

Appending Atomically in Byzantine Distributed Ledgers^{*}

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Abstract. A Distributed Ledger Object (DLO) is a concurrent object that maintains a totally ordered sequence of records, and supports two basic operations: APPEND, which appends a record at the end of the sequence, and GET, which returns the sequence of records. In this work we provide a proper formalization of a *Byzantine-tolerant Distributed Ledger Object* (BDLO), which is a DLO in a distributed system in which processes may deviate arbitrarily from their intended behavior, i.e. they may be Byzantine. Our formal definition is accompanied by algorithms to implement BDLOs by utilizing an underlying Byzantine Atomic Broadcast service.

We then utilize the BDLO implementations to solve the *Atomic Appends* problem against Byzantine processes. The Atomic Appends problem emerges when several clients have records to append, the record of each client has to be appended to a different BDLO, and it must be guaranteed that either *all* records are appended or *none*. We present distributed algorithms implementing solutions for the Atomic Appends problem when the clients (which are involved in the appends) and the servers (which maintain the BDLOs) may be Byzantine.

Keywords: Distributed Ledger Object · Byzantine Faults · Atomic Appends

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1 Introduction

There has been a great interest recently in the so-called crypto-technologies (e.g., blockchain systems [18]), and distributed ledger technology (DLT) in general [24], which are becoming very popular and are expected to have a high impact in multiple aspects of our everyday life. Although such a recent popularity is primarily due to the explosive growth of numerous crypto-currencies, there are many applications of this core technology that are outside the financial industry. These applications arise from leveraging various useful features provided by distributed ledgers, such as a decentralized information management, immutable record keeping for possible audit trail, robustness, availability, security, and privacy (see, for instance, [13,19,23,5]). However, there are many different blockchain systems, and new ones are proposed almost everyday. Hence, it is extremely unlikely that one single DLT or blockchain system will prevail. This is forcing the DLT community to accept that it is inevitable to come up with ways to make blockchains interconnect and interoperate.

In that direction, the work in [4] proposed a formal definition of a reliable concurrent object, termed Distributed Ledger Object (DLO), which tries to convey the essential elements of blockchains. In particular, a DLO maintains a sequence of records, and has only two operations, APPEND and GET. The APPEND operation is used to add a new record at the end of the sequence, while the GET operation returns the sequence. Using the above-mentioned formalism, in [8] the authors initiated the study of systems formed by multiple DLOs that interact among each other. Namely, they defined the *Atomic Appends problem*, in which several clients have records to append, the record of each client has to be appended to a different DLO, and it must be guaranteed that either all records are appended or none. Consider, for example, two clients A and B where the one, say A , buys a car from B . Record r_A includes the transfer of the car's digital deed from B to A , and r_B includes the transfer from A to B the agreed amount in some digital currency c . DLO_A is a ledger maintaining digital deeds and DLO_B maintains transactions in the digital currency c . So, while the two records are mutually dependent, they concern different DLOs, hence the Atomic Append problem requires that *either* record r_A is appended in DLO_A and record r_B is appended in DLO_B *or* none of the records are appended in the corresponding DLOs.

In [8] the clients were assumed to be selfish and rational [21], and could have different incentives for the different outcomes. Additionally, it was assumed that they could fail by crashing, which makes solving the problem more challenging. The authors showed that for some cases the existence of an intermediary is necessary for the problem solution, and proposed the implementation of such intermediary over a specialized blockchain (termed *Smart DLO*, SDLO), also showing how this can be used to solve the Atomic Appends problem even in an asynchronous, client competitive environment, in which all the clients may crash.

Related Work: The Atomic Appends problem we describe above is very related to the multi-party fair exchange problem [9], in which several parties exchange commodities so that everyone gives an item away and receives an item in return. However, the proposed solutions for this problem rely on cryptographic techniques [14,17] and are not designed for distributed ledgers.

Among the first problems identified involving the interconnection of blockchains was the Atomic Cross-chain Swap [10], which can also be seen as a version of the fair exchange problem. In this case, two or more users want to exchange assets (usually cryptocurrency) in multiple blockchains. Herlihy [10] has formalized and generalized atomic cross-chain swaps beyond one-to-one paths, and shows how multiple cross-chain swaps can be achieved if the transfers form a strongly connected directed graph. Herlihy proves that the best strategy, in Game Theoretic sense, for the users is to follow the proposed algorithm, and that someone that follows it will never end up worse than at the start. Unfortunately, these guarantees do not hold if the system is asynchronous.

Unlike in most blockchain systems, in Hyperledger Fabric [2,3] it is possible to have transactions that span several blockchains (blockchains are called *channels* in Hyperledger Fabric). This allows solving the atomic cross-chain swap problem using a third trusted channel or a mechanism similar to a two-phase commit [3]. Additionally, these solutions do not require synchrony from the system. The ability of channels to access each other's state and interact is a very interesting feature of Hyperledger Fabric, very in line with the techniques we assume from advanced distributed ledgers in this paper. Unfortunately, they seem to be limited to the channels of a given Hyperledger Fabric deployment.

There are other blockchain systems under development that, like Hyperledger Fabric, will allow interactions between the different chains, presumably with many more operations than atomic swaps. Examples are Cosmos [12] or PolkaDot [22]. These systems will have their own multi-chain technology, so only chains in a given deployment can initially interact, and other blockchain will be connected via gateways.

