Be Prepared When Network Goes Bad: An Asynchronous View-Change Protocol

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The popularity of permissioned blockchain systems demands BFT SMR protocols that are efficient under good network conditions (synchrony) and robust under bad network conditions (asynchrony). The state-of-the-art partially synchronous BFT SMR protocols provide optimal linear communication cost per decision under synchrony and good leaders, but lose liveness under asynchrony. On the other hand, the state-of-the-art asynchronous BFT SMR protocols are live even under asynchrony, but always pay quadratic cost even under synchrony. In this paper, we propose a BFT SMR protocol that achieves the best of both worlds – optimal linear cost per decision under good networks and leaders, optimal quadratic cost per decision under bad networks, and remains always live.

CCS Concepts: • Theory of computation → Distributed algorithms; • Security and privacy → Distributed systems security.

Additional Key Words and Phrases: Byzantine faults, state machine replication, asynchrony, view-change protocol, optimal

1 INTRODUCTION

The popularity of blockchain protocols has generated a surge in researching how to increase their efficiency and robustness. On increasing the efficiency front, Hotstuff [34] has managed to achieve linear communication complexity, hitting the limit for deterministic consensus protocols [32]. This linearity, however, is only provided during good network conditions and when the leader is honest. Otherwise a quadratic pacemaker protocol, described in a production version of HotStuff named DiemBFT [6], helps slow parties catch-up. In the worse case of an asynchronous adversary there is no liveness guarantee.

For robustness, randomized asynchronous protocols VABA [4], Dumbo [26] and ACE [33] are the state of the art. The main idea of these protocols is to make progress as if every node is the leader and retroactively decide on a leader. As a result, the network adversary only has a small probability of guessing which nodes to corrupt. To achieve this, however, these protocols pay a quadratic communication cost even under good network conditions.

In this paper we achieve the best of both worlds. When the network behaves well and the consensus makes progress we run DiemBFT [6], adopting its linear communication complexity. However, when there is a problem and the majority of nodes cannot reach the leader we proactively run an asynchronous view-change protocol that makes progress even under the strongest network adversary. As a result, depending on the conditions we pay the appropriate cost while at the same time always staying live.

In Table 1 we show a comparison of our work with the state of the art. In addition to the related work HotStuff, DiemBFT, VABA and ACE, a recent work [32] proposes a single-shot validated BA that has quadratic cost under asynchrony, with a synchronous fast path of cost \( O(nf') \) under \( f' \) actual faults, and \( O(n) \) when there are no faults. Inspired by [32], we propose a protocol for BFT state machine replication that achieves the best of both worlds, and keeps the amortized efficiency and simplicity of the chain-based BFT SMR protocols such as HotStuff and DiemBFT. More related work can be found in Appendix 5. Additionally we show in the Appendix 4 how to decrease the latency of our consensus protocol from 3-chain to 2-chain, leveraging the quadratic cost that the pacemaker anyway imposes during bad network conditions.

| Problem          | Comm. Complexity | Liveness                      |
|------------------|------------------|-------------------------------|
| HotStuff [34]/Diem [6] | partially sync SMR | sync \( O(n) \) | not live if async |
| VABA [4]/Dumbo [26]   | async BA         | \( O(n^2) \)       | always live     |
| ACE [33]           | async SMR        | \( O(n^4) \)       | always live     |
| Spiegelman’20 [32]  | async BA with fast sync path | \( O(nf'), \) async \( O(n^4) \) | always live |
| Ours              | async SMR with fast sync path | sync \( O(n) \), async \( O(n^4) \) | always live |

Table 1. Comparison to Related Works. For HotStuff/Diem and our protocol, sync \( O(n) \) assumes honest leaders.

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2 PRELIMINARIES

We consider a permissioned system that consists of an adversary and \( n \) replicas numbered \( 1, 2, \ldots, n \), where each replica has a public key certified by a public-key infrastructure (PKI). Some replicas are Byzantine with arbitrary behaviors and controlled by an adversary; the rest of the replicas are called honest. The replicas have all-to-all reliable and authenticated communication channels controlled by the adversary. An execution of a protocol is synchronous if all message delays between honest replicas are bounded by \( A \); is asynchronous if they are unbounded; and is partially synchronous if there is a global stabilization time (GST) after which they are bounded by \( A \). Without loss of generality, we let \( n = 3f + 1 \) where \( f \) denotes the assumed upper bound on the number of Byzantine faults, which is the optimal worst-case resilience bound for asynchrony, partial synchrony [14], or asynchronous protocols with fast synchronous path [8].

Cryptographic primitives and assumptions. We assume standard digital signature and public-key infrastructure (PKI), and use \( \langle m \rangle_i \) to denote a message \( m \) signed by replica \( i \). We also assume a threshold signature scheme, where a set of signature shares for message \( m \) from \( t \) (the threshold) distinct replicas can be combined into one threshold signature of the same length for \( m \). We use \( \{ m \} \) to denote a threshold signature share of a message \( m \) signed by replica \( i \). We also assume a collision-resistant cryptographic hash function \( H(\cdot) \) that can map an input of arbitrary size to an output of fixed size. We assume a strongly adaptive adversary that is computationally bounded. For simplicity, we assume the above cryptographic schemes are ideal and a trusted dealer equips replicas with the above cryptographic schemes. The dealer assumption can be lifted using the protocol of Kokoris-Kogias et al. [21].

BFT SMR. A Byzantine fault tolerant state machine replication protocol [3] commits client transactions as a log akin to a single non-faulty server, and provides the following two guarantees:

- Safety. Honest replicas do not commit different transactions at the same log position.
- Liveness. Each client transaction is eventually committed by all honest replicas.

Besides the two requirements above, a validated BFT SMR protocol also requires to satisfy the external validity [11], which requires any committed transactions to be externally valid, satisfying some application-dependent predicate. This can be done by adding validity checks on the transactions before the replicas proposing or voting, and for brevity we omit the details and focus on the BFT SMR formulation defined above. For most of the paper, we omit the client from the discussion and only focus on replicas.

