

*h*BFT: Speculative Byzantine Fault Tolerance With Minimum Cost

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Abstract—We present *h*BFT, a hybrid, Byzantine fault-tolerant, replicated state machine protocol with optimal resilience. Under normal circumstances, *h*BFT uses speculation, i.e., replicas directly adopt the order from the primary and send replies to the clients. As in prior work such as Zyzzyva, when replicas are out of order, clients can detect the inconsistency and help replicas converge on the total ordering. However, we take a different approach than previous work that has four distinct benefits: it requires many fewer cryptographic operations, it moves critical jobs to the clients with no additional costs, faulty clients can be detected and identified, and performance in the presence of client participation will not degrade as long as the primary is correct. The correctness is guaranteed by a three-phase checkpoint subprotocol similar to PBFT, which is tailored to our needs. The protocol is triggered by the primary when a certain number of requests are executed or by clients when they detect an inconsistency.

Index Terms—Byzantine, fault tolerance, state machine replication, performance, speculation

1 INTRODUCTION

As distributed systems develop and grow in size, Byzantine failures generated by malicious attacks, and software and hardware errors must be tolerated. Byzantine agreement protocols are attractive because they enhance reliability of replicated services in the presence of arbitrary failures. However, Byzantine protocols come at a cost of high overhead of messages and cryptographic operations. Therefore, protocols that can reduce overhead can be attractive building blocks.

A number of existing protocols also reduce overhead on Byzantine agreement by moving some critical jobs to clients [13, 17, 19, 21, 33, 34]. But these protocols come with trade-offs that we seek to avoid. Specifically, while they all provide better fault-free cases and reduce the message complexity, they sacrifice the performance of normal cases and may even degrade the performance of fault-free cases. For instance, the Zyzzyva [21] protocol is able to use roughly half of the amount of messages and cryptographic operations that PBFT [7] requires. However, Zyzzyva’s performance can be even worse than PBFT if at least one backup fails. Additionally, these protocols simplify the design by involving clients in the agreement. However, they all require clients to be correct in order to achieve correctness.

Therefore, our motivation for developing a new protocol is to improve performance over PBFT without being encumbered by some of these trade-offs. Specifically, we have three key goals: first, we wish to be able to show how critical jobs can be moved to the clients without additional costs. Second, we wish to tolerate Byzantine faulty clients. Third, we define the notion of *normal cases*, which means the primary is correct and the number of faulty backups does not

exceed the threshold. We wish to provide better performance for both fault-free cases and normal cases.

This paper presents *h*BFT, a leader-based protocol that uses speculation to reduce the cost of Byzantine agreement protocols with optimal resilience, utilizing $n \geq 3f + 1$ replicas to tolerate f failures. *h*BFT satisfies all of our stated goals. To accomplish this, *h*BFT employs several techniques. First, it uses speculation: backups speculatively execute requests ordered by the primary and replies to the clients. As a result, correct replicas may be temporarily inconsistent. *h*BFT employs a three-phase PBFT-like checkpoint subprotocol for both garbage collection and contention resolution. The checkpoint subprotocol can be triggered by the replicas when they execute certain number of operations, or by clients when they detect the divergence of replies. In this way replicas are able to detect any inconsistency through internal message exchanges. Even though the three-phase protocol is expensive, it is not triggered frequently. Eventually *h*BFT can ensure the total ordering of requests for all correct replicas with very low cost.

1.1 Motivation

Our goal for *h*BFT is to offer better performance by moving some critical jobs to the clients while minimizing side effects that can actually reduce performance in many cases in previous work [17, 21, 33, 34].

First, *h*BFT moves some critical jobs to the clients without additional costs. Moving critical jobs to the clients is effective in simplifying the design and reducing the message complexity, partly because replicas do not need to run expensive protocols to establish the order for every request. Nevertheless, it does not necessarily make protocols more practical. Indeed, it may sacrifice performance in normal cases or even in

fault-free cases, e.g. the output commit in Zyzzyva slows down both. *hBFT* achieves a simplified design and better performance for both fault-free and normal cases.

Second, *hBFT* can tolerate unlimited number of faulty clients. Previous protocols all rely on the correctness of clients. However, Byzantine clients can dramatically decrease performance. For instance, in the protocols that switch between subprotocols [17, 33, 34] (called abstracts in [17]), a faulty client can stay silent when it detects the inconsistency. Even if the next client is correct and makes the protocol switch to another abstract, replicas are still inconsistent because of this “faulty request”. Similarly, in Zyzzyva, faulty clients can keep silent when they are supposed to send a commit certificate to make all correct replicas converge. Faulty primaries in this case can not be detected, eventually leading to inconsistencies of replica states. Faulty clients can also intentionally send commit certificates to all replicas even if they receives $3f + 1$ matching messages, which slows down the performance.

Third, *hBFT* has the same operations for both fault-free and normal cases. This shows that in leader-based protocols, when the primary is correct, all the requests are totally ordered by all correct replicas. Previous protocols all achieve impressive performance in fault-free cases while they employ different operations when failure occurs, resulting in lower performance. Although Zyzzyva5 [21] makes the faulty cases faster, it requires $5f + 1$ replicas to tolerate f failures. In *hBFT*, we achieve better performance in both normal fault-free and normal cases using $3f + 1$ replicas.

2 RELATED WORK

Fig. 1 compares several features for *normal cases* between BFT protocols, a selection of which are plotted in Fig. 9. We provide the values for fault-free cases in the caption for protocols that have different values. The table is constructed based on the models to tolerate f failures. We measure throughput using the number of MACs each replica performs, including both generation and verification. The latency is evaluated by the number of communication steps (critical path), which refers to the number of one way latencies. Since we can batch concurrent requests for only the agreement subprotocol (as discussed in Section ??), the number of cryptographic operation between replicas and the clients becomes the major obstacle to throughput, especially when f grows. Compared to other known, prior work, *hBFT* achieves the lowest bound for almost every feature under high concurrency, and can handle faulty clients.

Most current practical Byzantine fault tolerant protocols are developed based on PBFT [7], which is a three phase leader-based protocol. Several subsequent work focus either on increasing the number of faults

systems can tolerate or on improving performance. There are trade-offs between the two. For instance, Fab [26] is a two-phase PBFT protocol that is proved to tolerate f failures by requiring at least $5f + 1$ replicas in total. The garbage collection in our protocol uses a tailored PBFT scheme, since it can guarantee correctness, but is too expensive to be used for fault-free and normal cases when the primary is correct.

Several protocols [17, 19, 21, 33, 34] move some critical jobs to the clients to improve performance. Zyzzyva and its variant [19] move output commit to the clients to reduce message complexity in fault-free cases. Other protocols [17, 33, 34] move the job of switching of subprotocols to the clients. When one subprotocol aborts, the protocol will switch to another. *hBFT* also switches between normal case operation and checkpoint subprotocol. However, *hBFT* does not order any single request using checkpoint subprotocol, instead, it is used only for contention resolving and garbage collection. Clients can facilitate the progress in *hBFT* but clients do not need to provide any “proof” to replicas.

Byzantine quorum systems [1, 25] tolerate Byzantine faults under low concurrency. HQ [13] is a hybrid quorum and Byzantine agreement protocol that also uses a PBFT-like subprotocol to resolve contention. Compared to HQ, *hBFT* does not have an additional garbage collection scheme and it works well under high concurrency.

3 SYSTEM MODEL

We consider a distributed system that tolerates a maximum of f faulty replicas using $3f + 1$ replicas and unlimited number of faulty clients. We consider Byzantine fault-tolerant replication problem, where faulty replicas and clients behave arbitrarily. In addition, we assume independent node failures, which can be obtained through techniques such as N -version programming [28].

Safety, which means requests are totally ordered by correct replicas, holds in any asynchronous system, where messages can be delayed, dropped or delivered out of order. Liveness, which means correct clients eventually receive replies to their requests, is ensured assuming partial synchrony [15]: synchrony holds only after some unknown global stabilization time, but the bounds on communication and processing delays are themselves unknown.

Operations are executed in an atomic broadcast model, where correct replicas agree on the set of requests and the order of them. In the description that follows, when we refer to *fault-free cases*, we mean there are no replica failures, and when we refer to *normal cases*, we mean the primary is correct and the number of faulty backups is between 1 and f .

