

Oracular Byzantine Reliable Broadcast

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Abstract

Byzantine Reliable Broadcast (BRB) is a fundamental distributed computing primitive, with applications ranging from notifications to asynchronous payment systems. Motivated by practical consideration, we study Client-Server Byzantine Reliable Broadcast (CSB), a multi-shot variant of BRB whose interface is split between broadcasting *clients* and delivering *servers*. We present **Draft**, an optimally resilient implementation of CSB. Like most implementations of BRB, **Draft** guarantees both liveness and safety in an asynchronous environment. Under good conditions, however, **Draft** achieves unparalleled efficiency. In a moment of synchrony, free from Byzantine misbehaviour, and at the limit of infinitely many broadcasting clients, a **Draft** server delivers a b -bits payload at an asymptotic amortized cost of 0 signature verifications, and $(\log_2(c) + b)$ bits exchanged, where c is the number of clients in the system. This is the information-theoretical minimum number of bits required to convey the payload (b bits, assuming it is compressed), along with an identifier for its sender ($\log_2(c)$ bits, necessary to enumerate any set of c elements, and optimal if broadcasting frequencies are uniform or unknown). These two achievements have profound practical implications. Real-world BRB implementations are often bottlenecked either by expensive signature verifications, or by communication overhead. For **Draft**, instead, the network is the limit: a server can deliver payloads as quickly as it would receive them from an infallible oracle.

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Related Version The extended version of this paper, which includes all detailed proofs and pseudocode, is available online [17].

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1 Introduction

Byzantine reliable broadcast (BRB) is one of the most fundamental and versatile building blocks in distributed computing, powering a variety of Byzantine fault-tolerant (BFT) systems [14, 28]. The BRB abstraction has recently been shown to be strong enough to process payments, enabling cryptocurrency deployments in an asynchronous environment [29]. Originally introduced by Bracha [9] to allow a set of processes to agree on a single message from a designated sender, BRB naturally generalizes to the multi-shot case, enabling higher-level abstractions such as Byzantine FIFO [44, 12] and causal [7, 4] broadcast. We study a practical, multi-shot variant of BRB whose interface is split between broadcasting *clients*



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44 and delivering *servers*. We call this abstraction Client-Server Byzantine Reliable Broadcast
45 (CSB).

46 **CSB in brief.** Clients broadcast, and servers deliver, *payloads* composed by a *context*
47 and a *message*. This interface allows, for example, Alice to announce her wedding as well as
48 will her fortune by respectively broadcasting

$$49 \quad \left(\underbrace{\text{"My wife is", "Carla"}}_{\text{context } c_w}, \underbrace{\text{"Carla"}}_{\text{message } m_w} \right) \quad \left(\underbrace{\text{"All my riches go to", "Bob"}}_{\text{context } c_r}, \underbrace{\text{"Bob"}}_{\text{message } m_r} \right)$$

50 CSB guarantees that: (*Consistency*) no two correct servers deliver different messages for
51 the same client and context; (*Totality*) either all correct servers deliver a message for a
52 given client and context, or no correct server does; (*Integrity*) if a correct server delivers a
53 payload from a correct client, then the client has broadcast that payload; and (*Validity*) a
54 payload broadcast by a correct client is delivered by at least one correct server. Following
55 from the above example, Carla being Alice's wife does not conflict with Bob being her sole
56 heir (indeed, $c_w \neq c_r$), but Alice would not be able to convince two correct servers that she
57 married Carla and Diana, respectively. Higher-level broadcast abstractions can be easily
58 built on top of CSB. For example, using integer sequence numbers as contexts and adding
59 a reordering layer yields Client-Server Byzantine FIFO Broadcast. For the sake of CSB,
60 however, it is not important for contexts to be integers, or satisfy any property other than
61 comparability. Throughout the remainder of this paper, the reader can picture contexts as
62 opaque binary blobs. Lastly, while the set of servers is known, CSB as presented does not
63 assume any client to be known a priori. The set of clients can be permissionless, with servers
64 discovering new clients throughout the execution.

65 **A utopian model.** Real-world BRB implementations are often bottlenecked either by
66 expensive signature verifications [21] or by communication overhead [10, 34, 35]. With the
67 goal of broadening those bottlenecks, simplified, more trustful models are useful to establish
68 a (sometimes grossly unreachable) bound on the efficiency that an algorithm can attain in
69 the Byzantine setting. For example, in a utopian model where any agreed-upon process can
70 be trusted to never fail (let us call it an *oracle*), CSB can easily be implemented with great
71 efficiency. Upon initialization, the oracle organizes all clients in a list, which it disseminates to
72 all servers. For simplicity, let us call *id* a client's position in the list. To broadcast a payload
73 *p*, a client with *id* *i* simply sends *p* to the oracle: the oracle checks *p* for equivocation (thus
74 ensuring consistency), then forwards (*i*, *p*) to all servers (thus ensuring validity and totality).
75 Upon receiving (*i*, *p*), a server blindly trusts the oracle to uphold all CSB properties, and
76 delivers (*i*, *p*). Oracle-CSB is clearly very efficient. On the one hand, because the oracle can
77 be trusted not to attribute spurious payloads to correct clients, integrity can be guaranteed
78 without any server-side signature verification. On the other, in order to deliver (*i*, *p*), a server
79 needs to receive just $(\lceil \log_2(c) \rceil + |p|)$ bits, where *c* denotes the total number of clients, and
80 $|p|$ measures *p*'s length in bits. This is optimal assuming the rate at which clients broadcast
81 is unknown¹ or uniform² [20].

¹ Lacking an assumption on broadcasting rates, an adversarial scheduler could have all messages broadcast by the client with the longest *id*, which we cannot guarantee to be shorter than $\lceil \log_2(c) \rceil$ bits.

² Should some clients be expected to broadcast more frequently than others, we could further optimize Oracle-CSB by assigning smaller *ids* to more active clients, possibly at the cost of having less active clients have *ids* whose length exceeds $\lceil \log_2(c) \rceil$. Doing so, however, is beyond the scope of this paper.

Matching the oracle. Due to its reliance on a single infallible process, Oracle-CSB is not a fault-tolerant distributed algorithm: shifting back to the Byzantine setting, a single failure would be sufficient to compromise all CSB properties. Common sense suggests that Byzantine resilience will necessarily come at some cost: protocol messages must be exchanged to preserve consistency and totality, signatures must be produced and verified to uphold integrity and, lacking the totally-ordering power that only consensus can provide, ids cannot be assigned in an optimally dense way. However, this paper proves the counter-intuitive result that an asynchronous, optimally-resilient, Byzantine implementation of CSB can asymptotically match the efficiency of Oracle-CSB. This is not just up to a constant, but identically. In a synchronous execution, free from Byzantine misbehaviour, and as the number of concurrently broadcasting clients goes to infinity (we call these conditions the *batching limit*³), our CSB implementation Draft delivers a payload p at an asymptotic⁴, amortized cost of 0 signature verifications⁵ and $(\lceil \log_2(c) \rceil + |p|)$ bits exchanged per server, the same as in Oracle-CSB (we say that Draft achieves *oracular efficiency*). At the batching limit a Draft server is dispensed from nearly all signature verifications, as well as nearly all traffic that would be normally required to convey protocol messages, signatures, or client public keys. Network is the limit: payloads are delivered as quickly as they can be received.

