DuoBFT: Resilience vs. Performance Trade-off in Byzantine Fault Tolerance

Balaji Arun
Virginia Tech
balajia@vt.edu

Binoy Ravindran
Virginia Tech
binoy@vt.edu

ABSTRACT

This paper presents DuoBFT, a Byzantine fault-tolerant protocol that uses trusted components to provide commit decisions in the Hybrid fault model in addition to commit decisions in the BFT model. By doing so, it enables the clients to choose the response fault model for its commands. Internally, DuoBFT commits each client command under both the hybrid and Byzantine models, but since hybrid commits take fewer communication steps and use smaller quorums than BFT commits, clients can benefit from the low-latency commits in the hybrid model.

DuoBFT uses a common view-change change protocol to handle both fault models. To achieve this, we enable a notion called Flexible Quorums in the hybrid fault model by revisiting the quorum intersection requirements in hybrid protocols. The flexible quorum technique enables having a hybrid view change quorum that is of the same size as a BFT view-change quorum. This paves a path for efficiently combining both the fault models within a single unified protocol. Our evaluation on a wide-area deployment reveals that DuoBFT can provide hybrid commits with 30% lower latency to existing protocols without sacrificing throughput. In absolute terms, DuoBFT provides sub-200-millisecond latency in a geographically replicated deployment.

1 INTRODUCTION

Byzantine fault-tolerant (BFT) protocols are a building block of many decentralized ledger or Blockchain systems [8, 12]. Traditionally, the design of a BFT protocol is driven by a set of assumptions that includes the timing model (synchrony, partial synchrony, or asynchrony) and the failure model (BFT, Hybrids [50], XFT [37]). These assumptions not only serve as the basis for safety and liveness guarantees, but also establishes performance expectations.

The BFT failure model, being the most general one, allows any arbitrary behavior in the system that deviates from the protocol specification. The PBFT protocol [16], a partially synchronous protocol in this fault model, can optimally tolerate less than 1/3 failures and requires three communication delays (not including client communication) to reach commitment among at least 2/3 replicas. Alternatively, the Hybrid fault model infuses a BFT protocol with trusted assumptions allowing construction of protocols that tolerate less than 1/2 failures and require only two communication delays to reach commitment among at least 1/2 replicas.

The ability to tolerate 50% more failures than BFT protocols with fewer communication delays and with only majority quorums make Hybrid protocols appealing for building low-latency Blockchain systems (e.g. Point of Sale Payment Systems [9]). Hybrid protocols require trusted components within each replica to prevent equivocating behavior of malicious replicas. Modern commodity processors have special mechanisms (e.g. Intel SGX [20], AMD SEV [41], and ARM TrustZone [44]) to implement these trusted components in software via Trusted Execution Environments (TEE) that is isolated from other parts of the system without any additional hardware.

The use of trusted execution environment raises some challenges. First, it greatly reduces the choice of hardware (e.g. Intel SGX, ARM TrustZone, AMD SEV) used to deploy such protocols. However, Byzantine protocols implicitly/explicitly require diversity in the deployment stack to reduce the number of correlated failures [23]. Furthermore, security vulnerabilities have been discovered in trusted execution environments recently [35, 47, 48]. Although active research in the area aims to solve these problems, the impact of undiscovered vulnerabilities raises concerns. This raises questions on their applicability to BFT and Blockchain systems.

This paper presents DuoBFT that encompasses a hybrid protocol and a BFT protocol in a single package, and enables the client to choose their response fault model. DuoBFT always commits commands under both the fault models, ensuring that they have the best BFT safety guarantees, but since the Hybrid protocol is cheaper and quicker, clients can opt-in for Hybrid commit response. This allows clients that require fast response to opt-in for Hybrid commit response, while clients that require higher resilience to wait for the BFT commit response. In doing so, DuoBFT provides a unique trade-off to the clients: quick decisions made possible by hybrid replicas versus uncompromising resilience to malicious behavior. Furthermore, our solution allows different clients to individually adapt their fault assumptions dynamically without depending on the replicas.

A major contribution that make DuoBFT possible is Flexible Hybrid Quorums. We show that the strictly majority quorums in hybrid protocols can be replaced with flexible intersecting quorums. Specifically, the commit agreement quorums need not intersect with each other, but only need to intersect with view change quorums. The net outcome is that our Hybrid quorums only require \( f \) replicas for commit agreement and \( N - f \) replicas for view-changes. We apply this technique to MinBFT [50] and call the resulting protocol Flexible MinBFT.

The quorum flexibility enables DuoBFT to have a common view change protocols for both the Hybrid and BFT assumptions. Since \( N = 3f + 1 \) for a BFT protocol, DuoBFT provides Hybrid commits with \( f + 1 \) quorum and BFT commits with a \( 2f + 1 \) quorum. The view change quorum is \( 2f + 1 \) for both the protocols.

In DuoBFT, the replicas propose and vote on blocks that contain client transactions or operations, and use separate commit rules for each fault model to make commit decisions on the blocks. Replicas internally collect two types of quorums that form the basis of the commit rules: the Hybrid quorum consists of votes from \( f + 1 \) replicas, and the BFT quorum consists of votes from \( 2f + 1 \) replicas.
Collecting separate quorums allows DuoBFT to tolerate any vulnerabilities affecting the Hybrid model. Specifically, the compromise of the trusted component only affects the Hybrid quorum but not the BFT quorum.

Furthermore, the flexibility provided by the DuoBFT’s dual fault model is better than speculation[24, 32], or tentative[15] execution capabilities provided by other known protocols. While speculation requires 50% larger quorums than PBFT [17] and the tentative execution only reduces the execution overhead by overlapping the last communication step with execution, the hybrid model uses 50% smaller quorums than PBFT and reduces one overall communication step. At the same time, DuoBFT does not incur more communication delays or larger quorums than that required to commit under the BFT model, unlike [24, 32].

We evaluate multiple variants of the DuoBFT and show that it provides similar throughput to existing protocols while providing significantly lower latency. MC-DuoBFT, which is optimization over DuoBFT to use multiple instances, provides 30% lower latency for clients expecting only hybrid commit responses.

This paper makes the following contributions:
- **Flexible Hybrid Quorums**: We show that the use of majority quorums in the Hybrid fault model can be relaxed and replaced with simple intersecting quorums. This allows flexibility in the sizes of quorums used for different parts of the protocol.
- **Flexible MinBFT**: We apply Flexible Hybrid Quorums to MinBFT and present a protocol that uses $f + 1$ quorums for commit agreement and larger $N - f$ quorums for view changes.
- **DuoBFT**: We present a BFT protocol under the partial synchrony timing model that can make Hybrid commit decisions with only $f + 1$ replicas in addition to making traditional BFT commit decisions with $2f + 1$ replicas. The protocol allows clients to choose their response fault model, making it possible for applications that require low latency to benefit from the Hybrid commits, while providing the ability to leverage traditional BFT guarantees.

The rest of the paper is organized as follows. Section 2 presents the terminology and system model. Section 3 presents Flexible Hybrid Quorums and Flexible MinBFT. Section 4 presents the DuoBFT protocol, explanation of its properties along with proofs, and some optimizations. A discussion on some unique features of DuoBFT with respect to existing solutions is presented in Section 5. Section 6 evaluates the protocols. Section 7 presents the related work and Section 8 concludes the paper.

2 PRELIMINARIES

In this section, we will discuss the necessary background for understanding the rest of the paper.

2.1 Byzantine Consensus

A Byzantine Consensus protocol reaches agreement on the order of client-issued commands among a set of replicas some of which can be malicious. The commands are then executed in the agreed order on the shared state fully-replicated among the replicas. A BFT protocol under the partial synchrony fault model can tolerate up to $f$ malicious failures in a system of $N = 3f + 1$ replicas. Most protocols are primary-based and proceed in a sequence of views, where in each view, a primary replica sequences client commands that every replica executes. Correct replicas execute only after ensuring that a significant number of other replicas are aware of the same command and its execution order. To accomplish this, the protocol executes the Agreement subprotocol that involves exchanging the command and metadata among replicas. The number of communication phases differ by protocols. PBFT [16], for example, uses three phases of communication to gather consent from a supermajority (i.e. 66%) of replicas to decide the ordering for each command.

The View Change subprotocol is used to rotate the primary when the protocol is unable to make progress, i.e. order commands, with the current primary. A new view is installed after replicas exchange state information about the previous view and a new primary takes over. If the new primary does not make progress, another one takes its place.

Since the agreement subprotocol requires only a supermajority of replicas, some replicas may fall behind other replicas. The state transfer subprotocol allows lagging replicas to catch up by transferring state from up-to-date replicas. To reduce the memory footprint, the checkpoint subprotocol is used to periodically garbage-collect state related to commands that have been executed in at least correct replicas.