Terminologies. We define several terminologies commonly used in the literature [6, 34].

- **Round Number and View Number.** The protocol proceeds in rounds \( r = 1, 2, 3, \ldots \), and each round \( r \) has a designated leader \( L_r \) to propose a new block of round \( r \). Each replica keeps track of the current round number \( r_{\text{cur}} \). In addition to the round number, every replica also keeps track of the current view number \( v_{\text{cur}} \) of the protocol. The original DiemBFT does not need to introduce the view number, but it is convenient to have it here for the asynchronous view-change protocol later. The view number starts from 0 and increments by 1 after each asynchronous fallback (so in original DiemBFT it is always 0 and can be neglected).
- **Block Format.** A block is formatted as \( B = [i, d, q, r, o, txn] \) where \( q \) is the quorum certificate of \( B \)’s parent block, \( r \) is the round number of \( B \), \( o \) is the view number of \( B \), \( txn \) is a batch of new transactions, and \( id = H(q, r, v, txn) \) is the unique hash digest of \( q, r, v, txn \). For brevity, we will only specify \( q, r \) and \( o \) for a new block, and \( txn, id \) will follow the same definition above. We will use \( B.x \) to denote the element \( x \) of \( B \). As mentioned, \( B.0 \) will always be 0 for any block in the original DiemBFT description.
- **Quorum Certificate.** A quorum certificate (QC) of some block \( B \) is a threshold signature of a message that includes \( B.id, B.r, B.o, B.txn \), produced by combining the signature shares \( \{ B.id, B.r, B.o, B.txn \} \) from a quorum of replicas \( (n - f = 2f + 1 \) replicas). We say a block is certified if there exists a QC for the block. The round/view number of \( q \) for \( B \) is denoted by \( q_c.r/q_c.v \), which equals \( B.r/B.o \). A QC or a block of view number \( o \) and round number \( r \) has rank \( rank = (o, r) \). QCs or blocks are ranked first by the view number and then by the round number, i.e., \( q_{c1}.rank > q_{c2}.rank \) if \( q_{c1}.o > q_{c2}.o \), or \( q_{c1}.o = q_{c2}.o \) and \( q_{c1}.r > q_{c2}.r \). The function \( \max(rank_1, rank_2) \) returns the higher rank between \( rank_1 \) and \( rank_2 \), and \( \max(q_{c1}.q_c, q_{c2}.q_c) \) returns the higher ranked QC between \( q_{c1} \) and \( q_{c2} \). As mentioned, in the original DiemBFT, the view number is always 0, thus QCs or blocks are ranked only by round numbers.
- **Timeout Certificate.** A timeout certificate (TC) is a threshold signature on a round number \( r \), produced by combining the signature shares \( \{ r \} \) from a quorum of replicas \( (n - f = 2f + 1 \) replicas).
Let $L_r$ be the leader of round $r$. Each replica keeps the highest voted round $r_{vote}$, the highest locked rank $r_{lock}$, the current round $r_{cur}$, the current view $v_{cur}$, and the highest quorum certificate $q_{cur}$. Initially, every replica initializes its $r_{vote} = v_{cur} = 0, r_{lock} = (0, 0), r_{cur} = 1, q_{high}$ to be the QC of the genesis block of round 0, and enters round 1. Without asynchronous fallback, $v_{cur}$ is always 0.

**Steady State Protocol for Replica $i$**

- **Propose.** Upon entering round $r$, the leader $L_r$ multicasts a block $B = [id, q_{high}, r, v_{cur}, txn]$.
- **Vote.** Upon receiving the first valid proposal $B = [id, q_c, r, v, txn]$ from $L_r$, execute Lock. If $r = r_{cur}, v = v_{cur}, r > r_{vote}$ and $q_c.rank \geq r_{lock}$, vote for $B$ by sending the threshold signature share $(i, r, v)$ to $L_{r+1}$, and update $r_{vote} \leftarrow r$.
- **Lock.** (2-chain lock rule) Upon seeing a valid $q_c$ (formed by votes or contained in proposal or timeout), execute Advance Round. Let $q_c'$ be the QC contained in the block certified by $q_c$ (i.e., $q_c'$ is the parent of $q_c$), the replica updates $r_{lock} \leftarrow \max(r_{lock}, q_c'.rank)$, and $q_{high} \leftarrow \max(q_{high}, q_c')$. Execute Commit.
- **Commit.** (3-chain commit rule) Whenever there exist three adjacent certified blocks $B, B', B''$ in the chain with consecutive round numbers, i.e., $B'' = B', r + 1 = B'.r + 2$, the replica commits $B$ and all its ancestors.

**Pacemaker Protocol for Replica $i$**

- **Advance Round.** The replica updates its current round $r_{cur} \leftarrow \max(r_{cur}, r)$, iff
  - the replica receives or forms a round-(r−1) quorum certificate $q_c$, or
  - the replica receives or forms a round-(r−1) timeout certificate $t_c$.
- **Timer and Timeout.** Upon entering round $r$, the replica sends the round-(r−1) timeout to $L_r$, stops all timers and stops voting for round $< r$, and sets a timer $T_r$ for round $r$. Upon the timer $T_r$ expires, the replica stops voting for round $r$ and multicasts a timeout message $(\{r\}_i, q_{high})$ where $\{r\}_i$ is a threshold signature share.

Fig. 1. DiemBFT Protocol.

### 2.1 DiemBFT

**Description of the DiemBFT Protocol.** The DiemBFT protocol (also known as LibraBFT) [6] is a production version of HotStuff [34] with a synchronizer implementation (Pacemaker), as shown in Figure 1. There are two components of DiemBFT, a Steady State protocol that aims to make progress when the round leader is honest, and a Pacemaker (view-change) protocol that advances the round number either due to the lack of progress or the current round being completed. The leader $L_r$, once entering the round $r$, will propose a block $B$ extending the block certified by the highest QC $q_{high}$. When receiving the first valid round-$r$ block from $L_r$, any replica tries to advance its current round number, update its highest locked rank and its highest QC, and checks if any block can be committed. A block can be committed if it is the first block among 3 adjacent certified blocks with consecutive round numbers. After the above steps, the replica will vote for $B$ by sending a threshold signature share to the next leader $L_{r+1}$, if the voting rules are satisfied. Then, when the next leader $L_{r+1}$ receives $2f + 1$ votes above that form a QC of round $r$, it enters round $r + 1$ and proposes the block for that round, and the above steps repeat. When the timer of some round $r$ expires, the replica stops voting for that round and multicasts a timeout message containing a threshold signature share for $r$ and its highest QC. When any replica receives $2f + 1$ such timeout messages that form a TC of round $r$, it enters round $r + 1$ and sends the TC to the leader $L_{r+1}$.