The practical need of blockchain systems to access the outside world to retrieve data (e.g., exchange rates, bank account balances) has been solved with the use of *blockchain oracles*. These are relatively reliable sources of data that can be used inside a blockchain, typically in a smart contract. The weakest aspect of blockchain oracles is trust, since the outcome or actions of a smart contract will be as reliable as the data provided by the oracle. As of now, it seems there is no good solution for this trust problem, and blockchains have to rely on oracle services like Oraclize [20].

Contributions: Contrary to what was assumed in [4,8] (i.e., both clients and servers can only fail by crashing), in existing blockchain systems, both the servers (e.g., miners) and the clients (e.g., users) could be acting maliciously. To this respect, in this work we present implementations where *both* the clients and the servers can be Byzantine, i.e., we present implementations of *Byzantine-tolerant* linearizable DLOs. Our contributions are as follows:

- We provide a formalization of *Byzantine-tolerant Distributed Ledger Objects* – BDLOs (Sect. 2).
- We present and prove the correctness of algorithms that implement a linearizable BDLO (Sect. 3) in an asynchronous setting (enriched with a Byzantine Atomic Braodcast service) in which up to f servers can fail, and (i) an unbounded number of clients can fail (Sect. 3.1); or (ii) only a bounded number t of clients can fail (Sect. 3.2). In the second case we can prevent spurious records to be appended by malicious clients without the need of any additional mechanism.
- We provide a definition of the *Atomic Appends* problem in a system with Byzantine failures (Sect. 2).
- We present and prove how the above algorithms implementing BDLOs can be combined and adapted to solve the Atomic Appends problem (Sect. 4).
 - (i) First, we build a Smart BDLO (SBDLO, first presented in [8] for tolerating crashes) to aggregate and coordinate the append of multiple records (Sect. 4.1). The SBDLO is implemented with a set N of $n \geq 2t + 1$ servers up to which at most t can fail. The BDLOs on which the Atomic Appends is applied are implemented as BDLOs with a bounded number t of Byzantine clients, so it is guaranteed that only if at least one correct process in N appends in them, the append takes place.
 - (ii) Then, we show how the problem can be solved by replacing the SBDLO with a “regular” BDLO and the use of a set N of at least $2t + 1$ “helper” processes, of which at most t can fail (Sect. 4.2). These processes monitor (by periodic GET operations) the BDLO for new Atomic Appends operations. Once matching Atomic Appends records are observed, the helper processes perform the APPEND operations to the corresponding BDLOs.

2 Model and Definitions

Distributed Ledger Objects: A Distributed Ledger Object (DLO) is a concurrent object that stores a totally ordered sequence of *records* (initially empty). A DLO \mathcal{L} supports two operations, $\mathcal{L}.\text{APPEND}(r)$ and $\mathcal{L}.\text{GET}()$, which append a new record r to the sequence and return the whole sequence, respectively [4]. A *record* is a triple $r = \langle \tau, p, v \rangle$, where p is the identifier of the process that created record r , v is the data of the record drawn from an alphabet Σ , and τ is a *unique* record identifier from a set \mathcal{T} (e.g., the cryptographic hash of $\langle p, v \rangle$). The DLO is implemented by a set of *servers* that collaborate running a distributed algorithm. The DLO is used by a set of *clients* that access it by invoking APPEND and GET operations, which are translated into request and response messages exchanged with the servers. An execution is a sequence of *invocation* and *return* events, starting with an invocation event. An operation π is *complete* in an execution ξ , if both the invocation and matching return of π appear in ξ . We say that an operation π_1 *precedes* an operation π_2 , or π_2 *succeeds* π_1 , in an execution ξ if the return event of π_1 appears before the invocation event of π_2 in ξ ; otherwise the two operations are *concurrent*. In this work we focus on *linearizable* DLOs [4]. Informally, under linearizability, the APPEND and GET operations

appear as if they occur instantaneously, which yields a total order among them. This order must respect real-time ordering, and be consistent with the semantics of operations: no $\text{GET}()$ preceding $\text{APPEND}(r)$ returns a sequence with r , and all GET operations that succeed $\text{APPEND}(r)$ do. By default any client can append records or access the state of a DLO with GET . However, if convenient, we may assume that the set of clients that can issue (APPEND and GET) operations is restricted. For instance, we assume that only the creator $r.p$ of a record r can append the record in a DLO \mathcal{L} , or restrict APPEND operations to a predefined set of clients N .

Failure Model: In this work we assume that processes (servers and clients) can fail arbitrarily, i.e., we assume that failures are Byzantine. Specifically, we assume a *Byzantine system* in which *up to f servers* can fail arbitrarily and that the total number of servers is at least $3f + 1$. For clients we consider two cases: (i) any number of clients can be Byzantine; (ii) up to t clients can be Byzantine. We assume that each process p (client or server) has a pair of public and private keys, and a cryptographic certificate containing its public key. These certificates are generated by a reliable authority, so we discard the possibility of spurious or fake processes (there cannot be Sybil attacks), and have been distributed to all the processes that may interact with each other. Hence, we also assume that the messages sent by any process (server or client) are authenticated, so that messages corrupted or fabricated by Byzantine processes are detected and discarded by correct processes [7]. Communication channels between correct processes are reliable but asynchronous.