2.2 Hybrid Consensus

The BFT model allows malicious replicas to behave arbitrarily. Corrupt replicas can stop sending messages to one or more replicas, or send conflicting messages (equivocate) to different replicas with an intention to break safety. Preventing equivocation can reduce the number of replicas and size of quorums required to reach agreement [18, 19, 34]. This is accomplished in the Hybrid fault model using a trusted component. The algorithm hosted in the trusted component attests messages in such a way to prove their uniqueness. A simple monotonically increasing counter can be used for this purpose [34]. By assigning a unique counter value per message and signing it, the trusted component ensures that the replica hosting it cannot send different messages with the same counter value. This property allows correct replicas to detect an attempt to send conflicting statements without requiring any additional communication mechanisms. Thus, hybrid replicas can tolerate $f$ failures using only $2f + 1$ replicas.
Figure 1 illustrates the agreement protocols of PBFT and MinBFT [50], a hybrid protocol, in a system tolerating $f = 1$ failures. It can be observed that PBFT requires one additional replica and one additional communication phase compared to MinBFT.

2.3 System Model

We consider a system that consists of a set of nodes, called replicas that communicate via message passing. These replicas implement a replicated service that receive commands from client and ensure that the same sequence of totally ordered commands are executed on the replicated state and responses are returned to the client. The goal of the consensus protocol is to ensure agreement on the replicated state among replicas withstanding a number of faulty servers.

Most consensus protocols offer a single fault model that the replicas use to commit the sequence of client commands and that the clients use to receive acknowledgement. In contrast, DuoBFT commits commands under two fault models and also lets clients choose the fault model for their response. Thus, based on the assumptions, replicas may commit command sequences differently. DuoBFT provides the following guarantees:

- **Safety.** Any two replicas with correct but potentially different assumptions commit the same sequence of client commands.
- **Liveness.** A command proposed by a replica will be eventually executed by every replica with a correct assumption.

**Fault Model.** DuoBFT supports two fault models: the Byzantine fault model and the hybrid fault model. In both the models, a replica is correct if it strictly follows the algorithm, otherwise it is faulty. In addition, faulty replicas can collude to harm the correct replicas.

To satisfy the hybrid model, we assume the existence of a trusted execution environment in each replica that hosts the protocol’s trusted code. Despite some replicas being faulty, the trusted execution environment in each replica is assumed to be tamperproof and the code it executes strictly follows the algorithm. The trusted component can only fail by crashing. Note that this requirement is not necessary for BFT guarantees.

**Timing Model.** We assume the partially synchronous timing model [14]. Eventually, there exists a time during which correct replicas communicate synchronously and messages are timely. We further, assume that the network can drop, reorder, and duplicate messages. To ensure reliable delivery of messages, we rely on generic retransmission techniques that use a buffer to store outgoing messages and retransmits them periodically. Furthermore, we do not assume any bounds on processing and communication delays except that such delays do not grow indefinitely.

**Cryptography.** We assume that the adversary cannot break cryptographic computation such as hashes and signatures. In addition, the hashing algorithms are collision resistant. Every replica is aware of other replicas’ public keys. Each replica can verify the messages they receive using the corresponding replica’s public key.

3 FLEXIBLE QUORUMS IN HYBRID MODEL

In this section, we revisit the quorum intersection in the Hybrid model, and introduce Flexible Hybrid Quorums, a technique that relaxes the majority quorum intersection requirement. With this technique, only quorums across views must intersect to ensure safety, while quorums within the same view need not intersect. Consequently, hybrid protocols using the flexible quorum technique can opt for using smaller non-majority quorums for agreement, in exchange for using much larger than majority quorums during view changes. We perform our analysis in the context of MinBFT, a state-of-the-art hybrid protocol [50]. Thus, we first overview MinBFT in Section 3.1, and then introduce the flexible quorum technique to produce Flexible MinBFT in Section 3.2.

3.1 Revisiting MinBFT

MinBFT [50] is a hybrid fault-tolerant protocol that uses a trusted component to require only $N = 2f + 1$ replicas to tolerate $f$ Byzantine faults. The trusted component prevents malicious replicas from equivocating to correct replicas, providing an efficient solution to the consensus problem under this hybrid model.

**USIG Trusted Component.** The protocol uses a trusted component called the Universal Sequential Identifier Generator (USIG) that is present in each replica and provides two interfaces: one for signing and another for verifying messages. The USIG component assigns monotonically increasing counter values to messages and signs them. The component provides the following properties: (i) Uniqueness: no two messages are assigned the same identifier; (ii) Monotonicity: a message is never assigned an identifier smaller than the previous one; and (iii) Sequentiality: the next counter value generated is always one more than the last generated value.

To access its service, USIG provides two interfaces:

- CreateUI $(m)$ creates a signed certificate $UI_i$ for message $m$ with the next value from the monotonic counter. The certificate is computed using the private key of the USIG instance $r$. $UI_i = (\text{ctr}, H(m))$, where $\text{ctr}$ is the counter value and $H(m)$ is the hash of the message.
- VerifyUI $(UI_i, m)$ uses the USIG instance $i$’s public key and verifies whether the certificate $UI_i$ was computed for message $m$.

MinBFT. The MinBFT protocol proceeds in a sequence of views. The primary for each view is replica $r_i$ where $i = v \mod N$, $v$ is
the view number and $N$ is the system size. The primary is responsible for handling client commands, assigning sequence number to those commands, and forwarding the commands to the replicas. The sequence numbers the primary assigns to commands is generated by the USIG instance within the primary. The replicas accept the command and execute it once they collect a commit certificate. A commit certificate indicates that a majority of replicas have observed the same message from the primary.

When the primary receives a client command $m$ with operation $o$, it assigns a sequence number to the command. The sequence number is the one generated by the USIG service. The primary $r_i$ sends the command in a message $(\text{Prepare}, v, r_i, m, U_i)$, where $U_i$ contains the unique sequence number and the signature obtained from the USIG module. Each replica $r_j$ in turn sends the $(\text{Commit}, v, r_j, m, U_i, U_j)$ message to all other replicas. A client command is accepted at a replica if it receives $f + 1$ valid Commit messages, called a commit certificate.

Correct replicas only responds to the primary’s Prepare message if the following conditions hold: $v$ is the current view number and the sender of the message is the primary of $o$; the USIG signature is valid; and that the messages are received in sequential order of the USIG counter value. To prevent a faulty replica from executing the same operation twice, each replica maintains a $V_{\text{reg}}$ to store the command identifier of the latest operation executed for each client. The messages are always processed in the order of the USIG sequence number to prevent duplicity of operations and holes in the sequence number space. Replicas only execute an operation if it has not been executed already.

The view change protocol is triggered if the current primary fails to make timely progress. Replica sends a $(\text{PrepareViewChange}, r_i, v, v')$ message to other replicas if it times out waiting for messages from the primary. A replica moves into a new view if it receives $f + 1$ PrepareViewChange messages and consequently broadcasts a $(\text{ViewChange}, r_i, v', C_i, O, U_i)$ message, where $C_i$ is the last stable checkpoint certificate. $O$ is the set of generated messages since the last checkpoint. The new primary computes and sends a $(\text{NewView}, v, v', V_{\text{reg}}, S, U_i)$, where $V_{\text{reg}}$ is the new view certificate that contains the set of $f + 1$ ViewChange messages used to construct the new view and $S$ is the set of prepared or committed commands since the last checkpoint. Replicas validate the received NewView message, update its sequence of operations to match $S$, executes the pending operations, and starts accepting messages in the new view $v'$.

For conciseness, we defer the explanation of the checkpoint and state transfer procedures to the original paper [50].

MinBFT uses simple majority quorums for both the commit and the new view certificates. Thus, every quorum intersects with every other quorum. Consequently, commit quorums $Q_c$ intersect with other commit quorums. However, this is excessive. In MinBFT, the replica at the intersection of any two commit quorums, ensures that an operation is assigned only one $U_i$ certificate. Note that the primary’s USIG service already ensures that an $U_i$ is assigned only once. If the primary and the intersecting replica are malicious, the replica may still vote for the same operation at two different $U_i$s. Correct replicas will handle this using the $V_{\text{reg}}$ data structure. Since they process the messages in $U_i$ order, they will observe that an operation has already been executed and not execute it again. This makes the intersection replica redundant. Thus, we relax the assumption that the different commit quorums intersect with each other. At the same time, to tolerate $f$ failures, the commit quorums should consist of more than $f$ replicas. Thus, we have that $|Q_c| > f$.

On the other hand, any view change quorum $Q_{\text{oc}}$ must intersect with any commit and view change quorums to ensure that the decisions made within a view are safely transitioned to future views. Hence, we have that $|Q_{\text{oc}}| > f$.

