Optimal Bootstrapping of PoW Blockchains

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ABSTRACT

Proof of Work (PoW) blockchains are susceptible to adversarial majority mining attacks in the early stages due to incipient participation and corresponding low net hash power. Bootstrapping ensures safety and liveness during the transient stage by protecting against a majority mining attack, allowing a PoW chain to grow the participation base and corresponding mining hash power. Liveness is especially important since a loss of liveness will lead to loss of honest mining rewards, decreasing honest participation, hence creating an undesirable spiral; indeed existing bootstrapping mechanisms offer especially weak liveness guarantees.

In this paper, we propose Advocate, a new bootstrapping methodology, which achieves two main results: (a) optimal liveness and low latency under a super-majority adversary for the Nakamoto longest chain protocol and (b) immediate black-box generalization to a variety of parallel-chain based scaling architectures, including OHIE [34] and Prism [4]. We demonstrate via a full-stack implementation the robustness of Advocate under a 90% adversarial majority.

CCS CONCEPTS

• Security and privacy → Distributed systems security; • Computer systems organization → Dependable and fault-tolerant systems and networks; • Theory of computation → Distributed algorithms.

1 INTRODUCTION

Bootstrapping PoW Blockchains. Proof of Work (PoW) blockchains, epitomized by Bitcoin, have proven themselves to be secure designs. Their security has been shown in theory [12] as well as in practice (Bitcoin has not seen any severe safety or liveness incidents in more than 13 years of being online). However, an important, and less studied, aspect of PoW blockchains is that they are particularly hard to bootstrap. At the early stages of a PoW blockchain, there is not much participation (in terms of mining hash power), making it relatively easy for an adversary to overpower the honest miners. If a PoW blockchain can avoid the dangers of such attacks in its infancy, eventually a significant amount of honest hashing power participates in the mining process and security is correspondingly strengthened. Thus, the focus of this paper is on principled approaches to secure bootstrapping, a crucial aspect to the successful development of any PoW blockchain.

1.1 Related Works

Checkpointing. Checkpointing is a standard technique used in state machine replication protocols [7], where a centralized server issues checkpoints attesting to the recent state of the protocol. In blockchains, checkpoints attest to the hash of well-embedded blocks every so often so that new users can securely bootstrap using a recent execution state of the protocol. A key benefit of such checkpointing is that an adversary even with super-majority mining power cannot create a long-range reversion attack (i.e., forking from a block created long ago). Since such a long-range fork will deviate from the stated checkpoint, clients will reject them. Practical blockchains utilizing checkpointing include Bitcoin [23, 24], Peercoin [18], Feathercoin [14], and RSK [20]. A centralized checkpointing mechanism was maintained by Satoshi Nakamoto himself (presumably honest) until late 2014. Additionally, checkpoints of some form have been central in the context of Proof-of-Stake (PoS) protocols, including Ouroboros [17], Snow White [9], and Ouroboros Praos [10], as well as e.g. in hybrid consensus [27], Thunderella [28], ByzCoin [19], and Algorand [13]. In a related context, Fantomette [3] employs distributed checkpoints to secure a blockDAG-based ledger.

Finality Gadgets. A crucial problem in the context of checkpointing is ensuring the safe delivery of checkpoints to the blockchain client. A new generation of blockchain algorithms have sought to
decentralize this process by designing a separate distributed consensus protocol to issue checkpoints. We will refer to this class of solutions as finality gadgets, which are comprised of a Byzantine Fault Tolerant (BFT) protocol for finalizing blocks created by a Proof-of-work (PoW) or Proof-of-stake (PoS) chain protocol. They have been very popular methods for combining the best features of the BFT and PoW protocols and are proposed for deployment in many major blockchains including Ethereum 2.0 [29, 32]. Depending on the context, the checkpoint committee can be comprised of a fixed committee (for example, run by independent community leaders) or the committee itself can be elected using stake deposits.

**Rationale for Finality Gadgets.** There are multiple reasons for utilizing finality gadgets, and different protocols emphasize different properties. We enumerate the properties that motivate the development of finality gadgets as follows.

