Hardening Cassandra Against Byzantine Failures

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Abstract

Cassandra is one of the most widely used distributed data stores these days. Cassandra supports flexible consistency guarantees over a wide-column data access model and provides almost linear scale-out performance. This enables application developers to tailor the performance and availability of Cassandra to their exact application’s needs and required semantics. Yet, Cassandra is designed to withstand benign failures, and cannot cope with most forms of Byzantine attacks.

In this work, we present an analysis of Cassandra’s vulnerabilities and propose protocols for hardening Cassandra against Byzantine failures. We examine several alternative design choices and compare between them both qualitatively and empirically by using the Yahoo! Cloud Serving Benchmark (YCSB) performance benchmark. We include incremental performance analysis for our algorithmic and cryptographic adjustments, supporting our design choices.

1 Introduction

Distributed data stores are commonly used in data centers and cloud hosted applications, as they provide fast, reliable, and scalable access to persistently stored data. Such data stores enable developers to treat scalable persistent storage as a service. While persistent storage is a fundamental aspect of almost any application, developing an effective one is notoriously difficult. Hence, the existence of such data stores relieves developers from the burden of creating and maintaining one themselves.

Due to inherent tradeoffs between semantics and performance [10, 12] as well as the desire to offer various flexible data management models, a plethora of products has been developed. These differ in the data access model, which can range from traditional relational databases, to wide-columns [15, 35], key-value stores [8, 21], as well as graph databases and more. Another axis by which such systems differ is the consistency guarantees, which can range from strong consistency [36] to eventual consistency [48] and a myriad of intermediate options.

In our work, we focus on Cassandra [35]. Cassandra follows the wide-column model, and offers very flexible consistency guarantees. Among open source data stores, it is probably the most widely used; according to the Cassandra Apache project page [4], more than 1,500 companies are currently using Cassandra, including, e.g., Apple, CERN, Comcast, eBay, Easou, GitHub, GoDaddy, Hulu, Instagram, Intuit, Microsoft, Netflix, Reddit, The Weather Channel and more.

Like many distributed data stores, Cassandra has very effective protection against benign failures, but was not designed to withstand Byzantine attacks, in which some nodes in the system may act arbitrarily, including in a malicious manner. Overcoming Byzantine failures requires sophisticated protocols and more resources. However, ever since the seminal PBFT work of Castro and Liskov [14], the practicality of building Byzantine fault tolerant replicated state machines has been demonstrated by multiple academic projects, e.g., [16, 28] to name a few. Interestingly, storage systems offer weaker semantics than general replicated
state machines, and therefore it may be possible to make them resilient to Byzantine failures using weaker timing and failure detection assumptions, as been proposed in \cite{13, 38, 41, 42}. Yet, to the best of our knowledge, we are the first to offer an extension of Cassandra that can withstand Byzantine failures.

Specifically, we analyze Cassandra’s structure and protocols to uncover their vulnerabilities to Byzantine behavior. We then propose alterations to Cassandra’s existing protocols that overcome these failures. In particular, we examine several alternative solutions and compare between them qualitatively and quantitatively. Let us emphasize that one of our main design principles is to maintain Cassandra’s basic interaction model as much as possible, to increase the likelihood of adoption and in order to minimize the number of lines of code we need to change. After all, our goal in this study is to harden the existing system, not to create a new one.

We have benchmarked both the original Cassandra and our hardened versions of Cassandra using the standard YCSB benchmark \cite{17}. We were able to demonstrate that the best performing configuration of the hardened Cassandra was only twice worse than the original Cassandra in the settings we measured. Interestingly, we discovered that a key factor to obtaining reasonable performance is in the type of cryptography used. That is, using traditional RSA signatures dramatically lowers the performance. In contrast, our novel combination of vectors of MACs with the more modern Elliptic Curve Digital Signature Algorithm (ECDSA) \cite{32} can yield a significant performance boost.

The rest of this paper is organized as follows: We survey related works in Section \ref{sec:related_work}. The system model and assumptions are presented in Section \ref{sec:system_model}. A brief overview of Cassandra is presented in Section \ref{sec:cassandra}. In Section \ref{sec:byzantine_vulnerabilities} we identify Byzantine vulnerabilities in Cassandra and suggest ways to overcome them. Section \ref{sec:performance_evaluation} details the performance evaluation. We conclude with a discussion in Section \ref{sec:conclusion}.

\section{Related Work} \label{sec:related_work}

Castro & Liskov \cite{14} were the first to show a practical BFT protocol using replicated state machine. Based on their work, Clement et al. \cite{16} introduced UpRight, a modular library to support BFT using replicated state machine. They have shown results for integrating the library with ZooKeeper \cite{30} and HDFS \cite{50}, two popular open-source systems. BFT-SMaRt \cite{9} and Prime \cite{2} have improved these algorithms in order to produce better performance even when facing Byzantine behaviour. Abstract \cite{28} is the state of the art in BFT replicated state machine. It adds the ability to abort a client request when faults occur. Then it can dynamically switch to a different BFT protocol that produces better performance under the new system conditions.

Replicating existing transactions-oriented databases using a middleware solution have been studied both in the context of benign failure \cite{19} and Byzantine failures \cite{27, 39}.

Quorum systems \cite{29} are common tools for ensuring consistency and availability of replicated data in spite of benign faults. In these protocols, each read request must be processed by a quorum (set) of nodes that intersects with all quorums of nodes that were used for earlier writes \cite{5}. Quorum systems are employed in many distributed storage systems such as Cassandra \cite{35}, Dynamo \cite{21} and Riak \cite{8}.

Malkhi & Reiter \cite{41, 42} were the first to discuss Byzantine quorum systems, i.e., using read and write quorums such that any two quorums intersects in at least one correct node. Furthermore, the system remains available in spite of having up to $f$ Byzantine nodes.

Aguilera & Swaminathan \cite{1} explored BFT storage for slow client-server links. In their solution, clients communicate with the system through a proxy and rely on a synchronized clock. Their goal was to implement a linearizable abortable register that provides the limited effect property. That is, partial writes due to benign client failures do not have any effect. To do so, they used unique timestamps and timestamp promotion when conflicts appear. Their work did not show an actual implementation nor performance analysis. As our work preserves Cassandra’s semantics, we are able to design faster operations requiring lighter cryptography measures even when conflicts occur.

Byzantine clients in quorum systems might try to perform split-brain-writes. A split-brain-write is a write performed to different servers using the same timestamp but not the same values. There are two main approaches for handling split-brain-writes in quorum systems. In both of them, the idea is to get
a commitment from a quorum to bind a timestamp and a value on every write. In Malkhi & Reiter’s approach [41], on every write, the servers exchange inter-servers messages agreeing on the binding. In Liskov & Rodrigues’s approach [38], the servers transmit signed agreements to the client that are later presented to the servers as a proof for the quorum agreement. In our work, we do not prevent split-brain-writes, but rather repair the object state on a read request (or in the background).

Basescu et al. [7] investigated how to build robust storage systems using multiple key-value stores generating a cloud-of-clouds, but focusing on benign failures.

Several BFT cloud storage systems provide eventual consistency semantics [48]. ZENO [52] requires at least $f + 1$ correct servers and guarantees causal order consistency [36] while DEPOT [40] can tolerate any number of Byzantine clients and servers and guarantees Fork-Join-Causal order consistency.

Aniello et al. [3] showed how Byzantine nodes can launch DoS attacks in distributed systems that use a gossip based membership protocol. In their paper, they have demonstrated their attack on CASSANDRA [35] and presented a way to prevent it by using signatures on the gossiped data. Other more general solutions for BFT gossip membership algorithms were shown in FIREFLIES [31] and BRAHMS [11]. The first uses digital signatures, full membership view and a pseudorandom mesh structure and the latter avoids digital signatures by sophisticated sampling methods.