The Flexible Hybrid Quorum requirement is captured by the following equations:

\begin{align}
|Q_c| & > f \quad (1) \\
|Q_{\text{oc}}| + |Q_c| & > N \quad (2)
\end{align}

By setting $Q_c$ to the smallest possible value i.e. $|Q_c| = f + 1$, we can observe that $|Q_{\text{oc}}| = f + 1$, but the variable $f$, the number of tolerated faults, is independent of $N$, the system size. Second, the size of view change quorums $Q_{\text{oc}}$ now equals $N - f$ instead of $f + 1$. The protocol does not require any other changes.

The safety and liveness guarantees provided by Flexible MinBFT are given below. We only present the intuition and the related lemmas here. The complete proof is presented in the Appendix A. Safety within a view. This is ensured by the trusted subsystem and the commit quorums. The trusted subsystem prevents equivocation, so a Byzantine replica cannot send conflicting proposals. Correct replicas only vote on the proposed operation if the proposal is valid, and if it has not voted for the same operation before. The following Lemma formalizes this notion.

**Lemma 1.** In a view $v$, if a correct replica executes an operation $o$ with sequence number $i$, no correct replica will execute $o$ with sequence number $i' \neq i$.

Safety across views. This is ensured by the trusted subsystem and the view change quorums. The intersection of the commit and the view change quorum consists of at least one replica. Thanks to the trusted component, the replica in the intersection cannot equivocate, and must reveal the correct sequence of operations executed, as otherwise there will be holes that correct replicas can detect. Thus, a correct primary will gather the correct sequence and apply it in the next view.

### 3.2 MinBFT with Flexible Quorums

In this section, we introduce the notion of Flexible Hybrid Quorums. First, we show that not all quorums need to intersect and consequently show that the system size $N$ need not be a function of $f$. Specifically, we show that only quorums of different kinds must intersect. Thus, sizes of commit quorums $Q_c$ can be reduced at the cost of increasing the sizes of the view change quorums $Q_{\text{oc}}$. We apply this technique to MinBFT and call the resulting protocol as Flexible MinBFT.
Figure 3: An example of normal execution steps in DuoBFT with quadratic and linear communication message complexities. The dotted arrows represent non-quorum messages and the green arrows denote the Hybrid commit path.

**Lemma 2.** If a correct replica executes an operation \( o \) with sequence number \( i \) in a view \( v \), no correct replica will execute \( o \) with sequence number \( i' \neq i \) in any view \( v' > v \).

**Quorum availability.** A non-faulty primary will always receive responses from a quorum of \( f + 1 \) replicas and this quorum will contain at least one honest replica.

**Lemma 3.** During a stable view, an operation requested by a correct client completes.

**Lemma 4.** A view \( v \) eventually will be changed to a new view \( v' > v \) if at least \( N - f \) correct replicas request its change.

4 DUOBFT

DuoBFT is a BFT protocol that infuses a trusted component to provide better performance by leveraging the hybrid fault model while providing provisions for ensuring BFT resiliency for every client command. Client commands are committed under both hybrid and Byzantine fault assumptions. This allows clients to take advantage of the quicker and cheaper hybrid commits and receive responses faster, improving system performance. However, since BFT commits also happen in tandem, Byzantine safety can be guaranteed despite trusted component compromises.

DuoBFT requires \( N = 3f + 1 \) replicas to tolerate up to \( f \) failures. To tolerate hybrid failures, we assume a non-Byzantine trusted execution environment in all replicas including malicious ones, but tolerating Byzantine failures require no such assumptions. The trusted execution environment in each replica will host the USIG service (described in Section 3.1) for certifying the messages shared by the replicas. For ease of exposition, we use \( f_B \) to denote Byzantine failures and \( f_H \) to denote hybrid failures. However, in the context of DuoBFT, \( f_B = f_H = f \). Replicas collect both the hybrid and BFT quorums, commit client commands under the respective fault models, and respond back to the client. The client can specify its response fault model along with the command sent to the replicas. Furthermore, we assume a mechanism for clients to obtain responses under both the fault models either via a long-lived client-replica connection or a separate request-response mechanism.

DuoBFT is composed of an agreement protocol that collects two kinds of quorum votes, and a view-change protocol with a single quorum type. DuoBFT’s ability to have one view-change protocol for both the fault models is made possible by the Flexible Hybrid Quorums model (Section 3.2). Recall that, to tolerate \( f \) failures, a traditional hybrid protocol requires \( N_H = 2f + 1 \) replicas, while a BFT protocol requires \( N_B = 3f + 1 \) replicas. The quorums are thus \( f + 1 \) and \( 2f + 1 \) respectively, including for view changes. In contrast, the Flexible Hybrid Quorums enable having more than \( N_H \) replicas without changing \( f \), since \( N \) is not a function of \( f \). This allows running a hybrid protocol in a system with \( N = 3f + 1 \) replicas by adapting the quorum sizes. We use \( f + 1 \) quorums for agreement subprotocol while \( 2f + 1 \) quorums for view-change protocol. Since the view-change procedure for both the BFT and hybrid fault models are the same, DuoBFT is able to have a unified view-change protocol using the matching view-change quorums in both fault models.

In the rest of this section, we will present the detailed description of DuoBFT, overview its properties, and discuss its guarantees. Similar to other recent works such as Casper [13], Hotstuff [52], and Flexible BFT [39], we explain DuoBFT in terms of a Blockchain protocol where the votes are pipelined. First, we present the terminologies.

4.1 Preliminaries

4.1.1 Blockchain. As presented in the previous sections, in classical BFT protocols, the agreement happens on a sequence of client commands. In a Blockchain protocol, the agreement happens on a chain of blocks, where each block contains one or more client commands. Each block has a reference to a predecessor block except the first block in the chain, also called the genesis block, which has no predecessors. Every block has a height parameter that indicates its position from the genesis block. A block \( B_k \) at height \( k \) has the following format: \( B_k := (b_k, h_{k-1}) \) where \( b_k \) refers to the block’s value and \( h_{k-1} = H(B_{k-1}) \), the hash of the predecessor block in the chain. For the genesis block, the predecessor hash is null, thus \( B_1 := (b_1, \perp) \). Note that only the genesis block can have a null predecessor hash; other block must specify a valid hash.

4.1.2 Block Prefix and Equivocation. Let \( S \) be a sequence of blocks in increasing height order. The prefix of a Block \( B_k \) at height \( k \) in sequence \( S \), denoted \( \text{prefix}(S, k) \), is the prefix of the sequence \( S \) containing the first \( k \) blocks from the genesis block. Equivocation happens when the sequence of blocks diverges. Given two blocks \( B_i \) and \( B_j \), we say these blocks diverge when \( B_i \) is not the ancestor of \( B_j \) or vice versa.

4.1.3 Block Certificates. Replicas vote on the blocks by signing on the hash of the block \( H(B_k) \). A quorum of these votes form a quorum certificate. In DuoBFT, replicas collect two kinds of certificates for a block: a Hybrid quorum certificate \( C_H(B_k) \) and a BFT quorum certificate \( C_B(B_k) \). The size of the quorums are discussed below.
A DuoBFT replica executes the following protocol:

**Normal Protocol**

1. **Propose.** The primary $P$ creates a block and sends it in a \langle Propose, $v$, $P$, $B_k$, $sp$ \rangle message to all replicas. It attests the block with a USIG certificate $UI$. The primary collects votes for the blocks from the replicas. The primary sends the next block when it receives a quorum certificate for its previous block.

2. **Vote.** A replica $R$ receives the \langle Propose, $v$, $P$, $B_k$, $sp$ \rangle message from the primary, validates if it extends the last proposed block, and votes for it. The vote is sent in a \langle Vote, $v$, $R$, $B_k$, $sp$, $sp2$ \rangle message to other replicas containing a $UI$ certificate.

In addition, Replica $R$ records the following information for a block:
- $q_{\theta}(B_k)$: The votes received for block $B_k$ by replica $R$ from any other replica in view $v$.
- $\mathcal{C}_H(B_k)$: A set of $f+1$ valid votes form a hybrid quorum certificate for block $B_k$.
- $\mathcal{C}_B(B_k)$: A set of $2f+1$ valid votes form a BFT quorum certificate for block $B_k$.

**View Change Protocol**

1. **View Change Request** A replica requests a view change if it does not receive proposals from the replicas in a timely manner, or if it observes equivocating blocks either via the proposal or the vote messages.
   - Replica $R$ sends a \langle ReqViewChange, $v$, $v'$ \rangle to request a view change from $v$ to $v' = v + 1$.
   - A replica that receives $f+1$ ReqViewChange messages transitions to the new view and multicasts the ViewChange message to other replicas.
   - A replica that receives $f+1$ ViewChange message also transitions to the new view and sends its ViewChange message to other replicas. The ViewChange message consists of all the blocks that the replicas have a quorum certificate for.

