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Brief Announcement: Holistic Verification of Blockchain Consensus

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1 INTRODUCTION AND PRELIMINARIES

Motivation. Today, the market capitalization of the seminal blockchain, Bitcoin, is about $803B which incentivizes malicious participants to find problematic executions that would allow them to steal financial assets. As the blockchain requires a distributed set of machines to agree on a unique block of transactions to be appended to the chain, attackers naturally try to exploit consensus vulnerabilities to double spend. As a result, formally verifying that a blockchain consensus protocol is safe and live is key to mitigate financial losses. Recent progress in mechanical proofs represent the first steps towards verifying blockchain consensus. The parameterized model checking of threshold automata (TAs) has recently proved instrumental in verifying fully asynchronous parts of consensus algorithms, like broadcast algorithms [4]. The aforementioned reduction technique cannot apply to partial synchrony: moving the message reception step to a later point in the execution might violate an assumed message delay.

Contribution. In this paper, we verify holistically the safety and liveness properties of the DBFT [2] Byzantine consensus used in the Red Belly Blockchain system [3], a scalable blockchain used in production. Our approach is holistic because it starts from the pseudocode of the distributed algorithm as typically presented in the distributed computing literature, models this pseudocode and its components into disambiguated TA, model checks the desired properties of these components expressed in LTL formulae, simplifying the TA of the consensus algorithm with these verified properties and model checks the safety and liveness of the consensus protocol. The advantage is that the formally verified algorithm matches the pseudocode and no user-defined invariants or proofs need to be checked, which drastically reduces the risks of human errors.

Model. We consider \( n \) asynchronous sequential processes \( \Pi = \{p_1, \ldots, p_n\} \) that communicate by exchanging messages through an asynchronous reliably connected point-to-point network. A set of \( f \leq t < n/3 \) processes are Byzantine, the rest are correct. Distributed algorithms are communication-closed and their execution consists in an interleaving of the individual steps taken by the processes. A threshold automaton (TA) describes the behavior of a process in a distributed algorithm. Its nodes represent local states, and labeled edges are guarded rules. In order to verify the safety and liveness properties of our distributed algorithms on a multi-round TA, we express these properties in fragments of linear temporal logic (LTL). Since the algorithms are communication-closed, the verification on the multi-round TAs reduces to one-round TAs. We then use the ByMC model checker to automatically verify these fragments.

2 THE BINARY VALUE BROADCAST

Algorithm 1 Binary value broadcast for process \( p_i \).

1. \( \text{bv-broadcast}(BV, \langle v, i \rangle) \)
2. \( \text{broadcast}(BV, \langle v, i \rangle) \)
3. repeat:\n4. \( \text{if} \) \( (BV, \langle v, * \rangle) \) received from \( (t + 1) \) distinct proc. (not yet re-bcast) \( \text{then} \)
5. \( \text{broadcast}(BV, \langle v, i \rangle) \)
6. \( \text{if} \) \( (BV, \langle v, * \rangle) \) received from \( (2t + 1) \) distinct processes \( \text{then} \)
7. \( \text{contestants} \leftarrow \text{contestants} \cup \langle v \rangle \)

Our holistic verification approach consists of decomposing a distributed algorithm into encapsulated components of pseudocode that can be modelled in TAs and verified in isolation to obtain a simplified TA that is amenable to automated verification. The binary value broadcast (bv-broadcast) [5] is a communication primitive guaranteeing that all binary values “bv-delivered” were “bv-broadcast” by a correct process. Each process starts this algorithm in one of two states, depending on its input value 0 or 1. Once a correct process receives a value from \( t+1 \) distinct processes, it broadcasts it if it did not do it already (line 4); broadcast is not
A fairness assumption to solve consensus. The traditional approach to establishing guaranteed liveness properties in verification is to require that all fair executions, instead of all executions, satisfy the properties. We thus introduce the fairness assumption that will be crucial in the rest of this paper. In order to define it, we first define a good execution of the bv-broadcast with respect to binary value $v$ as an execution:

**Definition 2.1 (v-good bv-broadcast).** A bv-broadcast execution is $v$-good if all its correct processes bv-deliver $v$ first, i.e., $\Box \{ x[C_{1-v}] = 0 \land x[C_{B1-v}] = 0 \}$.

Second, we consider an infinite sequence of bv-broadcast executions, tagged with $r \in \mathbb{N}$. Since we replace partial synchrony by our fairness assumption, the setting is fair but asynchronous, that is, processes invoke bv-broadcast infinitely many times, but at their own relative speed. Thus, they do not all invoke the bv-broadcast tagged with the same number $r$ at the same time. Nonetheless, every process invokes bv-broadcast infinitely many times and in the $r^{th}$ invocation its behavior depends on the messages sent in the $r^{th}$ invocation of other processes. Therefore, we refer to the $r^{th}$ execution of bv-broadcast even though the processes invoke it at different times.