We use digital signatures, message authentication codes (MACs), and message digests to prevent spoofing and to detect corrupted messages. For a message

		PBFT [7]	Q/U [1]	HQ [13]	FaB [26]	Zyzyva [21]	hBFT
Cost	Total replicas	$3f + 1$	$5f + 1$	$3f + 1$	$5f + 1$	$3f + 1$	$3f + 1$
Throughput (MAC ops/request)	Primary	$2 + \frac{8f}{b}$	$2 + 8f^{\parallel}$	$4 + 4f^{\parallel}$	$1 + \frac{5f}{b}$	$4 + 5f + \frac{3f}{b}^{\dagger}$	$2 + \frac{3f}{b}$
	Backup	$2 + \frac{8f+1}{b}$	$2 + 8f^{\parallel}$	$4 + 4f^{\parallel}$	$1 + \frac{2f+2}{b}$	$4 + 5f + \frac{1}{b}^*$	$2 + \frac{3f}{b}$
	Client	$2 + 2f$	$2 + 8f$	$4 + 4f$	$1 + 5f$	$4 + 10f^{\ddagger}$	$2 + 6f$
1-way Latency	Critical path	4	2	4	3	5^{\S}	3
Works well on concurrency?		Yes	No	No	Yes	Yes	Yes
Handle faulty clients?		No	No	No	No	No	Yes

Fig. 1. Comparison of BFT protocols in normal cases tolerating f faults and using batch size b . \dagger Fault-free cases: $2 + \frac{3f}{b}$. $*$ Fault-free cases: $2 + \frac{1}{b}$. \ddagger Fault-free cases: $2 + 6f$. \S Fault-free cases: 3. \parallel Q/U and HQ are leader-free quorum systems that do not differentiate primary and backups.

m , $\langle m \rangle_i$ denotes the message with digital signature signed by replica p_i , $D(m)$ denotes the message digest, and $\langle m \rangle$ denotes the message with MAC $\mu_{i,j}(m)$. The MAC $\mu_{i,j}(m)$ is generated using secret key shared by replica p_i and p_j .

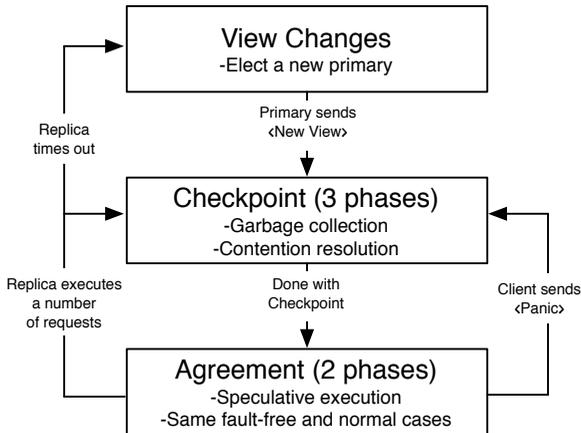


Fig. 2. Layered Structure of hBFT

4 THE hBFT PROTOCOL

The hBFT protocol is a hybrid, replicated state machine protocol. It includes four major components: (1) agreement, (2) checkpoint (3) view change, (4) client suspicion. As illustrated in Fig. 2, we employ a simple agreement protocol for fault-free and normal cases, and use a three-phase checkpoint subprotocol for contention resolution as well as garbage collection. The checkpoint subprotocol can be triggered by replicas when they execute a certain number of requests or by clients when they detect the divergence of replies. The view change subprotocol ensures the liveness of the system and can coordinate the change of the primary. View changes can occur during normal operations or in the checkpoint subprotocol. In both cases, the new primary initializes a checkpoint subprotocol immediately and resumes to the agreement protocol until a checkpoint becomes stable. The client suspicion subprotocol prevents faulty clients from attacking the system.

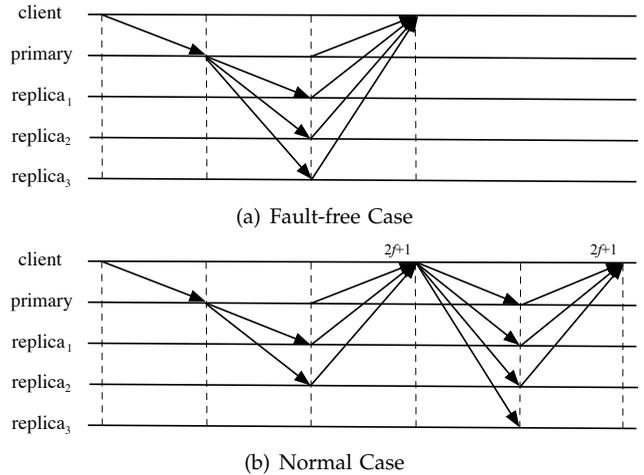


Fig. 3. Fault-free and Normal Cases of Zyzyva

Why another speculative BFT protocol?

hBFT uses speculation that overcomes some problems Zyzyva experiences. Zyzyva [21] also uses speculation and it moves output commit to the clients to enhance the performance. If we replace digital signatures with MACs and batch concurrent requests in Zyzyva, the performance degrades in normal cases and even fault-free cases. Fig. 3 illustrates the behavior of Zyzyva [21]. Replicas speculatively execute the requests and respond to the client. The client collects $3f + 1$ matching responses to complete the request. If the client receives between $2f + 1$ and $3f$ matching responses, it sends a commit certificate to all replicas, which contains the response with $2f + 1$ signatures. This helps replicas converge on the total ordering. However, a commit certificate must be verified by every other replica, which causes computing overhead for both clients and replicas. The use of MACs instead of digital signatures makes Zyzyva perform even worse than PBFT under certain configurations¹. For a

1. The use of MACs instead of digital signatures makes protocols much faster. As mentioned in Aardvark [11], on a 2.0GHz Pentium-M, openssl 0.9.8g can compute over 500,000 MACs per second for 64 byte messages, but it can only verify 6455 1024-bit RSA signatures per second or produce 309 1024-bit RSA signatures per second.

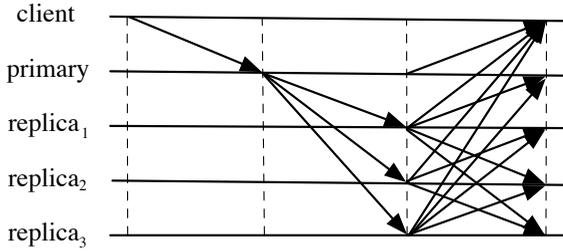


Fig. 4. The Agreement Protocol

reply message r by replica p_i , $\langle r', \mu_{i,c}(r') \rangle$ must be sent to the client, where $r' = \langle r, \mu_{i,1}(r), \mu_{i,2}(r) \cdots \mu_{i,n}(r) \rangle$ and $\mu_{x,y}(r)$ denotes the MAC generated using secret key shared by p_x and p_y . Therefore, every replica must include $3f + 1$ MACs for every reply message (compared with 1 if digital signatures are used). The performance is therefore dramatically degraded. Assuming b is the batch size, the primary must perform $4 + 5f + \frac{3f}{b}$ MACs in normal cases, which are even worse than the $2 + \frac{8f}{b}$ MACs for PBFT for some b and f . Thus in $hBFT$, we seek to avoid this problem.

4.1 Agreement Protocol

The agreement protocol orders requests for execution by replicas. The algorithms for the primary, backups, and clients are defined in Algorithm 1 to Algorithm 3. As illustrated in Fig. 4, a client c invokes the operation by sending a $m = \langle \text{Request}, o, t, c \rangle_c$ to all replicas where o is the operation, t is the local timestamp. Upon receiving a request, the primary p_i assigns a sequence number seq and then sends out a $\langle \text{Prepare}, v, seq, D(m), m, c \rangle$ to all replicas, where v is the view number, $D(m)$ is the message digest.

A $\langle \text{Prepare} \rangle$ message will be accepted by a backup p_j provided that:

- It verifies the MAC;
- The message digest is correct;
- It is in view v ;
- $seq = seq_l + 1$, where seq_l is the sequence number of its last accepted request;
- It has not accepted a $\langle \text{Prepare} \rangle$ message of the same view and sequence number but a different request.

If a backup p_j accepts the $\langle \text{Prepare} \rangle$ message, it speculatively executes the operation and sends a reply message $\langle \text{Reply}, v, t, seq, \delta_{seq}, c \rangle$ to c and also a commit message $\langle \text{Commit}, v, seq, \delta_{seq}, m, D(m), c \rangle$ to all other replicas except the primary, where δ_{seq} contains the speculative execution history.

