Pod: An Optimal-Latency, Censorship-Free, and Accountable Generalized Consensus Layer

Orestis Alpos¹, Bernardo David^{1,2}, and Dionysis Zindros¹

 1 Common Prefix 2 IT University of Copenhagen (ITU)

Abstract. This work addresses the inherent issues of high latency in blockchains and low scalability in traditional consensus protocols. We present pod-core, a novel notion of consensus whose first priority is to achieve the physically optimal latency of one round trip, *i.e.* requiring only one round for writing a new transaction and one round for reading it. To accomplish this, we first eliminate inter-replica communication. Instead, clients send transactions directly to all replicas, each replica independently processes transactions and appends them to its log, and then clients receive and extract information from these logs. The replicas employ techniques such as transaction timestamping and replica-log sequencing, which allow clients to extract valuable information about the transactions and the state of the system.

Necessarily, this construction achieves weaker properties than a total-order broadcast protocol, due to existing lower bounds. Our work models the primitive of pod and defines its security properties. We then prove that our pod-core construction satisfies properties such as transaction confirmation within 2δ , censorship resistance against Byzantine replicas, and accountability for safety violations. We show that a wire range of applications, such as payment systems, auctions, and decentralized data stores, can be based on a pod primitive.

1 Introduction

Despite the widespread adoption of blockchains, a significant challenge remains unresolved: they are inherently slow. The latency from the moment a client submits a transaction to its appearance in the blockchain's output can be prohibitively long for certain applications. Indeed, Nakamoto-style blockchain protocols require a large number of rounds in order to achieve consensus on a new block, even when considering the best known bounds [14]. On the other hand, it is known that less scalable protocols realizing traditional notions of consensus, such as broadcast and Byzantine agreement, require at least t+1 rounds in the synchronous case [1] and at least 2n/(n-t) rounds in the asynchronous case [13], for n parties out of which t are corrupted.

In a model where replicas maintain the network, writers submit transactions, and readers read the network, the minimum latency is one network round trip, or 2δ , letting δ denote the actual network delay, as the information must travel

from the writers to the replicas and then to the readers. This works is motivated by the following question.

Can we perform payments – and other tasks that blockchains are commonly used for – in optimal latency?

We define latency in terms of the blockchain *liveness* property, referring to finalized, non-reversible outputs: once a transaction is received by a reader, it remains in the protocol's output permanently. We do not assume "optimistic" or "happy" path scenarios, where transactions might finalize faster under favorable conditions (such as having honest leaders or optimal network conditions). Instead, we want that any transaction from an honest writer appears in the output of honest readers within 2δ time, regardless of the current value of δ .

To achieve the single-roundtrip latency, our first key design decision eliminates inter-replica communication entirely. Instead, writers send their transactions directly to all replicas. Each replica maintains its own *replica log*, processes incoming transactions independently, and transmits its log to readers. Readers then process these replica logs to extract relevant information.

This design raises two important questions. First, what meaningful information can readers derive from replica logs when replicas operate in isolation? Second, given that in two rounds even randomized authenticated broadcast is proven impossible [13], what capabilities can this necessarily weaker primitive offer? We demonstrate that, by incorporating simple mechanisms, such as transaction timestamping and replica-log sequencing, replicas can enable readers to extract valuable information beyond mere low-latency guarantees. Furthermore, we show how the properties of pod can enable various applications, including payment systems, auction platforms, and decentralized data stores.

Specifically, pod delivers the following guarantees:

- Transaction confirmation within 2δ latency, with each confirmed transaction assigned a *confirmation round*; we say that the transaction becomes *confirmed* at the time indicated by the confirmation timestamp.
- Censorship resistance when facing up to f Byzantine replicas, ensuring all confirmed transactions appear in every honest reader's output.
- A past-perfect round can be computed by readers, such that the reader has
 received all transactions that are or will be confirmed prior to this round,
 even though not all transactions are strictly ordered.
- Accountability for any safety violations.

1.1 Summary of our results

We consider that time proceeds in *rounds*, and that parties (replicas and clients) know the current round, so we can express timestamps in terms of rounds. The output of pod associates each transaction tx with timestamp values $r_{\min} \geq 0$ (minimum round), $r_{\max} \leq \infty$ (maximum round) and r_{conf} (confirmed round). The confirmation round may be initially $r_{\mathrm{conf}} = \bot$ but later becomes $r_{\min} \leq r_{\mathrm{conf}} \leq$

 $r_{\rm max}$, when a transaction is *confirmed*. While each party reads different values $r_{\rm min}, r_{\rm max}, r_{\rm conf}$ for the same tx, pod guarantees that values read by different parties stay within these limits.

When clients read the pod, they obtain a pod data structure $D = (\mathsf{T}, \mathsf{r}_{\mathrm{perf}}, C_{\mathrm{pp}})$, where T is set of transactions with their associated timestamps, $\mathsf{r}_{\mathrm{perf}}$ is a past-perfect round and C_{pp} is auxiliary data. The past-perfection safety property of pod guarantees that T contains all transactions that every other honest party will ever read with a confirmed round smaller than $\mathsf{r}_{\mathrm{perf}}$. A pod also guarantees past-perfection within w, meaning that $\mathsf{r}_{\mathrm{perf}}$ is at most w rounds in the past.

For each transaction tx in T, the reader obtains associated timestamps r_{\min} , r_{\max} , r_{conf} and auxiliary data C_{tx} , which may evolve. The protocol guarantees confirmation within u rounds, meaning that, at most u rounds after tx was written, every party who reads the pod will see tx as confirmed with some $r_{\text{conf}} \neq \bot$. Moreover, pod guarantees confirmation bounds, ensuring that the values r_{\min} and r_{\max} for tx, read by an honest party, determine the range of the r_{conf} value for tx that can ever be read by another honest party, i.e., $r_{\min} \leq r_{\text{conf}} \leq r_{\max}$.

In summary, pod provides past-perfection and confirmation bounds as safety properties, ensuring parties cannot be blindsided by transactions suddenly appearing as confirmed too far in the past, and that the different (and continuously changing) transaction timestamps stay in a certain range. The liveness properties of confirmation within u and past-perfection within w ensure that new transactions get confirmed within a bounded delay, and that each party's past-perfect round must be constantly progressing.

Besides introducing the notion of pod, we present a construction pod-core that requires minimal interaction among parties and achieves optimal latency, i.e., optimal parameters $u=2\delta$ and $w=\delta$, where δ is the current network delay (not a delay upper bound). Our construction relies on a set of n replicas to maintain a pod data structure, which can be read by an unbounded number of clients. The only communication is between each client and the replicas, not among clients nor among replicas.

Writing a transaction tx in pod-core only requires clients to send tx to the replicas, who each assign a timestamp ts (their current time) and a sequence number to tx and return a signature on (tx, ts, sn). When reading the pod, the client simply requests each replica's log of transactions, validates the responses, and determines r_{\min} and r_{\max} from the received timestamps. If the client receives responses from enough replicas, r_{conf} is determined by taking the median of the timestamps received from these replicas.

1.2 Related work

Reducing latency. Many previous works have lowered the latency of ordering transactions. HotStuff [25] uses three rounds of all-to-leader and leader-to-all communication pattern, which results in an end-to-end latency (i.e., from the moment a client submits a transaction until in appears in the output of honest replicas) of 8δ in the happy path. Jolteon [15], Ditto [15], and HotStuff-2 [18] are two-round versions of HotStuff with end-to-end latency of 5δ . MoonShot [10]

allows leaders to send a new proposal every δ time, before receiving enough votes for the previous one, but still achieves an end-to-end latency of 5δ . In the "DAG-based" line of word, Tusk [8] achieves and end-to-end latency of 7δ , the partially-synchronous version of BullShark [22] an end-to-end latency of 5δ , and Mysticeti [2] an end-to-end latency of 4δ . All these protocols aim at total-order properties, hence their lower latency is inherently restricted by lower bounds. Pod, in contrary, starts from the single-round-trip latency requirement and explores the properties that can be achieved.

Consensusless payments. The redundancy of consensus for implementing payment systems has been recognized by previous works [4,7,17,21]. The insight is that total transaction order is not required in the case that each account is controlled by one client. Instead, a partial order is sufficient, ensuring that, if transactions tx_1 and tx_2 are created by the same client, then every party outputs them in the same order. This requirement was first formalized by Guerraoui et al. [17] as the source-order property. The constructions of Guerraoui et al. [17] and Fast-Pay [4] require clients to maintain sequence numbers. ABC [21] requires clients to reference all previous transaction in a DAG (including its own last transaction). Cheating client might lose liveness [4,17,21], but equivocating is not possible.

Parallel consensusless payments. Bazzi and Piergiovanni [5] observe two limitations of consensusless protocols: As they employ sequence numbers and deterministic broadcast, clients can only submit one transaction at a time, and they must obtain signatures by at least 2f + 1 replicas on each transaction, where f is the maximum number of tolerated failures. The authors propose a new type of probabilistic Byzantine quorum systems [19], and a protocol that allows a user to initiate multiple concurrent payments, called fractional payments, each transferring amount b/s from their balance b, where s is a constant, and each requiring a signature from less than f replicas. Their solution, however, requires n > 8f and a large n for the probabilistic analysis to hold.

Auctions. The primitive of pod offers the past-perfection property: a read() operation outputs a timestamp r_{perf}, and it is guaranteed that the output of read() contains all transactions that can ever be confirmed with a timestamp smaller than r_{perf} in the view of any reading client, regardless of the network conditions. This implies that reading clients (such as an auctioneer) cannot claim not having received a transaction when reading the pod, as this is detectable by any other client who reads the pod. To the best of our knowledge, previous work in the consensusless literature has not considered or achieved this property, hence it cannot readily support applications like auctions.

2 Preliminaries

Notation. We denote by \mathbb{N} the set of natural numbers including 0. Let L be a sequence, we denote by L[i] the i^{th} element (starting from 0). We denote by |L|

the length of L. Negative indices address elements from the end, so L[-i] is the i^{th} element from the end, and L[-1] in particular is the last. consisting of the elements indexed from i (inclusive) to j (exclusive). The notation L[i:] means the subarray of L from i onwards, while L[:j] means the subsequence of L up to (but not including) j. We denote an empty sequence by []. We denote the concatenation of sequences L_1 and L_2 by $L_1 \parallel L_2$.

2.1 Execution Model

Parties. We consider n replicas $R = \{R_1, \ldots, R_n\}$ and an unlimited number of *clients*. Parties are *stateful*, *i.e.*, store *state* between executions of different algorithms. We assume that replicas are known to all parties and that their public keys (for which they have the corresponding secret key) are registered in a Public Key Infrastructure (PKI). The clients do not participate in the PKI.

