

# A Decentralized Sequencer and Data Availability Committee for Rollups Using Set Consensus

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Blockchains face a scalability challenge due to the intrinsic throughput limitations of consensus protocols and the limitation in block sizes due to decentralization. An alternative to improve the number of transactions per second is to use Layer 2 (L2) rollups. L2s perform most computations offchain using blockchains (L1) minimally under-the-hood to guarantee correctness. A *sequencer* receives offchain L2 transaction requests, batches them, and commits compressed or hashed batches to L1. Hashing offers much better compression but requires a data availability committee (DAC) to translate hashes back into their corresponding batches. Current L2s consist of a centralized sequencer which receives and serializes all transactions and an optional DAC. Centralized sequencers can undesirably influence L2s evolution.

We propose in this paper a fully decentralized implementation of a service that combines (1) a sequencer that posts hashes to the L1 blockchain and (2) the data availability committee that reverses the hashes. We call the resulting service a (decentralized) *arranger*. Our decentralized arranger is based on *Set Byzantine Consensus* (SBC), a service where participants can propose sets of values and consensus is reached on a subset of the union of the values proposed. We extend SBC for our fully decentralized arranger.

Our main contributions are (1) a formal definition of arrangers; (2) two implementations, one with a centralized sequencer and another with a fully decentralized algorithm, with their proof of correctness; and (3) empirical evidence that our solution scales by implementing all building blocks necessary to implement a correct server.

CCS Concepts: • General and reference → *Evaluation*; • Computer systems organization → **Dependable and fault-tolerant systems and networks**; • Theory of computation → **Distributed algorithms**.

Additional Key Words and Phrases: Layer 2, Rollups, Sequencer, Data Availability, Decentralization, Byzantine Fault-Tolerant

## 1 INTRODUCTION

*Distributed ledgers* (also known as *blockchains*) were first proposed by Nakamoto in 2009 [30] in the implementation of Bitcoin, as a method to eliminate trustable third parties in electronic payment systems. A current major obstacle for a faster widespread adoption of blockchain technologies in some application areas is their limited scalability, due to the limited throughput inherent to Byzantine consensus algorithms [12, 41], and the limitation in the block size due to the desire for decentralization. For example, Ethereum [42], one of the most popular blockchains, is limited to less than 4 blocks per minute, each containing less than two thousand transactions.

Layer 2 (L2) rollups provide a faster alternative to blockchains while still offering the same interface in terms of smart contract programming and user interaction. L2 rollups perform as much computation as possible offchain with the minimal blockchain interaction—in terms of the number and size of invocations—required to guarantee a correct and trusted operation. L2 rollups work in two phases: users inject transaction requests communicating with a service called *sequencer*, which orders and packs the requests into batches. The sequencer compresses batches and injects the result

into an underlying blockchain (L1). Once batches are posted to L1, the transaction order inside batches is determined. Then, the effects of executing transactions are computed *offchain* by agents called State Transition Functions (STFs), which publish the resulting state of the L2 blockchain in L1. STFs are independent parties that compute L2 blocks from batches and post them to L1.

There are two main categories of L2 rollups:

- *ZK-Rollups*: the STFs post zero-knowledge proofs that encode the correctness of the transaction batch effects, which are verified by the L1 contract that receives the L2 block.
- *Optimistic Rollups*: STFs post L2 blocks which are optimistically assumed to be correct, delegating block validation on fraud-proof mechanisms.

The most prominent Optimistic Rollups based on their market share [40] are Arbitrum One [4], Optimism mainnet [34], and Base [9]. Popular ZK-Rollups include Starknet [39], zkSync Era [26], and Linea [1]. Fig. 1 shows the architecture of ZK Rollups and Optimistic Rollups.

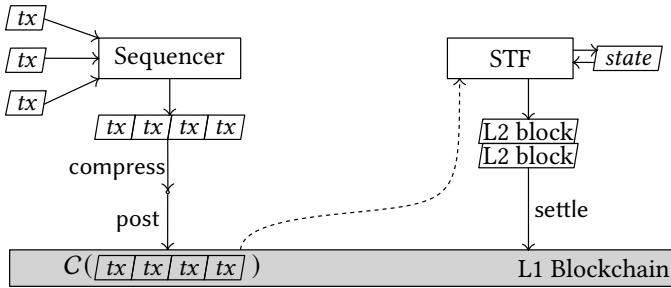


Fig. 1. Optimistic and ZK Rollups.

The execution part of L2 rollups can be decentralized<sup>1</sup> as the role of STF can be open to many parties. However, the ordering of transaction requests in most L2 rollups is decided by a single centralized sequencer node. These L2 rollups are then non-fully-decentralized, since the sequencer is a “decentralization bottleneck,” which results in a single point of trust and failure. This decentralization bottleneck poses risks such as transaction censorship or even liveness (fully halting the L2) because the sequencer can ignore transactions or users, fail to submit batches or provide incorrect data that does not correspond to batches of valid transaction requests. While the limitations of centralized sequencers are known, the development of decentralized sequencers is still in the early stages [29]. We tackle in this paper the problem of decentralized sequencers.

To increase scalability even further, the sequencer in some modern L2 rollups posts hashes of batches—instead of compressed batches—dramatically reducing the size of the L1 blockchain interaction. Using hashes to encode batches requires an additional data service—called *data availability committee* (DAC)—to translate hashes into their corresponding batches. If either the sequencer or the DAC is centralized the solution is still not a fully decentralized L2 rollup.

ZK-rollups that rely on DACs are known as *Validiums*, which include Immutable X [17], Sophon [38], and X Layer [32]. Optimistic rollups that use DACs are called *Optimiums*, which include Mantle [25], Metis [28] and Fraxtal [15].<sup>2</sup> Fig. 2 shows the architecture of Optimiums and Validiums.

To simplify notation, in the rest of the paper, we use simply L2 to refer to Optimistic Rollups and ZK Rollups that post batches of transaction requests as hashes and have a DAC, i.e. Validiums and Optimiums. We use the term *arranger* to refer to the combined service formed by the sequencer

<sup>1</sup>In the sense of *architectural* and *political* decentralization as defined in [6].

<sup>2</sup>A complete list of Ethereum scaling solutions and their current state of decentralization can be found in [40].

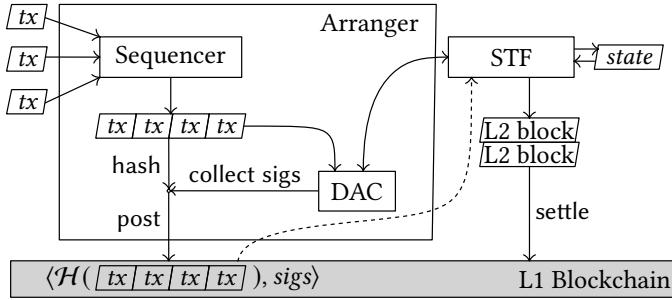


Fig. 2. Optimums and Validiums.

and DAC. Arrangers receive transaction requests, batch them, commit these batches hashed to L1 (as sequencers do), and can translate the hashes back into batches (as DACs do). Arrangers do not execute transactions.

**Problem.** *To implement a fully decentralized arranger.*

**Solution overview.** We adopt an open permissioned model [11] where permissionless L2 users can issue transaction requests to the permissioned arranger servers (which we call *replicas*). This model can also be adapted to a permissionless setting with committee sortition [16] without significant modifications. We consider a Byzantine failure model [22], in which there are two types of replicas: *Byzantine*, that behave arbitrarily, and *honest* replicas, which follow the protocol. We rely on algorithms whose trust is in the combined power of a collection of distributed replicas where correctness requires more than two-thirds of the replicas to run a correct version of the protocol.