For space limitation, we omit the correctness proof of the DiemBFT protocol, which can be found in [6].

The DiemBFT protocol has linear communication complexity per round under synchrony and honest leaders due to the leader-to-all communication pattern and the use of threshold signature scheme\(^1\), and quadratic communication complexity for synchronization caused by asynchrony or bad leaders due to the all-to-all multicast of timeout messages. Note that during the periods of asynchrony, the protocol has no liveness guarantees - the leaders may always suffer from network delays, replicas keep multicasting timeout messages and advancing round numbers, and no block can be certified or committed. To improve the liveness of the DiemBFT protocol and similarly other partially synchronous BFT protocols, we propose a new view-change protocol in the next section named the Asynchronous Fallback protocol, which has the optimal quadratic communication complexity and always makes progress even under asynchrony.

\(^1\)Although in the implementation, DiemBFT does not use threshold signature, in this paper we consider a version of DiemBFT that uses the threshold signature scheme.
3  AN ASYNCHRONOUS VIEW-CHANGE PROTOCOL

To strengthen the liveness guarantees of existing partially synchronous BFT protocols such as DiemBFT [6], we propose an asynchronous view-change protocol (also called asynchronous fallback [32]) that has quadratic communication complexity and always makes progress even under asynchrony. The Asynchronous Fallback protocol is presented in Figure 2, which can replace the Pacemaker protocol in DiemBFT (Figure 1) to obtain a BFT protocol that has linear communication cost for the synchronous path, quadratic cost for the asynchronous path, and is always live.

Additional Terminologies.

• **Fallback-block and Fallback-chain.** For the Asynchronous Fallback protocol, we define another type of block named **fallback-block** (**f-block**), denoted as $\mathcal{B}_f$. In contrast, the block defined earlier is called the **regular block**. An f-block $\mathcal{B}_f$ adds two additional fields to a regular block, formatted as $\mathcal{B}_f = [B, height, proposer]$ where $B$ is a regular block, $height \in \{1, 2, 3\}$ is the position of the f-block in the fallback-chain and **proposer** is the replica that proposes the block. We will use $\mathcal{B}_{h,i}$ to denote a height-$h$ f-block proposed by replica $i$. A fallback-chain (f-chain) consists of f-blocks. In the fallback protocol, every replica will construct its fallback-chain (f-chain) with f-blocks, extending the block certified by its $q_{\text{high}}$.

• **Fallback-QC.** A fallback quorum certificate (**f-QC**) $\mathcal{F}$ for an f-block $\mathcal{B}_{h,i}$ is a threshold signature for the message $(\mathcal{B}_{h,i}.id, \mathcal{B}_{h,i}.r, \mathcal{B}_{h,i}.v, h, i)$, produced by combining the signature shares $(\mathcal{B}_{h,i}.id, \mathcal{B}_{h,i}.r, \mathcal{B}_{h,i}.v, h, i)$ from a quorum of replicas $(n - f = 2f + 1)$ replicates. An f-block is certified if there exists an f-QC for the f-block. f-QCs or f-blocks are first ranked by view numbers and then by round numbers.

• **Fallback-TC.** A fallback timeout certificate (**f-TC**) $\mathcal{F}$ is a threshold signature for a view number $v$, produced by combining the signature shares $(v)$ from a quorum of replicas $(n - f = 2f + 1)$ replicates. f-TCs are ranked by view numbers.

• **Leader Election and Coin-QC.** We assume a black-box leader election primitive such as [25], that can randomly elect a unique leader $L$ among $n$ replicates with probability $1/n$ for any view $v$, by combining $f + 1$ valid coin shares of view $v$ from any $f + 1$ distinct replicates. A coin-QC $q_{\text{coin}}$ of view $v$ is formed with these $f + 1$ coin shares, each produced by a replica. The probability of the adversary to predict the outcome of the election is at most $1/n$ (we assume the cryptographic schemes are ideal).

• **Endorsed Fallback-QC and Endorsed Fallback-block.** Once a replica has a coin-QC $q_{\text{coin}}$ of view $v$ that elects replica $L$ as the leader, we say any f-QC of view $v$ by replica $L$ is endorsed (by $q_{\text{coin}}$), and the f-block certified by the f-QC is also endorsed (by $q_{\text{coin}}$). Any endorsed f-QC is handled as a QC in any steps of the protocol such as **Lock, Commit, Advance Round. An endorsed f-QC ranked higher than any QC have with the same view number.** As cryptographic evidence of endorsement, the first block in a new view can additionally include the coin-QC of the previous view, which is omitted from the protocol description for brevity.