In order to verify the correctness of the speculative executed request, a replica collects $2f + 1$ matching $\langle \text{Commit} \rangle$ messages from other replicas to complete a request. If a replica receives $f + 1$ matching $\langle \text{Commit} \rangle$ messages from different replicas but has not accepted any $\langle \text{Prepare} \rangle$ message, it also speculatively execute

the operation, sends a $\langle \text{Commit} \rangle$ message to all replicas, and sends a reply to the corresponding client. When the replica collects $2f + 1$ matching messages, it puts the corresponding request in its speculative execution history. However, it is possible that a replica receives $f + 1$ matching $\langle \text{Commit} \rangle$ messages from other replicas that are different from its accepted $\langle \text{Prepare} \rangle$ message. Under such circumstance, the replica can simply send a $\langle \text{View-Change} \rangle$ message to all replicas. If a replica votes for view change, it stops receiving any messages except the $\langle \text{New-view} \rangle$ and the checkpoint messages. See Section 4.3 for the detail of view change subprotocol. This is to ensure that if at least $f + 1$ correct replicas speculatively executes a request, all the correct replicas learn the result. If any other correct replicas receive inconsistent messages, the primary must be faulty and the replicas stop receiving messages until view change occurs.

A client sets a timeout for each request, if it gathers $2f + 1$ matching speculative replies from different replicas before the timeout expires, it completes the request. If a client receives fewer than $f + 1$ matching replies before the timeout expires, it retransmits the requests. Otherwise, when contention occurs (client receives between $f + 1$ and $2f + 1$ matching replies before timeout expires), client can facilitate the progress by sending a $\langle \text{PANIC}, D(m), t, c \rangle_c$ message to all replicas. If a replica receives a $\langle \text{PANIC} \rangle$ message, it forwards the message to all replicas. If a replica does not receive any $\langle \text{PANIC} \rangle$ message from the client but receives a $\langle \text{PANIC} \rangle$ message from other replicas, it forwards the $\langle \text{PANIC} \rangle$ message to all replicas. A $\langle \text{PANIC} \rangle$ message is valid if a replica has speculatively executed m . If a replica accepts a $\langle \text{PANIC} \rangle$ message, it stops receiving any messages except the view change and checkpoint messages. If the primary does not initialize the checkpoint subprotocol, the replica votes for view change. The forwarding of $\langle \text{PANIC} \rangle$ messages aims at two goals. On the one hand, this prevents checkpoint protocol from happening too frequently. Namely, all the correct replicas receive the $\langle \text{PANIC} \rangle$ message before the checkpoint protocol is triggered. On the other hand, this preventing the clients from attacking the system by sending $\langle \text{PANIC} \rangle$ message to a portion of replicas. If a fault client sends a $\langle \text{PANIC} \rangle$ message to a correct backup, the replica will stop receiving any messages while other replicas still continue the agreement protocol. This forwarding mechanism ensures that if at least one correct replica receives the $\langle \text{PANIC} \rangle$ message, all the replicas receive the $\langle \text{PANIC} \rangle$ message and enter the checkpoint protocol.

The primary initializes the checkpoint subprotocol if it receives the $\langle \text{PANIC} \rangle$ message from the client or $2f + 1$ $\langle \text{PANIC} \rangle$ messages from other replicas. The correctness of the protocol is therefore guaranteed by the three-phase checkpoint subprotocol.

The panic mechanism facilitates the progress when the primary is faulty. Specifically, in a partial syn-

chrony model where the value of client's timeout is properly set up, if a correct client does not receive enough matching replies before timer expires, the primary either sends inconsistent $\langle \text{Prepare} \rangle$ messages to the replicas or fails to send consistent messages to the replicas. In this case, instead of using traditional approach where replicas detect themselves by waiting for longer period of time, the client can directly trigger the checkpoint protocol in order to verify the correctness of the primary. See Section 4.2 for the detail of checkpoint subprotocol.

Algorithm 1 Primary

```

1: Initialization:
2:  $A$  {All replicas}
3:  $seq \leftarrow 0$  {Sequence number}

4: on event  $\langle \text{Request}, o, t, c \rangle_c$ 
5:    $seq \leftarrow seq + 1$ 
6:   send  $\langle \text{Prepare}, v, seq, D(m), m, c \rangle$  to  $A$ 
7:   send  $\langle \text{Reply}, v, t, seq, \delta_{seq}, c \rangle$  to  $c$ 

```

Algorithm 2 Backup

```

1: Initialization:
2:  $A$  {All replicas}
3:  $cnt \leftarrow 0$  {Counter of  $\langle \text{Commit} \rangle$  messages}
4:  $seq_i \leftarrow 0$  {Sequence number}

5: on event  $\langle \text{Request}, o, t, c \rangle_c$ 
6:   send  $\langle \text{Request}, o, t, c \rangle_c$  to the primary

7: on event  $\langle \text{Prepare}, v, seq, D(m), m, c \rangle$ 
8:   if  $seq = seq_i + 1$  then
9:      $seq_i \leftarrow seq$ 
10:    send  $\langle \text{Commit}, v, seq, \delta_{seq}, m, D(m), c \rangle$  to  $A$ 
11:    send  $\langle \text{Reply}, v, t, seq, \delta_{seq}, c \rangle$  to  $c$ 

12: on event  $\langle \text{Commit}, v, seq, \delta_{seq}, m, D(m), c \rangle$ 
13:    $cnt \leftarrow cnt + 1$ 
14:   if  $cnt = f + 1$  and  $seq = seq_i + 1$  then
15:      $seq_i \leftarrow seq$ 
16:     send  $\langle \text{Commit}, v, seq, \delta_{seq}, m, D(m), c \rangle$  to  $A$ 
17:     send  $\langle \text{Reply}, v, t, seq, \delta_{seq}, c \rangle$  to  $c$ 
18:   if  $cnt = 2f + 1$  then
19:      $cnt \leftarrow 0$  {Complete the request}

```

$h\text{BFT}$ guarantees correctness by only having two phases. If the client has received $2f + 1$ matching replies, at least $f + 1$ correct replicas receive consistent order from the primary. Therefore, all correct replicas receive at least $f + 1$ matching $\langle \text{Commit} \rangle$ messages. If those replicas do not receive the $\langle \text{Prepare} \rangle$ message, they will execute the request. Otherwise, if they detect the inconsistency, they stop receiving any messages until the current primary is replaced or the checkpoint subprotocol is triggered. In the latter case, the inconsistency will be reflected and fixed in the checkpoint subprotocol.

Algorithm 3 Client

```

1: Initialization:
2:  $A$  {All replicas}
3:  $cnt \leftarrow 0$  {Counter of reply messages}
4: send  $\langle \text{Request}, o, t, c \rangle_c$  to  $A$ 
5:  $start(\Delta)$  {Start a timer}

6: on event  $\langle \text{Reply}, v, t, seq, \delta_{seq}, c \rangle$ 
7:    $cnt \leftarrow cnt + 1$ 
8:   if  $cnt = 2f + 1$  then
9:      $cnt \leftarrow 0$  {Complete the request}

```

4.2 Checkpoint

We use a three-phase PBFT-like checkpoint protocol. The reasons are three-fold. First, the agreement protocol uses speculative execution and replicas may be temporarily out of order. The three-phase checkpoint protocols resolve the inconsistencies. Second, if a correct client triggers checkpoint protocol through panic mechanism, the checkpoint protocol resolves the inconsistencies immediately. Third, the checkpoint protocol detects the behavior of the faulty clients if they intentionally trigger the checkpoint protocol.

The checkpoint protocol works as follows. Only the primary can initialize the checkpoint subprotocol, which is generated under either of the two conditions:

- the primary executes certain number of requests.
- the primary receives $\langle \text{PANIC} \rangle$ message from the client or receives $2f + 1$ forwarded $\langle \text{PANIC} \rangle$ messages from other replicas.

In the latter condition, as mentioned in Section 4.1, when replicas receive a valid $\langle \text{PANIC} \rangle$ message, it forwards to all replicas. To goal is to ensure that all the replicas receive the $\langle \text{PANIC} \rangle$ message and prevent the faulty clients from sending a $\langle \text{PANIC} \rangle$ message to all backups so that replicas will suspect the primary even if it is correct.

The three-phase checkpoint subprotocol works as follows: the current primary p_i sends a $\langle \text{Checkpoint-I}, seq, D(M) \rangle$ to all replicas, where seq is the sequence number of last executed operation, $D(M)$ is the message digest of speculative execution history M . Upon receiving a well-formatted $\langle \text{Checkpoint-I} \rangle$ message, a replica sends a $\langle \text{Checkpoint-II}, seq, D(M) \rangle$ to all replicas. If the digest and execution history do not match its local log, the replica sends a $\langle \text{View-Change} \rangle$ message directly to all replicas and stops receiving any messages other than the $\langle \text{New-view} \rangle$ message.

