Efficient Fault-Tolerant Cluster-Sending*

Reliable and Efficient Communication between Byzantine Fault-Tolerant Clusters

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ABSTRACT

Traditional resilient systems operate on fully-replicated fault-tolerant clusters, which limits their scalability and performance. One way to make the step towards resilient high-performance systems that can deal with huge workloads, is by enabling independent fault-tolerant clusters to efficiently communicate and cooperate with each other, as this also enables the usage of high-performance techniques such as sharding and parallel processing.

To enable such efficient communication, we identify the *cluster-sending problem*: the problem of sending a message from one Byzantine cluster to another Byzantine cluster in a reliable manner, an essential communication primitive. We not only formalize this fundamental problem, but also establish lower bounds on the complexity of this problem under crash failures and Byzantine failures. Furthermore, we develop practical cluster-sending protocols that meet these lower bounds and, hence, have optimal complexity. Finally, we propose probabilistic cluster-sending techniques that only have an expected constant message complexity, this independent of the size of the clusters involved. Depending on the robustness of the clusters involved, these probabilistic techniques require only two-to-four message round-trips while supporting worst-case linear communication between clusters, which is optimal. As such, our work provides a strong foundation for the further development of resilient high-performance systems.

1 INTRODUCTION

The emergence of blockchain technology is fueling interest in the development of new data processing systems that can provide services continuously [14, 21, 23, 29, 30, 32], even during *Byzantine failures*, e.g., failures originating from network failure, hardware failure, software failure, or even coordinated malicious attacks. Recently, this has led to the development of several resilient data processing systems based on *permissioned blockchain technology* [2, 10, 11, 15, 25].

Unfortunately, the traditional fully-replicated *consensus-based* design of permissioned blockchain systems lacks the scalability required for modern data processing [28]. Consequently, recent data processing systems such as AHL [5], ByShard [18], Caper [2], Cerberus [17], Chainspace [1], ResilientDB [16], and SharPer [3] have proposed to combine sharding with consensus-based designs. Most of these systems follow a similar sharded design: the data is split up into individual pieces called *shards* and each shard is managed by different independent blockchain-driven clusters. To

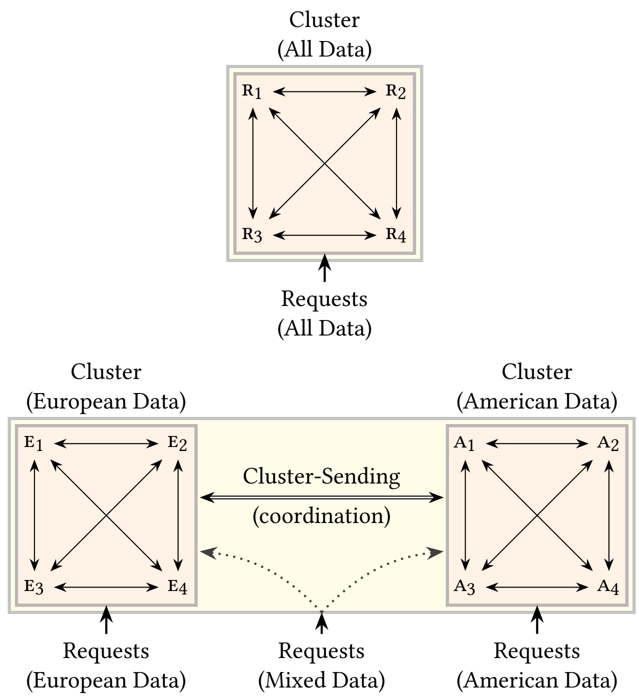

Figure 1: *Top*, a traditional fully-replicated resilient system in which all four replicas each hold all the data. *Bottom*, a *sharded* design in which each resilient cluster of four replicas holds only a part of the data.

illustrate the benefits of sharding, consider a system with a *sharded design* in which data is kept in *local Byzantine fault-tolerant clusters*, e.g., as sketched in Figure 1 by storing data relevant to American customers on systems located in the United States, whereas systems located in Europe contain data relevant to European customers. Compared to the traditional fully-replicated design of blockchain systems, this sharded design will improve *storage scalability* by distributing data storage and improve *performance scalability* by enabling concurrent transaction processing, e.g., transactions on American and European data can be performed independently of each other.

At the core of any sharded data processing system are two crucial primitives [26]. First, individual shards need primitives to independently make *decisions*, e.g., to execute transactions that only affect data held within that shard. In the setting where each shard is a fault-tolerant cluster, such per-shard decision making is formalized

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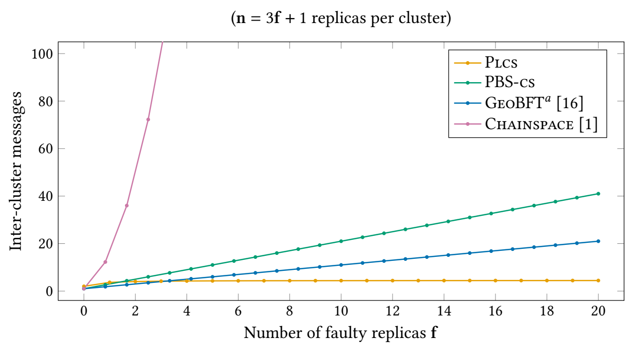
Figure 2: A comparison of *cluster-sending protocols* that send a value from cluster C_1 with $\mathbf{n}_{C_1}$ replicas, of which $\mathbf{f}_{C_1}$ are faulty, to cluster C_2 with $\mathbf{n}_{C_2}$ replicas, of which $\mathbf{f}_{C_2}$ are faulty. For each protocol P, *Protocol* specifies its name; *Robustness* specifies the conditions P puts on the clusters; *Message Steps* specifies the number of messages exchanges P performs; *Optimal* specifies whether P is worst-case optimal; and *Unreliable* specifies whether P can deal with unreliable communication.