1. Safety against long-range attacks;
2. Economic finality;
3. Availability vs. Finality tradeoff capability;
4. Responsiveness: low-latency block confirmation;

The *raison d’être* of finality-gadgets (including centralized checkpoints) is to provide property (1): safety against long-range attacks by an adversarial majority. In a PoW system, this is an important safeguard since an adversary can control a super-majority mining power temporarily, for example, by renting cloud mining equipment. Finality gadgets and checkpoints can prevent such attacks.

Beyond this basic reason, different protocols optimize for different criterion. Casper [5, 6] focuses on (2) that ensures that if safety is violated, the malicious action is detected and at least one-third of the staking nodes will lose their stake, a similar approach is taken by GRANDPA [32] and Afgjort [11]. Recent works [8, 31] have identified general BFT protocols which have such detectability. Some protocols like [25, 30] focus on (3) by designing gadgets that let users prioritize adaptivity or availability by implementing different confirmation rules. Some protocols like Winkle [2] guarantee (1) by utilizing transaction traffic for voting. Finally, other finality gadgets (e.g. Afgjort [11]) are optimized for property (4): responsiveness, the ability of the BFT to confirm blocks produced by the PoW chain near-instantaneously.

**Bootstrapping gadget:** A bootstrapping gadget is a finality gadget that has one additional property: **Liveness despite adversarial majority.** During the initial stages of a novel PoW protocol, liveness is required to ensure that honest miners are rewarded for their effort even under an adversarial majority. Lack of a live checkpointing protocol creates an undesired spiral: low honest participation → low honest miner rewards → honest miners leaving (lower participation).

### 1.2 Motivation and contributions

**Key shortcoming of existing solutions.** While all the aforementioned protocols satisfy several properties of finality gadgets, none of them can work as bootstrapping gadgets. This was observed in a recent paper [15] for even the simple centralized checkpointing protocol. An adversary controlling a majority mining power can issue a long private adversarial chain, which does not contain any honest transactions. When such a chain is checkpointed repeatedly, honest clients lose liveness in the system. The paper proposed the inclusion of a random nonce as well as a checkpoint certificate (issued by the central checkpointing or BFT) to reduce the impact of this attack. The key idea is that since this random nonce needs to be included in the next block, this creates a renewal event where the adversarial blocks stored prior to the event have to be disregarded, creating a new race between the honest and adversarial chains at each checkpoint. While this approach can ensure a non-zero chance that the honest chain can win, thus giving asymptotic liveness, the latency of transaction inclusion as well as the chain quality (fraction of honest blocks in the final ledger) and the corresponding mining rewards for honest miners decrease exponentially as mining power increases beyond 50% or as the inter-checkpoint interval increases.

**Main Contributions.** In this paper, we focus on building a bootstrapping gadget that achieves safety and liveness under an adversarial majority. We propose Advocate, a new scheme that achieves optimal chain quality. The core idea is the inclusion of appropriate reference links to checkpoint blocks. Variations of this idea have been proposed in different contexts in the literature: in [12] for achieving a 1/2 threshold Byzantine Agreement, in Fruitchains [26] for designing incentives, in inclusive protocols [21] for minimizing block wastage due to forking and in general DAG (directed acyclic graph) protocols, such as Conflux [22], for improving throughput.

We prove that Advocate achieves optimal chain quality while ensuring transaction inclusion for all honest transactions within two epochs even under an arbitrarily high adversarial mining power (the so-called "99% mining adversary"). The plots for chain quality of related works are in Figure 1; an upper bound on the chain quality of [15] diminishes rapidly with adversarial power ($\beta$) and epoch size ($\epsilon$), whereas Advocate achieves the **optimal chain quality** equal to the honest mining power ($1 - \beta$).

**General applicability.** We create appropriate blackbox interfaces through which our protocol can employ any BFT protocol for checkpointing, to make our construction widely applicable. We...
also demonstrate that our bootstrapping gadget Advocate work with a variety of PoW protocols beyond Nakamoto consensus.