Sit & Morris [53] mapped classic attacks in Distributed Hash Tables (DHT) systems. Some of the attacks can be disrupted by using SSL communication. According to the documentation of recent versions of CASSANDRA [20], it supports inter-nodes and client-node SSL communication. Other attacks described in [53], such as storage and retrieval attacks, are addressed in our work.

Okman et al. [47] showed security concerns in NoSQL systems, focusing on CASSANDRA [35] and MONGO DB [46]. Their work concentrated on implementation issues while our we focus on architectural concepts and algorithms that add BFT resilience.

3 Model and Assumptions

We assume a Cassandra system consisting of nodes and clients. Each of the entities may be correct or faulty according to the Byzantine failure model [37]. A correct entity makes progress only according to its specification while a faulty entity can act arbitrarily, including colluding with others.

In our proposed solutions, we assume that the maximal number of faulty nodes is bounded by $f$. We initially assume that all clients are correct, but later relax this assumption. When handling Byzantine clients, we do not limit the number of faulty clients nor change the assumption on the maximal number of $f$ faulty nodes. Yet, we assume that clients can be authenticated so correct nodes only respond to clients that are allowed to access the system according to some verifiable access control list (ACL). Let us emphasize that we use the terms nodes and processes interchangeably and only to refer to Cassandra nodes.

We assume a partially synchronous distributed system that is fully connected. Every node can directly deliver messages to every other node and every client can directly contact any system node. We also assume that each message that is sent from one correct entity to another will eventually arrive exactly once and without errors. That can be implemented, e.g., on top of fair lossy networks, using retransmission and error detection codes. We do not assume any bound on messages delay or computation time in order to support our safety and liveness properties. However, efficiency depends on the fact that most of the time messages and computation steps do terminate within bounded time [23].

Every system entity has a verifiable PKI certificate [18]. We assume a trusted system administrator. The system administrator can send signed membership configuration messages.

The system shares a loosely synchronized clock which enables detection of expired PKI certificates in a reasonable time but is not accurate enough to ensure coordinated actions. We discuss this clock in Chapter 5.7.
Figure 1: The read operation in Cassandra. Replication factor is 3. A client connects to a system node (proxy) and requests a read quorum (in this case, majority, satisfied with 2 responses). The proxy contacts the relevant nodes using its view of the system.

4 Brief Overview of Cassandra

Cassandra stores data in tables with varying number of columns. Each node is responsible for storing a range of rows for each table. Values are replicated on multiple nodes according to the configurable replication factor.

Specifically, mapping of data to nodes follows the consistent hashing principle [33], where nodes are logically placed on a virtual ring by hashing their ids. To be precise, on each node installation, multiple virtual nodes [21] are created. Each virtual node generates a randomized key on the ring, called a token, which we refer to as its place. This virtual node takes responsibility for hashed keys that fall in the range from its place up to the next node on the ring, known as its successor. Additionally, the node also stores keys in the ranges of the \(N-1\) preceding nodes that require replication, where \(N\) is the replication factor parameter. The \(N\) nodes responsible for storing a given value are called its replication set.

Cassandra uses a full membership view, where every node knows about every other node. A node that responds to communication is considered responsive and otherwise it is suspected. In order to ensure that the nodes’ views are consistent, nodes exchange their views via gossip [54]. The gossip is disseminated periodically and randomly; every second, each node tries to exchange views with up to three other nodes: one responsive, one suspected, and a seed [35]. On node installation, seed nodes can be configured to be the first point of contact. As these nodes are part of the system, they are constantly being updated about the membership changes and can provide an updated membership view.

Cassandra provides tunable consistency per operation. On every operation, the client can specify the consistency level that determines the number of replicas that have to acknowledge the operation. Some of the supported consistency levels are: one replica, a quorum [29] of replicas and all of the replicas. According to the consistency level requested in the write and in the respectively read of a value, eventual consistency [48] or strong consistency can be achieved.

On each operation, a client connects to any node in the system in order to perform the operation. This selected node acts as a proxy on behalf of the client and contacts the relevant nodes using its view of the system as illustrated in Figure 1. In the common configuration, the client selects a proxy from all of the system nodes in a Round Robin manner. The proxy node may contact up to \(N\) nodes that are responsible for storing the value according to the requested consistency level. If the required threshold of responses is satisfied, the proxy will acknowledge the write or forward the latest value, according to the stored timestamp, to the client. If the proxy fails to contact a node on a write, it stores the value locally and tries to update the suspected node at a later time. The stored value is called hinted handoff [20]. If a proxy receives multiple versions on a read query, it performs a read repair, a method to update nodes that hold a stale version with the most updated one.

If a node is unresponsive for a long time, hinted handoffs that were saved for this node may be deleted. Similarly, a hinted handoff may not get to its targeted node if the node that stores it fails. Cassandra
provides a manual anti-entropy tool for these cases. This tool can sync a node’s data by asking nodes that hold replicas for its range to compute and exchange Merkle trees [4] for their values and sync the outdated values.

The primary language for communicating with CASSANDRA is the Cassandra Query Language (CQL) [20]. CQL is similar to SQL with adjustments to the NoSQL concepts. For example, join queries are not available. In our work, we ignore the wide selection of options and focus on put and get commands as available in standard NoSQL key-value databases.

Previous versions of CASSANDRA supported sloppy quorums [21], by which responsive nodes outside the replication set were used instead of failed ones. This was deprecated in version 1.0 by switching the responsibility of storing the replica value to the proxy node. In both cases, only nodes of the true replication set count for the consistency level requirement.

While CASSANDRA can handle benign failures, it is unable to detect nor mask Byzantine failures. In our work, we suggest solutions that improve the Byzantine robustness of the system. We have analyzed the system mechanisms and extended them with the ability to mask up to \( f \) (configurable) Byzantine nodes.

5  Hardened Cassandra

In this section, we identify Byzantine vulnerabilities in CASSANDRA and suggest ways to overcome them.

5.1 Impersonating

CASSANDRA supports the use of SSL and enables each message to be authenticated by each party. In some cases, messages are required to be authenticated by a third party, e.g., a read response sent from a node to a client using a proxy node. In order to support such authentication, we use digital signatures. When using SSL or digital signatures, we depend on PKI.

Digital signatures are divided into two main categories according to the type of keys they use: public/private keys vs MAC tags. Public key signatures are more powerful than MAC tags as they enable anyone to verify messages without being able to sign them. MAC tags are mostly useful when there are exactly two entities that have to prove to each other that they have generated the messages. In the last case, the receiver should also be able to identify that received messages were not actually generated by itself. The trade-off for using public key signatures is the compute time, which is about two to three orders of magnitude slower than MAC tags and these signatures are significantly larger, e.g., RSA 2048b versus AES-CBC MAC 128b.

5.2 Consistency Level

Recall that in CASSANDRA the user can configure the replication factor \( N \) (the number of nodes that have to store a value) and in addition on each read and each write to require how many nodes (\( R \) and \( W \), respectively) must acknowledge it. This required threshold can be one node or a quorum (in CASSANDRA, always configured as majority) or all \( N \) nodes. When up to \( f \) nodes may be Byzantine, querying fewer than \( f + 1 \) nodes may retrieve old data (signed data cannot be forged), violating the consistency property. On the other hand, querying more than \( N - f \) nodes may result in loss of availability. In our work, we present two approaches: (1) using Byzantine quorums for obtaining Strong Consistency and (2) using CASSANDRA quorums with a scheduled run of the anti-entropy tool for obtaining Byzantine Eventual Consistency.

5.2.1 Byzantine Quorums

By requesting that each read and each write will intersect in at least \( f + 1 \) nodes, we ensure that every read will intersect with every write in at least one correct node. That is, \( R + W \geq N + f + 1 \). As for liveness, to be able to ensure that Byzantine nodes will not be able to block a write or a read, we must require that \( R \leq N - f, W \leq N - f \). By combining the above 3 requirements, we obtain: \( N \geq 3f + 1 \).
The last bound was formally proved by Malkhi & Reiter [41]. Cachin et al. [13] have lowered this bound to $2f + 1$ by separating between the actual data and its metadata; storing the metadata still requires $3f + 1$ nodes. The above separation was presented under the assumptions of benign writers and Byzantine readers. The last solution is beneficial for storing large data as it uses less storage space and network load. However, when storing small values, the method of [13] only increases the overhead. A system may offer either solution according to the system usage, or use them both in a hybrid way, according to each value’s size.