Byzantine-tolerant DLO: The first aim of this paper is to propose algorithms that implement a linearizable DLO \mathcal{L} in Byzantine systems. Since Byzantine clients and servers can behave arbitrarily, we define the properties that a DLO must satisfy adapted to Byzantine systems. In particular, since Byzantine processes may return any arbitrary sequence or append any record, the properties only consider the actions of *correct processes*.

- *Byzantine Completeness (BC):* All the GET and APPEND operations invoked by correct clients eventually complete.
- *Byzantine Strong Prefix (BSP):* If two *correct clients* issue two $\mathcal{L}.\text{GET}()$ operations that return record sequences S and S' respectively, then either S is a prefix of S' or vice-versa.
- *Byzantine Linearizability (BL):* Let G be the set of all complete GET operations issued by correct clients. Let A be the set of complete APPEND operations $\mathcal{L}.\text{APPEND}(r)$ such that $r \in S$ and S is the sequence returned by some operation $\mathcal{L}.\text{GET}() \in G$. Then linearizability holds with respect to the set of operations $G \cup A$. This property is similar to the one described in [16] for registers.

In the remainder we say that a DLO is *Byzantine Tolerant* if it satisfies the properties BC, BSP, and BL in a Byzantine system. We will be referring to a Byzantine-tolerant DLO by BDLO.

Observe that it is possible that some APPEND operations issued by Byzantine processes might not be distinguished by correct processes. To this respect, we consider the notion of *effective appends*. To add a record r to a BDLO, a Byzantine process p_k can invoke APPEND(r), in which case it behaves as if it was correct. It can also attempt to add a record to the BDLO without explicitly invoking an APPEND(). To this end, it can send underlying messages which, from the point of view of the correct processes, simulate an invocation of APPEND(r). It can also intertwine several such insertion of records to the BDLO. Such attempts to add records, without invoking the operation APPEND() may or not succeed. We say that such an attempt constitutes an *effective append* if no correct process can distinguish it from a correct invocation of APPEND(). Hence an effective append adds a record to the BDLO. We study this issue in Section 3.

Multiple DLOs (MDLO) and Multiple BDLOs (MBDLO): A *Multi-Distributed Ledger Object* \mathcal{M} , termed MDLO, consists of a collection D of (heterogeneous linearizable) DLOs and supports the following operations: (i) $\mathcal{M}.GET_p(\mathcal{L})$, and (ii) $\mathcal{M}.APPEND_p(\mathcal{L}, r)$ [8]. The GET operation returns the sequence of records $\mathcal{L}.S$, where $\mathcal{L} \in D$. Similarly, the APPEND operation appends the record r to the end of the sequence $\mathcal{L}.S$, where $\mathcal{L} \in D$. From the locality property of linearizability [11] it follows that a MDLO is linearizable, if it is composed of linearizable DLOs. *Multiple BDLOs*, termed MBDLO, are defined similarly over a collection of BDLOs (i.e., Byzantine-tolerant DLOs)⁷.

The Atomic Appends Problem: Following [8], we define the Atomic Appends problem, termed *AtomicAppends*, that captures the properties we need to satisfy when multiple operations attempt to append *dependent* records on different BDLOs of an MBDLO. Intuitively, *AtomicAppends* is analogous to the atomic cross-chain swap [10] in a MBDLO. In the crash failure model considered in [8], informally *AtomicAppends* requires that either *all* records will be appended on the involved BDLOs or *none*. However, in the Byzantine failures model it is impossible from preventing a faulty client to append its record without coordination with the rest of clients. Hence, the Atomic Appends problem has to be redefined for this failure model.

We say that a record r *depends* on a record r' , if r may be appended on its intended BDLO, say \mathcal{L} , only if r' is appended on a BDLO, say \mathcal{L}' . Two records, r and r' , are *mutually dependent*, if r depends on r' and r' depends on r .

Definition 1 (2-AtomicAppends). Consider two clients, p and q , with mutually dependent records r_p and r_q . We say that records r_p and r_q are appended atomically in BDLO \mathcal{L}_p and BDLO \mathcal{L}_q , respectively, when:

- AA-safety (AAS): The record (say r_p wlog) of a correct client (p) is appended (in \mathcal{L}_p) only if the record of the other client (q , which may be correct or not) is also appended (in \mathcal{L}_q).

⁷ Note that we do not restrict whether the BDLOs in the MBDLO are implemented by common servers, or each BDLO is implemented by different servers, as long as the total number of servers and the bound on how many can fail is respected.

- AA-liveness (AAL): *If both p and q are correct, then both records are appended eventually.*

As mentioned above, it is not possible to prevent a faulty client q from appending its record r_q even if the correct client p does not. What the safety property AAS guarantees is that the opposite cannot happen. This is analogous of the property in atomic cross-chain swaps [10] that a correct process cannot end up worse than at the beginning. For instance, when the records represent the transfer of assets between p and q , if a faulty client appends its record it is transferring its asset possibly without receiving anything in exchange.

An algorithm *solves* the 2-AtomicAppends problem under a given system, if it guarantees the safety and liveness properties AAS and AAL of Definition 1 in every execution of the system. Since we consider Byzantine failures, our system model with respect to the Atomic Appends problem is such that the correct processes want to proceed with the append of the records (to guarantee liveness AAL), while the Byzantine processes may try to get correct clients to append (to prevent safety AAS).