CSB's common bottlenecks. To achieve oracular efficiency, we focus on three types of server overhead that commonly affect a real-world implementation of CSB:

- *Protocol overhead.* Safekeeping consistency and totality typically requires some form of communication among servers. This communication can be direct (as in Bracha's original, all-to-all BRB implementation) or happen through an intermediary (as in Bracha's signed, one-to-all-to-one BRB variant), usually employing signatures to establish authenticated, intra-server communication channels through a (potentially Byzantine) relay.
- *Signature overhead.* Upholding integrity usually requires clients to authenticate their messages using signatures. For servers, this entails both a computation and a communication overhead. On the one hand, even using well-optimized schemes, signature verification is often CPU-heavy enough to dominate a server's computational budget, dwarfing in particular the CPU footprint of much lighter, symmetric cryptographic primitives such as hashes and ciphers. On the other hand, transmitting signatures results in a fixed communication overhead per payload delivered. While the size of a signature usually ranges from a few tens to a few hundreds of bytes, this overhead is non-negligible in a context where many clients broadcast small messages. This is especially true in the case of payments, where a message reduces to the identifier of a target account and an integer to denote the amount of money to transfer.
- *Identifier overhead.* CSB's multi-shot nature calls for a sender identifier to be attached to each broadcast payload. Classically, the client's public key is used as identifier. This is convenient for two reasons. First, knowing a client's identifier is sufficient to authenticate its payloads. Second, asymmetric keypairs have very low probability of collision. As such, clients can create identities in the system without any need for coordination: locally generating a keypair is sufficient to begin broadcasting messages. By cryptographic design, however, public keys are sparse, and their size does not change with the number of clients.

³ The batching limit includes other easily achievable, more technical conditions that we omit in this section for the sake of brevity. For the full definition, please refer to the extended version of this paper [17].

⁴ The asymptotic costs are reached quite fast, at rates comparable to C^{-1} or $\log(C) \cdot C^{-1}$.

⁵ This does not mean that batches are processed in constant time: hashes and signature aggregations, for example, still scale linearly in the size of a batch. The real-world computational cost of such simple operations, however, is several orders of magnitude lower than that of signature verification.

124 This translates to tens to hundreds of bytes being invested to identify a client from a set
 125 that can realistically be enumerated by a few tens of bits. Again, this communication
 126 overhead is heavier on systems where broadcasts are frequent and brief.

127 On the way to matching Oracle-CSB’s performance, we develop techniques to negate all
 128 three types of overhead: at the batching limit, a Draft server delivers a payload wasting 0
 129 bits to protocol overhead, performing 0 signature verifications, and exchanging $\lceil \log_2(c) \rceil$
 130 bits of identifier, the minimum required to enumerate the set of clients. We outline our
 131 contributions below, organized in three (plus one) take-home messages (T-HMs).

132 **T-HM1: The effectiveness of batching goes beyond total order.** In the totally
 133 ordered setting, batching is famously effective at amortizing protocol overhead [45, 3]. Instead
 134 of disseminating its message to all servers, a client hands it over to (one or more)⁶ batching
 135 processes. Upon collecting a large enough set of messages, a batching process organizes all
 136 messages in a batch, which it then disseminates to the servers. Having done so, the batching
 137 process submits the batch’s hash to the system’s totally-ordering primitive. Because hashes
 138 are constant in length, the cost of totally ordering a batch does not depend on its size. Once
 139 batches are totally ordered, so too are messages (messages within a batch can be ordered by
 140 any deterministic function), and equivocations can be handled at the application layer (for
 141 example, in the context of a cryptocurrency, the second request to transfer the same asset
 142 can be ignored by all correct servers, with no need for additional coordination). At the limit
 143 of infinitely large batches, the relative overhead of the ordering protocol becomes vanishingly
 144 small, and a server can allocate virtually all of its bandwidth to receiving batches. This
 145 strategy, however, does not naturally generalize to CSB, where batches lack total order. As
 146 payloads from multiple clients are bundled in the same batch, a correct server might detect
 147 equivocation for only a subset of the payloads in the batch. Entirely accepting or entirely
 148 rejecting a partially equivocated batch is not an option. In the first case, consistency could
 149 be violated. In the second case, a single Byzantine client could single-handedly “poison”
 150 the batches assembled by every correct batching process with equivocated payloads, thus
 151 violating validity. In Draft, a server can partially reject a batch, acknowledging all but
 152 some of its payloads. Along with its partial acknowledgement, a server provides a proof of
 153 equivocation to justify each exception. Having collected a quorum of appropriately justified
 154 partial acknowledgements, a batching process has servers deliver only those payloads that
 155 were not excepted by any server. Because proofs of equivocations cannot be forged for
 156 correct clients, a correct client handing over its payload to a correct batching process is
 157 guaranteed to have that payload delivered. In the common case where batches have little to
 158 no equivocations, servers exchange either empty or small lists of exceptions, whose size does
 159 not scale with that of the batch. This extends the protocol-amortizing power of batching to
 160 CSB and, we conjecture, other non-totally ordered abstractions.

161 **T-HM2: Interactive multi-signing can slash signature overhead.** Traditionally,
 162 batching protocols are non-interactive on the side of clients. Having offloaded its message to
 163 a correct batching process, a correct client does not need to interact further for its message
 164 to be delivered: the batching process collects an arbitrary set of independently signed
 165 messages and turns to the servers to get each signature verified, and the batch delivered.
 166 This approach is versatile (messages are not tied to the batch they belong to) and reliable
 167 (a client crashing does not affect a batch’s progress) but expensive (the cost of verifying

⁶ In most real-world implementations, a client optimistically entrusts its payload to a single process, extending its request to larger portions of the system upon expiration of a suitable timeout.

each signature is high and independent of the batch's size). In *Draft*, batching processes engage in an interactive protocol with clients to replace, in the good case, all individual signatures in a batch with a single, batch-wide *multi-signature*. In brief, multi-signature schemes extend traditional signatures with a mechanism to *aggregate* signatures and public keys: an arbitrarily large set of signatures for the same message⁷ can be aggregated into a single, constant-sized signature; similarly, a set of public keys can be aggregated into a single, constant-sized public key. The aggregation of a set of signatures can be verified in constant time against the aggregation of all corresponding public keys. Unlike verification, aggregation is a cheap operation, reducing in some schemes to a single multiplication on a suitable field. Multi-signature schemes open a possibility to turn expensive signature verification into a once-per-batch operation. Intuitively, if each client contributing to a batch could multi-sign the entire batch instead of its individual payload, all multi-signatures could be aggregated, allowing servers to authenticate all payloads at once. However, as clients cannot predict how their payloads will be batched, this must be achieved by means of an interactive protocol. Having collected a set of individually-signed payloads in a batch, a *Draft* batching process shows to each contributing client that its payload was included in the batch. In response, clients produce their multi-signatures for the batch's hash, which the batching process aggregates. Clients that fail to engage in this interactive protocol (e.g., because they are faulty or slow) do not lose liveness, as their original signature can still be attached to the batch to authenticate their individual payload. In the good case, all clients reply in a timely fashion, and each server has to verify a single multi-signature per batch. At the limit of infinitely large batches, this results in each payload being delivered at an amortized cost of 0 signature verifications. The usefulness of this interactive protocol naturally extends beyond CSB to all multi-shot broadcast abstractions whose properties include integrity.