Adversarial Model. We call a party (replica or client) honest, if it follows the protocol, and malicious otherwise. Malicious parties are Byzantine, i.e., deviate arbitrarily from the protocol. We assume static corruptions, i.e., the set of malicious replicas is decided before the execution starts and remains constant. The adversary has access to the internal state and secret keys of all malicious parties. We denote by $\beta \in [0, n]$ the resilience threshold, i.e., number of malicious replicas in an execution, and by $\alpha \in [0, n]$ the confirmation threshold. Our constructions assume limits on α and β , but make no honesty assumptions on clients.

Modeling time. Time proceeds in discrete *rounds*. We assume that parties know the current round. A *timestamp* is a round number assigned to an event, *e.g.*, receiving or sending a message. We assume that all honest parties do any probabilistic polynomial time computation and send any messages required by the protocol at every round (although message delivery is not guaranteed).

Modeling network. We denote by $\delta \in \mathbb{N}$ the actual delay (measured in number of rounds) it takes to deliver a message between two honest parties, a number which is *finite* but unknown to all parties. We denote by $\Delta \in \mathbb{N}$ an upper bound on this delay, i.e., $\delta \leq \Delta$, which is also *finite*. In the synchronous model, Δ is known to all processes. In the asynchronous model, Δ is unknown but still finite, i.e., all messages are eventually delivered. In both cases, messages are delivered in an order chosen by the adversary. A protocol is responsive if its liveness guarantees depend only on the actual network delay δ and it does not rely on knowledge of Δ , which is the case of our main protocol pod-core.

Digital Signatures. We assume that replicas (and auctioneers in bidset-core) authenticate their messages with digital signatures. A digital signature scheme is a triple of algorithms satisfying the EUF-CMA security [16] as defined below:

- $KeyGen(1^{\kappa})$: The key generation algorithm takes as input a security parameter κ and outputs a secret key sk and a public key pk.
- $Sign(sk, m) \to \sigma$: The signing algorithm takes as input a private key sk and a message $m \in \{0, 1\}^*$ and returns a signature σ .
- Verify(pk, m, σ) $\rightarrow b \in \{0,1\}$: The verification algorithm takes as input a public key pk, a message m, and a signature σ , and outputs a bit $b \in \{0,1\}$.

We say σ is a valid signature on m with respect to pk if $Verify(pk, m, \sigma) = 1$.

2.2 Accountable safety

Taking a similar approach as Neu, Tas, and Tse [20, Def. 4], we define accountable safety through an identification function.

Definition 1 (Transcript and partial transcript). We define as transcript the set of all network messages sent by all parties, related to an execution of a protocol. A partial subscript is a subset of a transcript.

Definition 2 (β -Accountable safety). A protocol satisfies accountable safety with resilience β if its interface contains a function identify $(T) \to \tilde{R}$, which takes as input a partial transcript T and outputs a set of replicas $\tilde{R} \subset R$, such that the following conditions hold except with negligible probability.

Correctness: If safety is violated, then there exists a partial transcript T, such that identify $(T) \to \tilde{R}$ and $|\tilde{R}| > \beta$ and all replicas in \tilde{R} are adversarial.

No-framing: For any partial transcript T produced during an execution of the protocol, the output of identify (T) does not contain honest replicas.

Remark 1. For the sake of simplicity, we have defined the transcript based on messages sent by all replicas. We can also define a local transcript as the set of messages observed by a single party. As will become evident from the implementation of identify(), in practice, adversarial behavior can be identified from the local transcript of a single party or the local transcripts of a pair of parties.

3 Modeling pod

In this section, we introduce the notion of a pod, a distributed protocol where replicas maintain transactions with an evolving partial order, which can be *read* and *written* by clients. We first define basic data structures and the interface of a pod. We then introduce the basic definition of a secure pod and its security properties, as well as some additional properties that it may satisfy, which we will later use for our applications. In particular, we define the notions of *timeliness* and *monotonicity* for a secure pod.

Definition 3 (Transaction and associated values). A transaction $tx \in \{0,1\}^*$ is associated with values $r_{min}, r_{max}, r_{conf}$, and C_{tx} . We call $r_{min} \in \mathbb{N}$ the minimum round, $r_{max} \in \mathbb{N} \cup \{\infty\}$ the maximum round, $r_{conf} \in \mathbb{N} \cup \{\bot\}$ the confirmed round, and $C_{tx} \in \{0,1\}^*$ contains some auxiliary data. We denote by $r_{max} = \infty$ an unbounded maximum round and by $r_{conf} = \bot$ an undefined confirmed round. For transaction tx, denote its associated values by $tx.r_{min}, tx.r_{max}, tx.r_{conf}$, and $tx.C_{tx}$. We remark that the associated values of a transaction change during the execution of a pod protocol.

In pod-core, C_{tx} will contain digital signatures used to achieve accountability.

Definition 4 (Confirmed transaction). A transaction with confirmed round r_{conf} is called confirmed if $r_{conf} \neq \bot$, and unconfirmed otherwise.

Definition 5 (Transaction set). A transaction set T is a set of tuples $(tx, r_{min}, r_{max}, r_{conf}, C_{tx})$. We say that a transaction tx appears in T when $\exists (tx', r_{min}, r_{max}, r_{conf}, C_{tx}) \in T$ such that tx' = tx. Conversely, we say that a transaction tx does not appear in T when this condition is not satisfied.

Definition 6 (pod data structure). A pod D is a triple (T, r_{perf}, C_{pp}) , where T is a transaction set, r_{perf} is a round number, called the past-perfect round, and $C_{pp} \in \{0,1\}^*$ contains auxiliary data.

In pod-core, $C_{\rm pp}$ will also contain signatures used to achieve accountability. Our construction will allow for deriving $C_{\rm pp}$ from all certificates $C_{\rm tx}$ in T, but we define $C_{\rm pp}$ explicitly for clarity and generality. Moreover, $r_{\rm perf}$ will imply a completeness property on T, defined by the past-perfection safety property of pod. We remark that transactions in T may be confirmed on unconfirmed.

Definition 7 (Interface of a pod). A pod protocol has the following interface.

- write(tx): It writes a transaction tx to the pod.
- read() \rightarrow D: It outputs a pod D = (T, r_{perf}, C_{pp}) .

We say that a client reads the pod when it calls read(). If tx appears in T, we say that the client observes tx and, if $tx.r_{conf} \neq \bot$, we say that the client observes tx as confirmed.

Definition 8 (View of the pod). We call view of the pod the output of read(), where read() is invoked by client c and the output is produced at round r, and denote it as D_r^c . We remark that r denotes the round when read() outputs, as the client may have invoked it at an earlier round. We denote the components of a view as $D_r^c = (D_r^c, T, D_r^c, r_{perf}, D_r^c, C_{pp})$. We write $tx \in D_r^c$ if tx appears in D_r^c, T .

Definition 9 (Secure pod). A protocol is a secure pod if it implements the pod interface of Definition 7 and satisfies the following properties.

(Liveness) Confirmation within u: Transactions become confirmed after at most u rounds. That is, if an honest client c writes a transaction tx at round r, then for any honest client c' (including c = c') it holds that $tx \in D_{r+u}^{c'}$ and $tx.r_{conf} \neq \bot$.

(Liveness) Past-perfection within w: Rounds become past-perfect after at most w rounds. That is, for any honest client c and round $r \ge w$, it holds that $D_r^c.r_{perf} \ge r - w$.

(Safety) Past-perfection: Let c be an honest client with view D_r^c at round r. Then, for any transaction $tx \in \{0,1\}^*$ that becomes confirmed in view $D_r^{c'}$ with confirmed round r_{conf} , where c' is an honest client and $r' \ge 0$ is a round, it holds that, if $r_{conf} < D_r^c$. r_{perf} then $tx \in D_r^c$.

(Safety) Confirmation bounds: For any honest clients c_1 , c_2 , if c_1 observes tx with r_{min} and r_{max} and c_2 observes tx as confirmed with confirmation round r'_{conf} , then $r_{min} \leq r'_{conf} \leq r_{max}$.

In the following we define an additional property of pod *timeliness*, which can be satisfied along with the standard safety and liveness properties of pod. Previous work has observed a similar property as orthogonal to safety and liveness [24].

Definition 10 (pod θ -timeliness for honest transactions). A pod is θ -timely if it is a secure pod, as per Definition 9, and the following properties hold for any transaction tx written by an honest client in round r (observe that, from the confirmation within u property, tx will become confirmed):

```
1. r_{conf} \in (r, r + \theta]
```

- 2. $r_{max} \in (r, r + \theta]$
- 3. $r_{max} r_{min} < \theta$, implying that $r_{min} \neq 0$ and $r_{max} \neq \infty$.

In Appendix A, we define the property of pod *Monotonicity* and show that it can be obtained from any secure pod protocol with stateful clients.

4 Protocol pod-core

Before we present protocol pod-core, we define basic concepts and structures.

Definition 11 (Vote). A vote is a tuple (tx, ts, sn, σ, R) , where tx is a transaction, ts is a timestamp, sn is a sequence number, σ is a signature, and R is a replica. A vote is valid if σ is a valid signature on message m = (tx, ts, sn) with respect to the public key pk_R of replica R.

Remark 2 (Processing votes in order). We require that clients process votes from each replica in the same order, namely in order of increasing timestamps. For this we employ sequence numbers. Each replica maintains a sequence number, which it increments and includes every time it assigns a timestamp to a transaction.

Remark 3 (Implicit session identifiers). We assume that all messages between clients and replicas are concatenated with a session identifier (sid), which is unique for each concurrent execution of the protocol. Moreover, the sid is implicitly included in all messages signed by the replicas.

Remark 4 (Streaming construction). The client protocol we show in Construction 1 is streaming, that is, clients maintain a connection to the replicas, and stateful, that is, they persist their state (received transactions, votes, and associated values) across all invocations of write() and read().

Pseudocode notation. For a timestamp ts, notation ts.getVoteMsg() denotes the vote message from some replica through which a client obtained timestamp ts. We abstract away the logic of how getVoteMsg() is implemented. Notation $x:a\in A\to b\in B$ denotes that variable x is a map from elements of type A to elements of type B. When obvious from the context, we do not explicitly write the types A or B. For a map x, the operations x.keys() and x.values() return all keys and all values in x, respectively. With \emptyset we denote an empty map.

Construction 1. We present pod-core, a pod construction in Algorithms 1–3, for the client code, and 4 for the replica code. It achieves accountable safety (see Section 2.2) with an identify() function described in Algorithm 8. In the remainder of this section we discuss how pod-core achieves its properties.

Initialization. The state of a client is shown in Algorithm 1 in lines 2–6. The state contains mrt, nextsn, tsps, and D. Variable tsps is a map from transactions tx to a map from replicas R to timestamps ts. The state gets initialized in lines 7–14. At initialization the client also sends a $\langle CONNECT \rangle$ message to each replica, which initiates a streaming connection from the replica to the client.

Receiving votes. A client maintains a connection to each replica and receives votes through $\langle VOTE \ (\mathsf{tx},\mathsf{ts},\mathsf{sn},\sigma,R_j) \rangle$ messages (lines 15–24). When a vote is received from replica R_j , the client first verifies the signature σ under R_j 's public key (line 16). If invalid, the vote is ignored. Then the client verifies that the vote contains the next sequence number it expects to receive from replica R_j (line 17). If this is not the case, the vote is backlogged and given again to the client at a later point (the backlogging functionality is not shown in the pseudocode).