The k -AtomicAppends problem, for $k \geq 2$, is a generalization of the 2-AtomicAppends that can be defined in the natural way (k clients, with k mutually dependent records, to be appended to up to k BDLOs.) From this point onwards, we will focus on the 2-AtomicAppends problem, and when clear from the context, we will refer to it simply as *AtomicAppends*.

Byzantine Atomic Broadcast: In the algorithms we propose in this paper for implementing BDLOs, we use a Byzantine Atomic Broadcast (BAB) service for the server communication [6,7,15], that satisfies the properties of validity, agreement, integrity, and total order, defined as follows:

- *Validity*: if a correct server BAB-broadcasts a message, then it will eventually BAB-deliver it.
- *Agreement*: if a correct server BAB-delivers a message, then all correct servers will eventually BAB-deliver that message.
- *Integrity*: a message is BAB-delivered by each correct server at most once, and only if it was previously BAB-broadcast.
- *Total Order*: the messages BAB-delivered by correct servers are totally ordered; i.e., if any correct server BAB-delivers message m before message m' , then every correct server must do it in that order.

Note that the work in [4] utilized a crash-tolerant Atomic Broadcast (AB) service to implement a crash-tolerant DLO. The properties assumed here for the BAB service are similar to their counterpart in the AB service, but applied only to correct processes (since in the AB service processes stop when they fail, these properties could be satisfied by the whole set of processes). It is important to mention that it is not enough to replace the AB service with a BAB service in the algorithms of [4] to implement a Byzantine DLO, and ensure the satisfaction of properties BC, BSP, and BL. Therefore, we need to introduce some additional machinery.

Code 1 API to the operations of a BDLO \mathcal{L} , executed by Client p

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1: Init:  $c \leftarrow 0$ 
2: function  $\mathcal{L}.\text{GET}()$ 
3:    $c \leftarrow c + 1$ 
4:   send request  $(c, p, \text{GET})$  to at least  $2f + 1$  different servers
5:   wait resp.  $(c, i, \text{GETRESP}, S)$  from  $f + 1$  different servers with the same sequence  $S$ 
6:   return  $S$ 
7: function  $\mathcal{L}.\text{APPEND}(r)$ 
8:    $c \leftarrow c + 1$ 
9:   send request  $(c, p, \text{APPEND}, r)$  to at least  $2f + 1$  different servers
10:  wait resp.  $(c, i, \text{APPENDRESP}, \text{ACK})$  from  $f + 1$  different servers
11:  return  $\text{ACK}$ 

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Code 2 Algorithm u-ByDL: Byzantine-tolerant DLO; Code for Server i

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1: Init:  $S_i \leftarrow \emptyset$ 
2: receive  $(c, p, \text{GET})$  from process  $p$ 
3:   BAB-broadcast $(c, p, \text{GET}, i)$ 
4:   upon  $(\text{BAB-deliver}(c, p, \text{GET}, j))$  do
5:     if  $((c, p, \text{GET}, -)$  has been BAB-delivered  $f + 1$  times from different servers) then
6:       send resp.  $(c, i, \text{GETRESP}, S_i)$  to  $p$ 
7:   receive  $(c, p, \text{APPEND}, r)$  from process  $p$ 
8:   BAB-broadcast $(c, p, \text{APPEND}, r, i)$ 
9:   upon  $(\text{BAB-deliver}(c, p, \text{APPEND}, r, j))$  do
10:    if  $(r \notin S_i)$  and
11:       $((c, p, \text{APPEND}, r, -)$  has been BAB-delivered from  $f + 1$  different servers) then
12:         $S_i \leftarrow S_i \parallel r$ 
13:        send resp.  $(c, i, \text{APPENDRESP}, \text{ACK})$  to  $p$ 

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3 Algorithms for Byzantine-tolerant DLOs

In this section, we introduce algorithms for implementing Byzantine-tolerant DLOs. First, we assume that there is no bound on the number of clients that can fail (Section 3.1). However, if all clients can be Byzantine, then there is no way to prevent a client from appending a meaningless record (unless we assume that servers are *clairvoyants*, in the sense of detecting such records simply by checking them). In other words, effective appends are possible (cf. Sect. 2). Thus, in Section 3.2 we assume that there is a bound t on the maximum number of clients that can fail, and provide the algorithms that implement the corresponding DLOs. In that case, we detect the meaningless records by requesting an append operation to be issued by, at least, $t + 1$ clients; hence, effective appends can be prevented.

3.1 Unbounded Number of Byzantine Clients

Client Algorithm: The algorithm executed by a client that invokes a GET or APPEND operation on a DLO \mathcal{L} is presented in Code 1. An operation starts with the **invocation** (event) of the corresponding function in Code 1, and it ends when the matching **return** instruction is executed (return event). A Byzantine client p may not follow Code 1 (as it may behave arbitrarily) but still be able to append a record r in the ledger (with an effective append). So, some correct client may obtain, in the response to a GET operation, a sequence that contains a record r appended by a Byzantine client.

When an operation is invoked, a correct client increments a local counter and then sends operation requests to a set of at least $2f + 1$ servers, to guarantee that at least $f + 1$ correct servers receive it. A GET operation completes when the client receives $f + 1$ *consistent* replies and an APPEND completes when the client receives $f + 1$ replies from different servers. Both cases guarantee the response from at least one correct server.