T-HM3: Dense id assignment can be achieved without consensus. In order to efficiently convey payload senders, *Oracle-CSB*'s oracle organizes all clients in a list, attaching to each client a successive integral identifier. Once the list is disseminated to all servers, the oracle can identify each client by its identifier, sparing servers the cost of receiving larger, more sparse, client-generated public keys. Id-assignment strategies similar to that of *Oracle-CSB* can be developed, in the distributed setting, building on top of classical algorithms that identify clients by their full public keys (we call such algorithms *id-free*, as opposed to algorithms such as *Draft*, which are *id-optimized*). In a setting where consensus can be achieved, the identifier density of *Oracle-CSB* is easily matched. Upon initialization, each client submits its public key to an id-free implementation of Total-Order Broadcast (TOB). Upon delivery of a public key, every correct process agrees on its position within the common, totally-ordered log. As in *Oracle-CSB*, each client can then use its position in the list as identifier within some faster, id-optimized broadcast implementation. In a consensus-less setting, achieving a totally-ordered list of public keys is famously impossible [26]. This paper, however, proves the counter-intuitive result that, when batching is used, the density of ids assigned by a consensus-less abstraction can asymptotically match that of those produced by *Oracle-CSB* or consensus. In *Dibs*, our consensus-less id-assigning algorithm, a client requests an id from every server. Each server uses an id-free implementation of FIFO Broadcast to order the client's public key within its own log. Having observed its public key appear in at least one log, the client publicly elects the server in charge of that log to be its *assigner*.

⁷ Some multi-signature schemes also allow the aggregation of signatures on heterogeneous messages. In that case, however, aggregation is usually as expensive as signature verification. Given our goal to reduce CPU complexity for servers, this paper entirely disregards heterogeneous aggregation schemes.

212 Having done so, the client obtains an id composed of the assigner’s public key and the client’s
 213 position within the assigner’s log. We call the two components of an id *domain* and *index*,
 214 respectively. Because the set of servers is known to (and can be enumerated by) all processes,
 215 an id’s domain can be represented in $\lceil \log_2(n) \rceil$ bits, where n denotes the total number of
 216 servers. Because at most c distinct clients can appear in the FIFO log of any server, indices
 217 are at most $\lceil \log_2(c) \rceil$ bits long. In summary, Dibs assigns ids to clients without consensus, at
 218 an additional cost of $\lceil \log_2(n) \rceil$ bits per id. Interestingly, even this additional complexity can
 219 be amortized by batching. Having assembled a batch, a Draft batching process represents
 220 senders not as a list of ids, but as a map, associating to each of the n domains the indices
 221 of all ids in the batch under that domain. At the limit of infinitely large batches ($C \gg N$),
 222 the bits required to represent the map’s keys are entirely amortized by those required to
 223 represent its values. This means that, while $(\lceil \log_2(n) \rceil + \lceil \log_2(c) \rceil)$ bits are required to
 224 identify a client in isolation, $\lceil \log_2(c) \rceil$ bits are sufficient if the client is batched: even without
 225 consensus, Draft asymptotically matches the id efficiency of Oracle-CSB.

226 **Bonus T-HM: Untrusted processes can carry the system.** In THM1, we outlined
 227 how batching can be generalized to the consensus-less case, and discussed its role in removing
 228 protocol overhead. In THM2, we sketched how an interactive protocol between clients and
 229 batching processes can eliminate signature overhead. In employing these techniques, we
 230 shifted most of the communication and computation complexity of our algorithms from servers
 231 to batching processes. Batching processes verify all client signatures, create batches, verify
 232 and aggregate all client multi-signatures, then communicate with servers in an expensive
 233 one-to-all pattern, engaging server resources (at the batching limit) as little as an oracle
 234 would. Our last contribution is to observe that a batching process plays no role in upholding
 235 CSB’s safety. As we discuss in detail throughout the remainder of this paper, a malicious
 236 batching process cannot compromise consistency (it would need to collect two conflicting
 237 quorums of acknowledgements), totality (any server delivering a batch has enough information
 238 to convince all others to do the same) or integrity (batches are still signed, and forged or
 239 improperly aggregated multi-signatures are guaranteed to be detected). Intuitively, the only
 240 damage a batching process can do to the system is to refuse to process client payloads⁸. This
 241 means that a batching process does not need to satisfy the same security properties as a
 242 server. CSB’s properties cannot be upheld if a third of the servers are faulty. Conversely,
 243 Draft has both liveness and safety as long as *a single* batching process is correct. This
 244 observation has profound practical implications. In the real world, scaling the resources of
 245 a permissioned, security-critical set of servers can be hard. On the one hand, reputable,
 246 dependable institutions partaking in the system might not have the resources to keep up with
 247 its demands. On the other, more trusted hardware translates to a larger security cross-section.
 248 Trustless processes, however, are plentiful to the point that permissionless cryptocurrencies
 249 traditionally waste their resources, making them compete against each other in expensive
 250 proofs of Sybil-resistance [39]. In this paper, we extend the classical client-server model
 251 with *brokers*, a permissionless, scalable set of processes whose only purpose is to alleviate
 252 server complexity. Unlike servers, more than two-thirds of which we assume to be correct,
 253 all brokers but one can be faulty. In Draft, brokers act as an intermediary between clients
 254 and servers, taking upon themselves the batching of payloads, verification and aggregation of
 255 signatures, the dissemination of batches, and the transmission of protocol messages.

⁸ Or cause servers to waste resources, e.g., by transmitting improperly signed batches. Simple account-ability measures, we conjecture, would be sufficient to mitigate these attacks in Draft. A full discussion of Denial of Service, however, is beyond the scope of this paper.

Roadmap. We discuss related work in Section 2. We state our model and recall useful cryptographic background in Section 3. In Section 4, we introduce our CSB implementation **Draft**: we overview **Draft**'s protocol in Section 4.1, and provide high-level arguments for **Draft**'s efficiency in Section 4.2. We draw our conclusions and propose future work in Section 5. The full formal analysis of our algorithms as well as their pseudocode can be found in the extended version of this paper [17].