A number of $2f + 1$ matching $\langle \text{Checkpoint-II} \rangle$ messages from different replicas form a certificate, denoted by $\mathcal{CER}_1(M, v)$. Any replica p_j that has the certificate sends a $\langle \text{Checkpoint-III}, seq, D(M) \rangle_j$ to all replicas. Similarly, $2f + 1$ $\langle \text{Checkpoint-III} \rangle$ messages form a certificate, denoted by $\mathcal{CER}_2(M, v)$. After collecting $\mathcal{CER}_2(M, v)$, the checkpoint becomes stable. All the previous checkpoint messages, $\langle \text{Prepare} \rangle$,

$\langle \text{Commit} \rangle$, $\langle \text{Request}, o, t, c \rangle_c$, and $\langle \text{Reply} \rangle$ messages with smaller sequence number than the checkpoint are deleted.

If a view change occurs in checkpoint subprotocol, as described in Section 4.3, the new primary initializes a checkpoint immediately after the $\langle \text{New-view} \rangle$ message. The same three-phase checkpoint subprotocol continues until one checkpoint is completed and the system stabilizes.

4.3 View Changes

The view change subprotocol elects a new primary. By default, the primary has id $p = v \bmod n$, where n is the total number of replicas, and v is the current view number. View changes may take place in the checkpoint subprotocol or the normal operations. In both cases, the new primary reorders requests using a $\langle \text{New-view} \rangle$ message and then initializes a checkpoint immediately. The checkpoint subprotocol continues until one checkpoint is committed.

A $\langle \text{View-Change}, v + 1, \mathcal{P}, \mathcal{Q}, \mathcal{R} \rangle_i$ message will be sent by a replica if any of the following conditions is true, where \mathcal{P} contains the execution history M from $\mathcal{CER}_1(M, v)$ the replica collected in previous view v , \mathcal{Q} denotes the execution history from the accepted $\langle \text{Checkpoint-I} \rangle$ message, and \mathcal{R} denotes the speculatively executed requests with sequence number greater than its last accepted checkpoint:

- It starts a timer for the first request in the queue. The request is not executed before the timer expires;
- It starts a timer after collecting $f + 1$ $\langle \text{PANIC} \rangle$ messages. It has not received any checkpoint messages before the timer expires;
- It starts a timer after it executes certain number of requests. It has not received any checkpoint messages before the timer expires.
- It receives $f + 1$ valid $\langle \text{View-Change} \rangle$ messages from other replicas.

Timers with different values are set for each case and are reset periodically.

When the new primary p_j receives $2f$ $\langle \text{View-Change} \rangle$ messages, it constructs a $\langle \text{New-view} \rangle$ message to order all the speculatively executed requests. The system then moves to a new view. The principle is that any request committed by the clients must be committed by all correct replicas. The new primary picks up an execution history M from the \mathcal{P} and a set of requests from the \mathcal{R} of checkpoint messages. To select a speculative execution history M , there are two rules.

A If some correct replica has committed on one checkpoint that contains execution history M , M must be selected, provided that:

- A1. At least $2f + 1$ replicas have $\mathcal{CER}_1(M, v)$.
- A2. At least $f + 1$ replicas have accepted $\langle \text{Checkpoint-I} \rangle$ in view $v' > v$.

B If at least $2f + 1$ replicas have empty \mathcal{P} components, then the new primary its last stable checkpoint.

Similarly, for each sequence number greater than the execution history M and smaller than the largest sequence number in \mathcal{R} of checkpoint messages, the primary assigns a request according to \mathcal{R} . A request m is chosen if at least $f + 1$ replicas include it in \mathcal{R} of their checkpoint messages. Otherwise, NULL is chosen. We claim that it is impossible for $f + 1$ replicas to include one request m , and another $f + 1$ replicas include m' with the same sequence number. Namely, if $f + 1$ replicas include a request m , at least one correct replica receives $2f + 1$ $\langle \text{Commit} \rangle$ messages. Similarly, at least one correct replica receives $2f + 1$ commit messages with request m' . The two quorums intersect in at least one correct replica. The correct replica must have sent both $\langle \text{Commit} \rangle$ message with m and $\langle \text{Commit} \rangle$ message with m' , a contradiction.

The execution history M and the set of requests form M' , which is composed of requests with sequence numbers between the last stable checkpoint and the sequence number that has been used by at least one correct replica. The new primary then sends a $\langle \text{New-View}, v + 1, \mathcal{V}, \mathcal{X}, M' \rangle_j$ message to all replicas, where \mathcal{V} contains $f + 1$ valid $\langle \text{View-Change} \rangle$ messages, \mathcal{X} contains the selected checkpoint. The replicas then run the checkpoint subprotocol using M' . The checkpoint subprotocol continues until one checkpoint is committed.

4.4 Client Suspicion

Faulty clients may degrade the performance of the system, especially for protocols that move some critical jobs to the clients. In $h\text{BFT}$, unlimited number of faulty clients can be detected. We would like to focus on the unfaithful but “legal” messages a faulty client can craft to slow down the performance or cause incorrectness. To be specific, a faulty client can do the following:

- It sends inconsistent requests to different replicas. The primary may not be able to order “every” request before the timeout expires. In this case, a correct primary may be removed.
- It intentionally sends $\langle \text{PANIC} \rangle$ messages while there is no contention. Unnecessary checkpoint subprotocol will be triggered, which slows down the performance. However, if the client frequently triggers “valid” checkpoint operations, the overall throughput degrades too.
- It does not send $\langle \text{PANIC} \rangle$ messages if it receives divergent replies, which leaves replicas temporarily inconsistent.

The client suspicion subprotocol in $h\text{BFT}$ focus on the first two. If the third one occurs, the checkpoint subprotocol can be triggered by the next correct client if it detects the divergence of replies or by the primary when replicas execute certain number of requests.

To solve the first problem, we ask clients to multicast the request to the replicas and every replica forwards the request to the primary. The primary orders a request if it receives the request or if it receives $f + 1$ matching requests forwarded by backups. If a replica p_i receives a $\langle \text{Prepare} \rangle$ message with a request that is not in its queue, it still executes the operation. Nevertheless, such faulty behavior of clients will be identified as suspicious, and if the number of suspicious incidents from the same client exceeds certain threshold, p_i will send a $\langle \text{Suspect}, c \rangle_i$ message to all replicas.

Another reason clients send their requests to all replicas is that there are many drawbacks clients send requests to the primary only². For instance, a faulty primary can delay any request, no matter it receives from the client or other replicas, which finally makes all clients multicast their requests to all replicas and experience long latency. Faulty primary can perform performance attack such as timeout manipulation discussed in previous works [2, 11, 29]. Furthermore, it is also difficult to make clients keep track of the primary. If the client sends its request to a faulty backup, the faulty backup can also ignore this request although it is supposed to forward the request to the primary. All these problems move the correctness of the protocols to the detection of faulty replicas.

For the second problem where a faulty client intentionally sends a $\langle \text{PANIC} \rangle$ message to the replicas to trigger the checkpoint subprotocol, the protocol naturally detects the faulty behavior. Intuitively, if the request is committed in both agreement protocol and checkpoint protocol without view change, the client can be suspected. Nevertheless, a correct client might be suspected as well. For instance, the following two cases are indistinguishable.

- The replicas are correct and reach an agreement in the agreement protocol. When they receiving the $\langle \text{PANIC} \rangle$ message from a faulty client, the request is committed without view change and the client is suspected.
- The primary is faulty and the client is correct. The primary sends the request to $f + 1$ correct replica and another fake request to the left f correct replicas. The f correct replicas will not execute th request. When the replicas receive $\langle \text{PANIC} \rangle$ message and starts checkpoint protocol. The f faulty replicas collude and make the request committed. Although the f correct replicas learn th result and remain consistent, the correct client will be suspected.

2. In some Byzantine agreement protocols, clients send requests to only their known primary. If a backup receives the request, it forwards the request to the primary, expecting the request to be executed. The client sets a timeout for each request it has. If it does not receive enough number of matching responses before timeout expires, it retransmits the request to all replicas.

To distinguish the above two cases, we modify the agreement protocol by simply replacing the MAC of $\langle \text{Prepare} \rangle$ message with digital signatures, which is called *Almost-MAC-agreement*. When a replica sends a $\langle \text{Commit} \rangle$ message, it appends the $\langle \text{Prepare} \rangle$ message. If a client does not receive valid $\langle \text{Prepare} \rangle$ message from the primary but receives from other replicas, it still execute the requests, sends $\langle \text{Commit} \rangle$ messages to other replicas and send reply to the client. Otherwise, if a replica receives two valid and conflicting $\langle \text{Prepare} \rangle$ messages, it directly sends inconsistent messages to all replicas and votes for view change. As proved in Claim 2, the protocol guaranteed that correct clients will not be removed. This optimization can also solves the problem as discussed in Section 5.1.