The client checks the vote against previous votes received from R_j . First, ts must be greater or equal to mrt_j , the most recent timestamp returned by replica R_j (line 19). Second, the replica must have not previously sent a different timestamp for tx (line 22), except if tx is a HEARTBEAT (as checked on line 21). If both checks pass, the client updates $\mathsf{mrt}[j]$ (line 20) and $\mathsf{tsps}[\mathsf{tx}][R_j]$ (line 23) with ts. If any of these checks fail, the client ignores the vote, since both of these cases constitute $\mathit{accountable}$ faults: In the first case, the client can use the message $\langle VOTE\ (\mathsf{tx},\mathsf{ts},\mathsf{sn},\sigma,R_j)\rangle$ and the vote it received when it updated $\mathsf{mrt}[R_j]$ to prove that R_j has misbehaved. In the second case, it can use $\langle VOTE\ (\mathsf{tx},\mathsf{ts},\mathsf{sn},\sigma,R_j)\rangle$ and the previous vote it has received for tx. The identify() function we show in Algorithm 8 can detect such misbehavior. However, in this paper we formalize accountability conditioned on safety being violated (Definition 2), hence we do not further explore this.

Writing to and reading from pod. Protocol pod-core implements functions write(tx) and read() (Definition 7) functions as shown in Algorithm 2. In order to write a transaction tx, a client sends $\langle WRITE \text{ tx} \rangle$ to each replica (lines 1–5). Since the construction is stateful and streaming, the client state contains at all times the latest view the client has of the pod, read() operates on the local state (lines 6–28). It returns a pod D (line 27) with a transaction set T, containing the transactions the client has received so far (line 8) and their associated values, a past-perfect round r_{perf} , and auxiliary data C_{pp} . We remind that notation tsps. keys() on line line 8 returns all entries in tsps.

The client uses the minPossibleTs() and maxPossibleTs() functions to compute r_{min} (line 9) and r_{max} (line 10). They return the minimum and maximum, respectively, round number that any client can ever confirm tx with. For r_{perf} (line 22) the client uses minPossibleTsForNewTx(), which returns the smallest round number that any client can ever assign to a transaction not yet seen by the

Algorithm 1 Protocol pod-core (Construction 1): Client code, part 1.

```
1: State:
 2: \mathcal{R} = \{R_1, \dots, R_n\}; \{\mathsf{pk}_1, \dots, \mathsf{pk}_n\}
                                                                        ▷ All replicas and their public keys
 3: \operatorname{mrt}: R \to \operatorname{ts}
                                            ▶ The most recent timestamp returned by each replica
 4 \colon \operatorname{nextsn}: R \to \operatorname{sn}
                                             ▶ The next sequence number expected by each replica
 5: tsps : tx \rightarrow (R \rightarrow ts)
                                                 ▶ Timestamp received for each tx from each replica
 6: D = (\mathsf{T}, \mathsf{r}_{\mathrm{perf}}, C_{\mathrm{pp}})
                                                                 ▶ The pod observed by the client so far
 7: upon event init(R_1, \ldots, R_n, k_1, \ldots, k_n) do
          \mathcal{R} \leftarrow \{R_1, \dots, R_n\}; \; (\mathsf{pk}_1, \dots, \mathsf{pk}_n) \leftarrow (k_1, \dots, k_n)
 8:
 9:
          \mathsf{tsps} \leftarrow \emptyset; \ D = (\emptyset, 0, [\,])
          for R_i \in \mathcal{R} do
10:
               mrt[R_j] \leftarrow 0; nextsn[R_j] = -1
11:
12:
               Send \langle CONNECT \rangle to R_j
13:
          end for
14: end upon
15: upon receive \langle VOTE (\mathsf{tx}, \mathsf{ts}, \mathsf{sn}, \sigma, R_j) \rangle do
                                                                          \triangleright Received a vote from replica R_j
          if not Verify(pk_i, (tx, ts, sn), \sigma) then return
                                                                                                      \triangleright Invalid vote
          if \operatorname{sn} \neq \operatorname{nextsn}[R_j] then return
17:
                                                                              18:
          nextsn[R_j] \leftarrow nextsn[R_j] + 1
          if ts < mrt[R[j]] then return
19:
                                                                                      \triangleright R_j sent old timestamp
20:
          mrt[R[j]] \leftarrow ts
          if tx = HEARTBEAT then return
21:
                                                                    ▷ Do not update tsps for heartBeat
          if tsps[tx][R_i] \neq \bot and tsps[tx][R_i] \neq ts then return \triangleright Duplicate timestamp
22:
23:
          \mathsf{tsps}[\mathsf{tx}][R_j] \leftarrow \mathsf{ts}
24: end upon
```

client. The auxiliary data C_{pp} contains the vote on the most recent timestamp $mrt[R_i]$ received from each replica R_i .

A transaction becomes confirmed (i.e., it gets assigned a confirmation round $r_{\rm conf} \neq \bot$) when the client receives α votes for tx from different replicas (line 12). Before it becomes confirmed, a transaction has $r_{\rm conf} = \bot$ and $C_{\rm tx} = []$ (line 11). When confirmed, $r_{\rm conf}$ is the median of all received timestamps (line 18), and the auxiliary data $C_{\rm tx}$ contains all the received votes on tx (line 16).

Computing the associated values and the past-perfect round. Function minPossibleTs() in Algorithm 3 fills a missing vote from replica R_j with $\mathsf{mrt}[R_j]$ (line 7), the minimum timestamp that can ever be accepted from R_j (smaller values will not pass the check in line 19 of Algorithm 2), and prepends β times the 0 value (line 11), pessimistically assuming that up to β replicas will try to bias tx by sending a timestamp 0 to other clients. Function $\mathsf{maxPossibleTs}()$ in Algorithm 3 fills a missing vote with ∞ (line 20) and appends β times the ∞ value (line 24), the worst-case timestamp that malicious replicas may send to other clients. Finally, $\mathsf{minPossibleTsForNewTx}()$ works similarly to $\mathsf{minPossibleTs}()$, except considering timestamps mrt as the minimum possible for any future transaction.

Algorithm 2 Protocol pod-core (Construction 1): Client code, part 2.

```
1: function WRITE(tx)
 2:
             for R_i \in \mathcal{R} do
 3:
                   Send \langle WRITE \mathsf{tx} \rangle to R_j
  4:
             end for
 5: end function
 6: function READ()
            \mathsf{T} \leftarrow \emptyset; \ C_{\mathsf{pp}} \leftarrow [\ ]
 7:
             for tx \in tsps.keys() do
 8:
                                                                                       ▶ Loop over all received transactions
 9:
                   r_{\min} \leftarrow \min PossibleTs(tx)
                   r_{\max} \leftarrow \mathit{maxPossibleTs}(tx)
10:
11:
                   \mathsf{r}_{\mathrm{conf}} \leftarrow \bot; \ C_{\mathrm{tx}} \leftarrow [\ ]; \ \mathsf{timestamps} = [\ ]
12:
                   if |tsps[tx].values()| \ge \alpha then
                          for R_j \in \text{tsps[tx]}.values() do
13:
14:
                                \mathsf{ts} \leftarrow \mathsf{tsps}[\mathsf{tx}][R_j]
15:
                                timestamps \leftarrow timestamps \parallel ts
16:
                                C_{\text{tx}} \leftarrow C_{\text{tx}} \parallel \text{ts.getVoteMsg()}
                          end for
17:
                         r_{\mathrm{conf}} \leftarrow \mathit{median}(\mathit{timestamps})
18:
19:
                   end if
                   \mathsf{T} \leftarrow \mathsf{T} \cup \{(\mathsf{tx}, \mathsf{r}_{\min}, \mathsf{r}_{\max}, \mathsf{r}_{\mathrm{conf}}, \mathit{C}_{\mathrm{tx}})\}
20:
21:
             end for
22:
             r_{perf} \leftarrow minPossibleTsForNewTx()
23:
             for R_j \in \mathcal{R} do
                   C_{\text{pp}} \leftarrow C_{\text{pp}} \parallel \mathsf{mrt}[R_j].getVoteMsg()
24:
25:
             end for
26:
             D \leftarrow (\mathsf{T}, \mathsf{r}_{\mathrm{perf}}, C_{\mathrm{pp}})
27:
             return D
28: end function
```

Replica code (Algorithm 4). The state of a replica (lines 1–4) contains, among others, the transaction log replicaLog, which is implemented as a sequence of votes (tx, ts, sn, σ , R_i) created by the replica, where ts is the timestamp assigned by the replica to tx, sn is a sequence number, and σ is its signature. A functionality round() allows the replica to determine the current round number. When the replica receives a $\langle CONNECT \rangle$ message from a client c, it appends c to its set of connected clients and sends to c all entries in replicaLog (lines 8–13).

When it receives $\langle WRITE \ \text{tx} \rangle$, a replica first checks whether it has already seen tx, in which case the message is ignored. Otherwise, it assigns tx a timestamp ts equal its local round number and the next available sequence number sn, and signs the message (tx, ts, sn) (line 19). Honest replicas use incremental sequence numbers for each transaction, so if a vote has a larger sequence number than another vote, it will have a larger or equal timestamp than the other. The replica appends (tx, ts, sn, σ) to replicaLog, and sends it via a $\langle VOTE \ (\text{tx}, \text{ts}, \text{sn}, \sigma, R) \rangle$ message to all connected clients (line 22).