Our main building block is Set Byzantine Consensus (SBC) [11], a Byzantine-resilient protocol where replicas agree on a set of elements, instead of single elements. Using SBC, users can inject transaction requests through any replica. The requests remain unordered until set consensus is executed. In the consensus phase, each replica proposes a set and replicas eventually agree on a set of transaction requests, which is guaranteed to be a sub-set of the union of the sets proposed by all replicas. We use the consented SBC sets as batches of L2 transaction requests. In our solution, an honest arranger replica includes as a building block an honest SBC replica. Therefore, honest arranger replicas agree on each batch and can locally compute its hash. Replicas also post signed hashes to L1 with the guarantee that all honest replicas can provide, for example to an STFs, the content of a batch given its hash.

Implementations of SBC [7, 11, 36] are reported to be two orders of magnitude faster than binary consensus (in the volume of transactions processed) by (1) exploiting the use of only one consensus execution to commit a set of elements, and (2) the independent validation of the elements in the sets (which only require checking the validity of request and not its effects). This enables a more efficient distributed protocol to disseminate transactions requests, and a much faster validation of each SBC set compared to validating blockchain blocks which requires executing all its transactions in order.

It is known that Byzantine-tolerant distributed algorithms do not compose well in terms of correctness and scalability [7], partly because these algorithms implement defensive mechanisms against misbehaving clients (local or remote). Consequently, using an off-the-shelf Byzantine solution as a building block composed with other building blocks as clients results in a poor performance. Instead, we implement here an arranger by combining in each replica a sequencer and a DAC member, so an honest replica includes an honest SBC replica and a cooperating honest

DAC implementation that can trust each other. Our decentralized arranger extends SBC to provide cryptographic certificates and perform reverse translation of hashes.

**Contributions.** In summary, the contributions of this paper are:

- (1) A rigorous definition of L2 arrangers;
- (2) Two implementations of arrangers with their proof of correctness, where the more advanced is a fully decentralized arranger based on Set-Byzantine-Consensus;
- (3) An empirical evaluation of all building blocks showing that replicas can be efficiently implemented.

**Structure.** The rest of the paper is organized as follows. Section 2 presents the preliminary definitions, assumptions and the model of computation. Section 3 gives a rigorous definition of L2 arrangers. Section 4 proposes a basic implementation of a semi-decentralized arranger. Section 5 describes a fully decentralized arranger using SBC and a proof its correctness. Section 6 shows empirical evidence that the fully decentralization implementation using SBC can scale to handle the current demand of L2s. Section 7 discusses the related work. Finally, Section 8 concludes the paper.

## 2 DEFINITIONS AND MODEL OF COMPUTATION

We state now our assumptions about L1s, describe the model of computation, and present an overview of the Set Byzantine Consensus protocol.

### 2.1 Model of Computation.

We adopt a standard distributed system model [8, 19] where messages are delivered within a bounded but unknown time limit and clocks are almost in synchrony, usually referred as partial synchrony [14].

Our system comprises arrangers replicas and clients. There are two types of clients: L2 users sending L2 transaction requests to arranger replicas, and STFs requesting arranger replicas the translation of hashes posted in L1 into batches. Arranger replicas can be classified as either *honest*, meaning they adhere to the arranger protocol, or *Byzantine*, which behave arbitrarily [22]. We assume that an upper bound  $f$  in the number of Byzantine replicas is known.

We consider a public-key infrastructure (PKI) that associates replica and client identities with their public keys, and that is common to all replicas and clients. Replicas and clients use a function  $sign$  to sign elements with their secret key. L2 users can create *valid* transaction requests and arranger replicas cannot impersonate clients. Valid transaction requests are those that have been correctly signed, so arranger replicas can locally check transaction requests validity using public-key cryptography.

Arranger replicas use a known collision-resistant hash function  $\mathcal{H}$  to hash batches.

### 2.2 Assumptions about L1

We assume that the L1 ensures both liveness and safety. Specifically, while the system tolerates temporary censorship of L1 transaction requests and reordering of L1 transactions, it guarantees that every transaction submitted to L1 is eventually processed correctly. The L1 includes a smart contract **logger** that arranger replicas use to post hashed batches of transaction requests. The **logger** smart contract knows the public key of all arranger replicas and the bound  $f$  on the number of Byzantine replicas. The **logger** smart contract only accepts new hashes from arranger replicas that are signed by at least  $f + 1$  arranger replicas, guaranteeing that at least one honest replica signed it.

### 2.3 Set Byzantine Consensus

Set Byzantine Consensus (SBC) [11] is a variant of Byzantine consensus where instead of proposing and agreeing on a single value, SBC replicas propose sets of values and agree on a non-empty subset of the union of the proposed sets. This allows committing more elements per consensus instance, improving the throughput, as empirically demonstrated in practical implementations [7, 11, 36]. Intuitively, SBC increases throughput by running many binary consensus simultaneously to determine the inclusion of elements in proposed sets. We use SBC to determine the set of transaction requests to be included in a batch.

SBC replicas provide two end-points.

- $\text{ADD}(e)$  is used to submit an element  $e$ . Honest replicas include  $e$  in their proposed set. Once  $e$  is known by all honest replicas, it is guaranteed to eventually be included in a decided set.
- $\text{SETDELIVER}(i, E)$  notifies when the  $i$ -th round of SBC finishes with  $E$  as the decided set.

The properties of set consensus relevant to our implementation of arrangers in Section 5 are:

- **SBC-Termination**: every honest SBC replica eventually decides a set of elements in each SBC round.
- **SBC-Agreement**: in each SBC round, all honest replicas decide the same set.
- **SBC-Validity**: the decided set in a given SBC round is a non-empty subset of the union of the proposed sets in that round and contains only valid elements.
- **SBC-CensorshipResistance**: elements known and proposed by all honest replicas are eventually included in the set decided in some round.
- **SBC-Integrity**: no element appears in more than one decided set across all SBC rounds.

There are several implementations of SBC, including Redbelly [11], Setchain [7] and ZLB [36]. These implementations assume that the Byzantine replicas are less than one third. However, there are nuances in how these implementations ensure certain properties. For example, ZLB does not mention **SBC-CensorshipResistance**, and a minor modification is required for RedBelly and ZLB to ensure **SBC-Integrity**: replicas must keep a log of all elements included in previously decided sets to detect and remove duplicates.

## 3 ARRANGER

In this section, we define the concept of arranger, the service in charge of both (1) receiving and serializing transaction requests, packing them into batches and efficiently posting them as hashes into L1; and (2) making the data available. Our arranger model seamlessly fits into the model of existing Optimums and Validiums (see Fig. 2).

### 3.1 Arranger API

Arranger replicas provide two end-points:

- $\text{add}(tr)$  used by L2 users to submit a transaction request  $tr$ , and
- $\text{translate}(id, h)$  used by STFs or any other external users to request the batch of transaction requests corresponding to a hash  $h$  with identifier  $id$ . If identifier  $id$  does not match any batch, the arranger returns error  $\text{invalidId}$ . If there is a batch  $b$  with identifier  $id$ , the arranger returns  $b$  if  $b$  hashes to  $h$  or error  $\text{invalidHash}$  otherwise.