5.2.2 Byzantine Eventual Consistency

As mentioned earlier, eventual consistency offers faster operations and higher availability in exchange for weakened semantics. To satisfy eventual consistency, all replication set nodes must eventually receive every update. Further, every writes order conflict should be resolved deterministically. In this model, there is no bound on the propagation time of a write, but it should be finite. In particular, if no additional writes are made to a row, eventually all reads to that row will return the same value.

Byzantine eventual consistency can be obtained through majority quorums. In this approach, the replication set is of size $2f + 1$ nodes while write and read quorums are of size of $f + 1$. Hence, each write operation acknowledged by $f + 1$ nodes is necessarily executed by at least one correct node. This node is trusted to update the rest of the nodes in the background. As this node is correct, it will eventually use the anti-entropy tool to update the rest of the replication set. Recall that the client request is signed so the servers will be able to authenticate this write when requested.

Every read is sent to $f + 1$ nodes and thus reaches at least one correct node. This correct node follows the protocol and accepts writes from proxy nodes and from the anti-entropy tool. So, eventually, it retrieves the latest update. Due to the cryptographic assumptions, a Byzantine node can only send old data and cannot forge messages. Hence, on receiving a value from the anti-entropy tool that does not pass the signature validation, we can use it as a Byzantine failure detector and notify the system administrator about a Byzantine behavior.

5.3 Proxy Node

Figures 2 and 3 present the current write and read flows in Cassandra, including the role of proxies. A Byzantine proxy node can act in multiple ways, such as (1) respond that it has successfully stored the value without doing so, (2) perform a split-brain-write, and (3) respond that the nodes are not available while they are. We augment the existing flows of writing and reading in Cassandra to overcome these vulnerabilities below.
5.3.1 Write Operation in Details

We present our modified write algorithm in Figures 4 and 5. In this solution, when storing a new value, the client signs the value and a node will store it only if it is signed by a known client according to the ACL and with a timestamp that is considered fresh (configurable). On each store, the storing node signs an acknowledgment so that the client can verify it. In addition, the signed acknowledgment covers the timestamp provided by the client, preventing replay attacks by the proxy. A client completes a write only after obtaining the required threshold of signed responses, which now the proxy cannot forge. If one proxy fails to respond with enough signed acknowledgments in a configurable reasonable time, the client contacts another node and asks it to serve as an alternative proxy for the operation. After contacting at most $f + 1$ proxy nodes when needed, the client knows for sure that at least one correct proxy node was contacted.

5.3.2 Read Operation in Details

The read algorithm of a proxy has three parts: (1) Reading data from one node and only a digest from the rest of the nodes. In some cases, as an optimization, the read will target only a known live quorum instead of to all relevant nodes. (2) On digests mismatch, a full read is initiated to all contacted nodes from the first phase, retrieving the data instead of a digest. (3) The proxy resolves the conflict by creating a row with the most updated columns according to their timestamps, using the lexicographical order of the values as tie breakers when needed. The resolved row is written back to out-dated nodes.

Figures 6 and 7 present our modified read algorithm, which consists of the following changes: (1) In case the first phase is optimized by addressing only a known live quorum of nodes, if a failure occurs, we do not fail the operation but move to a full read from all nodes. Thus, if a Byzantine node does not respond correctly, we do not fail the operation. (2) If there is a digest mismatch in the first phase, we do not limit the full read only to the contacted nodes from the first phase but rather address all replication set nodes. Hence, Byzantine nodes cannot answer in the first phase and fail the operation by being silent in the second phase. (3) During resolving, the nodes issue a special signature, notifying the client about the write back. The proxy then supplies the client with the original answers from the first phase, all are signed by the nodes.
Figure 4: Illustrating our write algorithm from Figure 5 where the proxy verifies each store acknowledgment. Configuration: $N=4$ and $W=3$.

```
1: function OnNodeToNodeWriteRequest(key, value, ts, clientSignature, clientID)
2:   if clientSignature is valid then
3:     nodeSignature ← ComputeSignature(clientSignature) ▷ The client signature covers a fresh ts
4:     Store locally < key, value, ts, clientSignature, clientID > ▷ A verifiable acknowledgment
5:     return nodeSignature
6:   end if
7: end function
8:
9: function OnClientToNodeWriteRequest(key, value, ts, clientSignature, clientID)
10:   for each node n that is responsible for the key do ▷ N nodes
11:     Send write request with < key, value, ts, clientSignature, clientID > to n
12:   end for
13:   Wait for $2f + 1$ verified acknowledgements OR timeout ▷ Verified in the manner of correct node signature
14:   return responses
15: end function
16:
17: function ClientWriteRequest(key, value)
18:   ts ← Current timestamp ▷ From a secure synchronized clock
19:   clientSignature ← ComputeSignature(key || value || ts)
20:   p ← Some random system node
21:   Send write request with <key, value, ts, clientSignature, clientID> to p
22:   Wait for acknowledgments OR timeout
23:   if |validResponses| ≥ $2f + 1$ then
24:     return Success
25:   end if
26:   p ← Some random system node that was not used in this function invocation
27:   if $p = \perp$ OR contactedNodes > $f$ then
28:     return Failure ▷ Use another node as proxy
29:   end if
30:   goto line 22
31: end function
```

Figure 5: Our hardened write algorithm. ClientWriteRequest is invoked by the client for each write. OnClientToNodeWriteRequest is invoked on the proxy node by the client. OnNodeToNodeWriteRequest is invoked on a node that has the responsibility to store the value. Store locally appends the write to an append log without any read. When key is queried, the latest store (according to timestamp) is retrieved.

This way, the client is able to authenticate that the resolving was executed correctly.

Without supplying the set of original answers in the last case, a Byzantine proxy that has an old value could fool the client into accepting this old value. This exploit is originated in the fast write optimization of
Figure 6: Illustrating our read algorithm from Figure 7 where the proxy verifies each answer. Configuration: N=4 and R=3.

**5.3.3 Targeting Irrelevant Nodes**

Another possible attack by a Byzantine proxy is directing read requests to irrelevant nodes. These nodes will return a verifiable empty answer.

To overcome this, we have considered three options: (1) Using clients that have full membership view, which is supported by CASSANDRA. This way, a client knows which nodes have to respond. (2) Using an authentication service that is familiar with the membership view and can validate each response. We do not elaborate on how this service should be implemented. A client can use this service to authenticate answers. (3) Configure the nodes to return a signed “irrelevant” message when requested a value that they are not responsible for. A client then only counts as valid answers correctly signed messages that are not marked as “irrelevant”.