Algorithm 3 Protocol pod-core (Construction 1): Client code, part 3, computing r_{\min} , r_{\max} , r_{conf} allowing up to β equivocations.

```
1: function MINPOSSIBLETS(tx)
         timestamps \leftarrow []
 2:
 3:
         for R_j \in \mathcal{R} do
 4:
              if tsps[tx][R_j] \neq \bot then
 5:
                  timestamps \leftarrow timestamps || [tsps[tx][R_i]]
 6:
              else
                  timestamps \leftarrow timestamps || [mrt[R_i]]
 7:
 8:
              end if
         end for
 9:
10:
         sort timestamps in increasing order
         timestamps \leftarrow [0, {}^{\beta} \overset{\text{times}}{\dots}, 0] \parallel \text{timestamps}
11:
         return median(timestamps[: \alpha])
12:
13: end function
14: function MAXPOSSIBLETS(tx)
15:
         timestamps \leftarrow []
16:
          for R_j \in \mathcal{R} do
              if tsps[tx][R_j] \neq \bot then
17:
18:
                  timestamps \leftarrow timestamps || [tsps[tx][R_i]]
19:
              else
20:
                  timestamps \leftarrow timestamps || [\infty]
21:
              end if
         end for
22:
23:
         sort timestamps in increasing order
         timestamps \leftarrow timestamps \parallel [\infty, \stackrel{\beta \text{ times}}{\dots}, \infty]
24:
         \textbf{return} \ median(\textit{timestamps}[-\alpha:])
25:
26: end function
27: function MINPOSSIBLETsForNewTx()
28:
         timestamps \leftarrow mrt
29:
         sort timestamps in increasing order
         timestamps \leftarrow [0, {}^{\beta} \overset{\text{times}}{\dots}, 0] \parallel \text{timestamps}
30:
         return median(timestamps[: \alpha])
31:
32: end function
33: function MEDIAN(Y)
         return Y[||Y|/2|]
35: end function
```

Heartbeat messages. Clients update their most-recent timestamp $\operatorname{mrt}[R_j]$ every time they receive a vote from replica R_j (line 20 in Algorithm 1). However, in case R_j has not written any transaction in round r (simply because no client called $\operatorname{write}()$ in round r), R_j will advance its round number, but clients will not advance $\operatorname{mrt}[R_j]$. We solve this by having replicas send a vote on a dummy HEARTBEAT transaction the end of each round (lines 26–28). An obvious practical implementation is to send HEARTBEAT only for rounds when no other trans-

Algorithm 4 Protocol pod-core (Construction 1): Code for a replica R_i , where sk denotes its secret signing key.

```
1: C
                                                                          \triangleright The set of all connected clients
 2: nextsn
                                                       ▶ The next sequence number to assign to votes
 3: replicaLog
                                                                       ▶ The transaction log or the replica
 4: round()
                                            \triangleright A function that returns the wall time of the replica
 5: upon event init() do
          \mathsf{nextsn} \leftarrow 0; \ \mathcal{C} \leftarrow \emptyset; \ \mathsf{replicaLog} \leftarrow []
 6:
 7: end upon
 8: upon receive \langle CONNECT \rangle from client c do
 9:
          \mathcal{C} \leftarrow \mathcal{C} \cup \{c\}
10:
          for (tx, ts, sn, \sigma) \in replicaLog do
               Send \langle VOTE (\mathsf{tx}, \mathsf{ts}, \mathsf{sn}, \sigma, R_i) \rangle to c
11:
12:
          end for
13: end upon
14: upon receive \( WRITE \t \t \t \) from a client \( \mathbf{do} \)
15:
          if replicaLog[tx] \neq \bot then return
                                                                             ▶ Ignore duplicate transactions
          doVote(tx)
16:
17: end upon
18: function DOVOTE(tx)
          ts \leftarrow round(); sn \leftarrow nextsn; \sigma \leftarrow Sign(sk, (tx, ts, sn))
19:
          \mathsf{replicaLog} \gets \mathsf{replicaLog} \parallel (\mathsf{tx}, \mathsf{ts}, \mathsf{sn}, \sigma)
20:
21:
          for c \in \mathcal{C} do
22:
               Send \langle VOTE (\mathsf{tx}, \mathsf{ts}, \mathsf{sn}, \sigma, R_i) \rangle to c
23:
          end forz
24:
          \mathsf{nextsn} \leftarrow \mathsf{nextsn} + 1
25: end function
26: upon end round do
                                                                     ▷ Executed at the end of each round
27:
          doVote(heartBeat)
28: end upon
```

actions were sent. When received by a client, a HEARTBEAT is handled as a vote (i.e., it triggers line 15 in Algorithm 1), except that we do not check for duplicate HEARTBEAT votes and do not update any associated values for the heartbeat transaction (see line 21 in Algorithm 1).

Security Analysis: We formalize the security of Construction 1 in the following theorem, which is proven in Appendix B. We show the identify() function for pod-core in Appendix B as well.

Theorem 1 (Pod-core security). In the asynchronous model with actual network delay δ (but unknown delay upper bound), assuming at most β malicious replicas, pod-core (Construction 1), instantiated with a secure signature scheme

and parameterized with $\alpha \geq 4\beta + 1$, is a responsive secure pod (Definition 9) with Confirmation within $u = 2\delta$ and Past-perfection within $w = \delta$, satisfying the property of β -accountable safety (Definition 2), except with negligible probability.

5 Auctions on pod through the bidset protocol

In this section, we construct single-shot distributed auctions based on top of pod by means of bidset, a primitive for collecting a set of bids, which guarantees accountable censorship resistance and consistency among honest parties. We first define bidset below and then construct it using an underlying pod.

Definition 12 (bidset protocol). A bidset protocol has a starting time parameter t_0 and exposes the following interfaces to bidder and consumer parties:

- function submitBid(b): It is called by a bidder at round t_0 to submit a bid b.
- event result(B, C_{bid}): It is an event generated by a consumer. It contains a bid-set B, which is a set of bids, and auxiliary information C_{bid} .

A bidset protocol satisfies the following liveness and safety properties:

(Liveness) Termination within W: An honest consumer generates an event result(B, C_{bid}) by round $t_0 + W$.

(Safety) Censorship resistance: If an honest bidder calls submitBid(b), then $b \in B$.

(Safety) Weak consistency: If two honest consumers generate result(B_1 , ·) and result(B_2 , ·) events, such that $B_1 \neq \emptyset$ and $B_2 \neq \emptyset$, then $B_1 = B_2$.

5.1 Construction

Construction 2 (bidset-core). Protocol bidset-core is parameterized by an integer Δ (looking ahead, we will prove security in synchrony, i.e., assuming the network delay δ is smaller than Δ) and assumes digital signatures and a pod with δ -timeliness, $w = \delta$ and $u = 2\delta$. At time t_0 , all parties start executing Algorithms 5–7. A pre-appointed auctioneer is responsible to reading the pod and writing back to it when a specific condition is met. For example, when instantiating bidset-core on top of pod-core, a replica can act as auctioneer.

Algorithm 5 bidset-core: Code for a bidder. It uses a pod instance pod.

- 1: **function** SUBMITBID(b)
- 2: pod.write(b)
- 3: end function

A bidder submits a bid by writing it on the pod (Algorithm 5) at round t_0 . The auctioneer (Algorithm 6) waits until the pod returns a past-perfect round **Algorithm 6** bidset-core: Code for the auctioneer. It uses a pod instance pod, and sk_a denotes the secret key of the auctioneer.

```
1: function READBIDS()
                (\mathsf{T}, \mathsf{r}_{\mathsf{perf}}, C_{\mathsf{pp}}) \leftarrow pod.read()
  3:
                while r_{perf} \leq t_0 + \Delta do
  4:
                       (\mathsf{T}, \mathsf{r}_{\mathrm{perf}}, C_{\mathrm{pp}}) \leftarrow pod.read()
               end while
  5:
               B \leftarrow \{\mathsf{tx} \mid (\mathsf{tx}, \cdot, \cdot, \cdot, \cdot) \in \mathsf{T}\}; \ C_{\mathrm{bid}} \leftarrow C_{\mathrm{pp}}
  6:
  7:
               \sigma \leftarrow Sign(\mathbf{sk}_a, (B, C_{bid}))
               \mathsf{tx} \leftarrow \langle BIDS \ (B, C_{\mathrm{bid}}, \sigma) \rangle
  9:
               pod.write(tx)
10: end function
```

Algorithm 7 bidset-core: Code for a consumer. It uses a pod instance pod.

```
1: function READRESULT()
 2:
             loop
 3:
                     (\mathsf{T}, \mathsf{r}_{\mathrm{perf}}, C_{\mathrm{pp}}) \leftarrow pod.read()
                    \textbf{if} \ \exists (\mathsf{tx}, \cdot, \cdot, \mathsf{r}_{\mathrm{conf}}, \cdot) \in \mathsf{T} \textbf{:} \ \mathsf{tx} = \langle \mathit{BIDS} \ (B, C_{\mathrm{bid}}, \sigma) \rangle \ \textbf{and} \ \mathsf{r}_{\mathrm{conf}} \leq t_0 + 3 \varDelta \ \textbf{then}
  4:
 5:
                           output event result(B, C_{bid})
 6:
                    else if r_{perf} > t_0 + 3\Delta then
 7:
                            output event result(\emptyset, C_{pp})
 8:
                    end if
 9:
              end loop
10: end function
```

larger than $t_0 + \Delta$ (line 3). The δ -timeliness property of the pod, given that $\delta \leq \Delta$, ensures that the bids of honest parties will have a confirmation round at most $t_0 + \Delta$, and the accountable past-perfection safety guarantees that a malicious auctioneer cannot exclude them from the bid-set B in line 6. The auctioneer concludes by signing B and C_{bid} (which can be used as evidence, in case of a safety violation) and writing $\langle BIDS\ (B, C_{\text{bid}}, \sigma) \rangle$ on pod. As an intuition on how bidset-core achieves its properties, observe that line 3 of Algorithm 6 becomes true in the view of auctioneer by round $t_0 + \Delta + \delta$ (from the past-perfection within $w = \delta$ property of pod-core), hence Algorithm 6 for an honest auctioneer terminates by that round. Observe also that the transaction $\langle BIDS\ (B, C_{\text{bid}}, \sigma) \rangle$ becomes confirmed in the view of all honest clients by round $t_0 + \Delta + 3\delta$ (from the confirmation within $u = 2\delta$ property), and it will have a confirmed round $r_{\text{conf}} \leq t_0 + \Delta + 2\delta$ (from the δ -timeliness property).

The code for a consumer is shown in Algorithm 7. The consumer waits until one of the following two conditions is met. First, a *confirmed* transaction $\langle BIDS\ (B, C_{\rm bid}, \sigma) \rangle$ appears in T, for which $r_{\rm conf} \leq t_0 + 3\Delta$ (line 4), in which case it outputs the bid-set B it the result() event. Second, a round higher than $t_0 + 3\Delta$ becomes past-perfect in pod (line 6), in which case it outputs $B = \emptyset$.

Observe that, from the past-perfection within $w = \delta$ property of pod, the condition in line 6 will become true at latest at round $t_0 + 3\Delta + \delta$, hence bidset-

core achieves termination within $W = 3\Delta + \delta$. If the network is synchronous and the auctioneer honest, the condition in line 4 becomes true at round at most $t_0 + \Delta + 3\delta$ for an honest consumer, hence it outputs B as the bid-set, hence bidset-core satisfies the *consistency* property.

Remark 5 (Implicit sub-session identifiers). We assume that each instance of the bidset-core protocol is identified by a unique sub-session identifier (ssid). All messages written to the underlying pod are concatenated with the ssid.

Theorem 2 (Bidset security). Assuming a synchronous network where $\delta \leq \Delta$, protocol bidset-core (Construction 2) instantiated with a digital signature and a secure pod protocol that satisfies the past-perfection within $w=\delta$, confirmation within $u=2\delta$ and δ -timeliness properties, is a secure bidset protocol satisfying termination within $W=3\Delta+\delta$. It satisfies accountable safety with an identifyAuctioneer() function that identifies a malicious auctioneer.