2 Related Work

Byzantine Reliable Broadcast (BRB) is a classical primitive of distributed computing, with widespread practical applications such as in State Machine Replication (SMR) [38, 15, 11], Byzantine agreement [40, 18, 32, 31, 47], blockchains [3, 22, 23], and online payments [29, 19, 33]. In classical BRB, a system of n processes agree on a single message from a single *source* (one of the n processes), while tolerating up to f Byzantine failures (f of the n processes can behave arbitrarily). A well known solution to asynchronous BRB with provably optimal resilience ($f < n/3$) was first proposed by Bracha [8, 9] who introduced the problem. Bracha's broadcast reaches $O(n^2)$ message complexity, and $O(n^2L)$ communication complexity (total number of transmitted bits between correct processes [48]), where L is the length of the message. Since $O(n^2)$ message complexity is provably optimal [27], the main focus of BRB-related research has been on reducing its communication complexity. The best lower bound for communication complexity is $\Omega(nL + n^2)$, although it is unknown whether it is tight. The nL term comes from all processes having to receive the message (length L), while the n^2 term comes from each of the n processes having to receive $\Omega(n)$ protocol messages to ensure agreement in the presence of $f = \Theta(n)$ failures [27]. One line of research focuses on worst-case complexity, predominantly using error correcting codes [43, 6] or erasure codes [41, 30, 16, 2], and has produced various BRB protocols with improved complexity [2, 16, 13, 24, 40], many of them quite recently. The work of Das, Xiang and Ren [24] achieves $O(nL + kn^2)$ communication complexity (specifically, $7nL + 2kn^2$), where k is the security parameter (e.g., the length of a hash, typically 256 bits). As the authors note, the value of hidden constants (and k , which is sometimes considered as a constant in literature) is particularly important when considering practical implementations of these protocols. Another line of research focuses on optimizing the good case performance of BRB, i.e., when the network behaves synchronously and no process misbehaves [13, 18, 32, 42, 1]. As the good case is usually the common case, in practice, the real-world communication complexity of these optimistic protocols matches that of the good case. A simple and widely-used hash-based BRB protocol is given by Cachin *et al.* [13]. It replaces the echo and ready phase messages in Bracha's protocol with hashes, achieving $O(nL + kn^2)$ in the good case (specifically, $nL + 2kn^2$), and $O(n^2L)$ in the worst-case. Considering practical throughput, some protocols also focus on the *amortized* complexity per source message [18, 42, 36]. Combining techniques such as *batching* [18] and threshold signatures [46], at the limit (of batch size), BRB protocols reach $O(nL)$ amortized communication complexity in the good case [42]. At this point, the remaining problem lies in the hidden constants. In the authenticated setting, batching-based protocols rely on digital signatures to validate (source) messages before agreeing to deliver them [42]. In reality, each source message in a batch includes its content, an identifier of the source (e.g., a k -sized public key), a sequence id (identifying the message), and a k -sized signature. When considering systems where L is small (e.g., online payments), these can take up a large fraction of the communication. To be precise, the good-case amortized communication complexity would be $O(nL + kn)$. In fact, message signatures (the kn factor)

are by far the main bottleneck in practical applications of BRB today [23, 47], both in terms of communication and computation (signature verification), leading to various attempts at reducing or amortizing their cost [22, 36]. For example, Crain *et al.* [22] propose *verification sharding*, in which only $f + 1$ processes have to receive and verify all message signatures in the good case, which is a 3-fold improvement over previous systems (on the kn factor) where all n processes verify all signatures. However, by itself, this does not improve on the amortized cost of $O(nL + kn)$ per message. When contrasting theoretical research with practical systems, it is interesting to note the gap that can surge between the theoretical model and reality. The recent work of Abraham *et al.* [1], focused on the good-case latency of Byzantine broadcast, expands on some of these mismatches and argues about the practical limitations of focusing on the worst-case. Another apparent mismatch lies in the classical model of Byzantine broadcast. In many of the applications of BRB mentioned previously (e.g., SMR, permissioned blockchains, online payments), there is usually a set of *servers* (n , up to f of which are faulty), and a set of external clients (X) which are the true sources of messages. The usual transformation from BRB's classical model into these practical settings maps the set of n servers as the n processes and simply excludes clients as system entities, e.g., assuming their messages are relayed through one of the servers. Since the number of clients can be very large ($|X| \gg n$), clients are untrusted (which can limit their usefulness), and the focus is on the communication complexity of the *servers*, this transformation seems reasonable and simplifies the problem. However, it can also limit the search for more practical solutions. In this paper, in contrast with the classical model of BRB, we explicitly include the set of clients X in our system while focusing on the communication complexity surrounding the servers (i.e., the bottleneck). Furthermore, we introduce *brokers*, an untrusted set B of processes, only one of which is assumed to be correct, whose goal is to assist servers in their operation. By doing this, we can leverage brokers to achieve a good-case, amortized communication complexity (for servers, information received or sent) of $nL + o(nL)$.

3 Model & background

3.1 Model

System and adversary. We assume an asynchronous message-passing system where the set Π of processes is the distinct union of three sets: **servers** (Σ), **brokers** (B), and **clients** (X). We use $n = |\Sigma|$, $k = |B|$ and $c = |X|$. Any two processes can communicate via reliable, FIFO, point-to-point links (messages are delivered in the order they are sent). Faulty processes are Byzantine, i.e., they may fail arbitrarily. Byzantine processes know each other, and may collude and coordinate their actions. At most f servers are Byzantine, with $n = 3f + 1$. At least one broker is correct. All clients may be faulty. We use Π_C and Π_F to respectively identify the set of correct and faulty processes. The adversary cannot subvert cryptographic primitives (e.g., forge signatures). Servers and brokers⁹ are permissioned (every process knows Σ and B), clients are permissionless (no correct process knows X a priori). We call *certificate* a statement signed by either a plurality ($f + 1$) or a quorum ($2f + 1$) of servers. Since every process knows Σ , any process can verify a certificate.

Good case. The algorithms presented in this paper are designed to uphold all their properties in the model above. *Draft*, however, achieves oracular efficiency only in the *good*

⁹ The assumption that brokers are permissioned is made for simplicity, and can be easily relaxed to the requirement that every correct process knows at least one correct broker.

344 *case*. In the good case, links are synchronous (messages are delivered at most one time unit
 345 after they are sent), all processes are correct, and the set of brokers contains only one element.
 346 To take advantage of the good case, **Draft** makes use of timers (which is uncommon for purely
 347 asynchronous algorithms). A timer with timeout δ set at time t rings: after time $(t + \delta)$, if
 348 the system is synchronous; after time t , otherwise. Intuitively, in the non-synchronous case,
 349 timers disregard their timeout entirely, and are guaranteed to ring only eventually.

350 3.2 Background

351 Besides commonly used hashes and signatures, the algorithms presented in this paper make
 352 use of two less often used cryptographic primitives, namely, multi-signatures and Merkle
 353 trees. We briefly outline their use below. An in-depth discussion of their inner workings,
 354 however is beyond the scope of this paper.

355 **Multi-signatures.** Like traditional signatures, multi-signatures [5] are used to publicly
 356 authenticate messages: a public / secret keypair (p, r) is generated locally; r is used to
 357 produce a signature s for a message m ; s is publicly verified against p and m . Unlike
 358 traditional signatures, however, multi-signatures for the same message can be *aggregated*. Let
 359 $(p_1, r_1), \dots, (p_n, r_n)$ be a set of keypairs, let m be a message, and let s_i be r_i 's signature for
 360 m . (p_1, \dots, p_n) and (s_1, \dots, s_n) can be respectively aggregated into a constant-sized public
 361 key \hat{p} and a constant-sized signature \hat{s} . As with individually-generated multi-signatures, \hat{s}
 362 can be verified in constant time against \hat{p} and m . Aggregation is cheap and non-interactive:
 363 provided with (p_1, \dots, p_n) (resp., (s_1, \dots, s_n)) any process can compute \hat{p} (resp., \hat{s}).

364 **Merkle trees.** Merkle trees [37] extend traditional hashes with compact *proofs of*
 365 *inclusion*. As with hashes, a sequence (x_1, \dots, x_n) of values can be hashed into a preimage
 366 and collision-resistant digest (or *root*) r . Unlike hashes, however, a proof p_i can be produced
 367 from (x_1, \dots, x_n) to attest that the i -th element of the sequence whose root is r is indeed x_i .
 368 In other words, provided with r , p_i and x_i , any process can verify that the i -th element of
 369 (x_1, \dots, x_n) is indeed x_i , without having to learn $(x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_n)$. The size of a
 370 proof of inclusion for a sequence of n elements is logarithmic in n .