**Definition 2.2 (fairness).** An infinite sequence of bv-broadcast executions is fair if there exists an $r$ such that the $r^{th}$ execution is $(r \mod 2)$-good.

For simplicity, we use the terminology fair bv-broadcast when the infinite sequence of bv-broadcast executions is fair.

**Algorithm 2** The Byzantine consensus algorithm at process $p_i$

1. Global scope variable:
2. $\text{contestants} \subseteq \{0, 1\}$, set of binary values, initially $\emptyset$.
3. propose($est$):
4. $r \leftarrow 0$
5. repeat:
6. bv-broadcast($est, (est, i)$)
7. wait until ($\text{contestants} \neq \emptyset$)
8. broadcast($aux, (\text{contestants}, i)$) $\rightarrow$ $favorites$
9. wait until $3i_1, \ldots, i, n-t: 1 \leq j \leq n-t$ favorites($c_j$) $\neq \emptyset$
10. $\land$ (qualifiers $\leftarrow \cup_{i \leq j \leq n-t}$ favorites($c_j$)) $\subseteq$ $\text{contestants}$
11. if qualifiers $\neq \{0\}$ then 12. $est \leftarrow v$
13. if $v = (r \mod 2)$ then decide($v$)
14. else $est \leftarrow (r \mod 2)$ 15. $r \leftarrow r + 1$

**3 CONSENSUS VERIFICATION**

In this section, we leverage our verification of bv-broadcast to simplify the verification of the TA of DBFT.

**The Byzantine consensus algorithm.** Since we replace the partial synchrony assumption by fairness, DBFT can be simplified into Algorithm 2, without coordinators and timeouts. The DBFT binary consensus invokes bv-broadcast($\cdot$) at line 6 and uses a set $\text{contestants}$ of binary values, whose scope is global, updated by the bv-broadcast (Alg. 1, line 7) and accessed by the procedure propose($\cdot$) (Alg. 2, line 7).

**Modeling deterministic consensus.** Figure 2 depicts the TA obtained by modeling Algorithm 2 with the aforementioned method.
Verification of Byzantine Consensus. Our objective is to formally prove that Algorithm 2 is unconditionally safe, and that it is live under the assumption of fairness at the bv-broadcast level. Since the TA of Fig. 2 is too large to be handled automatically, we build on the properties proved for the bv-broadcast to simplify in the TA from Fig. 2 the part representing the bv-broadcast. We obtain Fig. 3.

The TA depicts two iterations of the repeat loop (line 5), since Algorithm 2 favors different values depending on the parity of the round number. For simplicity, we refer to the concatenation of two consecutive rounds of the algorithm as a superround of the TA. As one can expect, this TA embeds the TA of the bv-broadcast that is depicted by the dashed arrows, just as Algorithm 2 invokes the bv-broadcast algorithm of Fig. 1. We thus distinguish the outer TA modeling the consensus algorithm from the inner TA modeling the bv-broadcast algorithm. Although Algorithm 2 is relatively simple, the global TA happens to be too large to be verified through model checking; the main limiting factor is its 14 unique guards that constrain the variables to enable rules in the TA.

Simplified threshold automaton. Our objective is to formally prove that Algorithm 2 is unconditionally safe, and that it is live under the assumption of fairness at the bv-broadcast level. Since the TA of Fig. 2 is too large to be handled automatically, we build on the properties proved for the bv-broadcast to simplify in the TA from Fig. 2 the part representing the bv-broadcast. We obtain Fig. 3.

Verification of Byzantine Consensus. We can formally verify that DBFT (Alg. 2) solves the Byzantine consensus with the fair bv-broadcast and without partial synchrony. The full proofs can be found in the companion technical report [1]. First, we verify safety (validity and agreement) by model-checking two well-chosen superround invariants. For both values of \( v \) we obtain:

\[
\forall R \in \mathbb{N}, \forall R' \in \mathbb{N} \left( 0 \land [D_0, R] \neq 0 \Rightarrow \Box \land [D_{1-v}, R'] = 0 \right) \quad \text{(Agree)}
\]

Second, we verify liveness (termination) by model-checking four properties with ByMC and conclude with a short proof that relies on our fairness assumption (cf. Def. 2.2):

**Theorem 3.1.** Assuming fairness of the bv-broadcast, Algorithm 2 terminates.

**Experiments.** Thanks to our modular approach, we are able to verify all properties of the Byzantine consensus automatically in about 70 seconds whereas a non-compositional approach timed out after more than 24 hours.

**REFERENCES**


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