**System Implementation.** We perform extensive experiments on a distributed testbed to demonstrate the robustness of our protocol under and up to 90% adversarial mining majority and compare performance gains with prior state-of-the-art. To demonstrate compatibility of Advocate with high throughput parallel-chain architectures, we implemented Advocate on Prism and demonstrated an honest throughput of 8,200 tx/s under a 70% adversary majoritarian.

The code for the systems implementation is available at [1].

**Organization.** The rest of the paper is organized as follows. Section 2 provides an overview of the preliminaries used in our work including the threat model and the distributed ledger’s properties and block production mechanisms. Section 3 describes Advocate under a single checkpointing node and provides its security analysis to show safety and liveness with optimal chain quality. Section 4 extends Advocate to ensure similar performance and security guarantees under a committee-based BFT-SMR protocol by providing a unified network functionality. Section 5 integrates Advocate into parallel-chain architectures by providing a meta-protocol that can be readily integrated into Prism, OHIE and ledger-combiner to achieve high throughput under an adversarial majority. Section 6 presents detailed experimental results on a distributed testbed of a full-stack implementation, stress testing performance with majority adversarial mining power.

2 PRELIMINARIES

2.1 The Distributed Ledger Model

The distributed ledgers analyzed in this work are constructed as blockchains. A ledger is formed as a hash chain (or tree) of blocks, each block containing transactions which alter the ledger’s state. New blocks, which extend the chain, are created by mining parties at regular intervals. Conflicts, i.e., forks in the chain, are resolved following Sybil resilience mechanisms, such as PoW. Given a tree of blocks, each party chooses a single branch as the main chain; blocks that are not part of the main chain are called **uncles**.

We assume a synchronous setting with a delay upper bound of $\Delta$. Specifically, the execution proceeds in rounds. On each round, every party is activated to participate in the protocol. Communication is performed via a “diffuse” functionality, i.e., a gossip protocol, such that no point-to-point communication channels exist, but rather a peer-to-peer network is formed. Therefore, every message produced at round $r$ is received by all other parties by round $r+1$. We also assume that the number of participating parties is fixed for the duration of the execution.

The ledger’s core properties, described in detail by the Bitcoin Backbone model [12], are provided in Definitions 2.1-2.3.

**Definition 2.1 (Stable Block and Transaction).** A block is stable if it is $k$-deep in the main chain. A transaction published in a stable block is also stable.

**Definition 2.2 (Safety).** A transaction reported as stable by an honest party on round $r$ is reported as stable by all honest parties on round $r+1$, at the same position in the ledger.

**Definition 2.3 (Liveness).** A transaction which is provided continuously as input to the parties becomes stable after $u$ rounds.

An additional important property of interest is chain quality (Definition 2.4) [12, 16]. Briefly, this property ensures that the number of blocks that each party contributes to the chain is bounded by a function of the party’s mining power $\mu$.

**Definition 2.4 (Chain Quality ($q, l$)).** Let $q$ be the proportional mining power of $A$. Chain quality with parameter $l$ states that for any honest party $P$ with chain $C$, it holds that, for any $l$ consecutive blocks of $C$, the ratio of adversarial blocks is at most $1 - q$.

2.2 Threat Model

Our work considers polynomial-time executions, such that all parties, including the adversary $A$, are locally polynomial-bounded. On each execution round, the adversary may "corrupt" a party, at which point it accesses the party’s internal state; following, when the corrupted party is supposed to be activated, the adversary is activated instead. Additionally, $A$ is "adaptive", i.e., corrupts parties on the fly, and "rushing", i.e., retrieves all honest parties’ messages before deciding its strategy at each round.

$A$ controls $\mu, A$ of the network’s mining power and tries to break safety and liveness. To break safety, $A$ forces two non-corrupted nodes to accept different chains as stable, i.e., to report different transactions as stable in the same position in their respective ledger. To break liveness, $A$ attempts to prevent a transaction from becoming stable within $u$ rounds. We explore settings where the honest majority assumption is violated, i.e., when the adversary may control more than 1/2 of the net mining power. In those settings, the ledger cannot be secure in a standalone fashion, hence the need for the checkpointing protocols presented in this work.