Proof. The proof and identifyAuctioneer() are shown in Appendix C. \Box

Remark 6. Observe that bidset-core terminates within $W=3\Delta+\delta$ in the worst case, but, if the auctioneer is honest, then it terminates within $W=\Delta+3\delta$. Moreover, bidset-core is not responsive because Algorithm 6 waits for a fixed Δ interval. This step can be optimized if the set of bidders is known (i.e., by requiring them to pre-register), which allows for the protocol to be made optimistically responsive $(i.e., W=4\delta)$ when all bidders and the auctioneer are honest.

Auctions using bidset. Building on a bidset protocol, it is trivial to construct single-shot first price and second price open auctions as follows: 1. Bidders place their open bids b by calling submitBid(b); 2. Consumers determine the winner by calling readResult() to obtain B and outputting either the first or second highest bid. We conjecture that single-shot sealed bid auction protocols such as those of [3,6,9,11,12,23] can also be instantiated on top of a bidset protocol. Intuitively, this holds because such protocols first agree on a set of sealed bids and then execute extra steps to determiner the winner. However, a formal analysis of sealed-bid auction protocols based on bidset is left as future work.

References

- 1. M. K. Aguilera and S. Toueg. A simple bivalency proof that t-resilient consensus requires t+1 rounds. Inf. Process. Lett., 71(3-4):155–158, 1999.
- K. Babel, A. Chursin, G. Danezis, L. Kokoris-Kogias, and A. Sonnino. Mysticeti: Low-latency DAG consensus with fast commit path. CoRR, abs/2310.14821, 2023.
- 3. S. Bag, F. Hao, S. F. Shahandashti, and I. G. Ray. Seal: Sealed-bid auction without auctioneers. *IEEE Transactions on Information Forensics and Security*, 15:2042–2052, 2020.
- 4. M. Baudet, G. Danezis, and A. Sonnino. Fastpay: High-performance byzantine fault tolerant settlement. In AFT, pages 163–177. ACM, 2020.
- 5. R. A. Bazzi and S. T. Piergiovanni. The fractional spending problem: Executing payment transactions in parallel with less than f+1 validations. In R. Gelles, D. Olivetti, and P. Kuznetsov, editors, 43rd ACM PODC, pages 295–305. ACM, June 2024.
- 6. T. Chitra, M. V. X. Ferreira, and K. Kulkarni. Credible, Optimal Auctions via Public Broadcast. In R. Böhme and L. Kiffer, editors, 6th Conference on Advances in Financial Technologies (AFT 2024), volume 316 of Leibniz International Proceedings in Informatics (LIPIcs), pages 19:1–19:16, Dagstuhl, Germany, 2024. Schloss Dagstuhl – Leibniz-Zentrum für Informatik.
- D. Collins, R. Guerraoui, J. Komatovic, P. Kuznetsov, M. Monti, M. Pavlovic, Y. Pignolet, D. Seredinschi, A. Tonkikh, and A. Xygkis. Online payments by merely broadcasting messages. In 50th Annual IEEE/IFIP International Conference on Dependable Systems and Networks, DSN 2020, Valencia, Spain, June 29 - July 2, 2020, pages 26–38. IEEE, 2020.
- G. Danezis, L. Kokoris-Kogias, A. Sonnino, and A. Spiegelman. Narwhal and tusk: a dag-based mempool and efficient BFT consensus. In *EuroSys*, pages 34–50. ACM, 2022.
- 9. B. David, L. Gentile, and M. Pourpouneh. FAST: Fair auctions via secret transactions. In G. Ateniese and D. Venturi, editors, *ACNS 22International Conference on Applied Cryptography and Network Security*, volume 13269 of *LNCS*, pages 727–747. Springer, Cham, June 2022.
- I. Doidge, R. Ramesh, N. Shrestha, and J. Tobkin. Moonshot: Optimizing chainbased rotating leader BFT via optimistic proposals. CoRR, abs/2401.01791, 2024.
- 11. H. S. Galal and A. M. Youssef. Trustee: Full privacy preserving vickrey auction on top of ethereum. In A. Bracciali, J. Clark, F. Pintore, P. B. Rønne, and M. Sala, editors, *Financial Cryptography and Data Security*, pages 190–207, Cham, 2020. Springer International Publishing.
- C. Ganesh, S. Gupta, B. Kanukurthi, and G. Shankar. Secure vickrey auctions with rational parties. Cryptology ePrint Archive, Paper 2024/1011, 2024. To appear at CCS 2024.
- J. A. Garay, J. Katz, C. Koo, and R. Ostrovsky. Round complexity of authenticated broadcast with a dishonest majority. In FOCS, pages 658–668. IEEE Computer Society, 2007.
- P. Gazi, L. Ren, and A. Russell. Practical settlement bounds for longest-chain consensus. In H. Handschuh and A. Lysyanskaya, editors, Advances in Cryptology CRYPTO 2023 43rd Annual International Cryptology Conference, CRYPTO 2023, Santa Barbara, CA, USA, August 20-24, 2023, Proceedings, Part I, volume 14081 of Lecture Notes in Computer Science, pages 107-138. Springer, 2023.

- 15. R. Gelashvili, L. Kokoris-Kogias, A. Sonnino, A. Spiegelman, and Z. Xiang. Jolteon and ditto: Network-adaptive efficient consensus with asynchronous fallback. In Financial Cryptography, volume 13411 of Lecture Notes in Computer Science, pages 296-315. Springer, 2022.
- 16. S. Goldwasser, S. Micali, and R. L. Rivest. A digital signature scheme secure against adaptive chosen-message attacks. SIAM J. Comput., 17(2):281-308, 1988.
- 17. R. Guerraoui, P. Kuznetsov, M. Monti, M. Pavlovic, and D. Seredinschi. The consensus number of a cryptocurrency. Distributed Comput., 35(1):1-15, 2022.
- D. Malkhi and K. Nayak. Extended abstract: Hotstuff-2: Optimal two-phase responsive BFT. IACR Cryptol. ePrint Arch., page 397, 2023.
- D. Malkhi, M. K. Reiter, A. Wool, and R. N. Wright. Probabilistic quorum systems. Inf. Comput., 170(2):184-206, 2001.
- 20. J. Neu, E. N. Tas, and D. Tse. The availability-accountability dilemma and its resolution via accountability gadgets. In I. Eyal and J. A. Garay, editors, FC 2022, volume 13411 of *LNCS*, pages 541–559. Springer, Cham, May 2022.
- 21. J. Sliwinski and R. Wattenhofer. ABC: asynchronous blockchain without consensus. CoRR, abs/1909.10926, 2019.
- 22. A. Spiegelman, N. Giridharan, A. Sonnino, and L. Kokoris-Kogias. Bullshark: The partially synchronous version. CoRR, abs/2209.05633, 2022.
- 23. N. Tyagi, A. Arun, C. Freitag, R. Wahby, J. Bonneau, and D. Mazières. Riggs: Decentralized sealed-bid auctions. In W. Meng, C. D. Jensen, C. Cremers, and E. Kirda, editors, ACM CCS 2023, pages 1227–1241. ACM Press, Nov. 2023.
- 24. A. Tzinas, S. Sridhar, and D. Zindros. On-chain timestamps are accurate. Cryptology ePrint Archive, Report 2023/1648, 2023.
- 25. M. Yin, D. Malkhi, M. K. Reiter, G. Golan-Gueta, and I. Abraham. Hotstuff: BFT consensus with linearity and responsiveness. In PODC, pages 347–356. ACM, 2019.

\mathbf{A} Definition of pod monotonicity

We define pod monotonicity as an intermediate notion that stands between a simple secure pod and a θ -timely pod. The property of pod monotonicity requires that, as time advances, r_{\min} does not decrease, r_{\max} does not increase and confirmed transactions remain confirmed

Definition 13 (pod monotonicity). A pod satisfies pod monotonicity, and called a monotone pod, if it is a secure pod, as per Definition 9, and the following properties hold for any rounds $r_1, r_2 > r_1$:

- 1. (Past-perfection Monotonicity) $D_{r_2}^{\mathsf{c}}.r_{perf} \geq D_{r_1}^{\mathsf{c}}.r_{perf};$ 2. (Transaction Monotonicity) If transaction tx appears in $D_{r_1}^{\mathsf{c}}.T$, then tx appears in $D_{r_2}^{c}$. T;
- 3. (Confirmation Bounds Monotonicity) For every tx that appears in $D_{r_1}^c$. Twith r_{min} , r_{max} , r_{conf} and appears in $D_{r_2}^c$. T with r'_{min} , r'_{max} , r'_{conf} , it holds that $r'_{min} \ge r_{min}$, $r'_{max} \le r_{max}$, $r'_{conf} \ge r_{conf}$.

We now observe that a monotone pod can be obtained from any secure pod and that monotonicity implies certain specific properties that may be useful for applications. In particular, our pod-core protocol naturally satisfies this property. Remark 7. Every secure pod can be transformed into a monotone pod if parties are stateful. Let r_1 be the last round when an honest client c read the pod obtaining view $D_{r_1}^c$, which is stored as state until c reads the pod again. At any round $r_2 > r_1$, if c reads the pod and obtains $D_{r_2}^c$, c can define a view $\overline{D_{r_2}^c}$ satisfying the properties of pod monotonicity:

- 1. If tx appears in $D_{r_1}^c$ with tx. r_{min} , tx. r_{max} , tx. r_{conf} , tx. C_{tx} , then tx appears in
- D_{r2} with tx. r_{min} = r_{min}, tx. r_{max} = r_{max}, tx. r_{conf} = r_{conf}, tx. C_{tx} = C_{tx}.
 If tx appears in D_{r2} with tx. r'_{min}, tx. r'_{max}, tx. r'_{conf}, tx. C'_{tx} and does not appear in D_{r1}, then tx appears in D_{r2} with tx. r_{min} = r'_{min}, tx. r_{max} = r'_{max}, tx. r_{conf} =
- r'_{conf} , $tx.\overline{C_{\text{tx}}} = C'_{\text{tx}}$.

 3. For every tx that appears in $D^{\text{c}}_{r_1}$. T and in $D^{\text{c}}_{r_2}$. T such that $r'_{\min} \geq r_{\min}$, $r'_{\max} \leq r_{\max}$, $r'_{\text{conf}} \geq r_{\text{conf}}$, update $tx.\overline{r_{\min}} = r'_{\min}$, $tx.\overline{r_{\max}} = r'_{\max}$, $tx.\overline{r_{\text{conf}}} = r'_{\text{conf}}$, $tx.\overline{C_{\text{tx}}} = C'_{\text{tx}}$.

 4. If $D^{\text{c}}_{r_2}$. $r_{\text{perf}} > D^{\text{c}}_{r_1}$. r_{perf} , then $\overline{D^{\text{c}}_{r_2}}$. $r_{\text{perf}} = D^{\text{c}}_{r_2}$. r_{perf} . Otherwise, $\overline{D^{\text{c}}_{r_2}}$. $r_{\text{perf}} = \overline{D^{\text{c}}_{r_2}}$.