When the arranger receives enough transaction requests or a timeout is reached, all honest arranger replicas decide a new batch  $b$ , order transaction requests in  $b$ , assign an identifier  $id$  to  $b$ , compute  $h = \mathcal{H}(b)$ , and create a *batch tag*  $(id, h)$ . Then, all honest replicas sign the new batch tag and propagate their signatures to the other replicas. When enough signatures are collected,

a combined signature  $\sigma^3$  is attached to the batch tag to form a *signed batch tag*  $(id, h, \sigma)$  and the signed batch tag is posted to L1. The **logger** L1 smart contract accepts signed batch tags validating only the signature of the batch.

### 3.2 Arranger Properties

We now define the properties that characterize a *correct* arranger. These properties include all *basic properties* and some safety properties of ideal arrangers introduced informally in [29].<sup>4</sup>

We introduce some definitions about signed batch tags. A signed batch tags is called *certified* when it contains at least  $f + 1$  arranger replicas signatures. Certified batch tags are guaranteed to include at least one honest replica signature, as the required number of signatures exceeds the maximum number of Byzantine replicas assumed.

A certified batch tag  $(id, h, \sigma)$  is legal if its corresponding batch  $b$  satisfies the following properties:

- **Validity**: Every transaction request in  $b$  is a valid transaction request added by an L2 user.<sup>5</sup>
- **Integrity<sub>1</sub>**: No transaction request appears twice in  $b$ .
- **Integrity<sub>2</sub>**: No transaction request in  $b$  appears in a legal batch tag previously accepted by the **logger** smart contract.

We require all certified batch tags posted by correct arrangers to be legal.

**Property 1 (Legality).** *Every certified batch tag posted by the arranger is a legal batch tag.*

Arranger replicas may post multiple signed batch tags with the same identifier because they concurrently try to post the next batch, but the **logger** accepts only the first one posted. A batch tag can be part of two signed batch tags when signed by a different subset of arranger replicas. However, certified batch tags with the same identifier must have the same batch and generate the same hash. This ensures that the reorder of L1 transactions cannot influence the evolution of the L2 blockchain.

**Property 2 (Unique Batch).** *Let  $(id, h_1, \sigma_1)$  and  $(id, h_2, \sigma_2)$  be two certified batch tags with the same identifier  $id$ . Then,  $h_1 = h_2$ .*

The following properties of correct arrangers prevent censorship and guarantee data availability.

**Property 3 (Termination).** *All valid transaction requests added to honest replicas eventually appear in a posted legal batch tag accepted by the **logger** smart contract.*

**Property 4 (Availability).** *Every posted legal batch tag can be translated into its batch by an honest replica.*

**Availability** is expressed formally as follows. Let  $(id, h, \sigma)$  be a legal batch tag posted by the arranger, s.t.  $h = \mathcal{H}(b)$ . Then, some honest replica will return  $b$  when requested  $\text{translate}(id, h)$ . This prevents halting the L2 blockchain by failing to provide batches of transaction requests from hashes. If a Byzantine replica returns a batch  $b' \neq b$ , then  $b'$  cannot hash to  $h$  because of collision resistance, and the client can locally detect this violation by computing  $\mathcal{H}(b')$ .

**Legality**, **Unique Batch**, and **Availability** are safety properties and **Termination** is a liveness property. Altogether, they characterize correct arrangers.

The combination of **Termination**, **Unique Batch**, and **Availability** guarantee that for correct arrangers all valid transaction requests added to honest arranger replicas are eventually executed

<sup>3</sup>A combined signature not only contains the result of combining all signatures but also an identifier of each signer.

<sup>4</sup>None of the L2s studied in [29] implement both a decentralized sequencer and a decentralized DAC.

<sup>5</sup>A transaction request is valid when it is properly formed and signed by the originating L2 user, which can be locally verified by arranger replicas.

in the L2 blockchain. When a valid transaction request  $tr$  is added to an honest arranger replica, **Termination** ensures that  $tr$  will eventually be included in a legal batch tag  $(id, h, \sigma)$  posted in L1. Then, when an STF requests the transaction requests in a legal batch tag with identifier  $id$ , **Availability** ensures that an honest arranger replica responds with the corresponding batch of transactions  $b$ . **Unique Batch** guarantees that all legal batch tags with identifier  $id$  correspond to the same batch of transactions. This means that  $b$  contains  $tr$ . Since the STF executes the entire batch  $b$ , transaction  $tr$  is executed. Therefore, *correct arrangers offer censorship resistance*. Additionally, since STFs only process legal batch tags, **Legality** prevents any transaction from being executed twice (properties **Integrity<sub>1</sub>** and **Integrity<sub>2</sub>** of legal batch tags), and guarantees that only valid transaction requests are executed (property **Validity** of legal batch tags). However, the properties listed above do not guarantee any order of transactions posted by L2 users.

#### 4 ARRANGER #1: CENTRALIZED SEQUENCER + DECENTRALIZED DAC

We present first a *semi-decentralized* distributed implementation of arrangers where a single replica acts as the sequencer and the remaining replicas implement a decentralized DAC. The centralized sequencer implements operation `add` locally, creates batches of transaction requests added by L2 users, communicates these batches to all DAC replicas, collect their signatures and post legal batch tags invoking the **logger** smart contract in L1. DAC replicas implement `translate` to provide the inverse resolution of hashes posted by the sequencer back into readable batches of transaction requests. Fig. 3 shows this semi-decentralized arranger architecture.

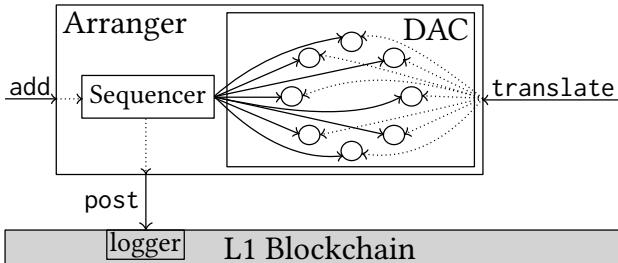


Fig. 3. Arranger #1: centralized sequencer + decentralized DAC.

##### 4.1 Implementation

Alg. 1 and Alg. 2 show the pseudo-code of the sequencer and DAC member, respectively. The **logger** smart contract is invoked only by the sequencer to store batch tags using function **post**. For simplicity, the sequencer uses a multicast service, **DC**, to send messages to all DAC members, which can be implemented with unicast channels simply by the sequencer contacting each DAC replica in parallel. DAC replicas answer back to the sequencer using a single unicast message.

Alg. 1 presents the sequencer pseudo-code. This algorithm maintains a set `allTxRqs` to store all valid transaction requests added, a sequence of transaction requests `pendingTxRqs` for transaction requests added but not posted yet, and a natural number  $id$  as the identifier of the next batch to be posted. L2 users add transaction requests to the arranger by invoking function `add` in the sequencer. Function `add` accumulates new valid transaction requests into sequence `pendingTxRqs` and set `allTxRqs`. When there are enough transaction requests in `pendingTxRqs` or enough time has elapsed since the last posted batch, a new event `time_to_post` is triggered (line 7) and Alg. 1 generates a new batch with all transaction requests currently stored in `pendingTxRqs` (line 8). Then, the sequencer sends the fresh new batch with its identifier and hash to all DAC replicas

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**Algorithm 1** Sequencer.