Server Algorithm: The algorithm executed by the servers is presented in Code 2. We denote it Algorithm u-ByDL (from unbounded Byzantine Distributed Ledger). The algorithm uses the Byzantine Atomic Broadcast service to impose a total order in the messages shared among the servers. Operations received from clients are BAB-broadcast using this service, which are eventually BAB-delivered. An operation is processed by a server only when it has been BAB-delivered $f + 1$ times (sent by different servers). This implies that at least one correct server sent it. The properties of the BAB service guarantee that all correct servers receive the same sequence of messages BAB-delivered, and hence process the operations at the same point, maintaining their states consistent.

Theorem 1. *Algorithm u-ByDL implements a linearizable Byzantine Tolerant Distributed Ledger Object.*

Proof. To prove the correctness of the algorithm we need to show that it satisfies both the liveness property BC and the safety properties BSP and BL.

Liveness: The algorithm guarantees the liveness property BC with respect to the failure model we assume. More precisely, each correct client sends requests to $2f + 1$ servers for an operation π and waits for $f + 1$ servers to reply. Given that the channels are reliable and up to f servers may fail (and thus not reply) then at least $f + 1$ correct servers will eventually receive and BAB-broadcast the request from π . According to the BAB-Validity property, each message broadcasted by a correct server will eventually be BAB-delivered. Furthermore, by the BAB-Agreement property, all correct servers will eventually BAB-deliver the messages broadcasted by correct servers. Thus, at least $f + 1$ correct servers will deliver at least $f + 1$ messages broadcasted by the correct client. Those servers will reply to operation π , and hence the client will receive at least $f + 1$ replies and terminate.

Safety: To prove safety we need to show that any execution of our algorithm satisfies properties BSP and BL.

BSP: Byzantine Strong Prefix (BSP) requires that if two GET operations from two correct clients return sequences S and S' resp., then either S is a prefix of S' or S' is a prefix of S . To derive contradiction let us assume that S is not a prefix of S' . Let $S = r_1 r_2 \dots r_n$ and $S' = r'_1 r'_2 \dots r'_m$ with $m \geq n$. As S' is not a prefix of S , then $\exists r_i$ in S , for $1 \leq i \leq n$ s.t. $r_i \neq r'_i$. From the algorithm it follows that the GET operations received S and S' from at least one correct server as each get operations waits for $f + 1$ *different* servers to reply with the *same* sequence. Let s be the correct server that sent S and s' be the correct server that replied with S' . Before appending a record r_j in its local ledger, a correct

server needs to wait for $f + 1$ messages that contain r_j to be BAB-delivered. This guarantees that at least a single correct server received the request for appending r_j and BAB-broadcasted that record. According however to BAB-Agreement if s BAB-delivers r_j then s' will BAB-deliver r_j as well. Furthermore, for each record r_k , for $1 \leq k \leq j$, that is BAB-delivered in s will also BAB-delivered in s' and according to the BAB-Total Order those records will be delivered in the same order in both correct servers. This can be seen with a simple induction. The first record of S , r_1 , will be BAB-delivered to both servers s and s' (by BAB-Agreement property). Record r_2 will be BAB-delivered after r_1 in s . By BAB-Agreement property r_2 will be BAB-delivered to s' as well and by BAB-Total Order r_2 cannot be delivered before r_1 . So by the delivery of r_2 to s and s' , both servers contain the sequence $r_1 r_2$. Suppose this is true up to record r_k , for $k < n$, i.e. both servers contain sequence $r_1 \dots r_k$ after the BAB-delivery of r_k . As noted before, record r_{k+1} will be BAB-delivered to both servers s and s' and by the total order property r_{k+1} cannot be delivered before any record r_j , with $j \leq k$. Thus, after the BAB-delivery of r_{k+1} both servers will contain the sequence $r_1 \dots r_k, r_{k+1}$. By the induction it follows that, after the BAB-delivery of r_n to both s and s' , they contain sequences $r_1 \dots r_n$. However this is sequence S . Furthermore any record r_m , for $m > n$, that is BAB-delivered to s' will be placed after r_n in its local sequence. Thus, S is a prefix of S' and that contradicts our initial assumption. With similar reasoning we may show that if S is longer than S' then S' be a prefix of S .

BL: Finally, Byzantine Linearizability (BL) requires that: (i) APPEND operations are ordered with respect to all other operations, (ii) if a GET operation returns a sequence that contains a record r_j then an APPEND(r_j) operation preceded that GET, and (iii) if a GET operation completes before the invocation of another GET operation, i.e. $GET_1 \rightarrow GET_2$, then GET_1 returns a sequence S_1 that is a prefix of the sequence returned by GET_2 , say S_2 . The total ordering of the APPEND operations is ensured by the BAB service. In particular, if APPEND(r_1) happens before APPEND(r_2), i.e. APPEND(r_1) \rightarrow APPEND(r_2), and both are executed by correct processes, then they will send the append message to $2f + 1$ servers, out of which at least $f + 1$ correct servers will receive and BAB-broadcast the append. Each correct server will BAB-deliver those appends by BAB-Validity and BAB-Agreement properties. Thus, each correct server will BAB-deliver at least $f + 1$ messages for both records and will reply to the operations. Since APPEND(r_1) \rightarrow APPEND(r_2) then there exists a correct server that replies to APPEND(r_1) before terminating. That server added r_1 in its sequence before receiving, and thus appending r_2 . Therefore, by BAB-Total Order all the correct servers will append r_1 before r_2 in their local sequences, proving this way (i). As for point (ii) a GET operation obtains a sequence that contains a record r only if that sequence is received from at least a single correct server s . Thus, since s appended r in its sequence then an APPEND(r) operation must have executed before or concurrently with the GET operation. Finally, for two operations GET_1 and GET_2 , s.t. $GET_1 \rightarrow GET_2$, it holds that the correct server, say s , that replies to GET_1 has delivered and replied to all APPEND operations with records in S_1