Using any of these solutions, a Byzantine proxy can always try to update the minimum number of nodes required for a successful write operation. This performance attack can decrease the availability. To overcome this attack and make sure that every value eventually gets updated to every correct node, we use the anti-entropy tool periodically. As this action is costly, nodes should not run it too often. The anti-entropy tool can be run correctly in a Byzantine environment as long as each value that is detected as new is delivered.
1: function OnNodeToNodeReadRequest(key, client − ts)
2: if key is stored in the node then
3:    < value, ts, clientSignature, clientID > ← The newest associated timestamp and value with key
4: else
5:    clientSignature ← EMPTY
6: end if
7: nodeSignature ← ComputeSignature(key||hash(value)||clientSignature||client − ts)
8: if isDigestQuery then
9:    return < hash(value), ts, clientSignature, clientID, nodeSignature >
10: else
11:    return < value, ts, clientSignature, clientID, nodeSignature >
12: end if
13: end function
14:
15: function OnClientToNodeReadRequest(key, client − ts)
16: targetEndpoints ← allRelevantNodes for key OR a subset of 2f + 1 fastest relevant nodes
17: dataEndpoint ← One node from targetEndpoints
18: Send read request for data to dataEndpoint
19: Send read request for digest to targetEndpoints \ {dataEndpoint}
20: Wait for 2f + 1 verified responses OR timeout
21: if timeout AND all relevant nodes were targeted at the first phase then
22:    return ⊥
23: end if
24: if got response from dataEndpoint AND all responses agree on the digest then
25:    return < value, nodesSignatures >
26: end if
27: Send read request for data from all nodes in allRelevantNodes OR 2f + 1 verified responses OR timeout
28: if timeout then
29:    return ⊥
30: end if
31: resolvedValue ← Latest response from responses that is client-signature verified.
32: Send write-back with resolvedValue to allRelevantNodes except those that are known to be updated
33: Wait for responses till we have knowledge about 2f + 1 verified updated nodes OR timeout
34: if timeout then
35:    return ⊥
36: end if
37: return < resolvedValue, nodesSignatures, originalValuesUsedForTheResolve >
38: end function
39:
40: function ClientReadRequest(key)
41: client − ts ← Current timestamp
42: p ← Some random system node
43: Send read request with < key, client − ts > to p
44: Wait for responses OR timeout
45: if |validNodesSignatures| ≥ 2f + 1 then
46:    return data
47: end if
48: p ← Some random system node that was not used in this function invocation
49: if p = ⊥ OR contactedNodes > f then
50:    return Failure
51: end if
52: goto line [7]
53: end function

Figure 7: Our hardened read algorithm. ClientReadRequest is invoked by the client for each read. OnClientToNodeReadRequest is invoked on the proxy by the client. OnNodeToNodeReadRequest is invoked on a node that has the responsibility to store the value. \( R \) is the quorum size for the read operation based on the consistency level. The read can be also sent to only \( R \) nodes (a subset of the \( N \) nodes) and only if some of them do not respond in the timeout interval, \( p \) will send the request to the remaining \( N − R \) nodes.

along with a correct client signature that can be authenticated.

5.3.4 Proxy Acknowledgments Verification

Our proposed hardened algorithms for read and write rely on digitally signed acknowledgments for later authenticating the actual completion of the operation by the nodes. These acknowledgments provide a verifiable proof to the client that the nodes indeed treated the operation. In our proposed solution as presented so far, we have requested the proxy to verify the nodes acknowledgments and accept a node
response only if it is signed correctly. In this section, we discuss the motivation for verifying the signatures in
the proxy node and suggest an alternative of only verifying them at the client. Specifically, when attempting
to eliminate verification at the proxy, we have identified the following two problematic scenarios:

1. Consider a correct proxy and $f$ Byzantine nodes. The Byzantine nodes manage to answer an operation
faster (they have the advantage as they do not have to verify signatures nor sign) with bad signatures.
The proxy then returns to the client $f+1$ good signatures and $f$ bad signatures. In this case, contacting
an alternative proxy might produce the same behavior.

2. Consider a Byzantine proxy, which is also responsible to store data itself and it is colluding with $f−1$
Byzantine nodes. On a write operation, the proxy asks the Byzantine nodes to produce a correct
signature without storing the value. The proxy also asks one correct node to store the data and in
addition produces false, non-verifiable, $f$ signatures for some nodes. The client will get $f+1$ correct
signatures and $f$ bad signatures, while only one node really stored the value.

To enable the client to overcome Byzantine behavior without proxy acknowledgement verification, we let
the client contact the proxy again in case it is not satisfied with the $2f+1$ responses it obtained. On a
write, the client requests the proxy to fetch more acknowledgments from new nodes. On a read, the client
requests the proxy to read again without contacting the nodes that supplied false signatures.

We would like to emphasize that if a client receives a bad signature, both the proxy and the node might
be Byzantine. In this case, we do not have evidence for the real Byzantine entity as one can try to frame
the other.

The motivation for this alternative is that signatures verification is a heavy operation. In the proxy
verification option, on every write, the proxy is required to perform at least $2f+1$ signature verifications.
In the alternative client only verification option, the latency penalty will be noticed only when Byzantine
failures are present and could be roughly bounded by the time of additional RTT (round-trip-time) to the
system and $f$ parallel RTT’s inside the system (counted as one), multiplying it all by $f$ (the number of
retries with alternative proxies). Assuming that in most systems Byzantine failures are rare, speeding the
common correct case is a reasonable choice.

Another significant motivation for using the client only verification option is that it enables using MAC
tags instead of public signatures, since only the client verifies signatures. To that end, a symmetric key for
each pair of system node and client should be generated. Every client has to store a number of symmetric
keys that is equal to the number of system nodes. Every node has to store a number of symmetric keys
that is equal to the number of (recently active) clients. These keys can be pre-configured by the system
administrator or be obtained on the first interaction through a secure SSL line. This produces significant
speedups both for the node signing and for the client verification.

The exact algorithms appear in Appendix A. Figures 19 and 20 describe the algorithms and Figures 22
and 23 illustrate their execution timelines.

5.3.5 Proxy Resolving vs. Client Resolving

Recall that when CASSANDRA’s read operation detects an inconsistent state, a resolving process is initiated
to update outdated replicas. This way, the chance for inconsistency in future reads decreases. In plain
CASSANDRA as well as in our solution as presented so far, the proxy is in charge of resolving such inconsistent
states. An alternative option is to let the client resolve the answers and write back the resolved value using
a write request that specifies to the proxy which replicas are already updated.

As we wish to prevent Byzantine nodes from manipulating the resolver with false values, the resolver
requires the ability to verify the client signature on each version. When using the client resolving option in
combination with using a proxy that is not verifying nodes acknowledgments (as discusses in Section 5.3.4),
the proxy is released from all obligations of verifying client signatures, improving its scalability.

The exact details of the this algorithm appear in Appendix A. Figure 21 describes the algorithm and
Figure 24 illustrates its execution timeline.
5.3.6 Switching From Public Key Signatures to MAC Tags

The use of public key signatures has a major performance impact while switching to MAC tag is not trivial. In Section 5.3.4, we have described a way to switch from public key signatures to MAC tags on messages sent from nodes to clients.

Supporting MAC tags on messages sent from clients to nodes present interesting challenges for certain CASSANDRA features. Such features are: (1) Joining new nodes to CASSANDRA. These nodes have to fetch stored values for load-balancing. As the client does not know who these future nodes are, it cannot prepare MAC tags for them. A solution for this could be that a new node will only store values that were proposed by at least $f + 1$ nodes. Alternatively, have the client re-store all of relevant values that the new node has to store. (2) Using the anti-entropy tool (exchanging Merkle trees and updating stale values) and resolving consistency conflicts need to ensure the correctness of the values by contacting at least $f + 1$ nodes that agree on the values. Alternatively, every node will have to store a vector of MAC tags for each responsible node. Storing a signature vector poses another challenge: a Byzantine proxy can manipulate the signatures vector sent to each node, leaving only the node’s signature correct and corrupting all other nodes’ signatures (turning the stored vector useless). This challenge can be overcome by adding another MAC tag on the signatures vector, proving to the node that the tags vector was not modified by the proxy.

Due to these limitations and in order to speed up the write path, we suggest a hybrid solution as presented in Figure 8. A write is signed with a public key signature and that signature is covered by MAC tags, one for each node. A node then verifies only the MAC tag and stores only the public key signature. Hence, in the common case, we will use a public key signature only once and will not use public key verifications at all. When things go bad, we fall back to the public key signature. Furthermore, some public key signature algorithms have better performance when signing, sacrificing their verification time. For example, the Elliptic Curve Digital Signature Algorithm (ECDSA) [32] in comparison with RSA [49]. In this case, ECDSA can greatly boost performance.
Table 1: Comparing the variants of our solution in the read and write flows with the most optimistic assumptions. C is the number of columns, (p) indicated public key signatures and (s) MAC tags. In the variants where the proxy does not verify, we refer both for the proxy resolves and client resolves modes. We assume that on a read, the proxy uses the optimization in the first phase and contacts only a Byzantine quorum and not all replicas. For example, the forth row presents a proxy that does not verify acknowledgments and MAC tags are used from client to nodes and from nodes to client. In this variant, the client signs the C columns using public key signatures and adds 3f + 1 MAC tag, one for each node. All nodes (3f + 1) have to store it and they verify only their MAC tags. All nodes issue verifiable acknowledgments (3f + 1) and the client verifies only a Byzantine quorum (2f + 1).