Description of the Asynchronous Fallback Protocol. The illustration of the fallback protocol can be found in Figure 3. Now we give a description of the Asynchronous Fallback protocol (Figure 2), which replaces the Pacemaker protocol in the DiemBFT protocol (Figure 1). Each replica additionally keeps a boolean value $\text{fallback-mode}$ to record if it is in a fallback, during which the replica will not vote for any regular block. When the timer for round $r$ expires, the replica enters the fallback and multicasts a timeout message containing its highest QC $q_{\text{high}}$ and a threshold signature share of the current view number. When receiving $2f + 1$ timeout messages of the same view number no less than the current view, the replica forms a fallback-TC $\mathcal{F}$ and enters the fallback. The replica also updates its current view number $v_{\text{cur}}$, and initializes the voted round number $\mathcal{F}_{\text{vote}}[j] = 0$ and the voted height number $\mathcal{F}_{\text{vote}}[j] = 0$ for each replica $j$. Finally, the replica starts to build the fallback-chain by multicasting the $\mathcal{F}$ and proposing the first fallback-block of height 1, round number $q_{\text{high}}.r + 1$, view number $v_{\text{cur}}$, and has the block certified by $q_{\text{high}}$ as the parent. When receiving such a height-1 f-block proposed by any replica $j$, replicas that are in the fallback and not yet voted for height-1 f-block by $j$, will verify the validity of the f-block, update the voted round and height number for the fallback, and vote for the f-block by sending the threshold signature share back to the replica $j$. When the replica receives $2f + 1$ votes that form a fallback-QC for its height-1 f-block, the replica can propose the next f-block in its f-chain, which has height and round number increased by 1, and has the height-1 f-block as the parent. When receiving such a height-2 f-block proposed by any replica $j$, replicas that are in the fallback and not yet voted for any height-2 f-block by $j$, will similarly update the voted round and height number and vote for the f-block, after verifying the validity of the f-block. Similarly, when the height-2 f-block gets certified, the proposer can propose the height-3 f-block extending the height-2 f-block. When the height-3 f-block gets certified by an f-QC, the proposer multicasts the height-3 f-QC. When the replica receives $2f + 1$ height-3 f-QCs of the current view, it knows that $2f + 1$ f-chains have been completed. The replica then will start the leader election by signing and multicasting a coin share for the
Each replica keeps a boolean value `fallback-mode`, initialized as `false`, to record whether it is in a fallback. During a fallback of view `v`, for every replica `j ∈ [n]`, each replica records all the f-QCs of view `v` by replica `j`, and keeps a voted round number `𝑣_𝑜𝑡𝑒[𝑖][𝑗]` and a voted height number `ℎ_𝑜𝑡𝑒[𝑖][𝑗]`.

Changes to the Steady State Protocol in Figure 1
- **Vote.** Before voting, each replica additionally checks whether `fallback-mode = false` and `𝑟 = 𝑞𝑐𝑟 + 1`.  
- **Commit.** Each of the three adjacent blocks can be a certified block or an endorsed fallback-block, but they need to have the same view number.

Async. Fallback Protocol for Replica `i`
- **Advance Round.** Upon receiving a valid `𝑞𝑐`, the replica updates its current round `𝑐𝑢𝑟 ← max(𝑐𝑢𝑟, 𝑞𝑐𝑟 + 1)`.
- **Timer and Timeout.** Upon entering a new round `𝑟`, the replica stops any timer and stops voting for regular blocks of round `𝑟 < 𝑟`, sets a timer `𝑇𝑟` for round `𝑟`.
- **Commit.** Upon receiving a valid timeout message, execute `Lock`.
- **Enter Fallback.** Upon receiving `2𝑓 + 1` timeout messages that form an f-TC `𝑇𝑐` of view `𝑣_𝑐𝑢𝑟 ≥ 𝑣_𝑐𝑢𝑟`, update `fallback-mode ← true`, and multicasts a timeout message `<{𝑐𝑢𝑟}, ℎ_𝑡𝑖𝑚𝑒>` to all replicas.
- **Exit Fallback.** Upon receiving a coin-QC `𝑞𝑐_𝑡𝑖𝑚𝑒` and `fallback-mode = true`, and multicasts `𝑞𝑐_𝑡𝑖𝑚𝑒` to all replicas.

Fig. 2. DiemBFT with Asynchronous Fallback.

(a) This figure illustrates the high-level picture of the protocol. During the fallback, each replica acts as a leader and tries to build a certified fallback-chain. When `2𝑓 + 1` f-chains are completed, randomly elects one leader from `𝑛` replicas, and all replicas continue the Steady State chain from the f-chain built by the elected leader.

(b) This figure illustrates of one fallback-chain built by replica `𝐿` in the asynchronous fallback of view `𝑣`. The first fallback-block `𝐵_𝐿` of height 1 contains the `𝑞𝑐_𝑡𝑖𝑚𝑒`, and the second and third f-block contains the f-QC of the previous f-block. `2𝑓 + 1` height-3 f-QCs will trigger the leader election to form a coin-QC `𝑞𝑐_𝑡𝑖𝑚𝑒` that randomly selects a replica as the leader with probability `1/𝑛`. Replicas continue the Steady State from the f-chain by the leader.

Fig. 3. Illustrations of the Asynchronous Fallback Protocol.

current view number, and a unique leader of the view can be elected by any of the `𝑓 + 1` valid coin share messages. When receiving such `𝑓 + 1` coin share messages, a coin-QC `𝑞𝑐_𝑡𝑖𝑚𝑒` can be formed. The fallback is finished once a `𝑞𝑐_𝑡𝑖𝑚𝑒` is received, and the replica updates `fallback-mode = false` to exit the fallback and enters the next view. To ensure consistency, the replica also updates the highest voted round number `𝑣_𝑜𝑡𝑒` to be the voted round number for the leader during the fallback, and updates its highest QC
Proof of Correctness

Recall that we say a fallback-block \( \overline{B} \) of view \( v \) by replica \( i \) is endorsed, if \( \overline{B} \) is certified and there exists a coin-QC of view \( v \) that elects replica \( i \) as the leader.

We say a replica is in the Steady State of view \( v \), if it has fallback-mode = false and \( v_{\text{curr}} = v \); otherwise if fallback-mode = true and \( v_{\text{curr}} = v \), we say the replica is in the asynchronous fallback of view \( v \).

We use \( C(B) \) to denote the set of replicas who provide votes for the QC or f-QC for \( B \).

If a block or f-block \( B \) is an ancestor of another block or f-block \( B' \) due to a chain of QCs or endorsed f-QCs, we say \( B' \) extends \( B \). A block or f-block also extends itself.

Rules for Leader Rotation. Let \( L = \{ L_1, L_2, \ldots \} \) be the infinite sequence of predefined leaders corresponding to the infinite round numbers starting from 1. To ensure the liveness of synchronous fast path, we rotate the leader once every 4 rounds, i.e., \( L_{4k+1}, \ldots, L_{4k+4} \) are the same replica for every \( k \geq 0 \).