The modification of agreement protocol results in $2 + \frac{1(\text{sig})}{b}$ cryptographic operations for the primary. To reduce the overall cryptographic operations, *hBFT* switches between the agreement protocol and *Almost-MAC-agreement* when executing certain number of requests.

The client will only be suspected when replicas are running *Almost-MAC-agreement*. In addition, the client must be suspected by $2f + 1$ replicas to be removed. If the number of such incidents exceeds certain threshold, replicas will suspect the client and send a $\langle \text{Suspect} \rangle$ message to all replicas. Similar to view change subprotocol, if a replica receives $f + 1$ $\langle \text{Suspect} \rangle$ messages, it generates a $\langle \text{Suspect} \rangle$ message and sends to the replicas. If a replica receives $2f + 1$ $\langle \text{Suspect} \rangle$ messages, indicating that at least one correct replica suspects the client, the client can be prevented from accessing the system in the future.

Worst Case Scenario We would like to analyze the worst case where a correct client can be suspected, mainly due to the network failure. It happens if any of the following is true:

- (1) The request from client fails to reach $f + 1$ correct backups before the backups receive the $\langle \text{Prepare} \rangle$ message. In this case, since the $f + 1$ correct backups do not receive the request in the $\langle \text{Prepare} \rangle$ message, they will suspect the client.
- (2) Reply message(s) from correct replica(s) fails to reach the client before the timeout expires. Since the client does not receive $2f + 1$ matching replies before the timeout expires, the client sends $\langle \text{PANIC} \rangle$ messages while there is no contention.

The latter condition may occur due to inappropriate value of the timeout regarding the network condition or due to the attack by the primary. For instance, a faulty primary can intentionally delay $\langle \text{Prepare} \rangle$ message for some correct replicas, making correct clients send $\langle \text{PANIC} \rangle$ message while replicas are “consistent”. However, if the value of the timeout is appropriately set up, as proved in Claim 2, a correct client will not be removed. We set up a large enough timeout for clients so that if at least $f + 1$ correct

replicas execute a requests, all the replicas will send reply messages to the client before its timer expires.

4.5 Correctness

In this section, we sketch proofs for the safety and liveness properties of $hBFT$ under optimal resilience. For simplicity, we assume there are $3f + 1$ replicas.

4.5.1 Safety

Theorem 1 (Safety): If requests m and m' are committed at two correct replicas p_i and p_j , m is committed before m' at p_i if and only if m is committed before m' at p_j .

Proof: The proof proceeds as follows. We first prove the correctness of checkpoint subprotocol, which follows the correctness of PBFT, as shown in *Claim 1*. We then show the proof of the theorem based on the claim.

Claim 1 (Safety of Checkpoint): The checkpoint subprotocol guarantees the safety property.

Proof: We now prove that if checkpoints M and M' are committed at two correct replicas p_i and p_j in checkpoint subprotocol, regardless of being in the same view or across views, $M = M'$.

(*Within one view*) If p_i and p_j commit both in view v , then p_i has collected $\mathcal{CER}_2(M, v)$, which indicates that at least $f + 1$ correct replicas send $\langle \text{Checkpoint-III} \rangle$ for M . Similarly, p_j has $\mathcal{CER}_2(M', v)$, which indicates that at least $f + 1$ correct replicas send $\langle \text{Checkpoint-III} \rangle$ for M' . Then excluding f faulty replicas, if M and M' are different, at least one correct replica has sent two conflicting messages for M and M' , which contradicts with our assumption. Therefore, $M = M'$.

(*Across views*) If M is committed at p_i in view v and M' is committed at p_j in view $v' > v$, $M = M'$. If M' is committed in view v' , then either condition A or B must be true in the construction of the $\langle \text{New-view} \rangle$ message in view v' (see Section 4.3). However, if M is committed at p_j in view v , p_j has $\mathcal{CER}_2(M, v)$, which indicates that at least $f + 1$ correct replicas have $\mathcal{CER}_1(M, v)$ and M in the \mathcal{P} component. Therefore, condition B cannot be true. For condition A, p_j can commit on M' in view v' if both A1 and A2 are true. A2 can be true if a faulty replica sends a $\langle \text{View-Change} \rangle$ message that includes $\langle M', D(M'), v_1 \rangle$, where $v < v_1 < v'$. However, condition A1 requires that at least $f + 1$ correct replicas have $\mathcal{CER}_1(M', v')$. Since at least $f + 1$ correct replicas have $\mathcal{CER}_1(M, v)$, they will not accept M' in any later views. At least one correct replica sends conflicting message(s), which contradicts with our assumption. Therefore, $M = M'$. \square

To prove Theorem 1, we first show that if two requests m and m' are committed at correct replicas p_i and p_j , m equals m' . Then we show that if m_1 is committed before m_2 at p_i , m_1 is committed before

m_2 at p_j . The former part is shown across views and within the same view.

- (Within the same view) There are three cases: the two requests are committed in agreement subprotocol, two requests are both committed in checkpoint subprotocol, one of them is committed in checkpoint subprotocol. In the first case, if m is committed at p_i , p_i receives $2f + 1$ $\langle \text{Commit} \rangle$ messages if the request is committed in agreement protocol or $2f + 1$ checkpoint messages as certificate if the request is committed in checkpoint protocol. On the other hand, if m' is committed at p_j , p_j receives $2f + 1$ $\langle \text{Commit} \rangle$ messages or $2f + 1$ checkpoint messages. The two quorums intersect in at least one correct replica. The correct replica must send inconsistent messages, a contradiction. Therefore, m equals m' .
- (Across views) If m is committed at replica p_j , $2f + 1$ replicas send $\langle \text{Commit} \rangle$ messages. At least $f + 1$ correct replicas accept m , which will be included in their $\langle \text{View-Change} \rangle$ messages. On every view change, the new primary initializes a checkpoint subprotocol to make the same order of requests committed at all the correct replicas in the $\langle \text{New-view} \rangle$ message. The correctness follows from Claim 1.

Then we show that if m_1 is committed before m_2 at p_i , m_1 is committed before m_2 at p_j . If a request is committed at a correct replica, $2f + 1$ replicas send $\langle \text{Commit} \rangle$ messages. Since two quorums of $2f + 1$ replicas intersect in at least one correct replica p_i , m_1 is committed with sequence number smaller than m_2 . According to the former proof, if m_1 and m_2 are committed at p_j , they are committed with the same sequence numbers.

By combining all the above, safety is proved. \square

4.6 Liveness

Theorem 2 (Liveness): Correct clients eventually receive replies to their requests.

Proof: It is trivial to show that if the primary is correct, clients receive replies to their requests. In the following, we first show that correct clients will not be removed. We then prove that faulty replicas and faulty clients cannot impede progress by removing a correct primary.

Claim 2 (Correct Client Condition): If the values of the timeouts are appropriately set up, correct clients will not be removed if they trigger a checkpoint.

Proof: If a correct client receives between $f + 1$ to $2f + 1$ matching replies for a request m , it triggers the checkpoint subprotocol. To remove a correct client, m must be executed by $f + 1$ replicas in Almost-MAC-agreement protocol and committed in the checkpoint subprotocol without view change. Among the $f + 1$ replicas that accept $\langle \text{Prepare} \rangle$ message in the agreement protocol, at least one is correct. If it receives a $\langle \text{Prepare} \rangle$ message, it appends

the message to $\langle \text{Commit} \rangle$ message and send to all replicas. If at least one correct replica receive valid and conflicting $\langle \text{Prepare} \rangle$ message from the primary, it will send inconsistent messages and eventually all the correct replicas vote for view change, a contradiction that view change does not occur. Therefore, not correct replica receives conflicting $\langle \text{Prepare} \rangle$ message. In addition, if a correct replica does not received valid $\langle \text{Prepare} \rangle$ message from the primary and receives valid $\langle \text{Prepare} \rangle$ message appended with the $\langle \text{Commit} \rangle$ message, it will accept the $\langle \text{Prepare} \rangle$ message and sends $\langle \text{Reply} \rangle$ message to the client. In this case, the client receives $2f + 1$ matching replies, a contradiction with the assumption that the client is correct. Therefore, correct clients will not be removed by the client suspicion protocol. \square

Claim 3 (Faulty Replica Condition): Faulty replicas cannot impede progress by causing view changes.

