$$k' = c(\operatorname{pk}_{\operatorname{smc}}^r)^{-1} = (\operatorname{pk}_{\operatorname{smc}}^r k')(\operatorname{pk}_{\operatorname{smc}}^r)^{-1}.$$

4. Retrieve k from k'.

In Item 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.

Step 4: Decryption and Execution.

- 1. Decrypt the transaction $tx = dec_k(c_{tx})$.
- 2. Execute the transaction following the consensus group's defined rules.

A.2 Slashing Protocol

We need to have a protocol that rewards anyone who can prove a trustee's or the entire secret-management committee's misbehavior to discourage the release of the shares prematurely. At the same time, we do not want anyone to accuse a secret-management committee or a specific trustee without repercussions if the SMC 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. Suppose 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. In this case, 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 $e_i = H_2\left(u_i, \hat{u_i}, \hat{h_i}\right)$ where $\hat{u_i} = \frac{u^{f_i}}{u_i^{e_i}}$ and $\hat{h_i} = \frac{g^{f_i}}{\hat{h_i}^{e_i}}$. 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).

B Security Analysis

In this section, we introduce the security analysis of F3B's protocol.

B.1 Front-Running Protection

From our threat model, we reason about 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. As the attacker cannot access the content of the transaction before it is committed on the underlying blockchain, then the attacker cannot benefit from the pending transaction. This prevents front-running attacks (by the definition of front-running). As we assume that the symmetric encryption we use is secure, the attacker cannot decrypt the transaction based on its ciphertext. Due to the properties of the TDH2 cryptosystem [54] and DKG [25] and our threat model, the attacker cannot obtain the private key and/or reconstruct the symmetric key. Recall that the attacker can collude with at most only f trustees, and that f+1 are required to recover or gain information about the symmetric key.

B.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 explain the reason the adversary is unable to benefit from such a strategy.

In the first scenario, the adversary copies completely the ciphertext c_k , the encrypted transaction c_{tx} from tx_w , and they make 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 it is hard to form a valid write-transaction with L' by the adversary. The adversary would need to generate $e' = H_1(c, u, \bar{u}, w, \bar{w}, L')$ and f = s + re', without knowing the random parameter r and s. Suppose the adversary generates $u = g^r, \bar{u} = \bar{g}^{r'}$ with $r \neq r'$ and $w = g^s, \bar{w} = \bar{g}^{s'}$ with $s \neq s'$. For tx'_w to be valid, we must have $g^f = wu^e$ and $\bar{g}^f = \bar{w}\bar{u}^e$, this implies that (s - s') + e(r - r') = 0. As $r \neq r'$, the adversary has only a negligible chance of having tx'_w pass verification.

C Discussion

In this section, we discuss some deployment challenges. We leave a detailed analysis for future work.

C.1 Transition of Epoch

Each epoch has its unique public epoch key for a user to encrypt his symmetric key used for encrypting a transaction. However, users will have difficulty choosing the correct epoch key when the time is close to the transition between two epochs. With Fairblock [41] and Shutter [55,56], undesirable transaction revealing occurs when a user chooses the wrong public key. Whereas, if the transaction is not committed, F3B never reveals any transaction, regardless of the chosen key; thus offering confidentiality to all uncommitted transactions. We also expect that such an epoch transition is infrequent, compared with a block transition, thus it causes much less trouble to users. In F3B, if a user uses an old epoch key for his encryption, he can safely try again to select the new epoch key. To mitigate the issue even more, the expiring epoch committee can offer some grace period, thus allowing both old and new epoch keys to be valid for a certain period. This significantly reduces the danger of a user choosing an incorrect key.

C.2 Ethereum Gas Fees

Ethereum uses gas fees to cover the cost of executing a transaction and implements a maximum gas limit per block. Incorporating F3B on Ethereum would then require (1) that the gas limit of each transaction to be in cleartext, and (2) that the summation of all transactions' gas limit within a block does not exceed the block gas limit. This opens the possibility for another type of spamming attack (Section 7.1), where an adversary submits transactions with substantial gas limits, thus leaving little room for other transactions.

Recall that the actual gas used by transactions cannot be determined because the sender encrypts its contents, and that accurately estimating the gas cost of a transaction is particularly difficult due to the uncertainty of the global state when validators process the transaction. One potential approach to mitigating this kind of attack would be to then burn the remaining (unused) gas. However, this approach could be too strict in practice, hence we can instead envision partial refunds: refunding the remaining gas up to a percentage.

C.3 Not every node needs to do reconstruction

Under our proposed protocol, to reconstruct the key, every consensus node must fetch the shares and run the Lagrange interpolation. Would it instead be possible for one of the consensus nodes to reconstruct the symmetric key k from the secret shares and to propagate it to other consensus nodes with a succinct proof?

Therefore, we propose a solution that requires additional storage overhead, in exchange for faster verification: Instead of constructing their encrypted transaction as $(c_k, c_{\rm tx})$, the sender additionally adds a hash of the symmetric key $h_k = H(k)$ as the third entry, creating the following signed write transaction: ${\rm tx}_{\rm w} = [c_k, c_{\rm tx}, h_k]_{{\rm sig}_{\rm sk}_A}$.

During key reconstruction, after recovering or receiving k, consensus nodes need to verify only 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 is discarded.

C.4 Reducing Storage Overhead

In the TDH2 cryptosystem, the label L is attached to the ciphertext during the encryption process; this includes the information that can be used by a secret-management committee to determine if the decryption is authorized [54]. Although we cannot remove L as its used for protection against replay attacks (Appendix B.2), each party (consensus group, secret-management committee, sender) knows L implicitly and can insert L in their computation and verification steps, the enabling the sender to exclude L from tx_{w} .

C.5 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, to launch speculative attacks, adversaries can rely on side channels such as transaction metadata. Concretely, as the sender needs to pay the storage fee (Section 7.1) 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 because an adversary might be able, based on the sender's history, to predict the sender's behavior. To prevent this second-order front-running attack, a sender can use a different address to pay for the storage fee. The underlying blockchain can also offer anonymous payment to users, such as Zerocash [47] or a mixing service [63]. 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 [43].

C.6 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 these keys independently from the blockchain, but this requires them to maintain an additional immutable ledger. As 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 when producing 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, thus 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 we need 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. Assuming that the key reconstruction step takes up to δ block times, the key should be written in or before the block $n+m+\delta$.

Although this setup would work well for a blockchain with fixed block time, care must be taken for blockchains where block time is probabilistic as the key might not have been replicated to all consensus nodes at block height $n+m+\delta$, thus some artificial delay for new blocks could be induced.