Lemma 1. Let \( B, B' \) both be endorsed f-blocks of the same view, or both be certified blocks of the same view. If the round number of \( B \) equals the round number of \( B' \), then \( B = B' \).

Proof. Suppose on the contrary that \( B \neq B' \). Let \( r \) be the round number of \( B, B' \).

Suppose that \( B, B' \) both are certified blocks of the same view. Since \( n = 3f + 1 \) and \( |C(B)| = |C(B')| = 2f + 1 \), by quorum intersection, \( C(B) \cap C(B') \) contains at least one honest replica \( h \) who voted for both \( B \) and \( B' \). Without loss of generality, suppose that \( h \) voted for \( B \) first. According to the Vote step, \( h \) updates its \( r_{\text{vote}} = r \) and will only vote for blocks with round number \( > r_{\text{vote}} \) in the same view. Therefore \( h \) will not vote for \( B' \), thus \( B' \) cannot be certified, contradiction.

Suppose that \( B, B' \) both are endorsed f-blocks of the same view. By quorum intersection, at least one honest replica \( h \) voted for both \( B \) and \( B' \). Without loss of generality, suppose that \( h \) voted for \( B \) first. Since \( B, B' \) are of the same view with elected leader \( L \), according to the Fallback Vote step, after voting for \( B \) of round \( r \), \( h \) updates \( r_{\text{vote}}[L] = r \) and will only vote for blocks of round number \( > r_{\text{vote}}[L] \). Thus \( h \) will not vote for \( B' \) and \( B' \) cannot be certified, contradiction.

Lemma 2. For any chain that consists of only certified blocks and endorsed f-blocks, the adjacent blocks in the chain have consecutive round numbers, and nondecreasing view numbers. Moreover, for blocks of the same view number, no endorsed f-block can be the parent of any certified regular block.

Proof. Suppose on the contrary that there exist adjacent blocks \( B, B' \) of round number \( r, r' \) where \( B \) is the parent block of \( B' \), and \( r' \neq r + 1 \). If \( B' \) is a certified block, according to the Vote step, honest replicas will not vote for \( B' \) since \( r' \neq r + 1 \), and \( B' \) cannot be certified, contradiction. If \( B \) is an endorsed f-block, according to the Fallback Vote step, honest replicas will not vote for \( B' \) since \( r' \neq r + 1 \), and \( B' \) cannot be certified, contradiction. Therefore, the blocks in the chain have consecutive round numbers.

Suppose on the contrary that there exist adjacent blocks \( B, B' \) of view number \( v, v' \) where \( B \) is the parent block of \( B' \), and \( v' < v \).

Since \( n = 3f + 1 \) and \( |C(B)| = |C(B')| = 2f + 1 \), by quorum intersection, \( C(B) \cap C(B') \) contains at least one honest replica \( h \) who
voted for both $B$ and $B'$. According to the Vote and Fallback Vote steps, $h$ has its $v_{\text{cur}} = v$ when voting for $B$. According to the protocol, $h$ only updates its $v_{\text{cur}}$ in steps Enter Fallback and Exit Fallback, and $v_{\text{cur}}$ is nondecreasing. Hence, $h$ will not vote for $B'$ since $v' < v_{\text{cur}}$. Contradiction. Therefore, the blocks in the chain have nondecreasing view numbers.

Suppose on the contrary that there exist adjacent blocks $B, B'$ of the same view number $v$ where $B$ is the parent block of $B'$, and $B$ is an endorsed f-block and $B'$ is a certified block. Since $n = 3f + 1$ and $|C(B)| = |C(B')| = 2f + 1$, by quorum intersection, $C(B) \cap C(B')$ contains at least one honest replica $h$ who voted for both $B$ and $B'$. According to the Fallback Vote step, $h$ has fallback-mode = true when voting for $B$. According to the Vote step, $h$ has fallback-mode = false when voting for $B'$. The only step for $h$ to set its fallback-mode to false is the Exit Fallback step, where $h$ also updates its current view to $v + 1$. Then, $h$ will not vote for the view-$v$ block $B'$, contradiction. Therefore, for blocks of the same view number, no fallback-block can be the parent of any regular block. □

**Lemma 3.** Let $B, B'$ both be endorsed f-blocks of the same view, then either $B$ extends $B'$ or $B'$ extends $B$.

**Proof.** Suppose on the contrary that $B, B'$ do not extend one another, and they have height numbers $h, h'$ respectively. Let $L$ be the replica that proposes $B, B'$ and elected by the coin-QC. Without loss of generality, assume that $h \leq h'$. According to the Fallback Vote step, each honest replica votes for f-blocks of $L$ with strictly increasing height numbers. Since by quorum intersection, there exists at least one honest replica $h$ that voted for both $B$ and $B'$, thus we have $h < h'$. Since $h' > h$, and according to the Fallback Vote step, there must be another endorsed f-block $B''$ by $L$ of height $h$ that $B''$ extends, and $B, B''$ do not extend one another. Similarly, by quorum intersection, at least one honest replica voted for both $B$ and $B''$, which is impossible since each honest replica votes for f-blocks of $L$ with strictly increasing height numbers. Therefore, $B, B'$ extend one another. □

**Lemma 4.** If there exist three adjacent certified or endorsed blocks $B_r, B_{r+1}, B_{r+2}$ in the chain with consecutive round numbers $r, r + 1, r + 2$ and the same view number $v$, then any certified or endorsed block of view number $v$ that ranks no lower than $B_r$ must extend $B_r$.

**Proof.** Suppose on the contrary that there exists a block of view number $v$ that ranks no lower than $B_r$ and does not extend $B_r$. Let $B$ be such a block with the smallest rank, then the parent block $B'$ of $B$ also does not extend $B_r$, but ranks no higher than $B_r$. By Lemma 2, there are 3 cases: (1) $B_r, B_{r+2}$ are certified blocks, (2) $B_r$ is a certified block and $B_{r+2}$ is an endorsed blocks, and (3) $B_r, B_{r+2}$ are endorsed blocks.