In the remarks below, we observe that pod monotonicity implies a number of useful properties about the monotonicity of past perfection and the values r_{\min} , r_{\max} , r_{conf} associated to a transaction in the pod.

Remark 8 (Confirmation Monotonicity). Properties 2 and 3 of pod monotonicity imply that for any honest client c and rounds $r_1, r_2 > r_1$, if $tx \in D_{r_1}^c$ and $\mathsf{tx.r_{conf}} \neq \bot$, then $\mathsf{tx} \in D_{\mathsf{r_2}}^{\mathsf{c}}$ and $\mathsf{tx.r_{conf}} \neq \bot$.

Remark 9 (Strong Confirmation Bounds Monotonicity). Properties 2 and 3 of pod monotonicity imply that if an honest client obtains r_{\min} and r_{\max} for tx in round r_1 , then the same client will later obtain r'_{\min} and r'_{\max} for tx in round $r_2 > r_1 \text{ such that } r'_{\min} \geq r_{\min} \text{ and } r'_{\max} \leq r_{\max}.$

Remark 10. Observe that the confirmation monotonicity property in Remark 8 is a specific version of a more general common subset property, which would demand the condition for any two honest clients c_1, c_2 . Construction 1 satisfies the confirmation monotonicity property.

Security of pod-core В

In order to prove Theorem 1 and establish the security of Protocol pod-core shown Construction 1, we first prove some useful intermediate results.

Lemma 1. Regarding Algorithm 3, we have the following. Assume we keep all received timestamps for a transaction tx (n values in total) in a structure timestamps, filling in a special value (0 or ∞) for missing votes, sorted in increasing order. Assume mrt is also sorted in increasing order of timestamps.

1. minPossibleTs() returns as r_{min} the timestamp at index $\lfloor \alpha/2 \rfloor - \beta$ of timestamps.

- 2. maxPossibleTs() returns as r_{max} the timestamp at index $n \alpha + \lfloor \alpha/2 \rfloor + \beta$ of timestamps.
- 3. minPossibleTsForNewTx() returns as r_{perf} the timestamp at index $\lfloor \alpha/2 \rfloor \beta$ of mrt.

Proof. Functions minPossibleTs() and minPossibleTsForNewTx() prepend β times the 0 value in the beginning of the list and return the median of the first α values, hence they return the timestamp at index $\lfloor \alpha/2 \rfloor - \beta$. Function maxPossibleTs() appends β times the ∞ value at the end of the list and returns the median of the last α values of that list, that is, it ignores the first $n - \alpha + \beta$ values and returns the timestamp at index $n - \alpha + \beta + \lfloor \alpha/2 \rfloor$.

Lemma 2. Assuming $\alpha \geq 4\beta + 1$, if a client outputs r_{perf} as the past-perfect round, then there exists some honest replica R_j , such that the most-recent timestamp (mrt) from R_j received by the client satisfies $mrt[R_j] \leq r_{perf}$.

Proof. From Lemma 1 we have that r_{perf} is the timestamp at index $(\lfloor \alpha/2 \rfloor - \beta)$ of sorted mrt. The condition $\alpha \geq 4\beta + 1$ implies that $\beta < \lfloor \alpha/2 \rfloor - \beta$, i.e., there are less than $\lfloor \alpha/2 \rfloor - \beta$ malicious parties, hence one of the indexes between 0 and $\lfloor \alpha/2 \rfloor - \beta$ (inclusive) will contain the timestamp sent to the client by an honest replica.

We now recall Theorem 1, which formally states that Construction 1 satisfies the security definition of pod (Definition 9) with accountable safety (Definition 2). We prove it through a series of lemmas.

Theorem 1 (pod security). In the asynchronous model with actual network delay δ (but unknown delay upper bound), assuming at most β malicious replicas, pod-core (Construction 1), instantiated with a secure signature scheme and parameterized with $\alpha \geq 4\beta + 1$, is a responsive secure pod (Definition 9) with Confirmation within $u = 2\delta$ and Past-perfection within $w = \delta$, satisfying the property of β -accountable safety (Definition 2), except with negligible probability.

Proof. In Lemmas 3-7.

Lemma 3 (Confirmation within u). Construction 1 satisfies the confirmation within u property for $u = 2\delta$.

Proof. Assume an honest client c calls write(tx) at round r. It sends a message $\langle WRITE \ tx \rangle$ to all replicas at round r (line 3). An honest replica receives this by round $r + \delta$ and sends a $\langle VOTE \ \rangle$ message back to all connected clients (line 22). An honest client c' receives the vote by round $r + 2\delta$. As are at least α honest replicas, c' receives at least α such votes, hence the condition in line 12 is satisfied and c' observes tx as confirmed.

Lemma 4 (Past-perfection within w). Construction 1 satisfies the past-perfection within w property for $w = \delta$.

Proof. Assume an honest client c at round r has view D_r^c . From Lemma 2, there exists some honest replica R_j , such that the most-recent timestamp $\mathsf{mrt}[R_j]$ that R_j has sent to c satisfies $D_r^c.\mathsf{r}_{\mathsf{perf}} \geq \mathsf{mrt}[R_j]$. Now, all honest replicas R_j send at least one heartbeat message per round (line 27) and an honest client updates $\mathsf{mrt}[R_j]$ when it receives a vote. Since messages from honest replicas arrive within δ rounds, client c will have $\mathsf{mrt}[R_j] \geq \mathsf{r} - \delta$ for all honest replicas R_j . All together, $D_r^c.\mathsf{r}_{\mathsf{perf}} \geq \mathsf{r} - \delta$.

Lemma 5 (Past-perfection safety). Construction 1 satisfies the past-perfection safety property.

Proof. Assume an honest client c at round r>0 reads the pod and obtains $(\mathsf{T},\mathsf{r}_{\mathrm{perf}},C_{\mathrm{pp}})$. Let \mathcal{R}_1 be the set of replicas R_i for which c stores at round r an $\mathsf{mrt}_i \geq \mathsf{r}_{\mathrm{perf}}$. From Lemma 1 $(\mathsf{r}_{\mathrm{perf}}$ is computed as the timestamp at index $\lfloor \alpha/2 \rfloor - \beta$ of sorted mrt) there exist at least $n - \lfloor a/2 \rfloor + \beta$ such replicas, hence $|R_1| \geq n - \lfloor a/2 \rfloor + \beta$. For each $R_i \in \mathcal{R}_1$, client c has received the whole log of R_i with timestamps up to mrt_i (line 17 of Algorithm 1 does not allow gaps in the sequence number of the received votes). That is, for each $R_i \in \mathcal{R}_1$ client c has received votes

$$(\mathsf{tx}_{i,1},\mathsf{ts}_{i,1},1,\sigma_{i,1},R_i),(\mathsf{tx}_{i,2},\mathsf{ts}_{i,2},2,\sigma_{i,2},R_i),\ldots,(\mathsf{tx}_{i,m_i},\mathsf{ts}_{i,m_i},m_i,\sigma_{i,m_i},R_i),$$
(1)

where m_i is the smallest sequence number for which $ts_{i,m_i} \ge r_{perf}$.

Assume another client \mathbf{c}' at some round $\mathbf{r}' > 0$ outputs a pod $(\mathsf{T}',\cdot,\cdot)$, such that $(\mathsf{tx},\cdot,\cdot,\mathsf{r}_{\mathrm{conf}},C_{\mathrm{tx}}) \in \mathsf{T}'$ and $\mathsf{r}_{\mathrm{conf}} < \mathsf{r}_{\mathrm{perf}}$ (where $\mathsf{r}_{\mathrm{perf}}$ is the past-perfect round observed by \mathbf{c}). For \mathbf{c}' to output a confirmation round $\mathsf{r}_{\mathrm{conf}} < \mathsf{r}_{\mathrm{perf}}$, it must have received timestamps ts_i on tx , such that $\mathsf{ts}_i < \mathsf{r}_{\mathrm{perf}}$, from at least $\lfloor \alpha/2 \rfloor + 1$ (because $\mathsf{r}_{\mathrm{conf}}$ is computed as the median of at least α votes). Let \mathcal{R}_2 be the set of these replicas, with $|\mathcal{R}_2| \geq \lfloor \alpha/2 \rfloor + 1$. For each $R_i \in \mathcal{R}_2$, client c' has received a vote

$$(\mathsf{tx}, \mathsf{ts}_i, \mathsf{sn}_i, \sigma_i, R_i), \tag{2}$$

such that $ts'_i < r_{perf}$.

Observe from the cardinality of \mathcal{R}_1 and \mathcal{R}_2 , that at least $\beta+1$ replicas must be in both sets, hence at least one honest replica must be in both sets (except if the adversary forges a signature under the public key of an honest replica, which happens with negligible probability). For that replica, the vote in eq. (3) must be one of the votes in eq. (1) since $\mathsf{ts}_i < \mathsf{r}_{\mathsf{perf}}$ and $\mathsf{ts}_{j,m_i} \ge \mathsf{r}_{\mathsf{perf}}$. Hence, client c has received at least one vote on tx , so $\mathsf{tx} \in \mathsf{T}$, as demanded by the past-perfection property.

Lemma 6 (Confirmation bounds). Construction 1 satisfies the confirmation bounds safety property.

Proof. Assume client c_1 computes r_{\min} and client c_2 computes $r_{\mathrm{conf}} < r_{\min}$ for tx. From Lemma 1, the number of replicas that have sent to c_1 a timestamp for tx smaller than r_{\min} can be at most $\lfloor \alpha/2 \rfloor - \beta$. Allowing up to β replicas to equivocate, there can be at most $\lfloor \alpha/2 \rfloor$ replicas that send c_2 a timestamp

smaller than r_{\min} . However, in order to assign $r_{\mathrm{conf}} < r_{\min}$ to tx, client c_2 must have received timestamps smaller than r_{\min} from at least $\lfloor \alpha/2 \rfloor + 1$ replicas, a contradiction. For r_{\max} , assume c_1 computes r_{\max} and c_2 computes $r_{\mathrm{conf}} > r_{\max}$. Using Lemma 1, the number of replicas that have sent to c_1 a timestamp larger than r_{\max} can be at most $\alpha - \lfloor \alpha/2 \rfloor - \beta - 1$, hence the number of honest replicas that will send a timestamp larger than r_{\max} to c_2 is at most $\alpha - \lfloor \alpha/2 \rfloor - 1$ (since β are malicious). If α is odd, this upper bound becomes $\alpha - \lfloor \alpha/2 \rfloor - 1 = \lfloor \alpha/2 \rfloor$, while c_2 would need at least $\lfloor \alpha/2 \rfloor + 1$ votes larger that r_{\max} , and if α is even, then $\alpha - \lfloor \alpha/2 \rfloor - 1 = \lfloor \alpha/2 \rfloor - 1$, while c_2 would need at least $\lfloor \alpha/2 \rfloor$ votes larger that r_{\max} in order to compute a median larger than r_{\max} (we remind that algorithm 3 returns as median the value at position $\lfloor \alpha/2 \rfloor$).