Finally, when using MAC tags on the client to node path, there is a need for the client to know what are the relevant nodes for that key. One solution is to ensure clients are updated about the nodes tokens. This way, on every write, the client knows what keys to use. Since our solution has a fallback option, even if there was a topology change that the client was late to observe, the new node (targeted by the proxy) can still use the public signature and not fail the write. On the write acknowledgment, the new node can attach the topological change evidence and update the client.

5.3.7 Column Families vs. Key-Value semantics

For clarity of presentation, the algorithms described so far reflect only key-value semantics. Yet, our work also supports CASSANDRA’s column family semantics. In the latter, a client has to sign each column separately, producing a number of signatures that is equivalent to the number of non-key columns. This is needed in order to be able to reconcile partial columns writes correctly according to CASSANDRA’s semantics. For example, consider a scheme with two non-key columns A and B. One node can hold an updated version of A and a stale version of B while another node might hold the opposite state. A correct read should return one row containing the latest columns versions for both A and B.

Nodes acknowledgments can still include only a single signature covering all columns. This is because the purpose of signatures here is to acknowledge the operation.

5.3.8 Comparing The Variants

In Tables 1, 2 and 3, we summarize the different algorithms proposed in this section. We focus on the number of signing and verification operations of the digital signatures as these are the most time consuming. We divide our analysis into three cases: (1) best case and no failures, (2) a benign mismatch on the read flow that requires resolving, and (3) worst case with f Byzantine nodes.

5.4 Handling Byzantine Clients

In addressing the challenge of handling Byzantine clients, we keep in mind that some actions are indistinguishable from correct clients behaviors. For example, erasing data or repeatedly overwriting the same value. Yet, this requires the client to have ACL permissions.

In our work, we focus on preserving the consistency of the data from the point of view of a correct client. A correct client should not observe inconsistent values resulting from a split-brain-write. Further, a correct client should not read values that are older than values returned by previous reads.
Table 2: Comparing the variants in the read flow in case of a benign mismatch that requires resolving. $C$ is the number of columns. $M$ is the number of outdated replicas in the used quorum, (p) indicated public key signatures and (s) MAC tags. We assume that the proxy uses the optimization in the first phase and contacts only a Byzantine quorum. For example, the first row presents a proxy that verifies the acknowledgments and resolves conflicts when mismatch values are observed. MAC tags are not in use. On a read request, a Byzantine quorum of nodes $(2f + 1)$ have to retrieve the row and sign it. The proxy verifies their signatures $(2f + 1)$ and detects a conflict. Then, the proxy requests all relevant nodes (except for the one that returned data in the first phase) for the full data $(3f$ nodes sign and the proxy verifies only $2f)$. The proxy resolves the mismatch (verifies $C$ columns) and sends the resolved row to the $M$ outdated nodes (write-back). These nodes verify the row $(C)$ and sign the acknowledgments that are later verified by the proxy. The proxy supply the client with the original $2f + 1$ answers and the resolved row signed also by $M$ nodes that approved the write-back.

Table 3: Comparing the variants in the read and write flows in the worst case and $f$ Byzantine nodes. Due to the wide options of Byzantine attacks and the fact that every Byzantine node can waste other node’s cycles, we compare the variants only from the point of view of a correct client. $C$ is the number of columns, $M$ is the number of outdated replicas in the used quorum, (p) indicated public key signatures and (s) MAC tags. For example, the second row presents a proxy that does not verify the acknowledgments in a write operation. MAC tags are not in use. On a write request, the client signs the $C$ columns and sends it to the proxy. The client receives from the proxy responses from a Byzantine quorum of nodes $(2f + 1)$ and detects that one is incorrect. The client requests the proxy $f$ more times for the missing signature and every time gets a false signature. Then, the client uses alternative proxies and the story repeats itself $f$ additional times. In the last round, the client successfully retrieves all $2f + 1$ correct signatures due to our assumption on $f$.

More precisely, we guarantee the following semantics, similar to plain CASSANDRA: (1) The order between two values with the same timestamp is their lexicographical order (breaking ties according to their value). (2) A write of multiple values with the same timestamps is logically treated as multiple separate writes with the same timestamp. (3) Deleting values is equivalent to overwriting these values with a tombstone. (4) A read performed by a correct client must return any value that is not older (in terms of timestamp order) than values returned by prior reads. (5) A read performed after a correct write must return a value that is not older (in terms of timestamp order) than that value.

As mentioned before, in CASSANDRA, if the proxy that handles a read observes multiple versions from different nodes, it first resolves the mismatch and writes the resolved value back to the nodes. The resolved version will be a row with the most updated columns according to their timestamps. If the proxy observes two values with the same timestamp, it will use the lexicographical order of the values as a tie breaker.

For performing split-brain-writes, Byzantine clients may collude with Byzantine proxies and sign multiple values with the same timestamp. Proxies can send these different values with the same timestamps to different nodes, setting the system in an inconsistent state. Even though we consider a split-brain-write as a Byzantine behavior, this kind of write could occur spontaneously in plain CASSANDRA by two correct clients that write in parallel since in CASSANDRA clients provide the write’s timestamp, typically by reading their local clock.
Consider a Byzantine client that colludes with a proxy. If they try to perform a split-brain-write, due to the resolve mechanism, all reads that witness both values will return only the latest value in lexicographical order. On a client read, no quorum will agree on one version. Consequently, the proxy will resolve the conflict and update a quorum of servers with that version, leaving the system consistent for that value after the first read.

If the Byzantine client and colluding proxy will try to update only part of the nodes with a certain \( v \), a read operation may return two kinds of values: (1) If the read quorum will witness \( v \), it will be resolved and propagated to at least a quorum of nodes meaning that \( v \) will be written correctly to the system. As a result of this resolve, every following read will return \( v \) (or a newer value). (2) If a read will not witness \( v \), the most recent version of a correct write will be returned. Hence, the hardened system protects against such attempts.

Finally, if a Byzantine client is detected by the system administrator and removed, its ACL and certificate can be revoked immediately. This way any potentially future signed writes saved by a colluder will be voided and the future influence of that client will cease.

5.5 Deleting Values

In Cassandra, deleting a value is done by replacing it with a tombstone. This tombstone is served to any system node that requests that value to indicate that it is deleted. Once in a while, every node runs a garbage collector that removes all tombstones that are older than a configurable time (10 days by default).

Even in a benign environment, some failures might result in deleted values reappearing. One case is when a failed node recovers after missing a delete operation and passing the garbage collection interval in all other nodes. In a Byzantine setting, a Byzantine node can ignore all delete operations and later (after the garbage collection interval) propagate the deleted values to correct nodes.

To overcome this, we define the following measures: (1) Every delete should be signed by a client as in the write operation previously defined. This signature will be stored in the tombstone. A client will complete a delete only after obtaining a Byzantine quorum of signed acknowledgments. (2) In the period of every garbage collection interval, a node will run at least once the anti-entropy tool against a Byzantine quorum of nodes, fetching all missed tombstones. (3) A node will accept writes of values that are not older than the configured time for garbage collection interval as previously defined. Since the node runs the anti-entropy tool periodically, even if a deleted value is being fetched, the tombstone will overwrite it. (4) A node that receives a store value that is older than the configured time for the garbage collector will handle this case as follows. It will issue a read for the value and accept it only if a Byzantine quorum approves that the value is live. When a new node joins the system, reading every value from a Byzantine quorum might be very expensive. In this case, we can improve the performance by batching these requests.