Suppose $B_r, B_{r+2}$ are certified blocks. By quorum intersection, $C(B) \cap C(B_{r+2})$ contains at least one honest replica $h$ who voted for both $B$ and $B_{r+2}$. According to the Vote and Lock step, when $h$ votes for $B_{r+2}$, it sets its $\text{rank}_{\text{lock}}$ to be the rank of $B_r$. Suppose that $B$ is a certified block, by Lemma 1, $B$ must has round number $\geq r + 3$ otherwise $B$ will extend $B_r$. If the parent block $B'$ of $B$ has view number $< v$, then $B'$ ranks lower than $B_r$. If $B'$ has view number $v$, by Lemma 2 and 1, $B'$ is a certified block and has round number $\leq r$, thus also ranks lower than $B_r$. According to the Vote step, $h$ will not vote for $B$ since $B'$ has rank lower than its $\text{rank}_{\text{lock}}$ in round $\geq r + 3$, contradiction. Suppose that $B$ is a endorsed block, let $B_1$ be the height-1 endorsed block of view $v$, and let $B_1'$ be the parent block of $B_1$, which ranks no higher than $B_r$. If $B_1'$ is a certified block, by the same argument above we have $B_1'$ ranks lower than $B_r$. If $B_1'$ is an endorsed block, since $B_1'$ ranks no higher than $B_r$ its has view number $\leq v$. By definition an endorsed block ranks higher than a certified block if they have the same view number, thus $B_1'$ must have view number $< v$ and rank lower than $B_r$. By quorum intersection, at least one honest replica $h'$ voted for both $B_1$ and $B_{r+2}$, and has $\text{rank}_{\text{lock}}$ to be the rank of $B_r$. However, according to the Fallback Vote step, $h'$ will not vote for $B_1$ since $B_1'$ ranks lower than its $\text{rank}_{\text{lock}}$. Contradiction.

Suppose $B_r$ is a certified block and $B_{r+2}$ is an endorsed blocks. Suppose that $B$ is a certified block, by Lemma 1, $B$ must has round number $\geq r + 1$ otherwise $B$ will extend $B_r$. Since $B, B_r$ does not extend one another, by Lemma 2, there exists a round- $r$ block $B_1' \neq B_r$ that $B$ extends. By Lemma 2, $B_1'$ has view number $\leq v$. If $B_1'$ has view number $v$, by Lemma 1, $B_r = B_1'$, contradiction. If $B_1'$ has view number $\leq v - 1$, by quorum intersection, there exists at least one honest replica that voted for both $B_r'$ and $B_r$. According to the steps Vote, Fallback Vote, after voting for $B_r'$, $h$ sets its $r_{\text{vote}} = r$ and will not vote for regular blocks of round number $\leq r$. Hence, $h$ will not vote for $B_r$ of round number $r$, contradiction. Suppose that $B$ is an endorsed block, by Lemma 3, $B$ and $B_{r+2}$ extend one another. By Lemma 2, no endorsed f-block can be the parent of any certified block of the same view, therefore $B$ must extend $B_r$, contradiction.

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Suppose $B_r, B_{r+2}$ are endorsed blocks. Suppose that $B$ is a certified block. Since $B, B_r$ both have view number $v$, and by definition an endorsed block ranks higher than a certified block if they have the same view number, $B$ ranks lower than $B_r$, contradiction.

Suppose that $B$ is an endorsed block. By Lemma 3, $B$ and $B_r$ extend one another. Since $B$ ranks no lower than $B_r$ and endorsed f-blocks in the chain have consecutive round numbers, we have $B$ extends $B_r$, contradiction.

Therefore, any certified or endorsed block of view number $v$ that ranks no lower than $B_r$ must extend $B_r$.

\[ \Box \]

**Lemma 5.** If a block $B_r$ is committed by some honest replica due to a 3-chain starting from $B_r$, and another block $B_r'$ is committed by some honest replica due to a 3-chain starting from $B_r'$, then either $B_r$ extends $B_r'$ or $B_r'$ extends $B_r$.

**Proof.** Suppose on the contrary that $B_r, B_r'$ are committed by honest replica, but they do not extend one another. Suppose there exist three adjacent certified or endorsed blocks $B_r, B_{r+1}, B_{r+2}$ in the chain with consecutive round numbers $r, r+1, r+2$ and the same view number $v$. Suppose there also exist three adjacent certified or endorsed blocks $B_r, B_r', B_{r'+1}, B_{r'+2}$ in the chain with consecutive round numbers $r', r'+1, r'+2$ and the same view number $v'$. Without loss of generality, suppose that $v \leq v'$.

If $v = v'$, without loss of generality, further assume that $r \leq r'$. By Lemma 4, any certified or endorsed block of view number $v$ that ranks no lower than $B_r$ must extend $B_r$. Since $v = v'$ and $r \leq r'$, $B_r'$ ranks no lower than $B_r$, and thus $B_r'$ must extend $B_r$, contradiction.

If $v < v'$, by Lemma 2, there exist blocks that $B_r'$ extends, have view numbers $\geq v$, and do not extend $B_r$. Let $B$ be such a block with the smallest view number. Then the parent block $B'$ of $B$ also does not extend $B_r$, and has view number $\leq v$. By quorum intersection, at least one honest replica $h$ voted for both $B_{r+2}$ and $B$. According to the Lock step, after $h$ voted for $B_{r+2}$ in view $v$, it sets its highest locked rank $\text{rank}_{\text{lock}}$ to be the rank of $B_r$. Then, when $h$ votes for $B$, according to the steps Vote, Fallback Vote, the rank of the parent block $B'$ must be $\geq \text{rank}_{\text{lock}}$, and thus no lower than the rank of $B_r$. By definition $B'$ has view number $\leq v$, hence $B'$ must have view number $v$. By Lemma 4, $B'$ of view number $v$ and ranks no lower than $B_r$ must extend $B_r$, contradiction.