3 ADVOCATE: OPTIMAL CHECKPOINTING OF LONGEST CHAIN PROTOCOLS

Our main contribution is a novel protocol, Advocate, that ensures both safety and liveness against a (arbitrarily high) super-majority mining adversary on the PoW chain. This section considers a single (honest) checkpointing node, in order to clearly present the main innovations, while the following sections relax this assumption by proposing a distributed checkpointing federation.

Checkpointing in Advocate is performed via certificates. Specifically, at regular intervals of $e$ blocks on the main chain, the checkpointing service issues a signed certificate, which is published on the chain within $c$ blocks on the main chain (PoW chain). The certificate defines the canonical chain that parties should adopt. Advocate is parameterized by two values $c$ and $e$ as described above.

3.1 Checkpointing Party Behavior

The checkpointing party is connected to the blockchain network, so at each round $t$ it holds a view of the PoW chain. Therefore, on any round, the checkpointing party maintains a list of leaves $L(t)$ of its local block-tree.

At regular intervals (i.e., every $e$ blocks), the party issues a checkpoint certificate. The $t$-th checkpoint certificate issued by the party is denoted $C_t$. A checkpoint certificate is constructed as follows: $C_t = \{B_t, R_t, S_t\}$; $B_t$ is the checkpointed block, i.e., the block of the main PoW chain that the party checkpointed; $R_t$ is a list of references of blocks that are not part of the main chain, i.e., leaves of the block tree which are not checkpointed; $S_t$ is the signature of the
With the introduction of checkpoints, the PoW node behavior needs to change appropriately. The key change is that, once a new certificate checkpoints block $B_i$, it should be published in at least one of the $c$ blocks that immediately extend $B_i$; the first block that includes the certificate is called the referring block. The nodes follow the longest checkpointed chain. In summary, Advocate modifies the main-chain rule as follows:

- Go to $B_i$ in the blocktree.
- If there exists a descendant block $B'_i$ within $c$ blocks of $B_i$ that contains $C_i$, pick the longest chain which contains $B'_i$ as the main chain. (Note: A block $B'_i$ which contains $C_i$ but is more than $c$ blocks after $B_i$ is not acceptable.)
- If no such $B'_i$ exists, then either of the following holds:
  1. $B_i$ is not $c$-deep in the longest chain: pick the longest chain containing $B_i$ as the main-chain.
  2. $B_i$ is $c$-deep in the longest chain: pick one of the chains which is $(c − 1)$-deep and contains $B_i$ as the main chain (breaking ties arbitrarily).

**Mining behavior** Miners follow the above main chain rules. Additionally, w.r.t. a checkpoint certificate $C_i$, two cases exist:

1. The main chain contains $C_i$ in some block $B'_i$: proceed mining as usual.
2. The main chain does not contain $C_i$: include $C_i$ alongside the list of transaction to be mined.

We suppose that when a miner creates a new block, the block contains all transactions in the miner’s mempool (in practice, this requires sufficiently incentivized transactions fees). With hindsight, this assumption will prove useful to argue that a transaction is published in the first honestly-generated block that is produced after the transaction’s creation.

Let main chain oracle $F_{mco}$ represent the view in the execution of the underlying consensus algorithm (Nakamoto and the public global tree $G_t$ at time $t$ is received by time $t + Δ$ (by the synchronous network assumption). The main chain oracle gets the additional checkpointing information from Advocate. The interaction of a main chain oracle ($F_{mco}$) with the Advocate functionality can be formalized using a functionality $F_{Advocate}$ described next.

### Checkpointing module $F_{cps}$

$F_{cps}$ receives the checkpointCandidate and unreferredBlocks in the form of the inputValue message from $F_{Advocate}$. This message takes zero delay once $F_{Advocate}$ receives potentialCandidate from $F_{mco}$. $F_{cps}$ queries $F_{Advocate}$ regarding the validity of this input using the isValidValue and inputValidity messages and gets a reply after a delay $t_{cps}$. If the input is valid, $F_{cps}$ immediately certifies the input and sends the message to $F_{Advocate}$.