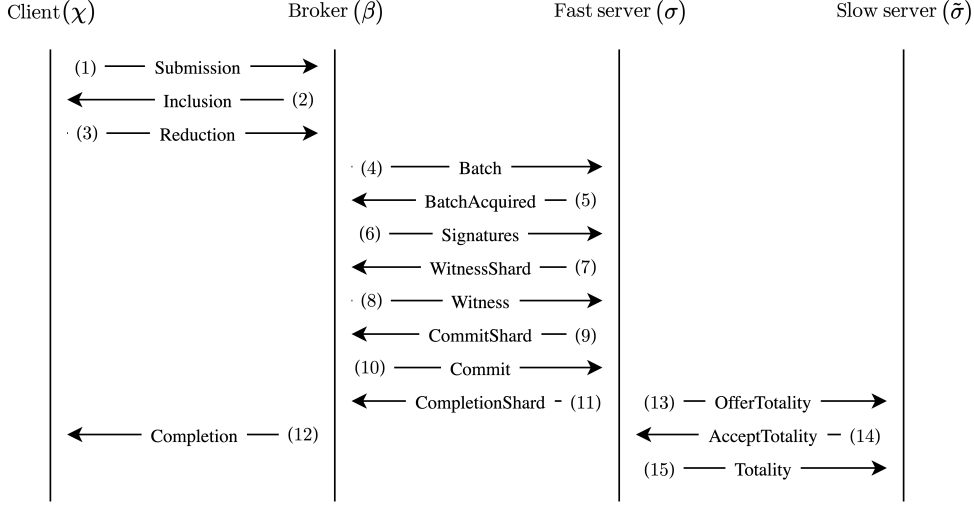
371 4 Draft: Overview

372 In this section, we provide an intuitive overview of our CSB implementation, **Draft**, as well
 373 as high-level arguments for its efficiency.

374 4.1 Protocol

375 **Dramatis personae.** The goal of this section is to provide an intuitive understanding of
 376 **Draft**'s protocol. In order to do this, we focus on four processes: a correct client χ , a correct
 377 broker β , a correct and fast server σ , and a correct but slow server $\tilde{\sigma}$. We follow the messages
 378 exchanged between χ , β , σ and $\tilde{\sigma}$ as the protocol unfolds, as captured by Figure 1.

379 **The setting.** χ 's goal is to broadcast a payload p . χ has already used **Draft**'s underlying
 380 Directory abstraction (DIR) to obtain an id i . In brief, DIR guarantees that i is assigned to
 381 χ only, and provides χ with an *assignment certificate* a , which χ can use to prove that its id
 382 is indeed i . As we discussed in Section 1, **Draft** uses DIR-assigned ids to identify payload
 383 senders. This is essential to **Draft**'s performance, as DIR guarantees *density*: as we outline in
 384 Section 4.2, $\lceil \log_2(c) \rceil$ bits are asymptotically sufficient to represent each id in an infinitely



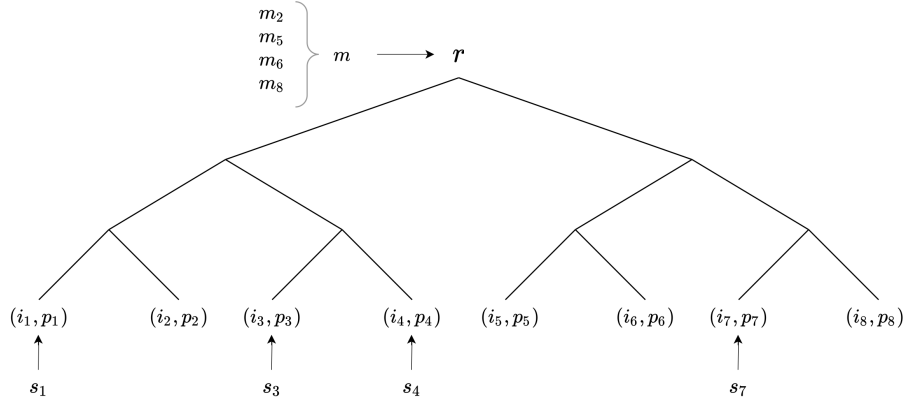
■ **Figure 1** Draft’s protocol. Having collected a batch of client payloads, a broker engages in an interactive protocol with clients to reduce the batch, replacing (most of) its individual payload signatures with a single, batch-wide multi-signature. The broker then disseminates the batch to all servers, successively gathering a witness for its correctness and a certificate to commit (some of) its payloads. Having had a plurality of servers deliver the batch, the broker notifies all clients with a suitable certificate. In the bad case, servers can ensure totality without any help from the broker, propagating batches and commit certificates in an all-to-all fashion.

large batch. Throughout the remainder of this paper, we say that a process π *knows* an id \hat{i} iff π knows the public keys to which \hat{i} is assigned.

Building a batch. In order to broadcast its payload p , χ produces a signature s for p , and then sends a **Submission** message to β (fig. 1, step 1). The **Submission** message contains p , s , and χ ’s assignment certificate a . Upon receiving the **Submission** message, β learns χ ’s id i from a , then verifies s against p . Having done so, β stores (i, p, s) in its *submission pool*. For a configurable amount of time, β fills its pool with submissions from other clients, before *flushing* it into a *batch*. Let us use $(i_1, p_1, s_1), \dots, (i_b, p_b, s_b)$ to enumerate the elements β flushes from the submission pool (for some n , we clearly have $(i, p, s) = (i_n, p_n, s_n)$). For convenience, we will also use χ_j to identify the sender of p_j (owner of i_j). Importantly, β flushes the pool in such a way that $i_j \neq i_k$ for all $j \neq k$: for safety reasons that will soon be clear, Draft’s protocol prevents a client from having more than one payload in any specific batch. Because of this constraint, some payloads might linger in β ’s pool. This is not an issue: β will simply flush those payloads to a different batch at a later time. When building the batch, β splits submissions and signatures, storing $(i_1, p_1), \dots, (i_b, p_b)$ separately from s_1, \dots, s_b .

Reducing the batch. Having flushed submissions $(i_1, p_1), \dots, (i_b, p_b)$ and signatures s_1, \dots, s_b , β moves on to *reduce* the batch, as exemplified in Figure 2. In an attempt to minimize signature overhead for servers, β engages in an interactive protocol with clients χ_1, \dots, χ_b to replace as many signatures as possible with a single, batch-wide multi-signature. In order to do so, β organizes $(i_1, p_1), \dots, (i_b, p_b)$ in a Merkle tree with root r (for brevity, we call r the batch’s root). β then sends an **Inclusion** message to each χ_j (fig. 1, step 2). Each **Inclusion** message contains r , along with a proof of inclusion q_j for (i_j, p_j) . Upon receiving its **Inclusion** message, χ checks q_n against r . In doing so, χ comes to two conclusions. First,

409 χ 's submission $(i, p) = (i_n, p_n)$ is part of a batch whose root is r . Second, because no Draft
 410 batch can contain multiple payloads from the same client, that batch does not attribute
 411 χ any payload other than p . In other words, χ can be certain that β will not broadcast
 412 some spurious payload $p' \neq p$ in χ 's name: should β attempt to do that, the batch would
 413 be verifiably malformed, and immediately discarded. This means χ can safely produce a
 414 multi-signature m for r : as far as χ is concerned, the batch with root r upholds integrity.
 415 Having signed r , χ sends m to β by means of a **Reduction** message (fig. 1, step 3). Upon
 416 receiving χ_j 's **Reduction** message, β checks χ_j 's multi-signature m_j against r . Having done
 417 so, β discards χ_j 's original signature s_j . Intuitively, with m_j , χ_j attested its agreement
 418 with whatever payload the batch attributes to χ_j . Because this is equivalent to individually
 419 authenticating p_j , s_j is redundant and can be dropped. Upon expiration of a suitable timeout,
 420 β stops collecting **Reduction** messages: clearly, if β waited for every χ_j to produce m_j , a
 421 single Byzantine client could prevent the protocol from moving forward by refusing to send
 422 its **Reduction** message. β aggregates all the multi-signatures it collected for r into a single,
 423 batch-wide multi-signature m . In the good case, every χ_j is correct and timely. If so, β
 424 drops all individual signatures, and the entire batch is authenticated by m alone.