5.6 Membership View

The membership implementation of Cassandra is not Byzantine proof as faulty nodes can temper other’s views by sending false data [3]. In addition, Byzantine seed nodes can partition the system into multiple subsystems that do not know about each other. This is by exposing different sets of nodes to different nodes.

To overcome this, in a Byzantine environment, each node installation should be signed by the trusted system administrator with a logical timestamp. The logical timestamp is used so a node will make sure it is using the updated configuration. Each node should be configured to contact at least \( f + 1 \) seed nodes in order to get at least one correct view. This solution requires also the system administrator to pre-configure manually the first \( f + 1 \) nodes view as they cannot trust the rest of the nodes. We would like to emphasize that Byzantine seeds cannot forge false nodes existence. Rather, they can only hide some nodes by not publishing them.

Here, we adopt the work on BFT push-pull gossip by Aniello et al. [3]. Their solution solves the dissemination issues by using signatures on the gossiped data. This way, a node’s local view cannot be mislead to think that a node is responsive or suspected.
5.7 Synchronized Clock

In plain Cassandra, as well as in our solution, each write includes a wall-clock timestamp that implies an order on the writes. Using this method, strong consistency cannot be promised unless local clocks are perfectly synchronized. For example, consider two clients that suffer from a clock skew of $\Delta$. If both clients write to the same object in a period that is shorter than $\Delta$, the later write might be attached with a smaller timestamp. As a result, the older write wins.

In a benign environment, when ensuring a very low clock skew, for most applications, these writes can be considered as parallel writes so any ordering of them is correct. For time synchronization, Cassandra requires the administrator to provide an external solution such as NTP. In our work, we follow this guideline using the latest version of NTP that can tolerate Byzantine faults when ensuring the usage of SSL and authentication measures \[6, 45\]. We configure this service so that all servers could use it as is and clients would be able only to query it, without affecting the time.

Alternatively, one could use external clocks such as GPS clocks, atomic clocks or equivalents \[20\], assuming Byzantine nodes can neither control them nor the interaction with them. Finally, Cassandra nodes can ignore writes with timestamps that are too far into the future to be the result of a normal clock’s skew.

5.8 Other Network Attacks

Cassandra might be targeted with known overlay networks attacks, such as Sybil attacks \[22\] and Eclipse attacks \[51\]. In a Sybil attack, attackers create multiple false entities. In Cassandra, they may create multiple node ids that lead to the same node, thereby fooling a client into storing its data only on a single Byzantine replica. As suggested in \[22\], here we rely on a trusted system administrator to be the sole entity for approving new entities that can be verified using PKI.

In an Eclipse attack, attackers try to divert requests towards malicious entities. In our solution, we authenticate each part of the communication using SSL. In Cassandra, a proxy might try to target only Byzantine replicas. To overcome this, clients request verifiable acknowledgments and count the number of correct repliers. If a proxy fails to provide these, alternative proxies are contacted until enough correct nodes have been contacted. Additionally, Section \[5.3.3\] explains how we handle a proxy that diverts requests to irrelevant nodes.

Yet, we currently do not provide any protection for data theft even when a single node has been breached. This can be overcome by encrypting the data at the client application side.

6 Performance

The algorithms reported here were implemented as patches to Cassandra 2.2.4.\[1\] We evaluated the performance of the variants of our solution and compared them to the original Cassandra using the standard YCSB 0.7.\[3\] benchmark, adjusted to use our BFT client library\[4\]. We used Datastax’s Java driver 2.1.8\[5\] on the client side. There are nearly 390K LOC (lines of code) in Cassandra. Our patch added about 3.5K LOC to the servers code and about 4K LOC to the client code (including YCSB integration), which uses the client driver as is. Our entire code adds less than 2% LOC.

All experiments were run on four to five machines (Ubuntu14, dual 64-bit 6 core 2.2GHz Intel Xeon E5 CPUs, 32GB of RAM, 7200 RPM hard drive and 10Gb ethernet), one for the client and three to four for the Cassandra nodes.

We pre-loaded the database with 100,000 rows and then benchmarked it with the following five YCSB workloads that vary in the ratio of the writes and reads: (1) Workload A - 50/50 reads/writes. (2) Workload B - 95/5 reads/writes. (3) Workload C - only reads. (4) Workload D - 95/5 reads/writes, where the reads are

\[1\]https://github.com/ronili/HardenedCassandra
\[2\]https://github.com/apache/cassandra/tree/cassandra-2.2.4
\[3\]https://github.com/brianfrankcooper/YCSB/tree/0.7.0
\[4\]https://github.com/ronili/HardenedCassandraYCSB
\[5\]https://github.com/datastax/java-driver/tree/2.1.8
for the latest inserts (and not random). (5) Workload F - 50/50 writes/Read-Modify-Writes. In all workloads except workload D, the write is for one column while in workload D it is for the entire row. Every workload ran with 100 client threads that in total preformed 100,000 operations with a varying throughput target. The tables consisted of 10 columns (default in YCSB) as well as tables consisting of one value, modeling a key-value datastore. Each value is of size 100 bytes while the key size is randomly chosen in the range of 5-23Bytes. Therefore, each record/line with 10 columns has an average length of 1014Bytes.

We implemented the algorithms presented in Figures 5 and 7 where the proxy authenticates the nodes acknowledgments. We refer to these as Proxy-Verifies. In addition, we implemented the variant where the proxy does not verify the acknowledgments and lets the client fetch more acknowledgments in case it is not satisfied, as appear in Figures 19 and 20. We will refer to it as Proxy-No-Verify. We ran that last algorithm in two modes, one where the proxy is in charge of resolving inconsistent reads, as appears in Figure 20 and one where the client is, as appears in Figure 21. In our work, we present only the version where the proxy resolves as it behaves similar to the client resolves version.

When using MAC tags, we analyzed it in two steps: (1) using MAC tags on messages from nodes to client, referred to as Half-Sym and (2) using it for both ways, referred to as Full-Sym.

We used two types of private key signatures: (1) RSA with keys of length of 2048b and (2) ECDSA with keys of length 256b and the secp256r1 curve. As for symmetric keys, we used keys of length of 128b with the HMAC [34] MAC algorithm. In all signatures algorithms, we have used SHA256 [24] for the hashing process.

To evaluate the cost of our algorithm without cryptographic overhead, we ran them also without any signatures. That is, we swapped the signing methods with a base64 encoded on a single char, referred to as No-Sign.

We ran CASSANDRA with SSL support and witnessed only a marginal performance impact. Therefore, all results presented here are without SSL support.

The YCSB tool we used is throttling the requests rate in correlation with the achieved maximum throughput. Given that, we run each experiment until achieving a stable throughput for several following request rates.

### 6.1 Performance In A Benign Environment

In Figures 9, 10, 11 and 12, we present the performance results in the standard CASSANDRA multi-column model. As can be seen, our best solution is the variant where the proxy does not verify the acknowledgments, and we use ECDSA and MAC tags for both ways (ECDSA Proxy-No-Verify Full-Sym 4Nodes). The slowdown of this solution is roughly a factor of 2-2.5 in terms of the maximum throughput, 2.5-3 in the write latency and 2-4 in the read latency. Interestingly, for plain CASSANDRA, increasing the cluster from 3 nodes to 4 nodes (while also increasing the quorums sizes from 2 to 3, respectively) actually improves the performance by about 10%. This is because the role of the proxy as well as the corresponding load is now split between 4 nodes rather than only 3. The No-Sign experiment represents the BFT algorithmic price that includes larger quorums, extra verifications and storing signatures. The ECDSA experiment represents the cryptography price. It can be seen that using the RSA signing algorithm has a significant negative impact on the performance.