Note that the above process will happen within a time $t_{cps}$ with $t_{cps}/Δ ≪ 1$, since the process is in the same machine. The message isValidValue and inputValidity seems redundant for now, however, we will see in section 4, that this message classification is critical.

### Decoupled Validity: Ledger Creation

Without loss of generality, we assume that the execution completes with the issuing of a final checkpoint. To construct the aggregate ledger at any point of the execution, the blocks of the main chain are concatenated with the blocks of the non-main branches. In the aggregate ordering, the main chain blocks, up to and including the referring block (i.e., the block which includes the checkpointing certificate), are prioritized over the blocks which are not part of the main chain (i.e., the “uncle” blocks).

Formally, let $T(L_i)$ be the tree corresponding to the leaves $L_i$. Let the forest $F_i$ be the difference between $T(L_i)$ and the previously checkpointed tree $F_i := T(L_i) \setminus \{T(L_{i−1}) \cup \text{Chain}_i\}$, where Chain is the main chain up to (and including) the referring block for checkpoint $C_i$, $π(·)$ denotes a topological sort of the blocks in a forest, with ties broken in a universal manner (e.g. via block hashes).
The aggregate ledger is constructed by concatenating the referring block (i.e., Chain_{i}) with \( \pi(F_i) \). Therefore, when the referring block for certificate \( C_i \) is read, the blocks referred by \( C_i \) (i.e., the blocks in \( \pi(F_i) \)) are also read in the order defined in \( C_i \). This procedure is exemplified in figure 2 where Blocks 3,5 are included after block 8. Note that we can follow other universal ordering approaches for blocks in \( F_i \) (e.g. sort by hash) without affecting the security of our protocol.

Figure 2 depicts the ledger construction, s.t. the sanitized ledger (figure 3) is obtained by parsing the main chain and referenced blocks and removing invalid (e.g. double spending) entries. Such post ordering ledger sanitization is required even under a honest setting since referred uncle blocks may have transactions that conflict with transactions on the main chain.

3.4 Security Properties of Advocate

In this section we show that Advocate, under the centralized setting of a single honest checkpointing party, satisfies a host of desirable properties. First and foremost, Theorems 3.1 and 3.2 prove that Advocate satisfies safety and liveness (cf. Section 2.1).

\[ \text{Theorem 3.1 (Safety). Let } B \text{ be a block which is checkpointed by Advocate via certificate } C. \text{ If } B \text{ is part of the main chain, then } B \text{ is stable (cf. Definition 2.1). If } B \text{ is an uncle, then } B \text{ is stable if } C \text{ is published in a block which is } k \text{-deep, with } k = e - c. \]

\[ \text{Proof: Let } C_i = \{B_i, R_i, S_i\} \text{ be the } i\text{-th certificate and } B \text{ a block checkpointed by } C_i. \text{ By definition of the protocol, all honest parties eventually accept a chain which contains a referring block } B_{C_i} \text{ which contains } C_i. \text{ Observe that, once } C_i \text{ is created, the ledger position of } B_i \text{ is finalized, given the ledger construction description in Section 3.3. Therefore, if } B \text{ is part of the main chain, its ledger position is also fixed as soon as } C_i \text{ is created. If } B \text{ is an uncle, then its ledger position depends on the referring block } B_{C_i}. \text{ Specifically, the ledger construction rules enforce that the uncle blocks which are checkpointed by } C_i \text{ are appended in the final ledger after the referring block for } C_i. \text{ However, a referring block can be reverted, if a chain appears which is both valid (i.e., contains a correct referring block) and long enough. Therefore, the position of uncle blocks, which are checkpointed by } C_i, \text{ is finalized only when the certificate } C_{i+1} \text{ is issued, which occurs after at most } e - c \text{ main chain blocks}. \]