2. **New View.** The new primary $P'$ collects $2f+1$ ViewChange messages and computes the sequence of blocks in the new view $v'$. It sends a \langle NewView \rangle message to all replicas.

3. **New View Install.** A replica that receives the new primary $P'$’s NewView messages, validates it, and installs $S$, the block sequence in the new view.

**Figure 4: DuoBFT Protocol Execution**

### 4.2 Protocol

The DuoBFT protocol proceeds in a view by view fashion. The primary of each view is decided using the formula $v = \theta \mod N$ i.e. primary roles are assigned to replicas in round-robin order. The primary of the view is responsible for proposing blocks that other replicas vote on. Figure 4 presents a concise algorithm description.

At a high level, DuoBFT works as follows. The primary proposes a block to replicas. Replicas vote on the block if it is safe to do so. A quorum of such votes on a block make a quorum certificate. After collecting a quorum certificate for a block, the primary moves on to propose the next block extending the previous one. We will discuss how commit decisions on blocks are made in Section 4.3. Replicas use the view change protocol to install a new view if they are unable to make progress in the current view. The view change protocol begin only if $f+1$ replicas request a view change.

#### 4.2.1 Normal Protocol

The normal protocol is executed when a view is stable. In a stable view $v$, the primary and $N-f$ replicas behave correctly and exchange messages in a timely manner. The primary creates a new block $B_k$ that extends the highest block in the chain it is aware of and signs the block using its USIG component. The primary $P$ sends the block to the replicas in a \langle Propose, $v$, $P$, $B_k$, $s$ \rangle message, where $v$ is the current view and $s$ is the USIG certificate $UI$.

A replica $R$ that receives the Propose message for block $B_k$, votes on the block if it extends the previously proposed block in the view. Similar to MinBFT, DuoBFT replicas only process blocks in increasing height order. When blocks are received out of order, replicas wait to receive the predecessor blocks to $B_k$ and validates the blocks, casts its vote in the height order. Replica $R$ creates a $UI$ certificate and sends its vote in a \langle Vote, $v$, $R$, $B_k$, $sp$, $sp2$ \rangle message to other replicas. The votes collected by a replica can form two kinds of quorum certificates for the block $B_k$. Every replica records the following information for a block:

- $\mathcal{C}_H(B_k)$: A set of $f+1$ votes with valid $UI$ certificates form a hybrid quorum certificate for block $B_k$.
- $\mathcal{C}_B(B_k)$: A set of $2f+1$ votes with valid certificate form a BFT quorum certificate for block $B_k$.

#### 4.2.2 View Change

If a replica detects equivocation or lack of progress by the primary, it will start the view change procedure to move from the current view $v$ to the next stable view $v'$. A replica requests a view change by sending a \langle ReqViewChange, $v$, $v'$ \rangle message to other replicas. When a replica receives at least $f+1$ ReqViewChange messages, it starts the view transition and sends a \langle ViewChange, $v'$, $O$, $UI_k$ \rangle message, where $O$ contains the sequence of blocks for which $R$ has collected any quorum certificate. The primary $P'$ of the new view $v'$ will collect $2f+1$ valid ViewChange messages to form the new view certificate. $P'$ will use this certificate to compute the set of blocks $S$ for which quorum certificates exist.

$P'$ sends a \langle NewView, $r$, $v'$, $V_{\text{new}}, S$, $UI_k$ \rangle, where $V_{\text{new}}$ is the new view certificate that contains the set of $f+1$ ViewChange messages used to construct the new view and $S$ is the set of prepared or committed requests. Replicas verify the validity of $S$ by performing the same computation as the new primary using the new view certificate. Then, replicas adjust their local state according to $S$ and start voting in the new view $v'$. 

4.3 Commit Rules

In DuoBFT, replicas commit blocks under two different fault models by reusing the same set of vote messages for a given block. The protocol enforces a set of commit rules that uses the vote messages and chain state to decide when to commit the blocks.

4.3.1 Hybrid Commit Rule. A replica can commit a block under the Byzantine fault model when it receives at least $2f + 1$ votes, called the hybrid quorum certificate, from replicas. Under the Hybrid Commit Rule, the protocol provides the same safety guarantees as Flexible MinBFT.

4.3.2 BFT Commit Rule. A replica can commit blocks under the Byzantine fault model when it receives at least $2f + 1$ votes, called the BFT quorum certificate, for the block $B_k$ and its parent block $B_{k-1}$. Under the BFT Commit Rule, the protocol provides the same safety guarantees as PBFT.

4.4 Proof

Lemma 5. If a replica commits a block $B_l$ in a view $v$, then no replica with the same assumptions will commit $B_l'$ that does not equal $B_l$ in view $v$.

Proof. BFT Commit Rule: We prove by contradiction. Say a replica commits block $B_l$. It will have $q_r$ votes for $B_l$ and its immediate successor. Suppose another replica commits block $B_l'$ then it will have $q_r$ votes for $B_l'$ and its immediate successor. However, the intersection of two $q_r$ quorums will have at least one correct replica that will not vote for two blocks at the same height. This is a contradiction.

Hybrid Commit Rule: We prove by contradiction. Say a replica commits block $B_l$. It will have $f + 1$ USIG votes for $B_l$. Suppose another replica commits block $B_l'$ then it will have $f + 1$ USIG votes for $B_l'$. However, a primary cannot sign two messages with the same USIG identifier. Thus, there is no way there can exist two blocks at the same height $l$. This is a contradiction.

Thus, it is not possible for any two replicas to commit different blocks at the same height in view $v$.

Lemma 6. If a replica commits a block $B_l$ in a view $v$, no replica with the same assumptions will commit block $B_l'$ that does not equal $B_l$ at the same height $l$ in any view $v' > v$.

Proof. BFT Commit Rule: We prove by contradiction. A replica commits block $B_l$ in view $v$ then it will have $q_r$ votes for $B_l$ and its immediate successor. Suppose another replica commits block $B_l'$ in view $v' > v$ then it should have $q_r$ votes for $B_l'$ and its immediate successor.

Since $B_l$ is committed in view $v$, there should exist quorum certificates for blocks $B_l$ and $B_{l+1}$. In the new view $v' = v + 1$, the NewView message sent by the new primary includes a NewView certificate with $q_r$ ViewChange messages that contains at least one correct replica. The ViewChange message from the correct replica will have the correct certificate for $B_l$ and $B_{l+1}$. Thus, the new primary must enforce blocks $B_l$ and $B_{l+1}$ in the new view $v + 1$. It will receive votes only for $B_l$ in the new view $v + 1$ For $B_l'$ to be committed, $q_r$ replicas must vote for it, which cannot happen since there is at least one correct replica in the intersection of $q_r$ and $q_r$ that received the NewView message with correct certificates. This is a contradiction. Thus, $B_l'$ cannot have been committed in $v + 1$.

Hybrid Commit Rule: We prove by contradiction. A replica commits block $B_l$ in view $v$ then it will have $f + 1$ votes for $B_l$. Suppose another replica commits block $B_l'$ in view $v' > v$ then it should have $f + 1$ votes for $B_l'$.

Since $B_l$ is committed in view $v$, there should exist a USIG quorum certificate for block $B_l$. In the new view $v' = v + 1$, the NewView message sent by the new primary includes a NewView certificate with $N - f$ ViewChange messages that contains at least one correct replica. The correct replica’s ViewChange message will have the correct quorum certificate for $B_l$. It might happen that the new primary might remove some block entries from the ViewChange message, but this will be detected as the USIG-signed NewView message will reveal the holes in the message log (See Lemma 12 for additional details.) Thus, the new primary must enforce blocks $B_l$ and $B_{l+1}$ in the new view $v + 1$. It will receive votes only for $B_l$ in the new view $v + 1$. For $B_l'$ to be committed, $q_r$ replicas must vote for it, which cannot happen since there is at least one correct replica in the intersection of $q_r$ and $q_r$ that received the NewView message with correct certificates. This is a contradiction. Thus, $B_l'$ cannot have been committed in $v + 1$.

For both commit rules above, the case for arbitrary $v' > v$ where $v' = v + k$ will fall under the case of $v + 1$, since at each view transition, the information from one view is propagated to the next view.

Theorem 1. Any two replicas with the same commit rule commit the same sequence of blocks in the same order.

Proof. To elaborate on the theorem, if a replica following a commit rule commits the sequence of blocks $S = \langle B_1, \ldots, B_l \rangle$, then another replica that follows the same commit rule will commit the same sequence of blocks $S$ or a prefix of it. We use $prefix(S, i)$ to represent the first $i$ blocks of the sequence $S$. We use the $\cdot$ operator to concatenate any two sequences.