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```

1: init: allTxRqs  $\leftarrow \emptyset$ , pendingTxRqs  $\leftarrow \epsilon$ , id  $\leftarrow 0$ 
2: function add( $tr$ )
3:   assert valid( $tr$ ) and  $tr \notin$  allTxRqs
4:   pendingTxRqs  $\leftarrow \langle$ pendingTxRqs,  $tr$  $\rangle$ 
5:   allTxRqs  $\leftarrow$  allTxRqs  $\cup \{tr\}$ 
6:   return
7: upon (time_to_post) do
8:    $b \leftarrow$  pendingTxRqs
9:    $h \leftarrow \mathcal{H}(b)$ 
10:  DC.Multicast(signReq( $b, id, h$ ))
11:  wait for  $f + 1$  responses signResp( $id, h, i, \sigma_i$ ) with  $\sigma_i$  a valid signature
12:  logger.post( $id, h, \text{CombineSignatures}(\bigcup_i \sigma_i)$ )
13:   $id \leftarrow id + 1$ 
14:  pendingTxRqs  $\leftarrow \epsilon$ 

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**Algorithm 2** DAC replica  $i$ .

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```

1: init: hashes  $\leftarrow \emptyset$ 
2: function translate( $id, h$ )
3:   if ( $id, \_$ )  $\notin$  hashes then return invalidId
4:   else
5:     if ( $id, h$ )  $\notin$  hashes then return invalidHash
6:     else return hashes( $id, h$ )
7: receive (signReq( $b, id, h$ ) from Sequencer) do
8:   assert  $h \equiv \mathcal{H}(b)$  and ( $id, \_$ )  $\notin$  hashes
9:   hashes  $\leftarrow$  hashes  $\cup \{((id, h), b)\}$ 
10:  send signResp( $id, h, i, sign_i(id, h)$ ) to Sequencer

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(line 10) and waits to receive  $f + 1$  signatures, which ensures that at least one honest DAC replica signed the batch and this replica can translate the batch upon request. Then, Alg. 1 aggregates all signatures received, generates a batch tag including the combined signature and posts the batch tag in the **logger** smart contract in L1 (line 12). Finally, Alg. 1 cleans pendingTxRqs and increments  $id$  (lines 14 and 13).

Alg. 2 presents the pseudo-code of honest DAC replicas, which maintain a map hashes mapping pairs of identifiers and hashes  $(id, h)$  into batches  $b$ , such that  $\mathcal{H}(b) = h$ . When the sequencer sends requests to sign a batch  $(b, id, h)$ , honest DAC replicas check that  $h$  corresponds to hashing  $b$  (line 8). If the hash matches, the replica adds the new triplet to hashes, signs it and send the signature back to the sequencer. Clients, such as STFs, can request the batch corresponding to a given hash  $h$  in a batch tag with identifier  $id$ . These clients perform the request by invoking translate( $id, h$ ). Honest DAC replicas return the value stored in hashes( $id, h$ ), or an error when they do not know the hash or the identifier does not match the hash.

Clients requesting to translate hashes from legal batch tags can obtain the corresponding batch by contacting at most  $f + 1$  DAC replicas. Answers can be locally verified by clients by checking that the batch returned by a DAC replica corresponds to the hash  $h$  provided, as we are assuming

that the hash function is collision-resistant. Therefore, clients need to contact multiple replicas only when they do not receive a response or when the response does not match the hash, but it suffices one correct answer by one replica, which can be locally authenticated. Since legal batch tags are signed by at least one honest replica, that replica can correctly translate hashes (see Lemma 5). In the worst case, clients translating batches may first contact all  $f$  Byzantine DAC replicas, who do not respond with the corresponding batch, before requesting and receiving the desired batch from an honest replica.

Clients can employ different strategies for contacting DAC members, such as reaching out to all replicas in parallel or contacting them sequentially until the desired batch is obtained. Studying the trade-offs between these strategies is beyond the scope of this paper.

## 4.2 Proof of Correctness

We prove that an arranger consisting of the following components is correct:

- a single sequential replica, denoted with  $S$ , running Alg. 1, and
- a data availability committee, denoted with  $DAC$ , composed of  $n$  replicas. Out of these, at most  $f < \frac{n}{2}$  replicas may be Byzantine, and the remaining  $n - f$  replicas are honest and implement Alg. 2.

We assume that a majority of  $DAC$  replicas are honest to guarantee **Termination** (see Lemma 4 below), and discuss the trade-off between this trust assumption and liveness in Section 4.3.

The arranger satisfies **Legality** and **Unique Batch** (Lemmas 2 and 3 below), because the sequencer  $S$  is the only replica that generates certified batch tags and all batch tags  $S$  generates are legal and have different identifiers.

**Lemma 1.** *Certified batch tags are generated only by sequencer  $S$ .*

PROOF. Certified batch tags require  $f + 1$  signatures, so at least one honest  $DAC$  replica signed the batch. Honest  $DAC$  replicas only sign batches received from the sequencer  $S$ .  $\square$

**Lemma 2.** *All certified batches generated and posted by sequencer  $S$  are legal.*

PROOF. Following Alg. 1,  $S$  generates batches taking transaction requests from  $pendingTxRqs$ , and thus, transaction requests come from L2 users invocations to add. Function `add` guarantees that each transaction request in  $pendingTxRqs$  is valid and new. Moreover,  $pendingTxRqs$  is emptied after generating batches so transaction requests are in only one batch generated by  $S$ . Before posting batch tags,  $S$  gathers at least  $f + 1$  signatures, and thus,  $S$  posts only legal batch tags.  $\square$

**Lemma 3.** *All certified batches generated by sequencer  $S$  have different identifier.*

PROOF. Once sequencer  $S$  creates a certified batch tag it increments variables  $id$  (see line 13 in Alg. 1), which is used to as the identifier for the next batch tag. Sequencer  $S$  never decreases variable  $id$ , so each batch tag has a different identifier.  $\square$

The following lemma implies **Termination**.

**Lemma 4.** *Valid transaction requests added through `add` eventually appear in a legal batch tag accepted by the `logger` smart contract.*

PROOF. Let  $tr$  be a valid transaction request. The first time  $add(tr)$  is invoked,  $S$  appends  $tr$  to  $pendingTxRqs$  where  $tr$  remains until it is added to a batch. At some point after  $tr$  was added, event `time_to_post` is triggered, so  $S$  generates a new batch with all transaction requests currently in  $pendingTxRqs$ . Then,  $S$  sends to all  $DAC$  members the batch (lines 7-10) and waits for  $f + 1$  responses (line 11). Since  $f < n/2$ , there are at least  $f + 1$  honest  $DAC$  replicas executing Alg. 2, all of which

sign the hash and send it back to S (lines 7-10). Therefore, S eventually receives enough signatures and posts the legal batch tag containing  $tr$  (line 12). Since sequencer S only generates one certified batch tag per identifier (see Lemma 3), the **logger** contract accepts the legal batch tag containing  $tr$ .  $\square$

Finally, we show each certified batch tag can be resolved by at least one honest DAC member. Let  $m$  be a DAC member that signed  $(id, h)$ , the result of executing  $m.translate(id, h)$  is a batch  $b$  such that  $\mathcal{H}(b) = h$ . Since all certified batch tags are signed by at least one honest DAC member, it follows that arrangers consisting of S and DAC satisfy **Availability**.

**Lemma 5.** *Honest DAC members resolve certified batch tags.*

**PROOF.** Let  $m$  be an honest DAC replica. Following Alg. 2,  $m$  only signs hashes answering requests from S. Upon receiving a request from S to sign  $(h, b, id)$ , after checking that  $h$  correspond to  $b$  and  $id$  has not been used,  $m$  saves the data received, signs the request and answers to S. As no entry in hashes is ever deleted, whenever  $m.translate(id, h)$  is invoked after  $m$  has singed the request,  $m$  uses map hashes to find batch  $b$  and returns it.  $\square$

Alg. 1 plus Alg. 2 guarantee that S and DAC form a correct arranger, which follows from the previous lemmas.