\[ \text{Theorem 3.2 (Liveness). Let } h \text{ be the probability that at least one honest block is created per round; Advocate satisfies liveness (cf. Definition 2.3) with parameter } u = \left\lceil \frac{h}{3} \right\rceil \cdot e. \]

\[ \text{Proof: The proof follows directly from the ledger construction (cf. Section 2.1) and Theorem 3.1. Specifically, let } t \text{ be the round on when block } B \text{ is created. If } B \text{ is a main chain block, then it becomes stable with the issuing of the first checkpoint after } t \text{ which, by definition of the checkpointing behavior (Section 3.1), occurs at most } \left\lceil \frac{h}{3} \right\rceil \text{ rounds after } t. \text{ If } B \text{ is an uncle block then, as shown in Theorem 3.1, it becomes stable with the issuing of the first checkpoint after } B \text{ becomes checkpointed; in other words, } B \text{ becomes stable when 2 checkpoints are issued after it is created. However, the chain growth depends at worst on the honest miners’ mining power (e.g. if the adversary abstains), therefore two checkpoints are issued on expectation at most } \left\lceil \frac{h}{3} \right\rceil \text{ rounds after } t. \text{ Finally, as mentioned in Section 3.2, a transaction is published in the first honestly-generated block which is produced after the transaction’s creation. In turn, this block is checkpointed, either as part of the main chain or as an uncle block, by the upcoming checkpoint}. \]

The next property that we explore is chain quality (cf. Definition 2.4). First, we observe that Advocate cannot guarantee chain quality over any fixed window of \( l \) consecutive blocks of the final ledger. Briefly, the adversary can produce blocks in private and release them, such that the checkpoint certificate refers to all of them at once, hence temporarily flooding the ledger with adversarial blocks. However, as Theorem 3.3 shows, Advocate does guarantee chain quality over the entire ledger. This is a direct improvement of the checkpoint protocol in [15], which guarantees safety and liveness but not chain quality.

\[ \text{Theorem 3.3 (Chain Quality). Let } \beta \text{ be the adversarial power. For every execution, during which } l \text{ blocks are created in aggregate by all parties, Advocate satisfies chain quality (cf. Definition 2.4) with parameters } l, (1 - \beta). \]

\[ \text{Proof: During the entire execution, the honest parties collectively create (on expectation) at least } (1 - \beta) \cdot l \text{ blocks. At the end of the} \]
execution, a checkpoint is issued, which references all main chain and uncle blocks that are not checkpointed. After the issuing of the last checkpoint, the aggregate ledger at the end of the execution contains all blocks created by all parties, hence the ratio of honest blocks in the final, aggregate ledger is at least \(1 - \beta\).

Advocate with hooks. To achieve chain quality for smaller windows of blocks, we propose a slightly modified version of Advocate. Now, each block contains a reference to the latest checkpoint certificate \(C_j\) at the time it was mined. Next, such block can be referenced by a certificate \(C_i\) only if \(i - j \leq t\), i.e., it can be referenced only by one of the \(t\) certificates that immediately follow \(C_j\). This constraint, called a hook, prevents \(A\) from releasing old blocks.

Theorem 3.4 shows that Advocate with hooks ensures chain quality for any window of blocks containing \(t\) consecutive checkpoints.

**Theorem 3.4 (Short Term Chain Quality).** Under Advocate with hooks, the ratio of honest blocks in any window of \(t\) consecutive blocks, which includes \(t\) checkpoints, is at least \(\frac{(1 - \beta) \cdot (t - 1)}{\frac{t}{\gamma + \beta - 1}}\), where \(\beta\) is the adversarial power.