Code 3 Algorithm b-ByDL: Byzantine-tolerant BDLO with bounded number of Byzantine clients; Code for processing the APPEND operation at Server i

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1: Init:  $S_i \leftarrow \emptyset$ 
2: receive  $(c, p, \text{APPEND}, r)$  from process  $p$ 
3:   BAB-broadcast $(c, p, \text{APPEND}, r, i)$ 
4: upon (BAB-deliver $(c, p, \text{APPEND}, r, j)$ ) do
5:   if  $(r \in S_i)$  then
6:     send response  $(c, i, \text{APPENDRESP}, \text{ACK})$  to  $p$ 
7:   else
8:     if  $((c, -, \text{APPEND}, r, -)$  has been BAB-delivered from  $f + 1$  different servers
9:       and received from a set  $C$  of  $t + 1$  different clients) then
10:       $S_i \leftarrow S_i \parallel r$ 
11:      send response  $(c, i, \text{APPENDRESP}, \text{ACK})$  to all  $q \in C$ 

```

before BAB-delivering $f + 1$ messages BAB-broadcasted for GET_1 . Since, $\text{GET}_1 \rightarrow \text{GET}_2$, the message for GET_2 will be BAB-delivered to s after the the delivery of the message of GET_1 at s . Since s is a corect server, then by BAB-Agreement and BAB-Total Order, all the correct servers will BAB-deliver the messages from GET_1 before the messages from GET_2 . It holds also, that all the correct servers delivered all the records appended before GET_1 , before the delivery of the messages from GET_2 as well. Thus, GET_2 will receive a sequence S_2 longer or the same size as S_1 . From the proof of BSP though it follows that S_1 is a prefix of S_2 and that completes the proof. \square

3.2 Bounded Number of Byzantine Clients

Observe that DLOs are oblivious to the syntax and semantics of the records they hold [4]. Hence, in general (and in particular in Section 3.1), we do not care about the records appended by Byzantine clients. Hence, the above algorithm does not prevent a Byzantine client from performing an effective append that adds a meaningless record r on the DBLO, which may be syntactically or semantically invalid.

In this section we assume that at most t clients can be Byzantine⁸, and prevent these spurious records. This is achieved by having valid records to be appended by several clients. It is hence assumed that a valid record r is appended by a set N of at least $2t + 1$ clients that invoke the operation $\text{APPEND}(r)$ using Code 1 in parallel. In this section we do not go into how these clients agree on appending the same record⁹. The processing of the append messages at the servers has to be changed as described in Code 3, which presents the Algorithm b-ByDL (from bounded Byzantine Distributed Ledger).

Theorem 2. *Algorithm b-ByDL implements a linearizable Byzantine Tolerant Distributed Ledger Object that only contains records appended by correct clients.*

Proof. To prove b-ByDL correctness, we need to show that satisfies both liveness and safety properties of a BDLO with the special requirement that any record is appended by a correct client.

⁸ Recall that Sybil attacks are not possible.

⁹ The next section shows a scenario where this is guaranteed.

Code 4 API for for the 2-AtomicAppend of records r_p and r_q in ledgers \mathcal{L}_p and \mathcal{L}_q by clients p and q , respectively, using SBDLO \mathcal{L} . Code for Client p .

```

1: function AtomicAppends( $p, \{p, q\}, r_p, \mathcal{L}_p, r_q$ )
2:    $\mathcal{L}.$ APPEND( $\langle r, p, v \rangle$ ), where  $v = \langle p, \{p, q\}, r_p, \mathcal{L}_p, r_q \rangle$ 
3:   return ACK

```

Liveness: We prove that property BC is satisfied. With similar arguments as in the proof of Theorem 1 we can show that an APPEND request issued by a correct client will be received by at least $f + 1$ correct servers, and hence each correct server will BAB-deliver an append message from at least $f + 1$ servers. In addition, since we assume that $2t + 1$ clients issue append requests for the same record r , then each correct server will receive at least $t + 1$ requests for r . Thus, correct servers will reply to each client requesting the append and hence each correct client will receive at least $f + 1$ replies and terminate.

Safety: Following the proof of Theorem 1 we can show that b-ByDL satisfies both BSP and BL properties. What remains to show is that any record appended in the ledger is sent by a correct client. This follows from the fact that at least $t + 1$ correct clients issue append requests for the same record r . Given that the communication channels are reliable, those messages will eventually be received by all correct servers. Since the servers wait to receive $t + 1$ append requests for server r then they ensure that at least a single correct client requested r to be appended. Hence, any record on the DL was appended by a correct client and this completes the proof. \square

4 Byzantine Atomic Appends

In this section we face the Atomic Appends problem in a system where clients and servers may be Byzantine. For simplicity, we first consider the 2-AtomicAppends problem, where two clients, p and q , attempt to append atomically two mutually dependent records r_p and r_q , in BDLOs \mathcal{L}_p and \mathcal{L}_q , respectively. In the rest of this section we assume that BDLOs \mathcal{L}_p and \mathcal{L}_q use Algorithm b-ByDL to tolerate up to t Byzantine clients and f Byzantine servers, and only accept APPEND operations from a known set N of at least $2t + 1$ clients, of which at most t can fail (hence, effective appends are prevented).

4.1 Atomic Appends Using a Smart BDLO

As proposed in [8], in order to coordinate the individual appends we will use a Smart BDLO \mathcal{L} , that is a special BDLO to which clients p and q delegate the task of appending their records in the respective ledgers. They do that by appending in the SBDLO a description of the Atomic Appends operation to be completed, as shown in Code 4. Client p uses the APPEND operation to provide the SBDLO with the data it requires to complete the Atomic Appends, namely

Code 5 Algorithm BAADL: Byzantine-tolerant Smart SBDLO; Only the code for the APPEND operation is shown; Code for Server i