Algorithm 8 The identify() function for Protocol pod-core (Construction 1).

```
1: function identify(T)
 2:
             \tilde{R} \leftarrow \emptyset
 3:
            for \langle VOTE (\mathsf{tx}_1, \mathsf{ts}_1, \mathsf{sn}_1, \sigma_1, R_1) \rangle \in T \ \mathbf{do}
 4:
                  if not Verify(pk_1, (tx_1, ts_1, sn_1), \sigma_1) then
                        continue
 5:
 6:
                  end if
 7:
                  for \langle VOTE (\mathsf{tx}_2, \mathsf{ts}_2, \mathsf{sn}_2, \sigma_2, R_2) \rangle \in T do
 8:
                         if not Verify(pk_2, (tx_2, ts_2, sn_2), \sigma_2) then
 9:
                              continue
10:
                         end if
11:
                        if R_1 = R_2 and \operatorname{sn}_1 = \operatorname{sn}_2 and (\operatorname{tx}_1 \neq \operatorname{tx}_2 \text{ or } \operatorname{ts}_1 \neq \operatorname{ts}_2) then
12:
                               R \leftarrow R \cup \{R_1\}
13:
                         end if
14:
                   end for
15:
             end for
16: end function
```

Lemma 7 (β -Accountable safety). Construction 1 satisfies accountable safety with resilience β .

Proof. We show that identify() (Algorithm 8) satisfies the *correctness* and *no-framing* properties required by Definition 2, in three steps.

1. If the past-perfection safety property is violated, there exists a partial transcript T, such that identify() on input T returns at least β adversarial replicas. Proof: Assume an honest client c at round c 0 reads the pod and obtains (T, r_{perf}, C_{pp}) , such that $tx \notin T$, for some $tx \in \{0, 1\}^*$, and another client c' outputs a pod (T', \cdot, \cdot) , such that $(tx, \cdot, \cdot, r_{conf}, C_{tx}) \in T'$ and $r_{conf} < r_{perf}$, thereby violating the past-perfection property for tx. We resume the proof of Lemma 5. There, we constructed the sets $\mathcal{R}_1, \mathcal{R}_2$, such that $\mathcal{R}_1 \cap \mathcal{R}_2$ contains at least $\beta + 1$. For each $R_i \in \mathcal{R}_1 \cap \mathcal{R}_2$, client c has received the replica log shown in (1), containing all votes with timestamp up to $\mathsf{ts}_{i,m_i} \geq \mathsf{r}_{\mathrm{perf}}$. Client c' has received from R_i the following m_i' votes (possibly more, but we care for the votes up to transaction tx)

$$(\mathsf{tx}'_{i,1},\mathsf{ts}'_{i,1},1,\sigma'_{i,1},R_i),(\mathsf{tx}'_{i,2},\mathsf{ts}'_{i,2},2,\sigma'_{i,2},R_i),\dots,(\mathsf{tx}'_{i,m'_i},\mathsf{ts}'_{i,m'_i},m'_i,\sigma'_{i,m'_i},R_i),$$
(3)

with $\mathsf{tx}'_{i,m'_i} = \mathsf{tx}$ and $\mathsf{ts}'_{i,m'_i} < \mathsf{r}_{perf}$. Obviously, for an honest R_i , the replications of (1) and (3) must be identical, i.e., $\mathsf{tx}_{i,j} = \mathsf{tx}'_{i,j}$ and $\mathsf{ts}_{i,j} = \mathsf{ts}'_{i,j}$, for $j \in [1, \min(m_i, m'_i)]$. We will show that they differ in at least one sequence number. If $m_i > m'_i$, then the replica logs differ at sequence number m'_i , because the transaction tx_{i,m'_i} in (1) cannot be tx , as c has not received a vote on tx , and $\mathsf{tx}'_{i,m'_i} = \mathsf{tx}$. If $m_i \leq m'_i$, the log of (1) should be identical with the first m_i positions of the log of (3), which would imply that $\mathsf{ts}_{i,m_i} = \mathsf{ts}'_{i,m_i}$ and, since c' only accepts non-decreasing timestamps, $\mathsf{ts}'_{i,m_i} \leq \mathsf{ts}'_{i,m'_i}$, and all together $\mathsf{ts}_{i,m_i} \leq \mathsf{ts}'_{i,m'_i}$. This is impossible, because $\mathsf{ts}_{i,m_i} > \mathsf{r}_{perf}$ and $\mathsf{ts}'_{i,m'_i} \leq \mathsf{r}_{perf}$. Hence, the two logs will contain a different timestamp for some sequence number in $[1, m'_i]$.

Summarizing, we have shown for at least $\beta+1$ replicas $R_i \in \mathcal{R}_1 \cap \mathcal{R}_2$, clients c and c' hold votes $(\mathsf{tx}_1, \mathsf{ts}_1, \mathsf{sn}_1, \sigma_1, R_i)$ and $(\mathsf{tx}_2, \mathsf{ts}_2, \mathsf{sn}_2, \sigma_2, R_i)$, such that $\mathsf{sn}_1 = \mathsf{sn}_2$ but $\mathsf{tx}_1 \neq \mathsf{tx}_2$ or $\mathsf{ts}_1 \neq \mathsf{ts}_2$. On input a set T that contains these votes, function identify T returns T0.

2. If the confirmation-bounds property is violated, there exists a partial transcript T, such that Algorithm 8 on input T returns at least β adversarial replicas. Proof: Assume a client c_1 outputs some r_{\min} and client c_2 outputs $r_{\text{conf}} < r_{\min}$ for tx. Let's look at the timestamps in timestamps when c_1 computes r_{\min} (function $\min PossibleTs()$ in Algorithm 3.) From Lemma 1, timestamps contains at least $n - \lfloor \alpha/2 \rfloor + \beta$ timestamps ts, such that ts $\geq r_{\min}$. Hence, there is a set \mathcal{R}_1 with at least $n - \lfloor \alpha/2 \rfloor + \beta$ replicas R_i , from each of which c_1 has received votes

$$(\mathsf{tx}_{i,1},\mathsf{ts}_{i,1},1,\sigma_{i,1},R_i),(\mathsf{tx}_{i,2},\mathsf{ts}_{i,2},2,\sigma_{i,2},R_i),\dots,(\mathsf{tx}_{i,m_i},\mathsf{ts}_{i,m_i},m_i,\sigma_{i,m_i},R_i), \tag{4}$$

up to some sequence number m_i , such that $\mathsf{ts}_{i,m_i} \geq \mathsf{r}_{\min}$ and either $\mathsf{tx}_{i,m_i} = \mathsf{tx}$ (i.e., R_i has sent to c_1 a vote on tx , and we only consider the votes up to this one), or $\mathsf{tx}_{i,j} \neq \mathsf{tx}, \forall j \leq m_i$ (i.e., R_i has not sent to c_1 a vote on tx , in which case timestamps contains the timestamp R_i has sent on tx_{i,m_i}).

Now, for c_2 to output $r_{\rm conf} < r_{\rm min}$, it must have received timestamps smaller than $r_{\rm min}$ from at least $\lfloor \alpha/2 \rfloor + 1$ replicas. Call this set \mathcal{R}_2 . From each of these replicas, c_2 has received votes

$$(\mathsf{tx}'_{i,1},\mathsf{ts}'_{i,1},1,\sigma'_{i,1},R_i),(\mathsf{tx}'_{i,2},\mathsf{ts}'_{i,2},2,\sigma'_{i,2},R_i),\dots,(\mathsf{tx},\mathsf{ts}'_{i,m'_i},m'_i,\sigma'_{i,m'_i},R_i),$$
 (5)

showing only votes up to tx, for which $\mathsf{ts}'_{i,m'_i} < \mathsf{r}_{\min}.$

By counting arguments there are at least $\beta+1$ replicas in $\mathcal{R}_1 \cap \mathcal{R}_2$. For each one, we make the following argument. Since $\mathsf{ts}_{i,m_i} \geq \mathsf{r}_{\min}$ and $\mathsf{ts}'_{i,m'_i} < \mathsf{r}_{\min}$, we get $\mathsf{ts}'_{i,m'_i} < \mathsf{ts}_{i,m_i}$, and it must be the case that $m'_i < m_i$ (otherwise, the two

logs will differ at a smaller sequence number, similar to the previous case). But in this case the two logs differ at sequence number m_i' , i.e., $\mathsf{tx}_{i,m_i'} \neq \mathsf{tx}_{i,m_i'}' = \mathsf{tx}$. This is because the log of (4) either does not contain tx , or contains it at sequence number $m_i > m_i'$, in which case it must contain a different transaction at sequence number m_i' . On input a set T that contains all votes for replicas in \mathcal{R}_1 and \mathcal{R}_2 votes, function identify(T) returns $\mathcal{R}_1 \cap \mathcal{R}_2$.

For the case client c_1 outputs some r_{\max} and client c_2 outputs $r_{\mathrm{conf}} \geq r_{\max}$ for tx, similar arguments apply. As explained in the proof of Lemma 6, c_2 has received at least $\lfloor \alpha/2 \rfloor$ or $\lfloor \alpha/2 \rfloor + 1$ votes on tx with timestamp larger than r_{\max} , and (from Lemma 1) at least $n - \alpha + \lfloor \alpha/2 \rfloor + \beta$ replicas have sent to c_1 a vote on tx with a timestamp smaller or equal than r_{\max} . As before, the replicas in the intersection of these two sets have sent conflicting votes for some sequence numbers.

3. The identify() function never outputs honest replicas.

Proof: The function only adds a replica to R if given as input two valid vote messages from that replica, in which it assigns the same sequence number to two different votes (line 11 on Algorithm 8). An honest replica always increments nextsn after each vote it inserts to its log (line 24 on Algorithm 4), hence, except with negligible probability, no such valid messages can be constructed for an honest replica.

Theorem 3 (θ -timeliness for honest transactions). Construction 1, parametrized with $\alpha \geq 4\beta + 1$, satisfies θ -timeliness for honest transactions, as per Definition 10, for $\theta = \delta$.

Proof. Assume an honest client c calls write(tx) at round r. It sends a message $\langle WRITE \ tx \rangle$ to all replicas at round r (line 3). An honest replica receives this by round $r + \delta$ and assigns its current round $r' \in (r, r + \delta]$ as the timestamp (line 19).

- 1. Regarding $r_{\rm conf}$, when a client calls read(), and since by assumption tx is confirmed, it will have received votes on tx from at least α replicas. All honest replicas have sent timestamps for tx in the interval $(r, r + \delta]$. Since $r_{\rm conf}$ is computed as the median of α timestamps and $\alpha > 4\beta + 1$, it will be a timestamp returned by an honest replica, or it will lie between timestamps returned by honest replicas. Hence, $r_{\rm conf} \in (r, r + \delta]$.
- 2. Regarding r_{max} , from Lemma 1, at least $\lceil \alpha/2 \rceil \beta\beta$ replicas have sent to c a timestamp greater or equal than r_{max} and, since $\alpha > 4\beta + 1$, at least one of those is a timestamp returned by an honest replica, hence $r_{\text{max}} \in (r, r + \delta]$.
- 3. Similarly, from Lemma 1 we get that r_{\min} is a timestamp returned by an honest replica, hence $r_{\min} \in (r, r + \delta]$ and $r_{\max} r_{\min} < \theta$.