Proof: To begin with, we show that faulty replicas cannot cause a view change by sending $\langle \text{View-Change} \rangle$ message. At least $f + 1$ $\langle \text{View-Change} \rangle$ messages are sufficient to cause a view change. Even if all faulty replicas vote for view change, they cannot cause a view change. A faulty primary *can* cause a view change. However, the primary cannot be faulty for more than f consecutive views.

In addition, no $\langle \text{View-Change} \rangle$ message makes a correct primary incapable of generating a $\langle \text{New-view} \rangle$ message. For one thing, a correct primary is able to pick up a stable checkpoint. Since at least $f + 1$ correct replicas have \mathcal{CER}_2 for a checkpoint, the new primary is able to pick it up. For another thing, the new primary is able to pick up a sequence of requests based on condition A or B. Either some correct replica(s) commits on a checkpoint or no correct replica does. Condition A1 can be verified because non-faulty replicas will not commit on two different checkpoint. Condition A2 is satisfied if at least one correct replica accepts a $\langle \text{Checkpoint-I} \rangle$ message for the same checkpoint and it votes for the authenticity of the checkpoint. Therefore, the checkpoint can be selected since it is authentic. Similarly, a set of executed request can be selected based on \mathcal{R} in view change. Namely, if the client completes a request, the request must be ordered and accepted by at least $2f + 1$ replicas. Among them, at least $f + 1$ replicas are correct. If other replicas receive inconsistent $\langle \text{Prepare} \rangle$ message and $f + 1$ $\langle \text{Commit} \rangle$ messages, they will abort. Therefore, it is not possible that a set of $f + 1$ replicas include one request and another set of $f + 1$ replicas include another request. In conclude, the new primary is able to select a $\langle \text{New-view} \rangle$ message. \square

Claim 4 (Faulty Client Condition 2): A faulty client cannot impede progress by causing view changes.

Proof: If a faulty client intentionally triggers the checkpoint subprotocol while replicas are consistent, a view change will not occur. Replicas will take an additional three-phase checkpoint subprotocol so that

requests committed in agreement subprotocol will be committed in checkpoint subprotocol. Since such faulty behavior of clients will be detected, the client will be removed. \square

To summarize, faulty backup(s) can not cause view changes according to Claim 3. In addition, faulty clients are not capable of removing a correct primary according to Claim 4. Since faulty clients are eventually moved, replicas will handle requests from correct clients. Finally, since the primary cannot be faulty for more than f continuous views, clients eventually receive replies to their requests. \square

5 DISCUSSION

5.1 Timeouts

Existing protocols rely on different timeouts to provide liveness. As discussed in Section 4.4, the values of timeouts are key to avoid some uncivil attacks. Since we assume the weak synchrony model, it is reasonable to set up timeouts according to the round-trip time such as the technique used in Prime [2]. However, in several corner cases inappropriate values of timeouts or network congestion makes a correct replica suspect or remove a correct primary.

hBFT employs a client suspicion subprotocol that is used to detect faulty clients. A faulty primary can play tricks on timeouts to remove faulty clients. For instance, the primary can send $\langle \text{Prepare} \rangle$ message to f correct replicas and delay the $\langle \text{Prepare} \rangle$ message to $f + 1$ correct replicas until the very end of timeout of the client. The $f + 1$ correct replicas receive the $\langle \text{Prepare} \rangle$ message and execute the request but they do not reply to the clients “on time”. Since the client does not receive enough number of replies before the timeout expires, it sends $\langle \text{PANIC} \rangle$ message. However, all replicas are “consistent” since the primary still sends out consistent $\langle \text{Prepare} \rangle$ messages. Correct clients will be suspected.

We solve this problem by using Almost-MAC-agreement protocol as discussed in Section [?]. The optimization allows all replicas to execute the request on time if at least one correct replica receives a valid $\langle \text{Prepare} \rangle$ message, which prevents a faulty primary from framing the clients.

5.2 Speculation

Speculation reduces the cost and simplifies the design of Byzantine agreement protocols, which works well especially for systems with highly concurrent requests. Speculation has been used by fault-free systems and by systems that tolerate crash failures. Therefore, *hBFT* also works well in adaptively tolerating crash failures to Byzantine failures. *hBFT* uses speculation because replicas are always consistent for both fault-free and normal cases where the primary is correct. Every request takes three communication

steps to complete, and is the theoretical lower bound for agreement-based protocols.

Speculation does not work well for systems that have highly computationally consuming tasks or systems that have a high attack rate. The former problem can be handled by separating execution from agreement [32]. The latter problem degrades the performance no matter with or without recovery. For instance, faulty clients can simply trigger the three-phase checkpoint subprotocol on every request, which makes *hBFT* achieve similar performance as *PBFT* before the faulty clients are evacuated. The advantage of *hBFT* indicates that the three-phase checkpoint subprotocol is triggered rarely. Therefore, *hBFT* improves the performance in fault-free and normal cases but achieves comparable performance as *PBFT* in the worst case.

6 EVALUATION

We evaluate the system on Emulab [31] utilizing up to 45 *pc3000* machines connected through a 100Mbps switched LAN. Each machine is equipped with a 2GHz, 64-bit Xeon processor with 2GB of RAM. 64-bit Ubuntu 10 is installed on every machine, running Linux kernel 2.6.32.

We identify several “good” provable secure cryptographic tools for our scheme. In particular, we use RSA-FDH [4] for our digital signature scheme, and HMAC-MD5 [5, 6] for the MAC algorithm. Both of them are very simple, fast and provably secure. We employ such tools due to the fact that we would like to abandon those vulnerable cryptographic tools used in papers like *PBFT* and *Zyzyva*. An additional reason is that we still want to compare our scheme with them since RSA-FDH and HMAC-MD5 have almost exactly the same efficiency as a naked RSA signature and MD5 (using with parameter as the key).

We compare our work with Castro et al.’s implementation of *PBFT* [7] as well as Kotla et al.’s implementation of *Zyzyva* [21]. All the experiments are carried out in normal case, where a backup is faulty. Four micro-benchmarks are used in the evaluation, also developed by Castro et-al. An x/y benchmark means x *KB* size request from clients and y *KB* size reply from the replicas.

6.1 Throughput

Fig. 5 compares throughput achieved for the 0/0 benchmark between *PBFT*, *Zyzyva* and *hBFT* where B is the size of the batch. Fig. 6 presents the performance for the four benchmarks where $B = 1$ for all benchmarks. All the data are tested in the configuration of $f = 1$.

As the number of clients increases, *Zyzyva* performs even worse than *PBFT*. As indicated in Section 1.1, without batching ($B = 1, f = 1$), bottleneck server of *Zyzyva* ($4 + 5f + \frac{3f}{b}$) performs 1.2 times

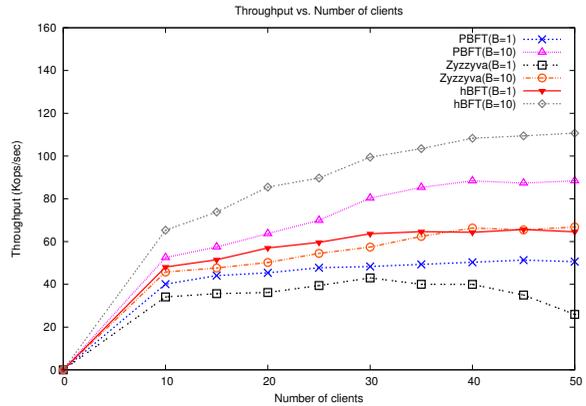


Fig. 5. Throughput vs. Number of Clients

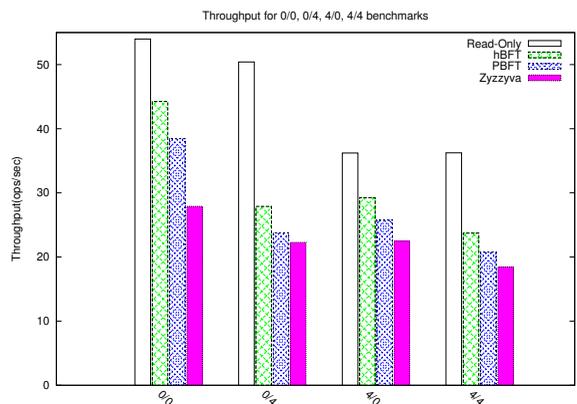


Fig. 6. Throughput for 0/0, 0/4, 4/0 and 4/4 benchmarks for systems to tolerate $f = 1$ faults

more MAC operations than *PBFT* ($2 + \frac{8f}{b}$) and 2.4 times more MAC operations than *hBFT* ($2 + \frac{3f}{b}$). With batching ($B = 10, f = 1$), *Zyzyva* performs 3.3 more MAC operations than *PBFT* and 4.0 more MAC operations than *hBFT*.