We have also explored the performance in the key-value model, i.e., in a table with one non-key column. In Figures 13 and 14, we present a comparison of our best algorithms in a key-value model, i.e., a table with one non-key column. As can be expected, the results show a small improvement compared to the multi-column model, as it requires a lower signatures overhead. This implies less network traffic that mostly affect the read path and fewer public key signing operations that affect the write path. The write latency improvement is marginal as in most of the workloads we update only one column as opposed to workload D where we update the entire row.

### 6.2 Performance When Facing Byzantine Behavior

In Figure 15, we present the performance of our best solution under the scenario of one stopped node. We run workload A on a fully synchronized, four nodes setup, on maximum throughput. After 50 seconds,
we stopped one node for 30 seconds and then restarted it. It took the node between 20 to 30 seconds to start. Immediately after it finished loading, the other nodes started retransmitting the missed writes to the failed node. In our best solution, the distributed retransmitting took about 250 seconds and in the plain CASSANDRA, about 170 seconds. We repeated this test with workloads B and C with one change, failing the node in t=40 instead of t=50. From this experiment, we can see that our solution behaves as plain CASSANDRA under this scenario, and can tolerate a one node outage with an acceptable performance impact.

In Figure 16, we present the performance of our best solution under the scenario of one node that always returns a bad signature. This impacts the entire system as on every failed signature verification, the client has to contact the proxy again. Additionally, on every read that addresses the Byzantine node, a resolving and a write-back process is initiated. As can be seen in the results, the performance degrades to about 40%-50%, still leaving the system in a workable state.

We have also explored the performance of our solution in case of a stalling proxy. In this case, following a correct execution of an operation, the proxy waits most of the timeout duration before supplying the client with the response. As a result, the system’s performance might decrease dramatically. Since the attack effects vary in correlation with the timeout configuration, the attack can be mitigated by lowering the timeout as low as possible. On the contrary, a tight timeout might fail correct requests during congestion times. The right optimization of timeouts relies on several deployment factors e.g., the application requirements, the connection path of the client to system, the network topology of the nodes and more. Therefore, we could not deduce interesting definitive insights when facing this case. Finally, we would like to point out that the client can be configured to contact the fastest responding nodes first and thus reduce the effect of this attack.

7 Conclusion

CASSANDRA’s wide adoption makes it a prime vehicle for analyzing and evaluating various aspects of distributed data stores. In our work, we have studied CASSANDRA’s vulnerabilities to Byzantine failures and explored various design alternatives for hardening it against such failures. Our solution addressed the use of quorums, the proxy mediated interaction between the client and replicas, conflict resolutions on the reply path, configuration changes, overcoming temporary unavailability of nodes, timestamps generation, and the use of digital signatures on stored values and messages.

We have also evaluated the attainable performance of our design alternatives using the standard YCSB benchmark. The results of the performance evaluation indicated that our best Byzantine tolerant design yields a throughput that is only 2-2.5 times lower than plain CASSANDRA while write and read latencies are only a factor of 2-3 and 2-4 higher, respectively, than in the non-Byzantine tolerant system. Interestingly, the performance we obtained with the Byzantine tolerant version of CASSANDRA is similar to the performance obtained for a non-Byzantine CASSANDRA in the YCSB paper from 2010 [17].

Performance wise, the two most significant design decisions are the specific use of cryptographic signatures and resolving all conflicts during reads only. Specifically, our novel design of sending a vector of MAC tags, signed by itself with the symmetric key of the client and target node, plus the ECDSA public key signature, means that the usual path involves no public key verifications and only one elliptic curve signature. This evades costly public key verifications and RSA signatures.

Looking into the future, we would like to extend our Byzantine support to the full range of CQL functionality. Also, optimizing the protocols for multi data-center operation and supporting light-weight transactions.

Exploring batching as a performance booster [26] is challenging, especially given the documentation of the BATCH command in DATASTAX’s reference manual:

“Using batches to optimize performance is usually not successful, as described in . . .”

The current batching implementation in CASSANDRA minimizes the client-to-system traffic, but increases the in-system traffic. We assume that CASSANDRA could be improved also in a benign environment by using
traditional batching. Once this is resolved, fitting such a batching solution to the Byzantine environment should also lower the cryptographic overhead of our solutions.

Finally, we would like to try quicker converging membership dissemination protocols in CASSANDRA, using protocols such as Araneola [43].

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Figure 9: Comparing the best variants against plain CASSANDRA and the algorithm with No-Sign using workloads A, B and C. In the write latency of (a), we left the RSA variants out as they rapidly grew to ≈65ms latency.
Figure 10: Same as Figure 9 while using workloads D and F. Here, the write latency graphs do not include the RSA variants as they rapidly reached the areas of 600 ms and 65 ms latency, respectively.
Figure 11: Focusing on the hardened variants only - finer scale than Figure 9.
Figure 12: Same as Figure 11 (hardened variants only), but with workloads D and F.
Figure 13: Comparing the best variants using a key-value model. In the write latency of sub-figure (a), we left the RSA variants out as they rapidly grew to around 65ms latency.
Figure 14: Same as Figure 13 (a key-value model), but using workloads D and F.
Figure 15: Comparing the best solution against plain Cassandra in a benign failure of one node.
Figure 16: Comparing the best solution in benign behavior and the scenario of one node that replies only with bad signatures.
1: function OnNodeToNodeWriteRequest(key, value, ts)
2: Store locally <key, value, ts>
3: return Success
4: end function
5:
6: function OnClientToNodeWriteRequest(key, value, ts)
7: for each node n that is responsible for the key do              ▷ N nodes
8: Send write request with <key, value, ts> to n
9: end for
10: Wait for \( f + 1 \) acknowledgments OR timeout
11: return Success
12: end function
13:
14: function ClientWriteRequest(key, value)
15: ts ← Current timestamp
16: p ← Some random system node
17: Send write request with <key, value, ts> to p
18: Wait for an acknowledgment OR timeout ▷ Retry options available
19: return Success
20: end function

Figure 17: The write flow in plain Cassandra. ClientWriteRequest is invoked by the client for each write. OnClientToNodeWriteRequest is invoked on the proxy node by the client. OnNodeToNodeWriteRequest is invoked on a node that has the responsibility to store the value.

A Appendix: Detailed Algorithms

In this appendix, we present in details a variety of the algorithms we described in the main part. All of them are divided into three parts: client algorithm, proxy algorithm and node algorithm.

In Figures 17 and 18 we present the write and read flows as in plain Cassandra, as described in Section 5.3.

In Figures 19 and 20 we present the variant of our original solution, presented in Figures 5 and 7, where the proxy does not verify the acknowledgments, as described in Section 5.3.4 Figures 22 and 23 illustrate the run of these algorithms.

In Figure 21 we present another variant, where the proxy does not verify the acknowledgments and the client has to resolve conflicts, as described in Section 5.3.5 Figure 24 illustrates the run of this algorithm.
1: function OnNodeToNodeReadRequest(key)
2:    < value, ts > ← The newest associated timestamp and value with key
3: if isDigestQuery then
4:    return < hash(value), ts >
5: else
6:    return < value, ts >
7: end if
8: end function

9: function OnClientToNodeReadRequest(key)
10: targetEndpoints ← allRelevantNodes for key or a subset of f + 1 fastest relevant nodes
11: dataEndpoint ← One node from targetEndpoints
12: Send read request for data to dataEndpoint
13: Send read request for digest to targetEndpoints \ {dataEndpoint}
14: Wait for responses from f + 1 nodes OR timeout
15: if timeout then
16:    return ⊥
17: end if
18: if got response from dataEndpoint AND all responses agree on the digest then
19:    return data
20: end if
21: Send read request for data from all nodes in respondedNodes \ {dataEndpoint}
22: Wait for responses from all contactedNodes OR timeout
23: if timeout then
24:    return ⊥
25: end if
26: resolved ← Latest response from responses
27: Send write-back with resolved to respondedNodes except those that are known to be updated
28: Wait for responses from all contactedNodes OR timeout
29: if timeout then
30:    return ⊥
31: end if
32: return resolved
33: end function