**Theorem 1.** *Arrangers composed by sequencer S and DAC DAC are correct arrangers.*

Finally, note that Alg. 1 orders transaction requests according to the invocation order to add, so transaction requests are ordered according to a first-come, first-served policy.

### 4.3 Trust Assumptions vs Liveness

Arrangers of some L2s also use a centralized sequencer ordering transaction requests and a DAC translating hashes back to batches. The main difference between the implementation described in this section and the implementation currently used in most Validiums and Optimiums is that the latter requires only a minority of DAC members to be honest, whereas our implementation requires a majority. Having a minority of honest DAC replicas and an honest sequencer is enough to guarantee all safety properties of a correct arranger but not to ensure progress.

Arrangers with just a minority of honest DAC members violate property **Termination** because collecting signatures from honest DAC replicas is not sufficient to generate certified batch tags. As a result, some of those L2s (like Arbitrum AnyTrust) implement a fallback mechanism: the sequencer can post a compressed version of batches if it is unable to collect enough DAC signatures.

In contrast, this is not necessary in our solution, as we assume that a majority of DAC replicas are honest guaranteeing **Termination** (see Lemma 4 above). This highlights a trade off between trust assumptions and liveness properties.

Regardless of the trust assumption for DAC replicas, both semi-decentralized arrangers rely on the centralized sequencer as a single point of trust and failure. In the next section, we eliminate this single point of trust and failure by presenting a fully decentralized arranger using SBC as the main building block.

## 5 ARRANGER #2: FULL DECENTRALIZATION

We present now a *fully decentralized* arranger implementation using Set Byzantine Consensus (see Fig. 4) that satisfies the correctness properties listed in Section 3.2. In this implementation, operations add and translate are completely decentralized.

Our implementation uses the sets decided by SBC rounds as batches. Arranger replicas *extend* SBC replicas instead of modularly using an SBC as clients. This is because Byzantine-tolerant

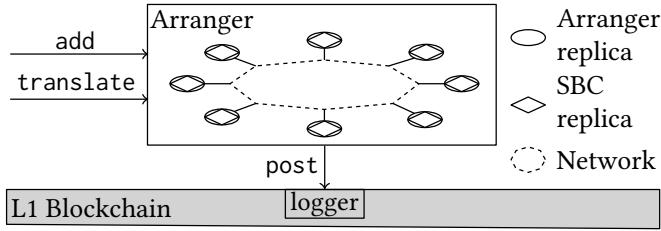


Fig. 4. Fully decentralized arranger using SBC.

blocks do not compose efficiently as they need to implement defensive mechanisms to protect against malicious clients and servers. Clients interacting with an SBC replica cannot determine whether the replica is honest or Byzantine and SBC replicas cannot determine whether a client is dishonest. As consequence, clients must contact multiple replicas to ensure that the data they receive is the data agreed upon by all honest SBC replicas. This is not necessary when extending honest SBC replicas to build honest arranger replicas, since replicas can trust the data maintain internally. In our fully decentralized arranger, all replicas perform both the roles of sequencers and DAC members, and thus, honest arranger replicas are honest SBC replicas, honest sequencers, and honest DAC replicas. Finally, arranger replicas take turns to post data to L1.

### 5.1 Implementation

Alg. 3 shows the pseudo-code of an honest arranger replica (here we only show code in addition to the SBC part of the replica). Replicas running Alg. 3 keep a local map hashes storing inverse translations of hashes and a local set signatures storing cryptographically signed batch tags.

---

#### Alg. 3 Replica $i$ implementation of Arranger using SBC

---

```

1: init: hashes  $\leftarrow \emptyset$ , signatures  $\leftarrow \emptyset$ 
2: function add( $t$ )
3:   SBC.ADD( $t$ )
4: function translate( $id, h$ )
5:   if ( $id, _$ )  $\notin$  hashes then return invalidId
6:   else
7:     if ( $id, h$ )  $\notin$  hashes then return invalidHash
8:     else return hashes( $id, h$ )
9: upon (SBC.SETDELIVER( $(id, S)$ )) do
10:    $b \leftarrow$  to_batch( $S$ )
11:    $h \leftarrow \mathcal{H}(b)$ 
12:   hashes  $\leftarrow$  hashes  $\cup \{(id, h) \mapsto b\}$ 
13:   broadcast( $id, h, sign_i(id, h)$ )
14: upon ( $deliver(id, h, \sigma_j)$  when  $\sigma_j$  is a valid signature) do
15:   signatures  $\leftarrow$  signatures  $\cup \{(id, h, \sigma_j)\}$ 
16: upon (my_turn) do
17:    $id \leftarrow$  next_batch_id()
18:   wait for  $f + 1$  signed batch tags  $(id, h, \sigma_j)$  in signatures
19:   logger.post( $id, h, CombineSignatures(\bigcup_j \sigma_j)$ )

```

---

Distributed arranger replicas implement add by adding transaction requests as elements into their SBC replica to be included in a later proposal and eventually in a decided set. When a new set is decided by SBC, each replica locally receives a SETDELIVER event with the round identifier and the consented set. As mentioned above, honest arranger replicas extend honest SBC replicas. Therefore, honest replicas know that the set received in the event SETDELIVER is the one that has been agreed upon by all other honest SBC replicas. Then, honest replicas order all new valid transaction requests in the consented and pack these to form a new batch using function `to_batch`. Then, they update their local variable hashes. After that, honest replicas sign the new batch tag and broadcast the signature. Each replica receives a *deliver* event informing about the correctly cryptographically signed batch tags they received which are stored in the local set signatures.

Arranger replicas take turns posting legal batch tags into the **logger** contract in L1, for example slicing time and distribute the time slices between the replicas, which is feasible because we assumed the system is partially synchronous and slices can be reasonably long intervals like seconds. Event `my_turn` tells replicas when it is their turn to post a new batch tag to L1. This is a simple way to guarantee eventual progress. Even if Byzantine replicas do not post legal batch tags in their turns, the rounds will continue to advance until it is the turn of an honest replica. Also, note that Byzantine replicas cannot possibly collect enough signatures of a fake batch tag to generate a certified batch tag so either (1) they post a batch tag without enough signatures (which will be discarded), or (2) they post the legal batch tag, or (3) they remain silent. Function `next_batch_id` returns the next batch identifier to be posted to the **logger** contract which is the minimum identifier for which there is no legal batch tag in the **logger** L1 smart contract. When it is the turn of arranger replica R to post, and R has received enough signatures for the batch, R computes a combined signature  $\sigma$  and posts the legal batch tag  $(id, h, \sigma)$  into the **logger** L1 smart contract.

## 5.2 Proof of Correctness

Alg. 3 implements a correct arranger. We inherit the assumptions from SBC that the number of Byzantine replicas are less than one third of all arranger replicas, so for  $N$  total replicas, the maximum number of Byzantine replicas is  $f$  such that  $f < N/3$ .

We first prove that a certified batch tag corresponds with the set consented in an SBC round. Formally, let  $(id, \mathcal{H}(b), \sigma)$  be a certified batch tag, then  $\text{to\_batch}(S) = b$  where set  $S$  corresponds to the set consented by SBC round number  $id$ .