Therefore, we have either $B_r$ extends $B_r'$, or $B_r$ extends $B_r'$.

\[ \Box \]

**Theorem 1 (Safety).** If blocks $B$ and $B'$ are committed at the same height in the blockchain by honest replicas, then $B = B'$.

**Proof.** Suppose that $B$ is committed due to a block $B_l$ of round $l$ being directly committed by a 3-chain, and $B'$ is committed due to a block $B_k$ of round $k$ being directly committed by a 3-chain. By Lemma 5, either $B_l$ extends $B_k$ or $B_k$ extends $B_l$, which implies that $B = B'$.

\[ \Box \]

**Lemma 6.** If all honest replicas enter the asynchronous fallback of view $v$ by setting fallback-mode = true, then eventually they all exit the fallback and set fallback-mode = false. Moreover, with probability $2/3$, at least one honest replica commits a new block after exiting the fallback.

**Proof.** Suppose that all honest replicas set fallback-mode = true and have $v_{\text{cur}} = v$.

We first show that all honest replicas will vote for the height-1 fallback-block proposed by any honest replica. Suppose on the contrary that some honest replica $h$ does not vote for the height-1 f-block proposed by some honest replica $h'$. According to the step Enter Fallback, Fallback Vote, the only possibility is that $\text{qc.rank} \prec \text{rank}_{\text{lock}}$, where $\text{qc}$ is the QC contained in the height-1 f-block by $h'$ and $\text{rank}_{\text{lock}}$ is the highest locked rank of $h$ when voting for the f-block. Suppose that $\text{rank}_{\text{lock}} = (v, r)$. According to the protocol, the only step for $h$ to set its $\text{rank}_{\text{lock}}$ is the Lock step, and $h$ must receive a QC for some block $B$ of round $r+1$ since all adjacent certified blocks have consecutive round numbers by Lemma 2 according to the Timer and Timeout step, honest replicas set fallback-mode $\leftarrow$ false when sending the timeout message for view $v$, and will not vote for any regular blocks when fallback-mode = true according to the Vote step. Since $B$ of round $r+1$ is certified, by quorum intersection, at least one honest replica votes for $B$ and then sends a timeout message with $\text{qc.high}$ of rank $(v, r)$ which is received by $h'$. Then, the highest ranked $\text{qc}$ among all timeout messages received by $h'$ should have rank $\text{qc.rank} \geq (v, r) = \text{rank}_{\text{lock}}$, contradiction. Hence, all honest replicas will vote for the height-1 fallback-block proposed by any honest replica.

After the height-1 f-block is certified with $2f + 1$ votes that forms an f-QC $\overline{\text{qC}}_1$, according to the Fallback Propose step, replica $i$ can propose a height-2 f-block extending the height-2. All honest replicas will vote for the height-2 according to the Fallback...
Vote step, and thus it will be certified with $2f + 1$ votes. Then similarly replica $i$ can propose a height-$3$ f-block which will be certified by $2f + 1$ votes, and replica $i$ will multicast the f-QC for this height-$3$ f-block.

Since any honest replica $i$ can obtain a height-$3$ f-QC and multicast it, any honest replica will receive $2f + 1$ valid height-$3$ f-QCs and then sign and multicast a coin share of view $v$ in the Leader Election step. When the $qc_{coin}$ of view $v$ that elects some replica $L$ is received or formed at any honest replica, at least one honest replica has received $2f + 1$ height-$3$ f-QCs before sending the coin share, which means that $2f + 1$ fallback-chains have $3$ f-blocks certified. All honest replicas will receive the $qc_{coin}$ eventually due to the forwarding. According to the Exit Fallback step, they will set $fallback\_mode = false$ and exit the fallback.

Since the coin-QC elects any replica to be the leader with probability $1/n$, and at least one honest replica receives $2f + 1$ height-$3$ f-QCs among all $3f + 1$ f-chains. With probability $2/3$, the honest replica has the height-$3$ f-QC of the f-chain by the elected leader, thus have the $3$ f-blocks endorsed which have the same view number and consecutive round numbers. Therefore, the honest replica can commit the height-$1$ f-block according to the Commit step.

\[\square\]

**Theorem 2 (Liveness).** All honest replicas keep committing new blocks with high probability.

**Proof.** We prove by induction on the view numbers.

We first prove for the base case where all honest replicas start their protocol with view number $v = 0$. If all honest replicas eventually all enter the asynchronous fallback, by Lemma 6, they eventually all exit the fallback, and a new block is committed at least one honest replica with probability $2/3$. According to the Exit Fallback step, all honest replicas enter view $v = 1$ after exiting the fallback. If at least one honest replica never set $fallback\_mode = true$, this implies that the sequence of QCs produced in view $0$ is infinite. By Lemma 2, the QCs have consecutive round numbers, and thus all honest replicas keep committing new blocks after receiving these QCs.

Now assume the theorem is true for view $v = 0, \ldots, k - 1$. Consider the case where all honest replicas enter the view $v = k$. By the same argument for the $v = 0$ base case, honest replicas either all enter the fallback and the next view with a new block committed with $2/3$ probability, or keeps committing new blocks in view $k$. When the network is synchronous and the leaders are honest, the block proposed in the Steady State will always extend the highest QC, and thus voted by all honest replicas. Therefore, by induction, honest replicas keep committing new blocks with high probability.

\[\square\]

**Theorem 3 (Efficiency).** During the periods of synchrony with honest leaders, the amortized communication complexity per block decision is $O(n)$. During periods of asynchrony, the expected communication complexity per block decision is $O(n^2)$.

**Proof.** When the network is synchronous and leaders are honest, no honest replica will multicast timeout messages. In every round, the designated leader multicast its proposal of size $O(1)$ (due to the use of threshold signatures for QC), and all honest replicas send the vote of size $O(1)$ to the next leader. Hence the communication cost is $O(n)$ per round and per block decision.