■ **Figure 2** An example of partially reduced batch. $B = 8$ submissions are organized on the leaves of a Merkle tree with root r . Each submission (i_j, p_j) is originally authenticated by an individual signature s_j . Upon collecting a multi-signature m_j for r , the broker drops s_j . Here the broker collected multi-signatures m_2, m_5, m_6 and m_8 , leaving a *straggler set* $S = \{(i_1, s_1), (i_3, s_3), (i_4, s_4), (i_7, s_7)\}$. Upon expiration of a suitable timeout, the broker aggregates m_2, m_5, m_6 and m_8 into a single multi-signature m . As such, every payload in the batch is authenticated either by m or by S .

425 **The perks of a reduced batch.** Having reduced the batch, β is left with a se-
 426 quence of submissions $(i_1, p_1), \dots, (i_b, p_b)$, a multisignature m on the Merkle root r of
 427 $(i_1, p_1), \dots, (i_b, p_b)$, and a *straggler set* S holding the individual signatures that β failed to
 428 reduce. More precisely, S contains (i_j, s_j) iff β did not receive a valid **Reduction** message
 429 from χ_j before the reduction timeout expired. We recall that m 's size is constant, and S is
 430 empty in the good case. Once reduced, the batch is cheap to authenticate: it is sufficient
 431 to verify the batch's multi-signature against the batch's root, and each straggler signature
 432 against its individual payload. More precisely, let T denote the set of *timely* clients (χ_j is
 433 in T iff (i_j, \dots) is not in S). Let t denote the aggregation of T 's public keys. Provided with
 434 $(i_1, p_1), \dots, (i_b, p_b)$, m and S , any process that knows i_1, \dots, i_b can verify that the batch
 435 upholds integrity by: (1) computing r and t from $(i_1, p_1), \dots, (i_b, p_b)$ and S ; (2) using t to
 436 verify m against r ; and (3) verifying each s_j in S against p_j . In the good case, authenticating

the batch reduces to verifying a single multi-signature. This is regardless of the batch's size.

The pitfalls of a reduced batch. As we discussed in the previous paragraph, reducing a batch makes it cheaper to verify its integrity. Reduction, however, hides a subtle trade-off: once reduced, a batch gets easier to authenticate *as whole*. Its *individual payloads*, however, become harder to authenticate. For the sake of simplicity, let us imagine that β successfully dropped all the individual signatures it originally gathered from χ_1, \dots, χ_b . In order to prove that $(\chi = \chi_n)$ broadcast $(p = p_n)$, β could naively produce the batch's root r , (i_n, p_n) 's proof of inclusion q_n , and the batch's multi-signature m for r . This, however, would not be sufficient to authenticate p : because the multi-signature m_n that χ produced for r was aggregated with all others, m can only be verified by the aggregation of *all* χ_1, \dots, χ_b 's public keys. This makes authenticating p as expensive as authenticating the entire batch: in order to verify m , *all* (i_j, p_j) must be produced and checked against r , so that all corresponding public keys can be safely aggregated.

Witnessing the batch. As we discuss next, proving the integrity of individual payloads is fundamental to ensure **Draft**'s validity. In brief, to prove that some χ_k equivocated its payload $p_k = (c_k, l_k)$, a server must prove to β that χ_k also issued some payload $p'_k = (c_k, l'_k \neq l_k)$. Lacking this proof, a single Byzantine server could, for example, claim without basis that χ equivocated p . This could trick β into excluding p , thus compromising **Draft**'s validity. As we discussed in the previous paragraph, however, proving the integrity of an individual payload in a reduced batch is difficult. While we conjecture that purely cryptographic solutions to this impasse might be achievable in some schemes¹⁰, **Draft** has β engage in a simple protocol to further simplify the batch's authentication, replacing all client-issued (multi-)signatures with a single, server-issued certificate. Having collected and reduced the batch, β sends a **Batch** message to all servers (fig. 1, step 4). The **Batch** message only contains $(i_1, p_1), \dots, (i_b, p_b)$. Upon receiving the **Batch** message, σ collects in a set U_σ all the ids it does not know (i_j is in U_σ iff σ does not know i_j), and sends U_σ back to β by means of a **BatchAcquired** message (fig. 1, step 5). Upon receiving σ 's **BatchAcquired** message, β builds a set A_σ containing all id assignments that σ is missing (a_j is in A_σ iff i_j is in U_σ). Having done so, β sends a **Signatures** message to σ (fig. 1, step 6). The **Signatures** message contains the batch's multi-signature m , the straggler set S , and A_σ . We underline the importance of sending id assignments upon request only. Thinking to shave one round-trip off the protocol, β could naively package in a single message all submissions, all (multi-)signatures, and all assignments relevant to the batch. In doing so, however, β would force each server to receive one assignment per submission, immediately forfeiting **Draft**'s oracular efficiency. At the batching limit we assume that all servers already know all broadcasting clients. In that case, both U_σ and A_σ are constant-sized, empty sets, adding only a vanishing amount of communication complexity to the protocol. Upon receiving the **Signatures** message, σ verifies and learns all assignments in A_σ . Having done so, σ knows i_1, \dots, i_b . As we outlined above, σ can now efficiently authenticate the whole batch, verifying m against the batch's root r , and each i_j in S against p_j . Having established the integrity of the whole batch, σ produces a *witness shard* for the batch, i.e., a multi-signature w_σ for **[Witness, r]**, effectively

¹⁰ For example, using BLS, β could aggregate the public keys of $\chi_1, \dots, \chi_{n-1}, \chi_{n+1}, \dots, \chi_b$ into a public key \tilde{t}_n , then show that the aggregation of \tilde{t}_n with χ 's public key correctly verifies m against r . Doing so, however, would additionally require β to exhibit a proof that \tilde{t}_n is not a rogue public key, i.e., that \tilde{t}_n indeed results from the aggregation of client public keys. This could be achieved by additionally having χ_1, \dots, χ_b multi-sign some hard-coded statement to prove that they are not rogues. β could aggregate such signatures on the fly, producing a rogue-resistance proof for \tilde{t}_n that can be transmitted and verified in constant time. This, however, is expensive (and, frankly, at the limit of our cryptographic expertise).