Assume the theorem is false i.e. there should exist two sequences $S$ and $S'$ committed by two replicas that is not a prefix of each other. Assume the sequences conflict at $i$, such that $prefix(S, i) = \cdot prefix(S', i - 1) \cdot (B_i)$ and $prefix(S, i) = \cdot prefix(S, i - 1) \cdot \cdot B_i'\cdot$. Precisely, there exists two blocks $B_i$ and $B_i'$ at the same height $i$ committed by two different replicas with the same commit rule.
Assume that block $B_i$ was committed in view $v$ and block $B'_i$ was committed in view $v'$. If $v = v'$, then this will contradict Lemma 5. If $v' > v'$, then this will contradict Lemma 6. Hence, the theorem must hold.

Lemma 7. During a stable view, a proposed block is committed by a replica.

Proof. In a stable view, the correct primary will propose blocks in a timely fashion. If the primary is hybrid, then it will generate an $U1 = (i, H(b))_P$ for the block. Correct replicas that receive the proposal will vote for it. Replicas that are hybrid will generate an $U1$ for their votes. Since there are at most $f$ faulty replicas, they will remain $N - f$ correct ones. For a hybrid quorum, at least $f + 1$ of these $N - f$ replicas will reply on time. Similarly, for a BFT quorum $N - f = 2f + 1$ replicas will reply on time. Thus, a replica will receive the votes on time and will commit the block using their commit rule.

Lemma 8. A view $v$ will eventually transition to a new view $v' > v$ if at least $N - f$ replicas request for it.

Proof. A replica $R$ can request a view change by sending a $(ReqViewChange, R, v, v')$ message. The view change mechanism is triggered when replicas receive $f + 1$ ReqViewChange messages for the same view. Assume that replicas collect $f + 1$ messages for transitioning from $v$ to $v + 1$. The primary for the new view is $(v+1)$ mod $N$ by definition. Consider the two cases:

1. the new view is stable: correct replicas will receive the $ReqViewChange$ messages. Consequently, correct replicas that receive at least $f + 1$ $ReqViewChange$ messages will enter the new view $v'$ and send a $ViewChange$ message to all replicas. The primary $p$, being stable, for view $v + 1$ will send a valid NewView message in time. Thus, correct replica that receive the message will transition to new view $v' = v + 1$.

2. the new view is not stable: We consider two cases:

   a. the primary $p$ is faulty and does not send the NewView message in time, or $p$ is faulty and sends an invalid NewView message, or $p$ is not faulty but the network delays $p$’s message indefinitely. In all these cases, the timer on other correct replicas that sent the ViewChange message will expire waiting for the NewView message. These replicas will trigger another view change to view $v + 2$.

   b. the primary $p$ is faulty and sends the NewView message to only a quorum $Q'$ of $q > f$ replicas but less than $q_c$ replicas are correct, or $p$ is correct but there are communication delays. The replicas in quorum $Q'$ may enter the new view and process requests in time. However, the correct replicas that do not receive the NewView message will timeout and request change to view $v + 2$. However, there will be less than $f + 1$ replicas, so a successful view change trigger will not happen. If the faulty replicas deviate from the algorithm, other correct replicas will join to change the view.

Theorem 2. A proposed block is eventually committed by replicas with correct commit rules.

Proof. When the view is stable, Lemma 7 shows that the proposed block is committed by the replicas. When the view is not stable and the replica timers expire properly, $f + 1$ replicas will request a view change. By Lemma 8, a new view $v'$ will be installed.

However, if less than $f + 1$ replicas request the view change, then the remaining replicas that do not request the view change will follow the protocol properly. Thus, the system will stay in view $v$ and the replicas will continue to commit blocks in the view. When proposals are not committed in time or when more than $f$ replicas request a view change, then all correct replicas will request a view change and it will be processed as in Lemma 7.

Even after a view change, the new view $v'$ may not necessarily be stable. If the new primary deviates from the algorithm or does not process messages in time, this will cause correct replicas to request another view change and move to the next view. Since there can only be at most $f$ faulty replicas, after at most $f + 1$ view changes, a stable view will be installed. Furthermore, if the faulty primary follows the algorithm enough such that a view change cannot be triggered, by Lemma 7, replicas will continue to commit the blocks.

4.5 Optimizations

4.5.1 Reducing Message Complexity. In the description of DuoBFT presented in the previous section, the replicas multicast their votes to all other replicas incurring an $O(N^2)$ message complexity in the common case. This complexity can be reduced to $O(N)$ by modifying the replicas to send their votes only to the primary and enabling the primary to collect the votes and share the quorum certificate with other replicas. This technique enables the use of threshold signatures schemes [46] to reduce the size of outgoing messages from the primary and to reduce the verification compute overheads when $N$ is large. Many existing protocols use this technique [24]. An illustration of this optimization is shown in Figure 3. While the aggregation increases the number of communication steps of the protocol, as we will show in Section 6, reducing the complexity helps reduce the latency of the protocol at large system sizes ($N \geq 49$).

4.5.2 MultiChain-DuoBFT. Chain-based protocols including DuoBFT do not support out-of-order processing and thus exhibit poor throughput compared to protocols that support out-of-order processing (e.g. PBFT). Since the protocol phases are pipelined in chain-based protocols, the votes for the previous block must be available before sending the next block. Therefore, the throughput of such protocols is dependent on the network message delays that prominently determine how quickly replicas can collect a quorum of votes. Hence, these protocols perform poorly in wide-area deployments where latencies between regions are large [28]. On the other hand, protocols such as PBFT can send propose blocks simultaneously and collect multiple phases of votes for each of those blocks and provide higher throughput and lower latency.

Despite, chain-based protocols are efficient in terms of the number of messages exchanged per block because they pipeline their votes. For DuoBFT, this means that collecting different kinds of votes is possible without increasing the number of message types and messages exchanged to commit per block. To compensate for the lost throughput, we propose running multiple instances of
DuoBFT concurrently to facilitate collecting votes for multiple blocks at the same time. Various techniques to run multiple instances of a BFT protocol and coordinate ordering among those instances have been proposed in the past [10, 22, 27, 45, 51]. We adopt a recent multi-primary paradigm RCC [27] and modify it slightly to run multiple instances with the same primary. Our choice of RCC was due to the fact that the approach does not require changing the underlying protocol unlike COP [22]. In RCC, each replica is primary for an instance of the Byzantine Agreement protocol and commits client commands in rounds, where in each round one command per replica is committed. Once all replicas have committed commands in a given round, they are executed in a pre-determined order. Since our intent is to improve DuoBFT’s performance with a single primary, we simply assign the same replica to be the primary of multiple instances. We call this variant of DuoBFT as MultiChain-DuoBFT or simply MC-DuoBFT.

The performance of the MC-DuoBFT protocol now depends on the number of concurrent instances. In our experiments, we manually fixed the number of instances depending on the system size. Typically, the number of instances was between 4 for large systems (N = 97) and 40 for smaller systems (N = 25). However, note that prior works [51] have investigated the idea of automatically tuning the number of concurrent instances based on the available network and compute resources. How those ideas integrate with RCC is beyond the scope of this paper.

5 DISCUSSION

Implications of Trusted Environment Compromises. As mentioned in the introduction, trusted execution environments are increasingly being scrutinized for security vulnerabilities. In the hybrid fault model, the compromise of the trusted component is enough to break the safety of the protocol. However, DuoBFT holds safety in such cases via the BFT commit rule. If the trusted component is compromised, per our assumption, this can only affect at most f replicas. Thus, the remaining 2f + 1 replicas will follow the algorithm correctly. While the hybrid quorum certificates can become invalid, recall that replicas also collect BFT quorum certificates in tandem. Thus, safety is still preserved for the sequence of blocks that have collected the BFT quorum certificates.

Comparison to FlexibleBFT. We now highlight the differences of our protocol from Flexible BFT [39], a recent protocol that provides diverse learner assumptions. The first important distinction is that Flexible BFT provides the a-b-c fault model in addition to the BFT model. The replicas under the a-b-c model are allowed to attack the safety of the system, but when they aren’t able to attack safety, they will ensure liveness. However, the implication of using this fault model is that Flexible BFT quorums are much larger than our flexible hybrid quorums. In Flexible BFT, the commit quorums used by the client qC should be at least as large as the view change quorum qV used by the replicas, i.e. qC ≥ qV. In contrast, DuoBFT uses hybrid commit quorums that are smaller than the view change quorums, and the BFT commit quorums are as large as the view change quorums. That is, in DuoBFT, qC ≤ qDC.

Furthermore, Flexible BFT uses the synchrony timing model as a means to provide commits using simple majority quorums, which are smaller than Byzantine quorums. The protocol also tolerate < 1/2 failures. On the other hand, DuoBFT tolerates only 1/3 failures, but under the hybrid model, its commit quorum sizes are really efficient, only a little over 1/3 replicas. Thus, Flexible BFT uses the timing model to reduce quorum sizes, while DuoBFT uses the trusted component to achieve a very similar purpose. Furthermore, partially synchrony model enables “network-speed” replicas those that do not need lock-step executions unlike in the synchrony model. Thus, assumptions such as globally synchronized clocks are not required in our case.