³ For this argument, $\alpha > 2\beta + 1$ would also be enough. The condition $\alpha > 2\beta + 1$ is necessary in order for $r_{\rm min}$ and $r_{\rm max}$ of a confirmed transaction to be timestamps returned by honest replicas.

C Security of bidset-core

In this section, we recall and prove Theorem 2.

Theorem 2 (Bidset security). Assuming a synchronous network where $\delta \leq \Delta$, protocol bidset-core (Construction 2) instantiated with a digital signature and a secure pod protocol that satisfies the past-perfection within $w = \delta$, confirmation within $u = 2\delta$ and δ -timeliness properties, is a secure bidset protocol satisfying termination within $W = 3\Delta + \delta$. It satisfies accountable safety with an identifyAuctioneer() function that identifies a malicious auctioneer.

Proof. In Lemmas 8–11. The function for identifying a malicious auctioneer is shown in Algorithm 9. \Box

Lemma 8 (Termination within W). Under the assumptions of Theorem 2, Construction 2 satisfies termination within $W = t_0 + 3\Delta + \delta$.

Proof. The result() event is generated by an honest consumer when its exits the loop of lines 2–9 in Algorithm 7. At the latest, this happens when round $t_0+3\Delta$ becomes past-perfect (line 6 in Algorithm 7), which, from the past-perfection within δ property of pod, happens at round at most $t_0+3\Delta+\delta$, hence $W=t_0+3\Delta+\delta$. We remark than an auctioneer (Algorithm 6) also terminates, because from the past-perfection within δ property of pod, the condition of line 3 becomes true by round $t_0+\Delta+\delta$.

Lemma 9 (Censorship resistance). Under the assumptions of Theorem 2, Construction 2 satisfies the censorship resistance property.

Proof. Assume the auctioneer is honest, and an honest bidder calls submitBid(b) at time t_0 . We will show that $b \in B$. First, the pod view D_r^a of the auctioneer a on the round r when it constructs B satisfies $D_r^a.r_{perf} > t_2$. Second, from the confirmation within u property of pod, the transaction containing b becomes confirmed, and from the θ -timeliness property of pod, it gets a confirmation round $r_{conf} \le t_0 + \theta$. For $\theta = \delta$, and since $\delta \le \Delta$, we get that $r_{conf} \le t_2$. Hence, from the past-perfection safety property of pod we get that $b \in D_r^a$, and, since the auctioneer is honest, $b \in B$.

Lemma 10 (Consistency). Under the assumptions of Theorem 2, Construction 2 satisfies the consistency property.

Proof. Assume the auctioneer is honest, and two honest consumers generate events $\operatorname{result}(B_1,\cdot)$ and $\operatorname{result}(B_2,\cdot)$. The condition in line 3 of Algorithm 6 becomes true in the view of auctioneer by round $t_0 + \Delta + \delta$ (from the past-perfection within $w = \delta$ property of pod-core), hence the auctioneer writes transaction $\langle BIDS\ (B, C_{\operatorname{bid}}, \sigma) \rangle$ to the pod by round $t_0 + \Delta + \delta$. This transaction gets assigned a confirmed round $\operatorname{r_{conf}} \leq t_0 + \Delta + 2\delta$ (from the δ -timeliness property of pod) and, by assumption of a synchronous network, $\operatorname{r_{conf}} \leq t_0 + 3\Delta$. The condition in line 4 of Algorithm 7 requires that a round $\operatorname{r'} > t_0 + 3\Delta$ becomes

past perfect. As $\mathbf{r'} > \mathbf{r_{conf}}$, and by past-perfection safety of pod, the consumer observes the transaction as confirmed before $\mathbf{r'}$ becomes past-perfect, hence the condition in line 4 becomes true before the condition in line 6 and an honest consumer outputs $\operatorname{result}(B, C_{bid})$.

Lemma 11 (Accountable safety). Under the assumptions of Theorem 2, and assuming that pod is an instance of pod-core, Construction 2 achieves accountable safety, using the identifyAuctioneer() function (Algorithm 9) to identify a malicious auctioneer.

Proof. Following Section 2.2, we show an identifyAuctioneer(T) function (Algorithm 9), that, on input a partial transcript T outputs true when safety is violated due to misbehavior of the auctioneer (i.e., it identifies the auctioneer as malicious), and false if the auctioneer is honest. We prove the theorem in three parts.

1. For violations of censorship-resistance:

Assume an honest bidder calls submitBid(b) at time t_0 and the network is synchronous. The transaction tx containing b becomes confirmed, and any honest party can observe $(\mathsf{tx},\mathsf{r}_{\mathsf{conf}},\cdot,\cdot,C_{\mathsf{tx}})$ in their view of the pod, where C_{tx} is the auxiliary data associated by tx , as returned by pod-core. Assume b is censored, i.e., an event $result(B,\,C_{\mathsf{bid}})$ is output by an honest consumer, such that $b \notin B$. Let σ be the signature of the auctioneer in the corresponding $\langle BIDS\ (B,C_{\mathsf{bid}},\sigma)\rangle$ message written on pod. We will show how the auctioneer can be made accountable, using $(C_{\mathsf{tx}},B,C_{\mathsf{bid}},\sigma)$ as evidence T. In order for $(C_{\mathsf{tx}},B,C_{\mathsf{bid}},\sigma)$ to be valid evidence, the following must hold:

Requirement 1: The signature σ must be a valid signature, produced by the auctioneer on message (B, C_{bid}) , as per line 7 of the auctioneer code (line 3).

Requirement 2: $C_{\rm tx}$ must contain at least α votes (line 18), on the same transaction ${\sf tx}^*$ (line 23), signed by a pod replica (line 24).

If any of these requirements are not met, T does not constitute valid evidence and the function exits. Otherwise, let r_{conf}^* be the median of all votes in C_{tx} . The function makes the following checks, and if any of them fails, then the auctioneer is accountable.

Check 1: Verify whether the votes that the auctioneer has included in $C_{\rm bid}$ are valid, obtained from the replicas that run pod (lines 5-11). If this is not the case, the auctioneer has misbehaved.

Check 2: Compute the r_{perf} from the timestamps found in the votes in C_{bid} (lines 12-17). This r_{perf} must be larger than $t_0 + \Delta$, as per line 3 of Algorithm 6.

Check 3: If $r_{\text{conf}}^* \leq t_0 + \Delta$ but tx^* is not in the bag, the auctioneer has misbehaved.

2. For violations of consistency:

The consistency property can be violated if the auctioneer writes two transactions $\langle BIDS\ (B_1,\cdot,\cdot)\rangle$ and $\langle BIDS\ (B_2,\cdot,\cdot)\rangle$ to pod, such that $B_1\neq B_2$, in which case B_1 and B_2 identify the auctioneer. As this is a simpler case, we do not show it in Algorithm 9.

3. A honest auctioneer cannot be framed:

Finally, we show that an honest auctioneer cannot be framed. If the auctioneer has followed Algorithm 6, then $C_{\rm bid}$ will contain valid votes, hence $Check\ 1$ will pass. Moreover, an honest auctioneer waits until the past-perfect round returned by the pod is larger than $t_0 + \Delta$, hence $Check\ 2$ will pass. Regarding $Check\ 3$, observe that for identifyAuctioneer() to compute $\mathsf{r}^*_{\rm conf} \le t_0 + \Delta$, $C_{\rm tx}$ must contain at least $\lfloor \alpha/2 \rfloor + 1$ votes on tx^* with a timestamp smaller or equal than $t_0 + \Delta$, and at least $\lfloor \alpha/2 \rfloor + 1 - \beta$ of them must be from honest replicas. Call this set \mathcal{R}' . The honest auctioneer, in order to output a past-perfect round greater than $t_0 + \Delta$, must have received timestamps greater than $t_0 + \Delta$ from at least $n - \lfloor a/2 \rfloor + \beta$ replicas (from Lemma 1). By counting arguments, at least one of these timestamps must be from one of the honest replicas in \mathcal{R}' , and, since honest replicas do not omit transactions, that replica will have sent a vote on tx^* to the auctioneer. Hence, the honest auctioneer will include tx^* in B.

Algorithm 9 The identifyAuctioneer() function for Construction 2, instantiated with an instance of pod-core (Construction 1) as pod, run by a set of replicas $\mathcal{R} = \{R_1, \dots, R_n\}$ with public keys $\{pk1, \dots, pk_n\}$, and using the median() operation defined by Construction 1. It identifies a malicious auctioneer, whose public key is pk_a , by returning true.

```
1: function identify(T)
 2:
             (C_{\text{tx}}, B, C_{\text{bid}}, \sigma) \leftarrow T
 3:
            require Verify(pk_a, (B, C_{bid}), \sigma)
 4:
            timestamps \leftarrow []
 5:
            for vote \in C_{\mathrm{bid}} do
 6:
                   (\mathsf{tx}, \mathsf{ts}, \mathsf{sn}, \sigma, R_j) \leftarrow \mathsf{vote}
 7:
                   if Verify(pk_i, (tx, ts, sn), \sigma = 0) then
                         return true
 8:
 9:
                   end if
                   timestamps \leftarrow timestamps || ts
10:
11:
             end for
12:
             sort timestamps in increasing order
             timestamps \leftarrow [0, {}^{\beta} \overset{\text{times}}{\dots}, 0] \parallel \text{timestamps}
13:
             r_{perf} \leftarrow median(timestamps[: \alpha])
14:
15:
             if r_{perf} \leq t_0 + \Delta then
16:
                   return true
17:
             end if
18:
             require |C_{\rm tx}| \geq \alpha
19:
             \mathsf{tx}^* \leftarrow C_{\mathsf{tx}}[0].\mathsf{tx}
             timestamps \leftarrow []
20:
21:
             \mathbf{for}\ \mathsf{vote} \in C_{\mathrm{tx}}\ \mathbf{do}
22:
                   (\mathsf{tx}, \mathsf{ts}, \mathsf{sn}, \sigma, R_j) \leftarrow \mathsf{vote}
23:
                   require tx = tx^*
                   require Verify(pk_i, (tx, ts, sn), \sigma)
24:
25:
                   timestamps \leftarrow timestamps || ts
26:
             \begin{aligned} \mathbf{r}_{\mathrm{conf}}^* &\leftarrow median(\textit{timestamps}) \\ \mathbf{if} \ \mathbf{r}_{\mathrm{conf}}^* &\leq t_0 + \Delta \ \mathbf{and} \ \mathbf{tx}^* \not\in B \ \mathbf{then} \end{aligned} 
27:
28:
29:
                   return true
30:
             end if
31: end function
```