478 affirming to have successfully authenticated the batch. σ sends w_σ back to β by means of a
 479 **WitnessShard** message (fig. 1, step 7). Having received a valid **WitnessShard** message from
 480 $f + 1$ servers, β aggregates all witness shards into a *witness* w . Because w is a plurality
 481 $(f + 1)$ certificate, at least one correct server necessarily produced a witness shard for the
 482 batch. This means that at least one correct server has successfully authenticated the batch
 483 by means of client (multi-)signatures. Because w could not have been gathered if the batch
 484 was not properly authenticated, w itself is sufficient to authenticate the batch, and β can
 485 drop all (now redundant) client-generated (multi-)signatures for the batch. Unlike m , w is
 486 easy to verify, as it is signed by only $f + 1$, globally known servers. Like m , w authenticates
 487 r . As such, any p_j can now be authenticated just by producing w , and (i_j, p_j) 's proof of
 488 inclusion q_j .

489 **Gathering a commit certificate.** Having successfully gathered a witness w for the
 490 batch, β sends w to all servers by means of a **Witness** message (fig. 1, step 8). Upon
 491 receiving the **Witness** message, σ moves on to check $(i_1, p_1), \dots, (i_b, p_b)$ for equivocations.
 492 More precisely, σ builds a set of *exceptions* E_σ containing the ids of all equivocating
 493 submissions in the batch (i_j is in E_σ iff σ previously observed χ_j submit a payload p'_j that
 494 conflicts with p_j ; we recall that p_j and p'_j conflict if their contexts are the same, but their
 495 messages are different). σ then produces a *commit shard* for the batch, i.e., a multi-signature
 496 c_σ for $[\text{Commit}, r, E_\sigma]$, effectively affirming that σ has found all submissions in the batch to be
 497 non-equivocated, *except* for those in E_σ . In the good case, every client is correct and E_σ is
 498 empty. Having produced c_σ , σ moves on to build a set Q_σ containing a *proof of equivocation*
 499 for every element in E_σ . Let us assume that σ previously received from some χ_k a payload
 500 p'_k that conflicts with p_k . σ must have received p'_k as part of some witnessed batch. Let
 501 r'_k identify the root of p'_k 's batch, let w'_k identify r'_k 's witness, let q'_k be (i_k, p'_k) 's proof of
 502 inclusion in r'_k . By exhibiting (r'_k, w'_k, p'_k) , σ can prove to β that χ_k equivocated: p_k conflicts
 503 with p'_k , and (i_k, p'_k) is provably part of a batch whose integrity was witnessed by at least
 504 one correct server. Furthermore, because correct clients never equivocate, (r'_k, w'_k, p'_k) is
 505 sufficient to convince β that χ_k is Byzantine. For each i_j in E_σ , σ collects in Q_σ a proof
 506 of equivocation (r'_j, w'_j, p'_j) . Finally, σ sends a **CommitShard** message back to β (fig. 1, step
 507 9). The **CommitShard** message contains c_σ , E_σ and Q_σ . Upon receiving σ 's **CommitShard**
 508 message, σ verifies c_σ against r and E_σ , then checks all proofs in Q_σ . Having collected
 509 valid **CommitShard** messages from a quorum of servers $\sigma_1, \dots, \sigma_{2f+1}$, β aggregates all commit
 510 shards into a *commit certificate* c . We underline that each σ_j signed the same root r , but
 511 a potentially different set of exceptions E_{σ_j} . Let E denote the union of $E_{\sigma_1}, \dots, E_{\sigma_{2f+1}}$.
 512 We call E the batch's *exclusion set*. Because a proof of equivocation cannot be produced
 513 against a correct client, β knows that all clients identified by E are necessarily Byzantine. In
 514 particular, because χ is correct, $(i = i_n)$ is guaranteed to not be in E .

515 **Committing the batch.** Having collected a commit certificate c for the batch, β sends
 516 c to all servers by means of a **Commit** message (fig. 1, step 10). Upon receiving the **Commit**
 517 message, σ verifies c , computes the exclusion set E , then delivers every payload p_j whose
 518 id i_j is not in E . Recalling that c is assembled from a quorum of commit shards, at least
 519 $f + 1$ correct servers contributed to c . This means that, if some i_k is not in E , then at least
 520 $f + 1$ correct servers found p_k not to be equivocated. As in most BRB implementations [9],
 521 this guarantees that no two commit certificates can be gathered for equivocating payloads:
 522 **Draft's consistency is upheld.**

523 **The role of equivocation proofs.** As the reader might have noticed, β does not attach
 524 any proof of equivocation to its **Commit** message. Having received β 's commit certificate c , σ

trusts β 's exclusion set E , ignoring every payload whose id is in E . This is not because σ can trust β to uphold validity. On the contrary, σ has *no way* to determine that β is not maliciously excluding the payload of a correct client. Indeed, even if σ were to verify a proof of exclusion for every element in E , a malicious β could still censor a correct client simply by ignoring its **Submit** message in the first place. Equivocation proofs are fundamental to **Draft**'s validity not because they *force* malicious brokers to uphold validity, but because they *enable* correct brokers to do the same. Thanks to equivocation proofs, a malicious server cannot trick a correct broker into excluding the payload of a correct client. This is enough to guarantee validity. As we discuss below, χ successively submits p to all brokers until it receives a certificate attesting that p was delivered by at least one correct server. Because we assume at least one broker to be correct, χ is eventually guaranteed to succeed.

Notifying the clients. Having delivered every payload whose id is not in the exclusion set E , σ produces a *completion shard* for the batch, i.e., a multi-signature z_σ for $[\text{Completion}, r, E]$, effectively affirming that σ has delivered all submissions in the batch whose id is not in E . σ sends z_σ to β by means of a **CompletionShard** message (fig. 1, step 11). Upon receiving $f + 1$ valid **CompletionShard** messages, β assembles all completion shards into a *completion certificate* z . Finally, β sends a **Completion** message to χ_1, \dots, χ_b (fig. 1, step 12). The **Completion** message contains z and E . Upon receiving the **Completion** message, χ verifies z against E , then checks that i is not in E . Because at least one correct server contributed a completion shard to z , at least one correct process delivered all payloads that E did not exclude, including p . Having succeeded in broadcasting p , χ does not need to engage further, and can stop successively submitting p to all brokers.

No one is left behind. As we discussed above, upon receiving the commit certificate c , σ delivers every payload in the batch whose id is not in the exclusion set E . Having gotten at least one correct server to deliver the batch, β is free to disengage, and moves on to assembling and brokering its next batch. In a moment of asynchrony, however, all communications between β and $\tilde{\sigma}$ might be arbitrarily delayed. This means that $\tilde{\sigma}$ has no way of telling whether or not it will eventually receive batch and commit certificate: a malicious β might have deliberately left $\tilde{\sigma}$ out of the protocol. Server-to-server communication is thus required to guarantee totality. Having delivered the batch, σ waits for an interval of time long enough for all correct servers to deliver batch and commit certificate, *should the network be synchronous and β correct*. σ then sends to all servers an **OfferTotality** message (fig. 1, step 13). The **OfferTotality** message contains the batch's root r , and the exclusion set E . In the good case, upon receiving σ 's **OfferTotality** message, every server has delivered the batch and ignores the offer. This, however, is not the case for slow $\tilde{\sigma}$, which replies to σ with an **AcceptTotality** message (fig. 1, step 14). Upon receiving $\tilde{\sigma}$'s **AcceptTotality** message, σ sends back to $\tilde{\sigma}$ a **Totality** message (fig. 1, step 15). The **Totality** message contains all submissions $(i_1, p_1), \dots, (i_b, p_b)$, id assignments for i_1, \dots, i_b , and the commit certificate c . Upon delivering σ 's **Totality** message, $\tilde{\sigma}$ computes r from $(i_1, p_1), \dots, (i_b, p_b)$, checks c against r , computes E from c , and delivers every payload p_j whose id i_j is not in E . This guarantees totality and concludes the protocol.