**Lemma 6.** *A batch of transaction requests in certified batch tag corresponds to transaction requests in a consented SBC set.*

**PROOF.** A certified batch tags requires  $f + 1$  signatures, so at least one honest replica has signed the batch. Honest replicas only sign the hash of the set consented by the SBC service.  $\square$

From the previous lemma and properties **SBC-Validity** and **SBC-Integrity**, we obtain the arranger property **Legality**. Moreover, the arranger property **Unique Batch** follows from the previous lemma and the property **SBC-Agreement**.

Byzantine replicas can re-post existing certified batch tags, but they can not forge fake batches or fabricate certified batch tags because this requires collecting  $f + 1$  signatures, which implies that at least one honest replica signed. Hence, all Byzantine replicas can do is to post the same batch tag several times (perhaps with different collections of  $f + 1$  signatures). Since the **logger** smart contract only accepts the first legal batch tag per identifier, no transaction is executed twice and repeated batches are discarded.

**Lemma 7.** *All SBC consented sets are posted in the **logger** L1 smart contract as legal batch tags.*

**PROOF.** Let  $id$  be the minimum number for which there is no legal batch tag posted in the **logger** contract, and let  $S$  be the set consented in the  $id$ -th SBC round of consensus. Property **SBC-Agreement** ensures that all honest replicas agree on the content of  $S$ . Honest arranger replicas cryptographically sign the hashes of the sets agreed by SBC consensus, and broadcast their signature to all other arranger replicas. Therefore, all arranger replicas eventually receive the signature from honest replicas. Let  $R$  be the first honest replica that is in charge of posting batch tags to the logger after having received at least  $f + 1$  signatures of the hash of set  $S$ . There are two cases: either `next_batch_id` returns  $id$  or it returns a larger identifier. In the former case,  $R$  has enough signatures to generate a legal batch tag for  $s$  and posts it in the **logger** contract (lines 16-19). In the latter case, a legal batch tag with identifier  $id$  has already been posted corresponding to set  $S'$  (see Lemma 6). By **SBC-Agreement**, we have that  $S' = S$ .  $\square$

All transaction requests added to at least one honest replica eventually appear in a legal batch tag, which follows from the previous lemmas and property **SBC-CensorshipResistance**. Therefore, L2 users that contact some honest replica are guaranteed **Termination**. L2 users can make sure that they contact at least one honest replica by contacting  $f + 1$  replicas sequentially or in parallel. Alternatively, clients can follow a lightweight protocol contacting just one replica, then waiting for some time to observe whether the transaction request is in a batch accepted by the **logger** smart contract. If some time passes and the transaction is not seen, the client can contact another replica. This protocol guarantees that the transaction request will eventually be included in a batch accepted by the **logger** smart contract. Moreover, since duplicated transaction requests will be discarded, this protocol also guarantee that the transaction is executed exactly once.

Finally, we prove that every hash in a legal batch tag posted by the arranger can be resolved by at least one honest arranger replica, satisfying Property **Availability**.

**Lemma 8.** *For every legal batch tag posted by the arranger, at least one honest replica  $R$  signed it and therefore  $R$  can resolve its hash.*

**PROOF.** Since legal batch tags have  $f + 1$  signatures, at least one honest replica signed it. By Lemma 6, all legal batch tags correspond to SBC consented sets. When SBC consent on a set, it triggers an event `SETDELIVER` signaling the arranger replica to add the hash to its local map `hashes`. Upon request, function `translate` uses `hashes` to obtain the batch that corresponds to a given hash. Honest replicas never delete information from `hashes`, so for every legal batch tag posted at least one of the honest replicas that signed the batch tag can resolve its hash.  $\square$

Lemma 8 guarantees that, when posting legal batch tags, at least one honest replica had signed the batch, and this replica will be capable of performing the translation. Eventually, *all* honest replicas will know the contents of every consented set so they will be able to translate as well. Similar to the clients in the semi-decentralized arranger from Section 4, clients in this fully decentralized system are guaranteed that after contacting all signing replicas of a certified batch tag, they will receive the batch of transaction requests. Additionally, they can also employ different strategies when contacting arranger replicas to translate hashes.

Since, we have proved that our arranger satisfies all correctness properties of an arranger, we can conclude:

**Theorem 2.** *Arrangers consisting of  $n$  replicas, with  $f < \frac{n}{3}$  being Byzantine and the remaining  $n - f$  being honest replicas implementing Alg. 3, are correct arrangers.*

## 6 EMPIRICAL EVALUATION

We provide now an empirical evaluation to asses whether the decentralized arranger from Section 5 can scale to handle the current demand of L2s and beyond.

## 6.1 Introduction

There are two elements to assess this scalability: (1) the number blocks and size of each block that Set Byzantine Consensus can achieve, and (2) the new computations required to implement the algorithm in Section 5.

*Setchain and Blockchain Scalability.* Several implementations of SBC exist, including RedBelly [11], Setchain [7], and ZLB [36]. All these implementations report a throughput exceeding 12,000 transactions per second (TPS). In comparison, the cumulative throughput of all Ethereum L2s amounts to 200 TPS,<sup>6</sup> which can be taken as the baseline of L2s *current demand*.<sup>7</sup>

*Evaluating Additional Building Blocks Locally.* Our approach extends SBC, and thus, we focus on assessing the efficiency of each new component forming the decentralized arranger: compressing, hashing, signing batches, verification and aggregation of signatures, and translation of hashes into compressed batches. We aim to evaluate empirically that these components impose a negligible computational overhead on top of the intrinsic set-consensus algorithm. All these components run locally and are easily parallelizable.

## 6.2 Empirical Evaluation

*Setup.* All experiments were carried out on a Linux machine with 256 GB of RAM and 72 virtual 3GHz-cores (Xeon Gold 6154) running Ubuntu 20.04. We used a sequence of 40,000 real transaction requests from Arbitrum One as our data set.

For the evaluation, we used Brotli [2] as compression algorithm and the root of Merkle trees [27] of batches as hash function *hash*. For signing, verifying and aggregating signatures, we employed the BLS signature scheme implemented in [21].

*Hypothesis and Experiments.* We intend to answer empirically the following research question: *these building blocks impose a negligible computational overhead on top of the set-consensus algorithm.*

In other words, our hypothesis is that the performance offered by the implementations of SBC is not affected by:

- (H.Hash) hashing batches of transactions,
- (H.Compress) compressing batches of transactions,
- (H.Sign) signing hashes of batches,
- (H.Agg) aggregating signatures,
- (H.Ver) verifying signatures,
- (H.Trans) translating hashes into batches.

Additionally, signed batch tags size is significantly smaller than their corresponding compressed batch (*hypothesis H.Size*). We report on each hypothesis separately.

- **H.Size.** To evaluate **H.Size**, we measured the size of both compressed batches and batch tags ranging from 400 to 4,400 transactions per batch.<sup>8</sup> For each batch size, we shuffled transaction requests from our data set, split them into 10 batches of equal size, and assigned them unique identifiers. For the compression of each batch, we used the Brotli compression algorithm [2], currently used in Arbitrum Nitro [4]. Additionally, for each batch, we computed its Merkle Tree [27] with their transactions as leaves. To create batch tags, we signed each batch

<sup>6</sup>Data obtained on Feb. 2025 from l2beat <https://l2beat.com/scaling/activity>

<sup>7</sup>The available documentation of L2s does not present theoretical or empirical limitations.

<sup>8</sup>When we run the experiments Arbitrum Nitro batches typically contained around 800 transaction requests, while in Arbitrum AnyTrust, batches contained approximately 4,000 transaction requests. As of February 2025, Arbitrum Nitro batches typically contain around 3,000 transaction requests, while in Arbitrum AnyTrust, batches contain approximately 100 transaction requests.