	Protocol	Robustness[a]	Message Steps (expected-case)	Message Steps (worst-case)	Optimal	Unreliable
This Work	PBS-cs	$\min(\mathbf{n}_{C_1}, \mathbf{n}_{C_2}) > \mathbf{f}_{C_1} + \mathbf{f}_{C_2}$	$\mathbf{f}_{C_1} + \mathbf{f}_{C_2} + 1$		✔	✖
This Work	PBS-cs	$\mathbf{n}_{C_1} > 3\mathbf{f}_{C_1}, \mathbf{n}_{C_2} > 3\mathbf{f}_{C_2}$	$\max(\mathbf{n}_{C_1}, \mathbf{n}_{C_2})$		✔	✖
This Work	Plcs	$\min(\mathbf{n}_{C_1}, \mathbf{n}_{C_2}) > \mathbf{f}_{C_1} + \mathbf{f}_{C_2}$	4	$\mathbf{f}_{C_1} + \mathbf{f}_{C_2} + 1$	✔	✔
This Work	Plcs	$\min(\mathbf{n}_{C_1}, \mathbf{n}_{C_2}) > 2(\mathbf{f}_{C_1} + \mathbf{f}_{C_2})$	$2\frac{1}{4}$	$\mathbf{f}_{C_1} + \mathbf{f}_{C_2} + 1$	✔	✔
This Work	Plcs	$\mathbf{n}_{C_1} > 3\mathbf{f}_{C_1}, \mathbf{n}_{C_2} > 3\mathbf{f}_{C_2}$	3	$\max(\mathbf{n}_{C_1}, \mathbf{n}_{C_2})$	✔	✔
	GeoBFT [16]	$\mathbf{n}_{C_1} = \mathbf{n}_{C_2} > 3\max(\mathbf{f}_{C_1}, \mathbf{f}_{C_2})$	$\mathbf{f}_{C_2} + 1$[b]	$\Omega(\mathbf{f}_{C_1}\mathbf{n}_{C_2})$	✖	✔
	Chainspace [1]	$\mathbf{n}_{C_1} > 3\mathbf{f}_{C_1}, \mathbf{n}_{C_2} > 3\mathbf{f}_{C_2}$	$\mathbf{n}_{C_1}\mathbf{n}_{C_2}$		✖	✖

[a]Protocols that have different message step complexities depending on the robustness assumptions have been included for each of the robustness assumptions.
[b]Complexity when the coordinating primary in C_1 is non-faulty and communication is reliable.



[a]Complexity when the coordinating primary in C_1 is non-faulty and communication is reliable.

Figure 3: Comparison of the expected-case complexity of the probabilistic cluster-sending protocol Plcs, the worst-case optimal cluster-sending protocol PBS-cs, and the complexity of communication protocols proposed in related work.

by the well-known *consensus problem*, which can be solved by practical consensus protocols such as Pbft, even though it has high lower-bounds on its complexity [6–9, 12, 13, 22, 27]. Second, shards need primitives to *communicate* between each other, e.g., to coordinate the execution of transactions that affect data hold by multiple shards. Unfortunately, even though inter-shard communication is a *fundamental basic primitive*, it has not yet been studied in much detail: existing sharded blockchain-inspired data processing systems all use rather expensive system-specific techniques to enable coordination between shards (e.g., Chainspace [1] uses expensive multicasts and ResilientDB [16] uses an optimistic primitive with an expensive failure recovery path).

In this work, we improve on this situation by fully studying the problem of inter-shard communication in a permissioned fault-tolerant setting. In specific, we formalize the *cluster-sending problem*—the problem of sending a message from one fault-tolerant cluster to another fault-tolerant cluster in a reliable manner that is verifiable by all replicas involved—and fully study its complexity. Our contributions are as follows:

(1) We formalize the cluster-sending problem.
(2) We prove strict lower bounds that are only *linear* in the size of the clusters involved on the complexity of the cluster-sending problem in terms of the number of messages (when faulty replicas only crash) and in terms of the number of signatures (when faulty replicas can be malicious and messages are signed via public-key cryptography).
(3) We introduce *bijective sending* and *partitioned bijective sending*, powerful techniques to reliably perform cluster-sending with *optimal complexity* in practical environments (matching the established lower bounds).
(4) We introduce *probabilistic cluster-sending* to provide cluster-sending in *expected constant* steps and we show how to fine-tune probabilistic cluster-sending protocols to also match the established lower bounds.

A summary of our findings in comparison with existing techniques can be found in Table 2 and a visualisation of the complexity of the proposed cluster-sending protocols can be found in Figure 3.

Although *cluster-sending* can be solved using well-known permissioned techniques such as consensus, interactive consistency, Byzantine broadcasts, and message multicasting [1, 4, 6–9, 12, 13, 15, 22, 27], our lower-bound results shows that these primitives are not suitable as they are unnecessary costly. Likewise, our results show that existing approaches towards inter-shard communication (e.g., as used in Chainspace [1]) are unnecessary costly.

Our cluster-sending problem is closely related to cross-chain coordination in *permissionless blockchains* such as Bitcoin [24] and Ethereum [31], e.g., as provided via atomic swaps [19], atomic commitment [33], and cross-chain deals [20]. Unfortunately, such permissionless solutions are not fit for a permissioned environment.

From the results we provide, it is clear that cluster-sending is an independent problem with much lower complexity than traditional Byzantine primitives such as consensus. Hence, our work provides a novel direction for the design and implementation of high-performance sharded fault-tolerant data processing systems.

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