6 EVALUATION

In this section, we evaluate Flexible MinBFT, DuoBFT, and MC-DuoBFT alongside state-of-the-art protocols to answer the following questions:

(1) What is the impact of batching on protocol performance?
(2) How does scale affect protocol performance?
(3) How well do the protocols cope with replica failures?
(4) Does DuoBFT integrate with the recent multi-primary paradigms?

Throughout our evaluation of DuoBFT, we also measured the overhead of committing commands under two different fault models within the same protocol.

6.1 Protocols under test

We evaluate the following single-primary protocols: PBFT [17], SBFT [24], and MinBFT [50]. We use the variant PBFT [17] that uses MACs that are computationally cheaper than signatures. SBFT [24] provides fast-path commitment using 3f + c + 1 replicas out of 3f + 2c + 1 replicas and linear communication. Chained Hotstuff [52] is a rotating-primary protocol that changes its view for each proposal, and pipelines protocol messages as well as commit decisions.

Flexible MinBFT is evaluated with f failures among N = 3f + 1 replicas, thus the normal commit quorums are f + 1 while the view-change quorums are 2f + 1. We evaluate both the single-chain and multi-chain variants of DuoBFT, namely DuoBFT, and MC-DuoBFT.

We also apply DuoBFT in the context of multi-primary paradigm leveraging the RCC [27] in order to allow each replica to act as primary. With this approach, replicas can use all their resources effectively and provide better throughput over single-primary solutions. We evaluate the RCC variant of MC-DuoBFT with RCC-PBFT and MirBFT [45].

We implemented all the protocols within a common framework written in Go. The framework uses gRPC [2] for communication and protobuf [25] for message serialization. The ECDSA [30] algorithms in Go’s crypto package are used for authenticating the messages exchanged by the clients and the replicas. The trusted component, namely USIG [50], was implemented in C using the Intel SGX SDK [20]. We implemented two variants of USIG. For MinBFT and Flexible MinBFT, the signatures were computed using the ECDSA algorithm. For DuoBFT, the signatures were computed using Ed25519 signature scheme [11] that supports batch verification to facilitate linear communication pattern (see Figure 3b).

Using our own implementation ensures a consistent evaluation of all protocols. Moreover, the source code for RCC and MinBFT were not publicly available at the time of evaluation. The publicly available Hotstuff implementation only proposed command
hashes [45], whereas our implementations propose the actual payload. The evaluation uses a key-value store benchmark because it serves as a good abstraction for building higher level systems [24].

6.2 Experimental setup

We deployed the protocols using the SGX-enabled DC8v2 virtual machines (8 vCPUs and 32GB of memory) available in the Microsoft Azure cloud platform [1]. The virtual machines were evenly spread across ten different geographical regions. The regions were East US, West US, South Central US, Canada Central, Canada East, UK South, North Europe, West Europe and South East Asia. The round-trip latencies were under 30ms between regions in North America, under 150ms between regions in Europe and North America, and around 240ms between Canada and South East Asia. We obtained multiple VMs per region and organized them into a Kubernetes cluster. Each replica pod was deployed in its own VM, while multiple clients pods were deployed per VM. The primary role was assigned to a replica in the East US region.

The clients are spread equally across all regions, and they send requests to the replicas in a closed-loop, i.e. clients wait for the response before sending the next request. We measured the throughput and latency for each of the protocols. The payload size is set at 512 bytes. Unless otherwise stated, the batch size defaults to 200 commands per batch. We evaluated DuoBFT and MC-DuoBFT by varying the ratio of Hybrid and BFT commit responses received by the client. The suffix in the legend indicates the percentage of hybrid commit responses.

6.3 Batching Experiment

We measured the impact of command batch size on the performance of the protocols. Batching amortizes the cost of consensus by having proposing multiple commands together in a single block, but it also increases the network consumption on the primary since it should multicast the batch to all replicas. For this experiment, we deployed 49 replicas, and varied the number of commands per batch between 10 and 400 and measure the throughput and latency for each of the protocols. All protocols tolerate 16 failures except MinBFT that tolerates 24 failures. The results are in Figure 6.

Due to the lack of out-of-order processing in chain-based protocols including DuoBFT and ChainHotstuff, replicas cannot pipeline multiple proposals at the same time. Thus, their throughput tend to be very low compared to other protocols. On the other hand, MC-DuoBFT protocols leverages multiple instances to boost throughput and thus is able to compete better with other single-primary protocols. Since all single-primary protocols are able to process multiple command batches at the same time, they perform as fast as their primary replicas are able to disseminate batches.

Flexible MinBFT provides the lowest latency among all protocols, due to its two phase commit protocol with only $f + 1$ quorum. MC-DuoBFT due to its linear communication exhibits slightly higher latency but within 200-milliseconds. MC-DuoBFT 100% provides 25% and 50% lower latency than PBFT and SBFT without sacrificing throughput. Due to additional communication steps as a result of linear message patterns, MC-DuoBFT with 50% and 0% hybrid commit responses incur a latency penalty compared to PBFT. Furthermore, the overhead of collecting multiple quorums per command batch affects the throughput of MC-DuoBFT 50% and 0%. Thus, these two protocols reach their peak throughput only at batch size 400, and incur a 10% throughput hit compared to PBFT.

6.4 Scalability Experiment

Next, we measured the performance of the protocols as the system size is increased. In this experiment, we measure the performance of the protocols at four system sizes: 25, 49, 73, and 97, tolerating 8, 16, 24, and 32 failures. MinBFT tolerates 12, 24, 36, and 48 hybrid failures, respectively. The batch size is set to 200 because most of the protocols reached their peak throughput at this batch size in the previous experiment. The result is in Figure 7.
Similarly to the previous experiment, the chain-based protocols yield low performance due to lack of out-of-order processing. MC-DuoBFT makes up for the performance impact by using multiple chains, which allows it to provide similar throughput as other protocols. MC-DuoBFT 100% is able to provide sub-200-milliseconds latency even at 97 replicas. While MC-DuoBFT’s throughput is at least 10% lower than other protocols at 25 replicas, it scales better as system size increases and performs at par with other protocol starting at 73 replicas. Furthermore, its latency is at least 30% lower than PBFT at all system sizes. This shows that with MC-DuoBFT, it is possible to provide low-latency commits under the hybrid model at scale.

On the other hand, MC-DuoBFT incurs both throughput and latency penalty when providing BFT commits. The throughput overhead was around 5% while the latencies were 30% higher due to an additional communication round-trip.

### 6.5 Failure Experiment

We also measured the impact of minority $f$ failures on performance at scale. To do so, we repeated the previous experiment but in the presence of $f$ failures evenly spread across all regions. The result is in Figure 8.

Since all protocols must visit additional regions to collect quorums, the latencies of all protocols are higher. The throughput gap between MC-DuoBFT 100% and other protocols narrows at smaller system sizes, while the gap is larger for 50% and 0% cases. This is because for BFT commits replicas need to gather votes from all the replicas, which slows down MC-DuoBFT due to their additional communication steps. Since the hybrid commits only needs half of replicas, the throughput of MC-DuoBFT 100% is same as other protocols at all system sizes despite its overheads. Furthermore, Flexible MinBFT provides the lowest latency due to its two-step protocol without any overheads unlike MC-DuoBFT.

### 6.6 Multi-Primary Experiment

In the previous experiments, we showed that the MC-DuoBFT protocol, at least with hybrid commits, is competitive with other single-primary protocols in terms of throughput and provide better latency than single-primary protocols. We ran a separate experiment to observe whether MC-DuoBFT can improve throughput in the context of multi-primary paradigms at scale. The experiment parameters are same as described in Section 6.4. We evaluated the RCC paradigm with PBFT and MC-DuoBFT, and MirBFT. The results are in Figure 9.

We observed that MC-DuoBFT 100% takes advantage of the linear communication along with one round-trip commit and scales better than any other protocol. At 97-replicas, MC-DuoBFT 100% provides 1.5x more throughput than RCC-PBFT and MirBFT. MC-DuoBFT with 50% and 0% Hybrid commits perform better by up to 30% than RCC-PBFT at higher scale by taking advantage of the linear communication. By distributing the responsibility of collecting signatures to different replicas, the RCC paradigm and the linear communication pattern distributes any compute and network bottlenecks. Thus, protocols scale better than protocols with quadratic message complexity. We also observed higher latencies for DuoBFT protocols since the RCC paradigm optimizes for throughput. Since, all instances must complete a round before the commands belonging to the round can be executed, the commands are usually executed at the speed in which the slowest/farthest replica commits its commands. We also noticed that MC-DuoBFT's signature computation overheads increased linearly with the number of replicas, and it contributed to elevated latencies at higher system sizes. We believe replacing the Ed25519 signatures with threshold signatures such as BLS [46] signatures can help lower the latency.