Merkle Tree root along with an identifier using a BLS Signature scheme [3] implemented in [21]. Our experiments show there is a ratio of *more than two orders* of magnitude between compressed batches and batch tags with the same number of transactions. Fig. 5 shows the average size of compressed batches of 400 transactions is approximately 80,000 Bytes, whereas the average size for 4,400 transactions is around 780,000 Bytes. In contrast, the average size of signed batch tags remained around 480 Bytes independently of the number of transactions within the batch. Therefore, hypothesis **H.Size** holds.

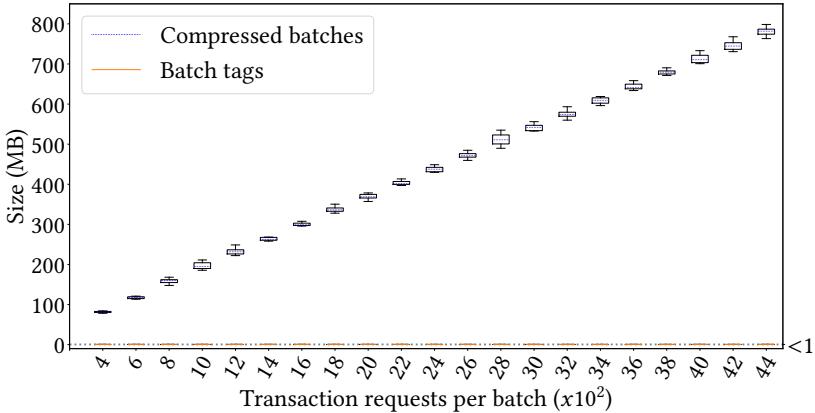


Fig. 5. Average size of compressed batches and batch tags for varying numbers of transaction requests per batch.

For the rest of the experiments, we loaded all the required information into local memory and applied each procedure for a duration of 1 second, cycling over the input as much as necessary. We ran each experiment 10 times and report the average performance. Fig. 6, Fig. 7, and Fig. 8 summarize the results.

- **H.Hash and H.Compress.** To test compressing and hashing procedures, we use the full data set of 40,000 transaction requests. We again ranged from 400 to 4,400 transaction requests per batch. Fig. 6 shows that hashing can scale from 260,000 to 275,000 TPS, depending on the batch size, while the compression procedure achieves a throughput ranging from 75,000 TPS for batches of 400 transaction requests to 50,000 TPS for batches of 4,400 transaction requests. Both hashing and compression procedures significantly outperform the SBC implementation throughput of 12,000 TPS, and thus, these procedures do not impact the overall throughput. Therefore, hypotheses **H.Hash** and **H.Compress** hold.
- **H.Sign.** To evaluate the signing procedure performance, we used a file containing 50 pairs batch hash-identifier. We assess the performance of signing each pair using the provided secret key with the BLS signature scheme implemented in [21]. Our results show that our system can sign approximately 2,300 hash-identifier pairs per second. Considering a throughput of 12,000 TPS and batches of at least 400 transaction requests, no more than 30 batches per second will be generated. Thus, each arranger replica can sign more than 75 times the number of batches required, empirically supporting hypothesis **H.Sign**.
- **H.Agg.** The performance of the signature aggregation procedure depends on the number of signatures aggregated, which is bounded by the number  $N$  of arranger replicas. We

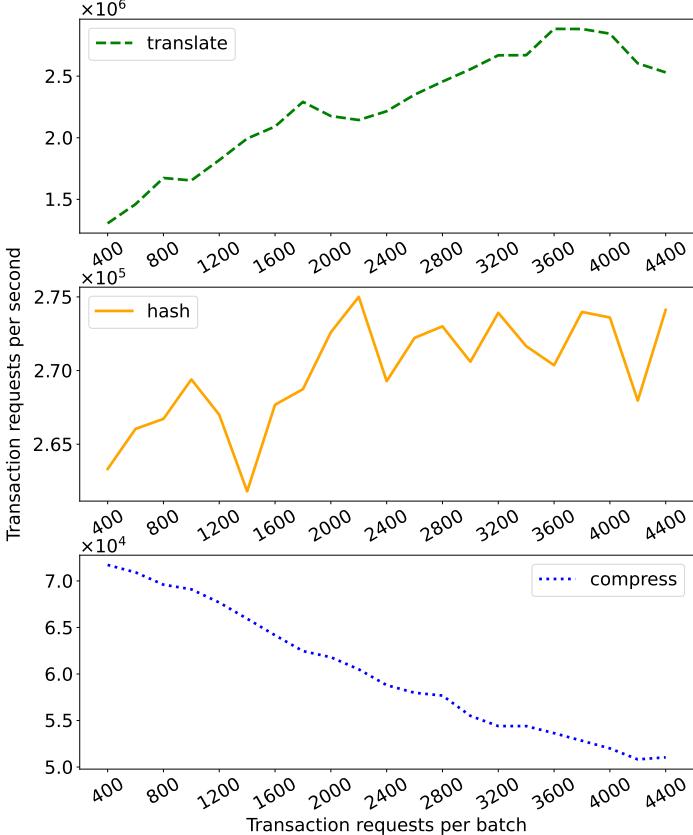


Fig. 6. Throughput of compressing, hashing and translating procedures for varying number of transaction requests per batch.

studied the performance of signature aggregation ranging from 8 to 256 replicas<sup>9</sup>. Our data set consists of a directory with  $N$  files. Each file contains 50 signed hash-identifier pairs signed by the same signer. The list of pairs hash-identifier is the same across all files. We measured the performance of aggregating  $N$  signatures of the same hash-identifier pair using BLS [21]. Fig. 7 shows an aggregation ratio ranging from 5,000 procedures per second, when aggregating 256 signatures in each invocation, to 115,000 per second when aggregating 8 signatures. Assuming at most 30 batches per second are generated, the aggregation procedure can easily handle its workload, even for  $N = 256$  arranger replicas, empirically validating hypothesis **H.Agg**.

- **H.Ver.** To assess the performance of the signature verification procedure, we used a file containing 50 batch tags and the public key of the signer of all hashes. We analyzed the performance of verifying that each signature was generated by signing the corresponding hash-identifier pair using the corresponding private keys. Fig. 8 shows that signature verification can be performed at a rate of approximately 600 signatures per second. This rate

<sup>9</sup>As reference, currently, the DAC of Arbitrum AnyTrust comprises 7 members <https://docs.arbitrum.foundation/state-of-progressive-decentralization#data-availability-committee-members>.

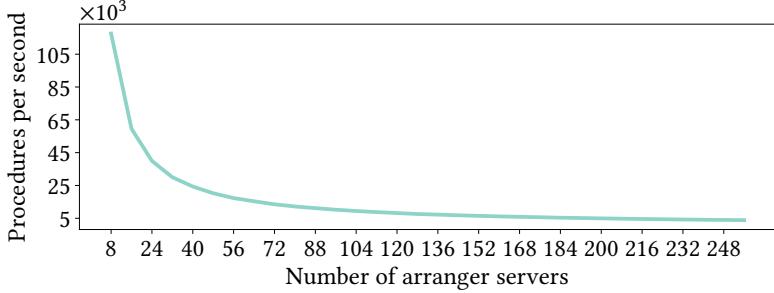


Fig. 7. Signature aggregations per second, in terms of the number of signature aggregated per procedure.

is sufficient to verify all signatures generated by  $N = 128$  replicas, considering a throughput of 12,000 TPS and batches containing 4,400 transaction requests (dotted line in Fig. 8). Replicas must verify the highest number of signatures when the arranger is maintained by 256 replicas and batches contain only 400 transaction requests, which amounts to verifying 7,680 signatures per second, surpassing the throughput of the signature verification procedure (dashed line in Fig. 8). However, verifying signatures can be done in parallel because each signature can be verified independently from the other signatures.<sup>10</sup> Our empirical evaluation suggests that using 16 parallel processes to verify signatures achieves a rate exceeding 8,500 signature verified per second, sufficiently for  $N = 256$  replicas and batches containing 400 transaction replicas at 12,000 TPS. Consequently, the verifying procedure does not influence the throughput, and hypothesis **H.Ver** holds.