The simulation validates the theoretical results. According to Fig. 5, without batching, *hBFT* achieves more than 40% higher than that of *PBFT* and 20% higher than that of *Zyzyva*. With batching, *hBFT* achieves a peak throughput that is 2 times better than *Zyzyva*, and still achieves 40% improvement over *PBFT*. The difference is due to the cryptographic overhead of each protocol.

Additionally, *hBFT* works better than both *Zyzyva* and *PBFT* under high concurrency. As the number of clients grows, all three protocols scale better with batching than without. When the number of clients exceeds 40, throughput of *Zyzyva* degrades obviously. All other cases remain stable when the number of clients exceeds 30. When the number of clients is fewer than 30, *hBFT* with batching has an outstanding growth. Other than that, throughput of *PBFT* with batching also grows faster compared with all the left cases. The reply message cannot be batched and replicas need to reply to every client in the batch,

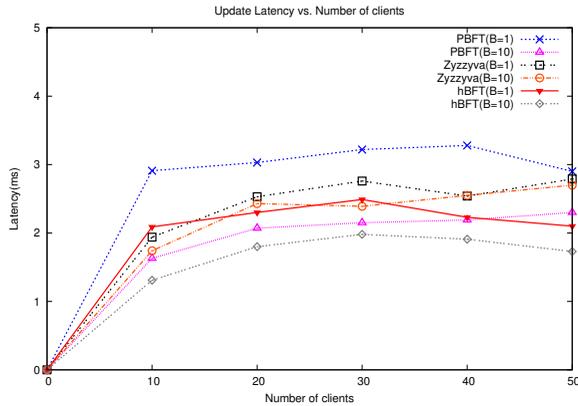


Fig. 7. Latency vs. Number of Clients

which explains the result why Zyzzyva achieves the lowest throughput in normal cases.

For all benchmarks as shown in Fig. 6, *hBFT* achieves higher throughput as well. All three protocols achieve the best throughput for 0/0 benchmark and the worst for 4/4 benchmark. Zyzzyva performs worse for 0/4 and 4/4 benchmarks than 4/0 benchmark. *hBFT* has similar result. PBFT achieves almost the same throughput for 0/4 and 4/0 benchmarks. This implies that the size of reply messages has more effect for speculation-based protocols. In addition, without batching, PBFT performs worse than both Zyzzyva and *hBFT*. The outstanding performance of read-only requests is due to the read-only optimization, where replicas send reply directly to the clients without running agreement protocol.

To summarize this section, *hBFT* outperforms both Zyzzyva and PBFT in normal cases. Since PBFT achieves almost the same throughput for 0/4 and 4/0 benchmarks and it achieves higher throughput with batching, it works well for systems that have more computationally consuming tasks. Comparably, *hBFT* and Zyzzyva work well for systems that have highly concurrent but lightweight requests.

6.2 Latency

The performance depends on both cryptographic overhead and one way message latencies. Cryptographic overhead controls the latency of processing one message and the number of one way latencies controls the number of phases that the agreement protocol goes through. In terms of critical paths between sending and completing a request, PBFT has four if replicas send reply to the clients after prepare phase. *hBFT* has only three, which is the theoretical lower bound of agreement protocols. Even though the checkpoint subprotocol takes three phases in contrast to two in other protocols, it will not decrease the overall performance significantly since the checkpoint subprotocol is triggered rarely. Zyzzyva takes three in fault-free cases and five in normal cases.

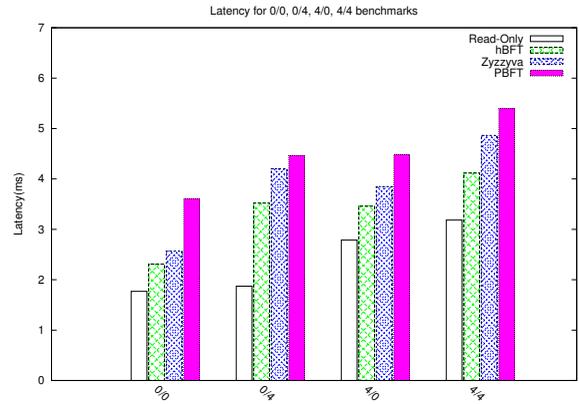


Fig. 8. Latency for 0/0, 0/4, 4/0 and 4/4 benchmarks for systems to tolerate $f = 1$ faults

Additionally, the performance of all protocols is also related to the frequency of checkpoint subprotocol as well. It has a direct impact on *hBFT* due to the reason that checkpoint subprotocol of *hBFT* is more expensive than the other two. By default, we assume that a checkpoint subprotocol starts every 1000 requests or batches. *hBFT* outperforms the other two under this setting. If we make checkpoint subprotocol more rarely, it can be expected that *hBFT* will achieve even better performance and vice versa.

As illustrated in Fig. 7 and Fig. 8, without batching, *hBFT* achieves 40% lower latency than that of PBFT and 30% lower latency than that of Zyzzyva. With batching, similar with the performance of throughput, Zyzzyva achieves higher latency than that of PBFT, and *hBFT* outperforms both. When the number of clients increases, all the protocols scale well without an obvious increase in latency, which shows that all three protocols work well under high concurrency. When the number of clients exceeds 40 and with batching, Zyzzyva has an increase of latency. Since every $\langle \text{Reply} \rangle$ message in Zyzzyva contains $3f + 1$ MACs and cannot be batched, the increase in latency indicates that the cryptographic operations in the $\langle \text{Reply} \rangle$ message limits the behavior of a protocol.

The performance for all the four benchmarks shows similar results as indicated in Fig. 8. All the three protocols have the lowest latency for 0/0 benchmark and the highest for 4/4 benchmark. *hBFT* and PBFT achieve almost the same latency for both 4/0 and 0/4 benchmarks. Zyzzyva achieves lower latency for 4/0 benchmark than 0/4 benchmark. The length of reply message also reduces the latency per request for Zyzzyva. The effect is not as apparent as the effect on throughput though. Although *hBFT* performs better on throughput for the 4/0 benchmark than the 0/4 benchmark, it achieves almost the same latency for both benchmarks, which indicates that the checkpoint subprotocol has a more direct effect on the throughput than the latency.

Overall, the latency validates the results of throughput. Our statements in Section 5 are verified by the results of latency. By observing the curves of latency, we can summarize the performance of protocols under normal operations. On the other hand, by observing the curves of throughput, the effects of other subprotocols are included.

6.3 Fault Scalability

We also examine the performance when the number of replicas increases. As indicated in Fig. 1, the throughput is related to f . We view the primary as the bottleneck server not only because of the number of MAC operations in the agreement, but also because of other effort such as processing requests. For PBFT and h BFT, the backups do not perform many fewer cryptographic operations than the primary. Comparably, backups in Zyzzyva perform many fewer cryptographic operations than the primary, which can be viewed as an advantage of Zyzzyva. However, this does not have a direct positive effect on the throughput and latency since the primary performs more cryptographic operations. As f increases, the performance for all three protocols will degrade due to the cryptographic overhead, especially without batching.

Fig. 9 compares the number of cryptographic operations that the primary and clients perform as the number of faults increases. In addition to PBFT, Zyzzyva and h BFT, we also include Q/U and HQ, which are two (hybrid) Byzantine quorum protocols. For the performance of a primary with or without batching, as illustrated in Fig. 9(a) and Fig. 9(b), it can be observed that batching greatly reduces the number of cryptographic operations as the number of total replicas increases. For instance, although the number of cryptographic of PBFT is the most outstanding without batching and increases quite fast, the cryptographic overhead is almost the smallest without batching and remains stable as the number of faults increases. Comparably, the number of cryptographic operations of Zyzzyva does not decrease too much without batching. Since both HQ and Q/U are quorum-based protocols, they cannot use batching and work better under low concurrency. h BFT achieves the smallest numbers with or without batching. Combined with Fig. 9(c), we observe that there is a trade-off between the number of cryptographic operations of the bottleneck server and the clients. HQ requires the most cryptographic operations for the bottleneck server but the fewest for clients among all the five protocols. Zyzzyva requires a comparably large number for both the bottleneck server and the clients. h BFT requires the fewest for the bottleneck server but still a high number for clients.