34: function ClientReadRequest(key)
35: p ← Some random system node
36: Send read request with key to p
37: Wait for data OR timeout
38: return data
39: end function

Figure 18: The read flow in plain Cassandra. ClientReadRequest is invoked by the client for each read. OnClientToNodeReadRequest is invoked on the proxy node by the client. OnNodeToNodeReadRequest is invoked on a node that has the responsibility to store the value.
function OnNodeToNodeWriteRequest(key, value, ts, clientSignature, clientID)
  if clientSignature is valid then
    nodeSignature ← ComputeSignature(clientSignature)
    Store locally < key, value, ts, clientSignature, clientID >
    return nodeSignature
  end if
end function

function OnClientToNodeWriteRequest(key, value, ts, clientSignature, clientID)
  for each node n that is responsible for the key do
    Send write request with <key, value, ts, clientSignature, clientID> to n
  end for
  Wait for 2f + 1 acknowledgments OR timeout
  return responses
end function

function ClientWriteRequest(key, value)
  ts ← Current timestamp
  clientSignature ← ComputeSignature(key || value || ts)
  p ← Some random system node
  Send write request with <key, value, ts, clientSignature, clientID> to p
  Wait for acknowledgments OR timeout
  if |validAcknowledgments| ≥ 2f + 1 then
    return Success
  end if
  if |validAcknowledgments| ≥ f + 1 AND retryNumber ≤ f then
    Send same write request to p asking for 2f + 1 − |validAcknowledgments| from new nodes
    Wait for acknowledgments OR timeout
  end if
  if |newAcknowledgments| ≥ 1 then
    goto line 23
  else
    goto line 36
  end if
  p ← Some random system node that was not used in this function invocation
  if p = ⊥ OR contactedNodes > f then
    return Failure
  end if
  goto line 21
end function

Figure 19: A variant of our hardened write algorithm. In this variant, the proxy does not verify the acknowledgments and lets the
client contact it again if it is unsatisfied. ClientWriteRequest is invoked by the client for each write. OnClientToNodeWriteRequest
is invoked on the proxy node by the client. OnNodeToNodeWriteRequest is invoked on a node that has the responsibility to store
the value. Changes from figure 5 are marked in blue.
function OnNodeToNodeReadRequest(key, client − ts)

if key is stored in the node then

< value, ts, clientSignature, clientID > ← The newest associated timestamp and value with key

else

clientSignature ← EMPTY

end if

nodeSignature ← ComputeSignature(key||hash(value)||clientSignature||client − ts)

if isDigestQuery then

return < hash(value), ts, clientSignature, clientID, nodeSignature >

else

return < value, ts, clientSignature, clientID, nodeSignature >

end if

end function

function OnClientToNodeReadRequest(key, client − ts)

targetEndpoints ← allRelevantNodes for key or a subset of 2f + 1 fastest relevant nodes

dataEndpoint ← One node from targetEndpoints

Send read request for data to dataEndpoint

Wait for 2f + 1 responses OR timeout ◐ Not verifying signatures

if timeout AND all relevant nodes were targeted at the first phase then

return ⊥

end if

if got response from dataEndpoint AND all responses agree on the digest then

return < value, nodesSignatures >

else

Send read request for data from all nodes in allRelevantNodes ◐ N nodes

Wait for 2f + 1 responses OR timeout ◐ Not verifying signatures

if timeout then

return ⊥

resolvedValue ← Latest response from responses that is client-signature verified.

Send write-back with resolvedValue to allRelevantNodes except those that are known to be updated

Wait for responses till we have knowledge about 2f + 1 updated nodes OR timeout ◐ Not verifying signatures

if timeout then

return ⊥

end if

end if

end function

function ClientReadRequest(key)

client − ts ← Current timestamp

p ← Some random system node

Send read request with < key, client − ts > to p

Wait for responses OR timeout

if |validNodesSignatures| ≥ 2f + 1 then

return data

else if |validNodesSignatures| ≥ f + 1 then

blackList ← Nodes that returned bad signatures

Send same read request to p asking for full read from 2f + 1 nodes that are not in blackList

Wait for responses OR timeout

if |validNodesSignatures| ≥ 2f + 1 then

return data

end if

blackList ← blackList ∪ new nodes that returned bad signatures

if blackList size increased AND retryNumber ≤ f then

goto line 52 ◐ Try again without the bad nodes

end if

p ← Some random system node that was not used in this function invocation ◐ Failed reading from p

if p = ⊥ OR contactedNodes > f then

return Failure

end if

goto line 45

end function

Figure 20: A variant of our hardened read algorithm. In this variant, the proxy does not verify the answers and lets the client contact it again if it is unsatisfied. ClientReadRequest is invoked by the client for each read. OnClientToNodeReadRequest is invoked on the proxy node by the client. OnNodeToNodeReadRequest is invoked on a node that has the responsibility to store the value. Changes from figure 7 are marked in blue.
function OnNodeToNodeReadRequest(key, client\_ts)
if key is stored in the node then
< value, ts, clientSignature, clientID > ← The newest associated timestamp and value with key
else
clientSignature ← EMPTY
end if
nodeSignature ← ComputeSignature(key||hash(value)||clientSignature||client – ts)
if isDigestQuery then
return < hash(value), ts, clientSignature, clientID, nodeSignature >
else
return < value, ts, clientSignature, clientID, nodeSignature >
end if
end function

function OnClientToNodeReadRequest(key, client\_ts)
targetEndpoints ← allRelevantNodes for key or a subset of 2f + 1 fastest relevant nodes
for key or a subset of 2f + 1 fastest relevant nodes
Send read request for data to dataEndpoint
Send read request for digest to targetEndpoints \{dataEndpoint\}
Wait for 2f + 1 responses or timeout
if timeout AND all relevant nodes were targeted at the first phase then
return ⊥
end if
if got response from dataEndpoint AND all responses agree on the digest then
return < value, nodesSignatures >
end if
Send read request for data from all nodes in allRelevantNodes
Wait for 2f + 1 responses OR timeout
if timeout then
return ⊥
end if
return 2f + 1 data versions
end function

function ClientReadRequest(key)
client\_ts ← Current timestamp
p ← Some random system node
Send read request with < key, client\_ts > to p
Wait for responses OR timeout
if got one version AND |validNodesSignatures| ≥ 2f + 1 then
return data
end if
if got 2f + 1 versions with valid nodes signatures then
goto line 59

Resolve data
end if
if |validNodesSignatures| ≥ f + 1 then
blackList ← Nodes that returned bad signatures
Send same read request to p asking for full read from 2f + 1 nodes that are not in blackList
Wait for responses OR timeout
if |validNodesSignatures| ≥ 2f + 1 then
return data
end if
Add to blackList new nodes that returned bad signatures
if blackList size increased AND retryNumber ≤ f then
goto line 48
end if
end if
if got 2f + 1 versions with valid nodes signatures then
resolved ← Latest response from responses that is client-signature verified.
Send write-back with resolved to all stalled nodes
if write success then
return resolved data
end if
end if
p ← Some random system node that was not used in this function invocation
if p = ⊥ OR contactedNodes > f then
return Failure
end if
goto line 59
end function

Figure 21: A variant of our hardened read algorithm. In this variant, the proxy does not verify the answers and the client is responsible to resolve conflicts. ClientReadRequest is invoked by the client for each read. OnClientToNodeReadRequest is invoked on the proxy node by the client. OnNodeToNodeReadRequest is invoked on a node that has the responsibility to store the value. Changes from Figure 20 are marked in blue.
Figure 22: Illustrating our write algorithm from Figure 19 where the proxy does not verify the store acknowledgments. Configuration: N=4 and W=3.

Figure 23: Illustrating our read algorithm from Figure 20 where the proxy does not verify the answers. Configuration: N=4 and R=3.
Figure 24: Illustrating our read algorithm from Figure [21] where the proxy does not verify the answers and the client is responsible to resolve conflicts. Configuration: N=4 and R=3.