### 7 RELATED WORK

Since Lamport et al. formulated the Byzantine Generals problem [33], numerous solutions to solve the agreement problem in the face of Byzantine failures have been proposed. These solutions have varied widely in terms of their fault assumptions and the timing models. A review of these solutions is beyond the scope of the paper. We defer the interested readers to books on distributed computing [14, 38].

The literature is rich in protocols that adopt the hybrid fault model [36]. While early protocols depended on an attested append-only log abstraction provided by the trusted component [18], the counter-based abstraction [34] became popular due to its simplicity, and have been adopted by numerous protocols [10, 31, 36, 49, 50]. We used MinBFT to perform our analysis and construction, because of its presentation as the hybrid counterpart to PBFT, and its use of a simple counter-based trusted attestation mechanism.

**Speculation.** Some partially-synchronous BFT protocols [7, 24, 32, 40] use speculation to make commit decisions using fewer communication steps. These protocol adopt fast BFT quorums that are at least 50% larger than normal BFT quorums and reduce communication delays under favorable conditions. At times, a fast quorum may not be enough or unattainable, in which case, the replicas fall back to a slow protocol with normal quorums and additional communication steps. Thus, such protocol collect larger quorum than normal protocols in the best case, and spend more communication steps than normal protocols in the worst case. DuoBFT’s provides a cheaper and stronger alternative to these solutions. The hybrid commit rule can be used to make commit decisions on a block by collecting votes from quorums of 1/3 replicas. For the BFT commit rule, a replica only needs to collect additional 1/3 votes for the block and 2/3 votes for the next block. In total, a replica does not
need to collect more votes or spend more communication steps than that in normal BFT protocols.

Similarly, Thunderella [43] and Sync Hotstuff [3] commit optimistically under the partial synchrony model using quorums of size \( \geq 3/4 \), and fallback to a synchronous slow commit rule. DuoBFT’s guarantees are completely based in the partial synchrony model.

SACZyzzyva [26] uses a trusted counter to increase the resiliency of Zyzzyva to tolerate \( f \) slow nodes. The protocols requires only \( f + 1 \) replicas to host the trusted counters in a system with \( 3f + 1 \) replicas. While DuoBFT requires all replicas to host the trusted component, it allows any replica to be the primary. Moreover, with the Flexible Hybrid Quorums approach, we also provide the flexibility to choose \( f \) independently of \( N \), the number of replicas.

**Tentative Execution and Optimistic Agreement.** Some protocols like PBFT and MinBFT use tentative execution [15] to execute the proposed operations before the final commit step. This can improve the overall performance under favorable conditions. Furthermore, the optimistic agreement [21] technique uses only a subset of replicas to run agreement, while the remaining replicas update their state passively. Such techniques are orthogonal and applicable to DuoBFT as well.

Some benign protocols [53] enable clients to obtain a speculative response that sometimes deviates from the final response due to replica crashes or network faults. Similarly, DuoBFT’s hybrid commits can deviate from BFT commits during trusted component compromises.

**Hierarchical Protocols.** Steward [5, 6] and GeoBFT [28] follow the hierarchical fault model by using a combination of crash and Byzantine fault tolerant mechanisms. The replicas are divided into groups. Replicas with a group run a BFT protocol while inter-group agreement is achieved using a crash-fault tolerant protocol. However, the protocol exposes a single combined fault model to the learners: the protocols can tolerate \( f + z \) failures in \( z \) groups of which at most \( f \) can happen in a single group. Such techniques are aimed towards WAN deployments.

**Flexible Quorums.** In Flexible PAXOS [29], Howard et al. introduced the notion of flexible quorums in the crash fault model. Malkhi et al. then developed the flexible quorums approach in the Byzantine fault model. [39]. The Flexible Hybrid Quorums presented in this paper can be seen as the hybrid variant of the flexible quorum technique. DuoBFT adds support for the BFT fault model over the hybrid fault model and exposes the choice to the learners.

**Adversaries.** Different kinds of adversaries have been explored in prior works. Both the BAR and a-a-c fault models [4, 39] consider an adversary that does not collude. With the hybrid fault model, we consider an adversary that does not break the protections around the trusted component, but they can otherwise collude with other Byzantine replicas.

**Diverse learners.** Bitcoin [42] uses a probabilistic commit rule that depends on the depth of the confirmation. Typically, a block depth of six implies a commit with a very high probability, although a block depth of one is enough to commit for some learners. The Cross fault-tolerant (XFT) [37] model offers two kinds of learners: learners that follow the crash fault model under the asynchronous timing model, or learners that from the Byzantine fault model under the synchronous timing model.

### 8 Conclusion and Future Work

In this paper, we present DuoBFT, a BFT protocol that provides commits under two fault models – BFT and Hybrid – under the partial synchrony timing model. The clients can wait for responses from either or both the hybrid and BFT commit. DuoBFT uses the Flexible Hybrid Quorum technique to provide cheap Hybrid commits with \( f + 1 \) replicas and has a unified view-change mechanism for both fault models. Our experimental evaluation show that MC-DuoBFT, the multi-chain variant of DuoBFT, is able to provide up to 30% lower latency than state-of-the-art protocols with comparable throughput. Furthermore, MC-DuoBFT is compatible with recent multi-primary paradigms and provides better scalable throughput than existing protocols. These characteristics make DuoBFT a better fit for applications that almost always only requires hybrid commits with a small percentage of BFT commits.

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A FLEXIBLE MINIBFT CORRECTNESS

Note that our proof structure overlaps with MinBFT’s original proof for ease of exposition.

LEMMA 9. In a view $o$, if a correct replica executes an operation $o$ with sequence number $i$, no correct replica will execute $o$ with sequence number $i' \neq i$.

Proof. If $r$ executes $o$ with sequence number $i$, then it will have $f + 1$ valid $commit$ messages for $(o,i)$ from a quorum $Q_\ell$. We prove by contradiction. Suppose another correct server $r'$ executes $o$ with sequence number $i' > i$. This can happen if $s'$ received $f + 1$ valid $commit$ messages for $(o,i')$ from quorum $Q_\ell'$. Note that $Q_\ell \cap Q_\ell' = \emptyset$ if any two $Q_\ell$ quorums need not intersect. There are two cases to consider depending on the primary:

(1) Primary is correct: This is trivial since a correct primary will not generate two UIs for the same operation $o$. 

(2) Primary is faulty: This is shown by employing the same argument as in the proof of Lemma 5.
Thus, it is not possible for any two replicas to execute the same primary. Given this, we consider the following cases:

1. **Primary is correct and replica \( r \in Q_{oc} \) is correct:** If primary \( p \) is correct, it inserts \( N - f \) ViewChange messages into \( V_{oc} \) including the one from \( r \). There are two possibilities.

   a. \( o \) was executed after checkpoint: \( r \) is correct, so \( O \) contains Commit that \( r \) sent for \( o \), therefore \( V_{oc} \) and \( S \) in the NewView message assert \( O \) was executed explicitly.

   b. \( o \) was executed before the checkpoint: The latest checkpoint \( C_t \) shared by \( r \) implies that \( o \) was executed implicitly. Since the \( V_{oc} \) sent in the NewView contains the \( C_t \), it implies that \( o \) was executed.

2. (The primary \( p \) is correct, but there is no correct replica in \( Q_{oc} \) that executed \( o \)): There should exist at least a faulty replica \( r \in Q' \) that accepted \( o \) because \( Q' \cap Q_{oc} \neq \emptyset \) (\( q_{sem} + q_{oc} > 1 \)).

   a. \( o \) was executed after checkpoint: \( r \) might be tempted to not include \( o \)'s messages in \( O \), but if it did, \( p \) being correct would not put \( r \)'s ViewChange message in \( V_{oc} \) as \( p \) can detect its invalid. There are two possible ways a detection will happen: (i) if \( r \) executed a request \( o' \) after \( o \), \( r \) might put the Commit message for \( o' \) but not \( o \) leaving a hole in the log that \( p \) will detect. (ii) if \( r \) sent Commit for \( o \) with a USIG value \( c_o \), it might leave out all commit after \( o \) with \( c_o' > c_o \) from the \( O \) log. But, this log will also be considered invalid by \( p \) since \( r \) must sign the ViewChange message containing \( O \) before sending it. The USIG will sign with \( c_o'' > c_o + 1 \) that will allow a correct \( p \) to detect an incomplete \( O \). Thus, \( r \) must include all commits and Case 1 above will apply.

   b. \( o \) was executed before the stable checkpoint: One way this can happen is when \( r \) includes an older checkpoint message but \( p \) will detect the invalid ViewChange message because the USIG value of the message will disclose that there are messages since the checkpoint message that \( r \) failed to disclose.