As illustrated in Fig. 10, as the number of faulty replicas increases, which indicates an increase of

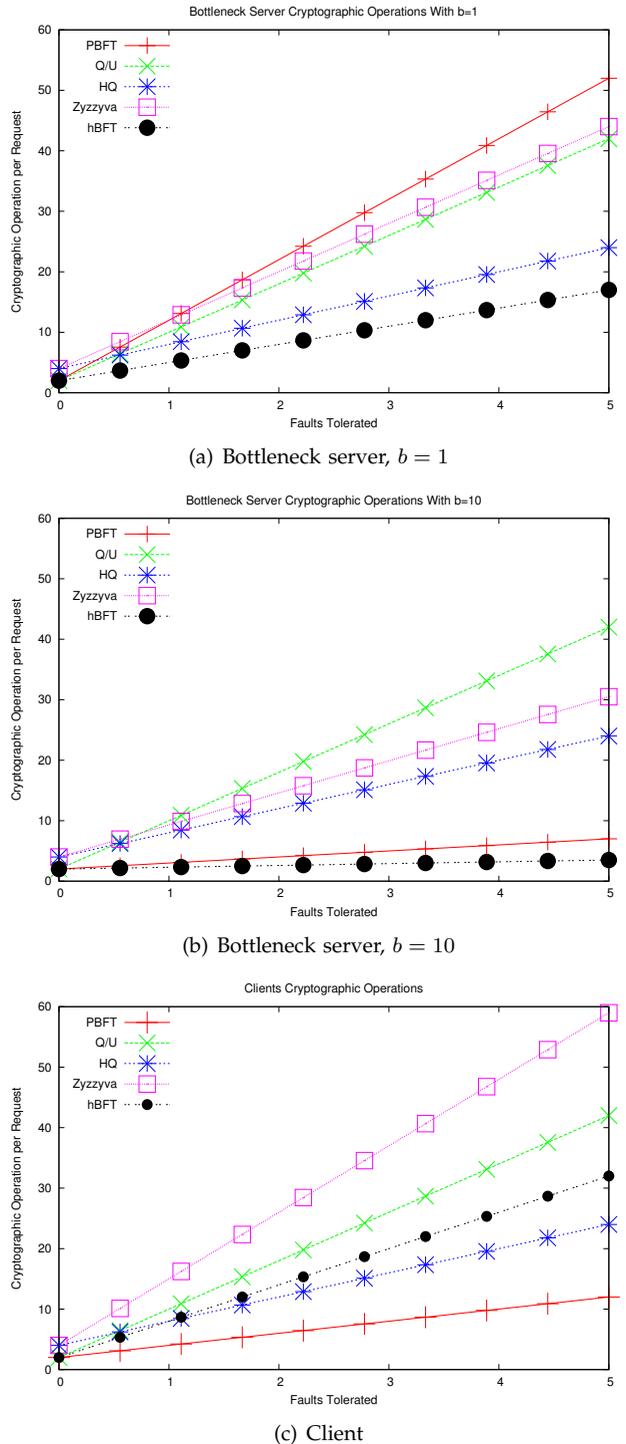


Fig. 9. Server and client cryptographic operations

the number of total replicas, the latency of PBFT increases quickly without batching. With batching, PBFT achieves a more stable curve. Zyzzyva achieves higher latency than the other two protocols for each case. The latency of h BFT on the other hand, stabilizes and does not show any trend of growing to a large degree with or without batching. The key factors in the performance are not only the critical paths and the number of cryptographic operations, but also

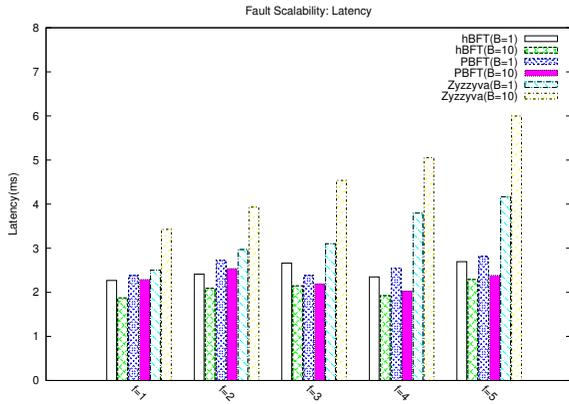


Fig. 10. Fault Scalability: Latency

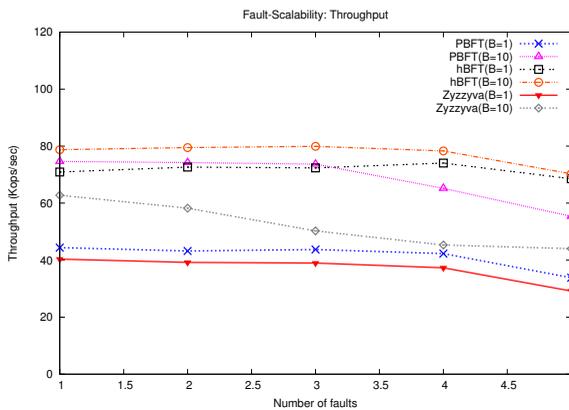


Fig. 11. Fault Scalability: Throughput

the message complexity. Although Zyzzyva has more cryptographic overhead, it requires the same number of messages as *hBFT*, which explains why both scale better than PBFT.

Not surprisingly, as shown in Fig. 11, the throughput shows a similar trend with latency. As the system scales, when f is greater than 2, throughput of Zyzzyva decreases obviously, especially without batching. Zyzzyva scales better than PBFT but the performance degrades obviously when f is greater than 4. *hBFT* scales better than both Zyzzyva and PBFT with or without batching. The difference between the numbers of cryptographic operations is still the key to the overall performance. When the number of faults is 5 and assuming b equals 10 if used, PBFT requires 42 MACs without batching and only 6 with batching, Zyzzyva requires 44 MACs without batching and 30.5 with batching, and *hBFT* requires 17 MACs without batching and 3.5 with batching. For systems with high concurrency, PBFT and *hBFT* are preferred and scale well as the number of faults increases.

6.4 A BFT Network File System

This section describes our evaluation of a BFT-NFS service implemented using PBFT [?], Zyzzyva [21],

and *hBFT*, respectively. Similarly, in the NFS service, we evaluate the performance of normal cases where a backup server fails. The NFS service exports a file system, which can then be mounted on a client machine. The replication library and the NFS daemon is called to reach agreement on the order when replicas receive client requests. Once processing is done, replies are sent to clients. The NFS daemon is implemented using a fixed-size memory-mapped file.

We use the Bonnie++ benchmark [12] to compare our three implementations with NFS-std, an unrepliated NFS V3 implementation, using an I/O intensive workload. The Bonnie++ benchmark includes the following directory operations (DirOps): (1) create files in numeric order; (2) stat() files in the same order; (3) delete them in the same order; (4) create files in an order that will appear random to the file system; (5) stat() random files; (6) delete the files in random order.

We evaluate the performance when a failure occurs at time zero, as detailed in Fig. 12. In addition, up to 20 clients run bonnie++ benchmark concurrently. The results show that *hBFT* completes every type of operations with lower latency than all of other protocols. The main difference lies on the write operations. This is due to the fact that all the three protocols use read-only optimization, where replicas sends reply messages to the clients directly without running the agreement protocol. Compared with NFS-std, *hBFT* only causes 5% overhead while PBFT and Zyzzyva cause 10% and 15% overhead, respectively.

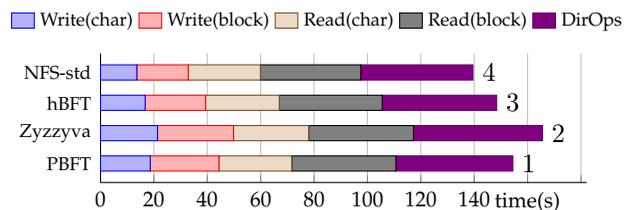


Fig. 12. NFS Evaluation with the Bonnie++ benchmark.

7 CONCLUSION

In this paper, we presented *hBFT*, a hybrid, Byzantine fault-tolerant, replicated state machine protocol with optimal resilience. By re-exploiting speculation, the theoretical lower bound for throughput and latency, as well as the requirement on clients' participation have been achieved for both *fault-free* and *normal cases* in *hBFT*. *hBFT* is a fast protocol that moves some jobs to the clients but can still tolerate faulty clients. We have also proven the safety and liveness properties of *hBFT* and demonstrated how *hBFT* improves on the performance of PBFT without several of the trade-offs of other protocols, some of which also use speculation.

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