```

1: Init:  $S_i \leftarrow \emptyset$ 
2: receive  $(c, p, \text{APPEND}, r)$  from process  $p$ 
3:   BAB-broadcast $(c, p, \text{APPEND}, r, i)$ 
4: upon (BAB-deliver $(c, p, \text{APPEND}, r, j)$ ) do
5:   if  $(r \notin S_i)$  and
6:      $((c, p, \text{APPEND}, r, -)$  has been BAB-delivered from  $t + 1$  different servers) then
7:      $S_i \leftarrow S_i \parallel r$ 
8:     if  $r.v = \langle p, \{p, q\}, r_p, \mathcal{L}_p, r_q \rangle$  and  $\exists r' \in S_i : r'.v = \langle q, \{p, q\}, r_q, \mathcal{L}_q, r_p \rangle$  then
9:        $\mathcal{L}_p.\text{APPEND}(r_p)$ 
10:       $\mathcal{L}_q.\text{APPEND}(r_q)$ 
11:   send response  $(c, i, \text{APPENDRESP}, \text{ACK})$  to  $p$ 

```

the participants in the Atomic Appends, the record r_p , the BDLO \mathcal{L}_p , and the record r_q the other client is appending.

The SBDLO \mathcal{L} is a BDLO with unbounded number of faulty clients but that *only allows the creator of a record to append it*. \mathcal{L} is implemented with a set N of at least $2t + 1$ servers, out of which at most t may be Byzantine. Hence, the APPEND operation in the client side (Line 2 in Code 4) is implemented as described in Code 1, with t instead of f as the maximum number of faulty servers.

Code 5 describes the APPEND operation of Algorithm BAADL (from Byzantine Atomic Appends Distributed Ledger) that implements the SBDLO (the rest of the algorithm is as in Code 2). As expected, it is very similar to the implementation of a BDLO without restrictions in the number of Byzantine clients, but with a difference. Every time a record r is added to the sequence S_i , it is checked whether a matching record r' is already there. This is the case if $r.v = \langle p, \{p, q\}, r_p, \mathcal{L}_p, r_q \rangle$, and $r'.v = \langle q, \{p, q\}, r_q, \mathcal{L}_q, r_p \rangle$. If so, the corresponding append operations are issued in the respective BDLOs \mathcal{L}_p and \mathcal{L}_q .

As mentioned above, each of the ledgers \mathcal{L}_p and \mathcal{L}_q are BDLOs with a known, bounded set N , of at least $2t + 1$ clients (which are the servers implementing the SBDLO \mathcal{L}), out of which at most t can be Byzantine. These ledgers are implemented in a system of at least $2f + 1$ servers out of which at most f can be Byzantine, as presented in Algorithm b-ByDL (Code 3). Hence, a record is appended only if at least $t + 1$ clients from N issue append operations of the record. Notice that unlike in the case of ad-hoc clients, in the case of SBDLO at least $t + 1$ correct SBDLO servers will receive the requests by the external clients p and q and will issue the same APPEND operation in ledgers \mathcal{L}_p and \mathcal{L}_q , making bounded BDLOs a practical system. Moreover, Line 2 of Code 3 is modified to verify that a client p attempting to append is in fact in the set N of authorized clients.

Theorem 3. *The combination of the API of Code 4 and the Algorithm BAADL solves the 2-AtomicAppends problem.*

Proof. Let us first prove the liveness property AAL. Consider two correct clients p and q with records r_p and r_q , to be appended atomically in BDLOs \mathcal{L}_p and \mathcal{L}_q , respectively. Since it is correct, eventually p will issue

the call `AtomicAppends`($p, \{p, q\}, r_p, \mathcal{L}_p, r_q$), which from Code 4 will trigger $\mathcal{L}.\text{APPEND}(\langle \tau, p, v \rangle)$, with $v = \langle p, \{p, q\}, r_p, \mathcal{L}_p, r_q \rangle$. From Code 1 (with t instead of f) and the process of the append messages in Algorithm BAADL, eventually all the correct servers i of the SBDLO will insert $\langle \tau, p, v \rangle$ in their sequences S_i . Similarly, eventually all the correct servers i of the SBDLO will insert $\langle \tau', q, v' \rangle$ with $v' = \langle q, \{q, p\}, r_q, \mathcal{L}_q, r_p \rangle$ in their sequences S_i .

Let us consider one such server i , and assume wlog that $\langle \tau, p, v \rangle$ is inserted first in S_i . Then, as soon as $\langle \tau', q, v' \rangle$ is also inserted, the condition in Line 9 of Code 5 holds, and the operations $\mathcal{L}_p.\text{APPEND}(r_p)$ and $\mathcal{L}_q.\text{APPEND}(r_q)$ are issued. Since the SBDLO is implemented with at least $2t+1$ servers out of which at most t are Byzantine, at least $t+1$ servers will issue these APPEND operations. Hence, from Theorem 2, r_p and r_q will be appended to BDLOs \mathcal{L}_p and \mathcal{L}_q , respectively.

We now prove the safety property AAS. Let us assume to reach a contradiction that AAS is not satisfied because, wlog, the record r_p of correct client p is appended in \mathcal{L}_p while r_q is never appended in \mathcal{L}_q . Observe that \mathcal{L}_p is a BDLO implemented with Algorithm b-ByDL, which requires at least $t+1$ different clients appending the same record for the record to be in fact appended. There are two possibilities depending on who are these processes that append r_p in \mathcal{L}_p : they are (1) SBDLO servers or (2) they include processes that are not SBDLO servers. Let us consider each case separately.

In Case (1), there are at least $t+1$ SBDLO servers that append r_p in \mathcal{L}_p . Then, at least one is correct, and does it by executing Lines 9 and 10 in Code 5. But then, all correct servers of SBDLO execute these lines, and since there are at least $t+1$ correct servers, record r_q is also appended in \mathcal{L}_q , which is a contradiction.

In Case (2), by assumption only the set N of servers of the SBDLO are allowed to issue append operation in \mathcal{L}_p , and any append message sent by a process not in N will be rejected (recall that messages are authenticated). Hence, this case is not possible. \square

Code 4 and the Algorithm BAADL are easily generalized to k -AtomicAppends. In Line 2 of Code 4 the client p sends the set of k clients appending records, and the $k-1$ records appended in addition to r_p . Similarly, in Line 9 of Code 5 the condition becomes that all k records to be appended are already in S_i . If so, all of them are appended in the k corresponding BDLOs.

4.2 Atomic Appends Using a BDLO and a Set of Helper Processes

While using a Smart BDLO solves the Atomic Appends problem as described above, it requires to implement a DLO that is aware of the contents of the records that are appended into it. This is at conflict with the initial spirit of the DLO definition, that meant to be a data structure that was oblivious to the records syntax and semantics. In this section we describe how in fact the SBDLO can be replaced by a regular BDLO implemented with Algorithm u-ByDL (Code 2) and a set N of at least $2t+1$ helper processes, of which at most t can fail.

Code 6 Algorithm used by a helper process to complete Atomic Appends operations;
Code for process x