When the network is asynchronous and honest replicas enter the asynchronous fallback, each honest replica in the fallback only broadcast $O(1)$ number of messages, and each message has size $O(1)$. Hence, each instance of the asynchronous fallback has communication cost $O(n^2)$, and will commit a new block with probability $2/3$. Therefore, the expected communication complexity per block decision is $O(n^2)$.

\[\square\]

4 GET 2-CHAIN COMMIT FOR FREE

In this section, we show how to slightly modify the 3-chain commit protocol in Figure 2 into a 2-chain commit protocol, strictly improving the commit latency without losing any of the nice guarantees. Earlier solutions that can be adapted into the chain-based BFT SMR framework with 2-chain commit either pay a quadratic cost for the view-change [12, 20], or sacrifices responsiveness (cannot proceed with network speed) [9, 10, 34]. Since our protocol already pays the quadratic cost, which is inevitable for the asynchronous view-change [4], we can get the improvement over the commit latency of the protocol from 3-chain commit (6 rounds) to 2-chain commit (4 rounds), without sacrificing anything else.

The difference compared with the protocol in Figure 2 with 3-chain commit is marked red in Figure 4. Intuitively, 2-chain commit means the protocol only needs two adjacent certified blocks in the same view to commit the first block, and to ensure
Changes to the Steady State Protocol in Figure 1

- **Lock. (1-chain lock rule)** Upon seeing a valid QC (formed by votes or contained in proposal or timeouts), execute **Advance Round**. The replica updates \( r_{\text{lock}} \leftarrow \max(r_{\text{lock}}, \text{QC}.r) \), and \( \text{QC.high} \leftarrow \max(\text{QC.high}, \text{QC}).r \). Execute **Commit**.

- **Commit. (2-chain commit rule)** Whenever there exists two adjacent blocks \( B, B' \) in the chain, each can be a certified block or an endorsed fallback-block, with the same view number, the replica commits \( B \) and all its ancestors.

Changes to the Async. Fallback Protocol in Figure 2

- **Fallback Propose.** Upon the first height-\( h \) f-block \( B_{h,j} \) (by any replica \( j \)) is certified by some \( \text{QC} \) and \( \text{fallback-mode} = \text{true} \),
  - if \( h = 2 \), replica \( i \) signs and multicasts \( \text{QC} \);
  - if \( h = 1 \), replica \( i \) multicasts \( B_{h+1,i} = [id, \text{QC}, B_{h,i},r + 1, v, \text{txn}, h + 1, i] \).

- **Leader Election.** Upon receiving \( 2f + 1 \) valid height-\( 2 \) view-\( \text{QC} \)s signed by distinct replicas and \( \text{fallback-mode} = \text{true} \), sign and multicast a leader-election coin share for view \( \text{QC} \).

Fig. 4. DiemBFT with Asynchronous Fallback and 2-chain Commit. Differences Marked in red.

safety, now replicas lock on the highest QC’s rank (1-chain lock) instead of the parent QC’s rank of the highest QC. Moreover, since now a block can be committed with 2-chain, the asynchronous fallback only needs every replica to build a fallback-chain of 2 fallback-blocks instead of 3, to ensure progress made during the fallback. Hence, 2 rounds can be reduced during the fallback if the protocol uses a 2-chain commit. Another main difference is that, with 2-chain commit and 1-chain lock, only one honest replica \( h \) may have the highest QC among all honest replicas when entering the asynchronous fallback. Then, only the fallback-chain proposed by \( h \) will get \( 2f + 1 \) votes from all honest replica and be completed, while other f-chains proposed by other honest replica extending a lower-ranked QC may not get \( 2f + 1 \) votes, since \( h \) will not vote due to the 1-chain locking. A straightforward solution is to allow replicas to adopt f-chains from other replicas, and build their f-chains on top of the first certified f-chain they know. With the changes above, even if only one fallback-chain is live, all honest replicas can complete their fallback-chain and ensure the liveness of the asynchronous fallback.

To summarize, the 2-chain-commit version of the protocol strictly improves the latency of the 3-chain commit version, by reducing the commit latency by 2 rounds for both Steady State and Asynchronous Fallback. The correctness proof of the 2-chain commit protocol would be analogous to that for the 3-chain commit version, and we omit it here for brevity.

5 RELATED WORKS

**Byzantine fault tolerant replication.** BFT SMR has been studied extensively in the literature. For partial synchrony, PBFT is the first practical protocol with \( O(n^3) \) communication cost per decision under a stable leader and \( O(n^3) \) communication cost for view-change. A sequence of efforts\([2, 9, 10, 17, 22, 34]\) have been made to reduce the communication cost of the BFT SMR protocols, with the state-of-the-art being HotStuff \([34]\) that has \( O(n) \) cost for decisions and view-changes under synchrony and honest leaders, and \( O(n^2) \) cost view-changes otherwise. For asynchrony, several recent proposals focus on improving the communication complexity and latency, including HoneyBadgerBFT \([28]\), Dumbo-BFT \([18]\), VABA \([4]\), Dumbo-MVBA \([26]\), ACE \([33]\) and Aleph \([15]\). The state-of-the-art protocols for asynchronous SMR have \( O(n^2) \) cost per decision \([33]\). There are also recent works on BFT SMR under synchrony \([3, 5, 19, 31]\).

**Flexibility in BFT protocols.** A related line of work investigates synchronous BFT protocol with an asynchronous fallback, focusing on achieving optimal resilience tradeoffs between synchrony and asynchrony \([7, 8]\) or optimal communication complexity \([32]\). FBFT \([27]\) proposes one BFT SMR solution supporting clients with various fault and synchronicity beliefs, but the guarantees only hold for the clients with the correct assumptions. Another related line of work on optimistic BFT protocols focuses on including a fast path in BFT protocols to improve the performance such as communication complexity and latency under the optimistic scenarios, for asynchronous protocols \([23, 24]\), partially synchronous protocols \([1, 16, 22]\) and synchronous protocols \([13, 29–31]\).
6 CONCLUSION

We present an asynchronous view-change protocol that improves the liveness of the state-of-the-art partially synchronous BFT SMR protocol. As a result, we obtain a BFT SMR protocol that has linear communication cost under synchrony, quadratic communication cost under asynchrony, and remains always live.

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