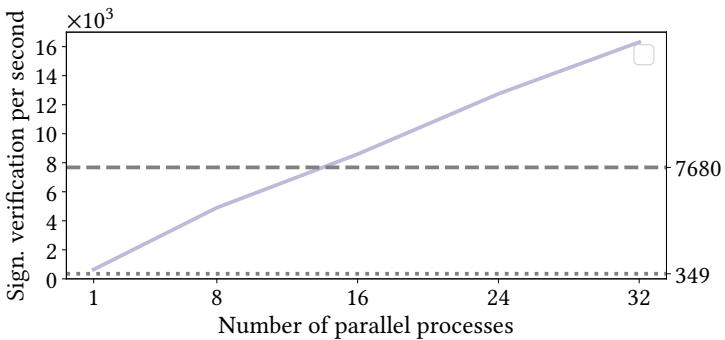


Fig. 8. Signature verification per second. The dotted line represents the maximal number of signatures that each arranger replica must verify (for 12,000 TPS, the batch size of 4,400 and 128 replicas). The dashed line represents the maximal number of signatures that each arranger replica must verify (for 12,000 TPS, batch size of 400 and 256 replicas).

- **H.Trans.** Finally, we implemented a *translation server* that takes two input files and generates a dictionary mapping hashes to their compressed data. One file contains hashed batches together with identifiers while the other contains compressed batches with identifiers. The translation server opens a local TCP connection port to receive hash translation requests receiving an identifier and returning a compressed batch according to the dictionary.

<sup>10</sup>All other local procedures described can use parallelism easily as well.

Our experiments involve making sequential requests to a single translation server asking to translate input hashes for a duration of 1 second. All batches contained the same number of transaction requests, ranging from 400 to 4,400 transactions.

Fig. 6 shows that the translation for batches of 400 transactions can be performed at a rate of about 1,300,000 TPS. The translation throughput increases as the number of transaction requests per batch increases, peaking at nearly 2,900,000 TPS for batches of 3,800 transactions. However, the throughput decreases slightly after that point, due to the increased size of compressed batches. The translation procedure can easily handle two orders of magnitude more transaction requests than the throughput of implementation of SBC, confirming hypothesis **H.Trans**.

### 6.3 Experiment Conclusions

The conclusions of our experiments are the following:

- (1) hashing and signing batches of transaction requests take significantly less space than compressing batches of transaction requests, and
- (2) local procedures are very efficient and do not limit the throughput provided SBC implementations, which is the main bottleneck for scalability.

Since the overhead of the procedures added to the set-consensus algorithm is negligible, our decentralized arranger does not introduce any significant performance bottlenecks to SBC implementations, even if the workload of L2 systems was increased by two orders of magnitude and there were 256 arranger replicas.

Finally the reduction in space, which remains constant as batch size increases, contributes to reduce the L1 gas needed.

## 7 RELATED WORK

While the limitations of centralized arrangers in L2s are known, the development of decentralized arrangers is still in its early stages [29].

Many L2s implement an arranger as centralized sequencer and separate data availability committee [40], as the one we presented in Section 4. However, to the best of our knowledge, Metis [13] is the only L2 that currently implements a decentralized arranger. Metis is based on proof-of-stake and uses Tendermint [5] to select a rotating leader. The leader collects transaction requests and generates batches. These batches are signed using multi-party computation and, when enough signatures are gathered, the leader posts a signed batch in L1. However, Metis does not provide a proof of correctness. This is in contrast to our fully decentralized arranger, presented in Section 5, which we proved correct under the assumption that less than one-third of the replicas are Byzantine.

Other attempts to implement arrangers include Radius [35], Espresso [37] and Astria [31]. Radius also uses leader election, based on the RAFT algorithm [33], which is not Byzantine-tolerant. Radius replicas remain consistent and can reach consensus even when the leader fails, but [35] does not discuss what happens when replicas refuse to disclose block contents to users. Radius allows encryption of transactions to prevent maximum extractable value (MEV), but we do not address this problem here. Both Espresso and Astria use one protocol for sequencing transaction requests and a different protocol for data availability. In particular, Espresso uses HotStuff2 [24] as consensus mechanism and its own Data Availability layer known as *tiramisu*, while Astria uses CometBFT [10] for sequencing transaction requests and leverages Celestia Data Availability Service [20]. We tackled both challenges in a single protocol because Byzantine-resilient solutions do not compose efficiently (see e.g. [7]).

Finally, Malachite [18] is a flexible Byzantine Fault-Tolerant engine currently under development aimed at decentralizing only the sequencer component of arrangers. Malachite could be directly applied to both Optimistic Rollups and ZK Rollups, (where batches are posted compressed and a DAC is not required to translate hashes) or combined with a DAC service to obtain an arranger.

## 8 CONCLUSION

Layer 2 Blockchains aim to improve the scalability of current smart contract based blockchains, offering a much higher throughput without modifying the programming logic and user interaction. Two crucial elements of all L2s schemes are the *sequencer*, which receives and orders transaction requests from users, packs them into batches and sends the hash of the batch to L1, and the *data availability committee* which make sure that the data corresponding to the hash is available. We introduced the notion of *arranger* which combines the sequencer and DAC in a single service. Current implementations of arrangers in most L2s are based on centralized sequencers, either posting compressed batches (ZK-Rollups and Optimistic Rollups), or hashes of batches with a fixed collection of servers providing data translation (Validiums and Optimiums). The resulting L2s are fully controlled by the centralized sequencer, that has full power for censoring transactions and the ability to post fake batches without penalties.

In this paper, we rigorously defined the correctness criteria for arrangers and presented a fully decentralized arranger proof-of-concept based on the efficient Set Byzantine Consensus protocol. We showed our solution is correct when the portion of Byzantine replicas is less than one third. We implemented all building blocks required to extend SBC into an honest arranger replicas, and presented an empirical evaluation that shows that the overhead will not reduce the throughput of SBC implementations to handle several times the current demand.

### Future work

Future work includes extending a production SBC implementation transforming it into a decentralized arranger implementation, allowing all components to run together and enabling a stronger empirical evaluation and study other factors, such as latency.

Throughout the paper, we assumed that the number of Byzantine arranger replicas is bounded by  $f$ , a known fraction of the total number of arranger replicas. However, we did not explore what the incentive for an arranger replica to be honest or Byzantine is. This requires both (1) a system of rewards for replicas that make the L2 blockchain progress (for example, extending the assignment of rewards to STFs in optimistic rollups) and (2) a collection of new fraud-proof games to punish replicas that are proven to behave dishonestly. This requires that replicas place a stake to account for the penalties, which is recovered after claims consolidate. An interesting avenue for future work is to study incentives and punishments to align the behavior of rational arranger with the honest arranger replicas, creating a system that is *incentive compatible* [23].

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