```

1: Init:  $O_x \leftarrow \emptyset$ 
2: loop ▷ Loop forever; execute loop body periodically
3:    $S_x \leftarrow \mathcal{L}.\text{GET}()$ 
4:   while  $\exists r, r' \in S_x \setminus O_x : r.v = \langle p, \{p, q\}, r_p, \mathcal{L}_p, r_q \rangle \wedge r'.v = \langle q, \{p, q\}, r_q, \mathcal{L}_q, r_p \rangle$  do
5:      $\mathcal{L}_p.\text{APPEND}(r_p)$ 
6:      $\mathcal{L}_q.\text{APPEND}(r_q)$ 
7:      $O_x \leftarrow O_x \cup \{r, r'\}$ 

```

From the point of view of clients p and q , the new approach is transparent. Still they execute Code 4 to issue an Atomic Appends operation, with the difference that now ledger \mathcal{L} is not “smart” anymore, but a regular Byzantine tolerant DLO (e.g., implemented with Code 2). Similarly, from the point of view of ledgers \mathcal{L}_p and \mathcal{L}_q the new approach is transparent, except that now their set N of legal clients to append in them is the set of helper processes described above.

Hence, the main difference is in the helper processes in set N . These processes are continuously running a loop that monitors \mathcal{L} for new Atomic Appends operations to complete. This process is described in Code 6. As can be seen there, a helper process x periodically issues a GET operation on \mathcal{L} to obtain its latest contents. Then it checks if it contains pairs of matching Atomic Appends records that correspond to operations that have not been completed yet. (Observe that x maintains a set O_x of records from \mathcal{L} that have been already used.) If so, it issues the corresponding APPEND operations to complete them.

The proof that this new approach solves the AtomicAppends problem is almost verbatim to the proof of Theorem 3, and it is omitted.

5 Conclusions

In this work we formalized the notion of a Byzantine Tolerant Distributed Ledger Object (BDLO) and proposed algorithms implementing such objects in distributed settings where a subset of clients and servers may be Byzantine. We demonstrated the utility of our BDLO implementations by providing solutions to the Atomic Appends problem, where clients have mutually dependent records to be appended, the record of each client has to be appended to a different BDLO, and either all records are appended or none.

Our formalization of BDLOs requires a strong prefix property, which prevents the existence of more than one sequence at any point in time (i.e., no “forks” allowed, as termed in the blockchain literature). As shown in [1,4], this property requires consensus. Therefore, it would be interesting to investigate more relaxed (weaker) versions of this property (that might not require consensus) and study the guarantees than can be provided within our framework.

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