(3) Primary is faulty but \( r \in Q_{oc} \) is correct and executed \( o \). In this case, the faulty primary \( p \) may attempt to modify the contents of \( O \) that it receives from \( r \) before inserting into \( V_{oc} \). However, this will leave a hole and other correct replicas will detect this mishandling since they run the same procedure the primary runs for computing the NewView message. If \( p \) removes \( o \) and all further operations after \( o \), correct replicas can also detect it because the USIG value of the \( r \)'s ViewChange message inside \( V_{oc} \) will indicate the missing messages (as in Case 2). Similarly, if the primary tries to add an older checkpoint certificate, correct replicas will detect it from the holes in the USIG values. Therefore, a fault primary cannot tamper with a ViewChange message without detection. Thus, Case 1 will happen.

4. (Primary is faulty and no correct \( r \in Q_{oc} \) has executed \( o \). A faulty \( r \in Q_{oc} \) may exist. Given \( |Q_c| + |Q_{oc}| > N \), \( r \) cannot successfully convince the primary to behave as if it did not execute \( o \). Even if the primary being faulty uses \( r \)'s ViewChange message in \( V_{oc} \), other replicas will detect the missing sequence number and the corresponding commit message for \( o \). Thus, we will fall back to Cases 2 and 3 above.

The above four cases show that if \( o \) is executed after \( o' \) in the certificate \( V_{oc} \). Now, we show no correct replicas will execute \( o \) with \( i' \neq i \) in \( v' \). There are two cases:

1. **Primary is correct:** A correct primary \( p \) will never generate a second USIG certificate for the same operation and correct replicas will not send a commit message \( o \) with \( i' \) in view \( v' \).

   2. **Primary is faulty:** It is possible for a faulty primary to create a new \( \text{Prepare} \) message for \( o \) and successfully create a new USIG \( U_1p \) = \( \langle i, H(o) \rangle \). \( p \) and send it to a replica \( r \). However, every replica maintains the \( V_{req} \) that holds the last executed operation identifier \( seq \) for each client. Thus, \( r \) will discover that \( o \) was already executed since \( o.seq \leq V_{req} \[c] \). Thus, \( o \) will not be executed again.

This proves that if a correct replica executed \( o \) at sequence number \( i \) in view \( v \), then no correct replica will execute \( o \) at sequence number \( i' \neq i \) in view \( v' = \emptyset + 1 \).

We now generalize for arbitrary values of \( o' > v \). There are two cases:

1. \( o' = v + k \) but no request was accepted in view \( v'' \) such that \( o' < v'' < v + k \). This case is trivial and falls under the case of \( o' = v + 1 \) since only view change related messages are sent in \( o'' \) which mirrors the \( v \) to \( v' \) transition.
(2) \( v' = v + k \) but requests were prepared/accepted in view \( v'' \) such that \( v' < v'' < v + k \): At each view change, replicas must propagate information about operations from one view to its consecutive view (e.g. \( v \) to \( v + 1 \), and so on). This is done either via the checkpoint certificate or the via the O log set. Thus, each transition becomes the case of \( v' = v + 1 \) above.

\[ \square \]

**Theorem 3.** Let \( s \) be a correct replica that executed more operations of all correct replicas up to a certain instant. If \( s \) executed the sequence of operations \( S = \langle a_1, ..., a_i \rangle \), then all other correct replicas executed this same sequence of operations or a prefix of it.

**Proof.** Let \( \text{prefix}(S, k) \) be a function that gets the prefix of sequence \( S \) containing the first \( k \) operations, with \( \text{prefix}(S, 0) \) being the empty sequence. Let \( \bullet \) be an operation that concatenates sequences.

We prove by contradiction. Assume the theorem is false, i.e there exists a correct replica \( r' \) that executed some sequence of operations \( S' \) that is not a prefix of \( S \). Let \( \text{prefix}(S, i) = \text{prefix}(S', i-1) \bullet (a_j) \) and \( \text{prefix}(S', i) = \text{prefix}(S, i-1) \bullet (a'_j) \) such that \( a_j \neq a'_j \). In this case, \( a_j \) was executed as the \( i \)th operation by replica \( r \) and \( a'_j \) was executed as the \( i \)th operation by replica \( r' \). Assume \( a_j \) was executed in view \( v \) and \( a'_j \) was executed in view \( v' \). Setting \( v = v' \) will contradict Lemma 9 and setting \( v \neq v \) will contradict Lemma 10.

\[ \square \]

**Lemma 11.** During a stable view, an operation requested by a correct client completes.

**Proof.** A correct client \( c \) will send an operation \( o \) with an identifier larger than any previous identifiers to the replicas. The primary \( p \) being correct, will construct a valid Prepare message with a valid USIG certificate \( UI_p = \langle i, H(o) \rangle_p \) and send it to all replicas. At least \( f + 1 \) correct replicas will validate the Prepare message, verify the UI, and send a corresponding Commit message. Since there can be only \( f \) faults, there should exist at least \( N - f \) correct replicas, out of which \( f + 1 \) \( (q_{\text{commit}}) \), should successfully produce these Commit messages. When a correct replica receives \( q_{\text{commit}} \) valid Commit messages, \( o \) will be executed and replied to the client \( c \). Since \( q_{\text{commit}} \) correct replicas exist, a correct client will receive \( f + 1 \) same replies indicating that operation \( o \) was properly executed at sequence number \( i \).

\[ \square \]

**Lemma 12.** A view \( v \) eventually will be changed to a new view \( v' \) if at least \( N - f \) correct replicas request its change.

**Proof.** A correct replica \( r \) sends a \( \langle \text{ReqViewChange}, r, v, v' \rangle \) message requesting a view change to all replicas. However, at least \( N - f \) correct replicas must send such a message to actually trigger a view change. Say a set of \( N - f \) correct replicas request a view change from \( v \) to \( v + 1 \) by sending the ReqViewChange message. The primary for the new view is \( p = (v + 1) \mod N \). Consider the two cases:

(1) \( \text{the new view is stable:} \) correct replicas will receive the ReqViewChange messages. Consequently, correct replicas that receive at least \( N - f \) ReqViewChange messages will enter the new view \( v' \) and send a ViewChange message to all replicas. The primary \( p \), being stable, for view \( v + 1 \) will send a valid NewView message in time. Thus, correct replica that receive the message will transition to new view \( v' = v + 1 \).

(2) \( \text{the new view is not stable:} \) We consider two cases:

(a) \( \text{the primary } p \) is faulty and does not send the NewView message in time, or \( p \) is faulty sends an invalid NewView message, or \( p \) is not faulty but the network delays \( p \)'s message indefinitely. In all these cases, the timer on other correct replicas that sent the ViewChange message will expire waiting for the new view message. These replicas will trigger another view change to view \( v + 2 \).

(b) \( \text{the primary } p \) is faulty and sends the NewView message to only a quorum \( Q_{\text{fc}} \) of \( N - f \) replicas but less than \( N - f \) replicas are correct, or \( p \) is correct but there are communication delays. The replicas in quorum \( Q_{\text{fc}} \) may enter the new view and process requests in time. However, the correct replicas that does not receive the NewView message will timeout and request change to view \( v + 2 \). However, there will be less than \( N - f \) replicas, so a successful view change trigger will not happen. If the faulty replicas deviate from the algorithm, other correct replicas will join to change the view.

\[ \square \]

**Theorem 4.** An operation requested by a correct client eventually completes.

**Proof.** The proof follows from the Lemmas 11 and 12. When the view is stable, Lemma 11 shows that the client operations are properly committed. However, when the view \( v \) is not stable, there are two possibilities:

(1) \( \text{at least } f + 1 \text{ replicas timeout waiting for messages and request a view change:} \) Lemma 12 handles this case and ensures that a stable view \( v' > v \) is established.

(2) \( \text{less than } f + 1 \text{ replicas request a view change:} \) There should exist at least a quorum \( Q \) of \( f + 1 \) replicas that are in the current view \( v \). As long as these replicas continue to follow the algorithm, they will continue to stay in view \( v \) and client requests will be committed in time. However, if the replicas are not timely, then the correct replica from \( Q \) in view \( v \) will send the ReqViewChange message. With this message, a successful view change is triggered and the previous case takes happens.

If the new view \( v' \) is not stable, another view change will be triggered depending on whether Cases 1 or 2 above holds. However, this process will not continue forever. Since there are only \( f \) byzantine replicas and due to the assumption that the network delays do not grow indefinitely, eventually there should exist a view \( v'' \) that is stable such that the primary responds in a timely manner and follows the algorithm.

\[ \square \]