4.2 Complexity

Directory density. As we introduced in Section 4.1, **Draft** uses ids assigned by its underlying Directory (DIR) abstraction to identify payload senders. A DIR-assigned id is composed of two parts: a *domain* and an *index*. Domains form a finite set \mathbb{D} whose size does not increase with the number of clients, indices are natural numbers. Along with safety (e.g.,

no two processes have the same id) and liveness (e.g., every correct client that requests an id eventually obtains an id), DIR guarantees *density*: the index part of any id is always smaller than the total number of clients c (i.e., each id index is between 0 and $(c - 1)$). Intuitively, this echoes the (stronger) density guarantee provided by Oracle-CSB, the oracle-based implementation of CSB we introduced in Section 1 to bound Draft's performance. In Oracle-CSB, the oracle organizes all clients in a list, effectively labeling each client with an integer between 0 and $(c - 1)$. In a setting where consensus cannot be achieved, agreeing on a totally-ordered list of clients is famously impossible: a consensus-less DIR implementation cannot assign ids if $|\mathbb{D}| = 1$. However, DIR can be implemented without consensus if servers are used as domains ($\mathbb{D} = \Sigma$). In our DIR implementation Dibs, each server maintains an independent list of public keys. In order to obtain an id, a client χ has each server add its public key to its list, then selects a server σ to be its *assigner*. In doing so, χ obtains an id (σ, n) , where $n \in 0..(c - 1)$ is χ 's position in σ 's log. In summary, a consensus-less implementation of DIR still guarantees that indices will be smaller than c , at the cost of a non-trivial domain component for each id. This inflates the size of each individual id by $\lceil \log_2 (|\mathbb{D}|) \rceil$ bits.

Batching ids. While DIR-assigned ids come with a non-trivial domain component, the size overhead due to domains vanishes when infinitely many ids are organized into a batch. This is because domains are constant in the number of clients. Intuitively, as infinitely many ids are batched together, repeated domains become compressible. When building a batch, a Draft broker represents the set I of sender ids not as a list, but as a map \tilde{i} . To each domain, \tilde{i} associates all ids in I under that domain (n is in $\tilde{i}[d]$ iff (d, n) is in I). Because \tilde{i} 's keys are fixed, as the size of I goes to infinity, the bits required to represent \tilde{i} 's keys are completely amortized by those required to represent \tilde{i} 's values. At the batching limit, the cost of representing each id in \tilde{i} converges to that of representing its index only, $\lceil \log_2 (c) \rceil$.

Protocol cost. At the batching limit we assume a good-case execution: links are synchronous, all processes are correct, and the set of brokers contains only one element. We additionally assume that infinitely many clients broadcast concurrently. Finally, we assume all servers to already know all broadcasting clients. Let β denote the only broker. As all broadcasting clients submit their payloads to β within a suitably narrow time window, β organizes all submissions into a single batch with root r . Because links are synchronous and all clients are correct, every broadcasting client submits its multi-signature for r in time. Having removed all individual signatures from the batch, β is left with a single, aggregated multi-signature m and an empty straggler set S . β compresses the sender ids and disseminates the batch to all servers. As m and S are constant-sized, the amortized cost for a server to receive each payload p is $(\lceil \log_2 (c) \rceil + |p|)$ bits. As m authenticates the entire batch, a server authenticates each payload at an amortized cost of 0 signature verifications. The remainder of the protocol unfolds as a sequence of constant-sized messages: because all broadcasting clients are known to all servers, no server requests any id assignment; witnesses are always constant-sized; and because all processes are correct, no client equivocates and all exception sets are empty. Finally, again by the synchrony of links, all offers of totality are ignored. In summary, at the batching limit a server delivers a payload at an amortized cost of 0 signature verifications and $(\lceil \log_2 (c) \rceil + |p|)$ bits exchanged.

Latency. As depicted in Figure 1, the latency of Draft is 10 message delays in the synchronous case (fast servers deliver upon receiving the broker's Commit message), and at most 13 message delays in the asynchronous case (slow servers deliver upon receiving other servers' Totality messages). By comparison, the latency of the optimistic reliable

618 broadcast algorithm by Cachin *et al.* [13] is respectively 4 message delays (synchronous case)
 619 and 6 message delays (asynchronous case). Effectively, **Draft** trades oracular efficiency for a
 620 constant latency overhead.

621 **Worst-case complexity.** In the worst case, a **Draft** server delivers a b -bits payload by
 622 exchanging $O((\log(c) + b)kn)$ bits, where c , k and n respectively denote the number of clients,
 623 brokers and servers. In brief, the same id, payload and signature is included by each broker
 624 in a different batch (hence the k term) and propagated in an all-to-all fashion (carried by
 625 **Totality** messages) across correct servers (hence the n term). By comparison, the worst-case
 626 communication complexity of Cachin *et al.*'s optimistic reliable broadcast is $O(ln)$ per server,
 627 where l is the length of the broadcast payload. A direct batched generalization of the same
 628 algorithm, however, would raise the worst-case communication to $O(ln^2)$ per server, similar
 629 to that of **Draft** when $n \sim k$. Both batched Bracha and **Draft** can be optimized by polynomial
 630 encoding, reducing their per-server worst-case complexity to $O(ln)$ and $O((\log(c) + b)k)$
 631 respectively. Doing so for **Draft**, however, is beyond the scope of this paper.

632 5 Conclusions

633 **Our contributions.** In this paper we study Client-Server Byzantine Reliable Broadcast
 634 (CSB), a multi-shot variant of Byzantine Reliable Broadcast (BRB) whose interface is
 635 split between broadcasting clients and delivering servers. We introduce **Oracle-CSB**, a toy
 636 implementation of CSB that relies on a single, infallible oracle to uphold all CSB properties.
 637 Unless clients can be assumed to broadcast at a non-uniform rate, **Oracle-CSB**'s signature
 638 and communication complexities are optimal: in **Oracle-CSB**, a server delivers a payload p
 639 by performing 0 signature verifications, and exchanging $(\lceil \log_2(c) \rceil + |p|)$ bits, where c is the
 640 number of clients. We present **Draft**, our implementation of CSB. **Draft** upholds all CSB
 641 properties under classical BRB assumptions (notably asynchronous links and less than a third
 642 of faulty servers). When links are synchronous and all processes are correct, however, and at
 643 the limit of infinite concurrently broadcasting clients, **Draft**'s signature and communication
 644 complexities match those of **Oracle CSB**.

645 **Future work.** We hope to extend **Draft** to allow multiple messages by the same client in
 646 the same batch. We envision that this could be achieved by using other types of cryptographic
 647 accumulators or variants of Merkle trees, such as Merkle-Patricia trees [25]. It would also be
 648 interesting to see if the worst-case performance of **Draft** could be improved, e.g. by using
 649 error correction codes (ECC) or erasure codes, without significantly affecting its good-case
 650 performance. Lastly, we hope to use **Draft**'s keys ideas to implement a total-order broadcast
 651 primitive, improving the scalability of existing SMR implementations.

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