**Proof:** Let \(t\) be the maximum number of blocks that are produced on expectation by all parties (honest and adversarial) between two consecutive checkpoints. Without loss of generality, assume a window of blocks which begins with the checkpointed block of certificate \(C_i\) and ends with the checkpointed block of certificate \(C_{i+t}\). \(C_i\) can reference at most \(t \cdot \beta \cdot \gamma\) adversarial blocks (i.e., which have been created after certificate \(C_{i-1}\)) and at minimum 0 honest blocks (i.e., if all honest blocks created between certificates \(C_{i-1}\) and \(C_i\) are part of the main chain). Also, certificate \(C_{i+t}\) can reference at most \((1 - \beta) \cdot \gamma\) honest blocks and at minimum 0 adversarial blocks (i.e., if all honest blocks created between certificates \(C_{i+t-1}\) and \(C_{i+t}\) are uncle blocks and all such adversarial blocks are part of the main chain). In this case, the above window of blocks contains \(2 \cdot t \cdot \beta \cdot \gamma\) adversarial blocks and \((t - 1) \cdot (1 - \beta) \cdot \gamma\) honest blocks, hence the ratio of honest blocks is \(\frac{(1 - \beta) \cdot (t - 1)}{\frac{t}{\gamma + \beta - 1}}\).

Finally, we introduce two performance metrics that accentuate the functionality of Advocate. First, the *chain inclusion gap* (Definition 3.5) expresses the expected number of blocks until a new block is stable. Corollary 3.8 shows that plain Advocate cannot ensure a chain inclusion gap, whereas Advocate with hooks guarantees a chain inclusion gap of \((\beta \cdot t - \beta + 1) \cdot \gamma\) blocks, where \(\gamma\) is the maximum number of blocks that all parties produce on expectation between two consecutive checkpoints; the proof follows directly from Theorems 3.3 and 3.4. We know that the chain grows at the rate \(1 - \beta\); thus, the maximum number of blocks mined between two checkpoints is \(\frac{t}{\gamma + \beta - 1} = \gamma\). Observe that the chain inclusion gap increases linearly with \(\gamma\) and, consequently, with the epoch length, this is a direct improvement on the result of [15], where it increases exponentially under adversarial mining majority.

**Definition 3.5 (Chain Inclusion Gap).** Let party \(P\) with a main chain \(C\) of length \(l\), which creates a new block \(B\). The chain inclusion gap with parameter \(g\) states that, when \(B\) becomes stable, its position in the aggregate ledger is at most \(l + g\).

**Corollary 3.6 (Advocate Chain Inclusion Gap).** Advocate guarantees chain inclusion gap (cf. Definition 3.5) with parameter \(g = \infty\). Advocate with hooks guarantees chain inclusion gap with parameter \(g = \frac{(\beta \cdot t - \beta + 1)}{e}\), where \(\beta\) is the adversarial power, \(t\) is the hook parameter, and \(e\) is the checkpoint epoch length.

Second, *optimistic serializability* (Definition 3.7) ensures that the checkpointing service does not trivialize the ledger maintenance. Specifically, under fully honest conditions, i.e., \(\beta = 0\), transactions are ordered in the ledger in the order of their arrival, if such arrival order exists.

**Definition 3.7 (Optimistic Serializability).** For two transactions \(tx, tx'\), where \(tx\) was given as an input to all honest nodes at round \(r\) and is valid w.r.t. ledger \(L_P(r)\) at round \(r\) and \(tx'\) was given as an input to all honest parties after round \(r\), it holds that for any \(r' > r\), the ledger \(L_P(r')\) of any honest party \(P\) cannot include \(tx', tx\) in this order, given that the network consists of all honest nodes.

Permissionless protocols like Nakamoto longest chain ensures optimistic serializability and the checkpointing service does not affect the block ordering; playing a supplementary role. Evidently, Advocate satisfies optimistic serializability by design.

**Corollary 3.8 (Advocate Optimistic Serializability).** Advocate guarantees optimistic serializability (cf. Definition 3.7).

Consider a Nakamoto longest chain protocol; it is easy to show that it guarantees optimistic serializability. Since the honest nodes received \(tx\) before \(tx'\), all miners will mine ledger with \(tx\) before \(tx'\). Even when the ledger is forked, within each fork, the parent is known and hence the order is maintained for all parties. In Advocate, it may happen that the certificate refers to a transaction \(tx\) again; hence the ledger \(L_P(r)\) might have transactions \(tx, tx'\) in that order. However, since the base consensus is Nakamoto, it will ensure that \(tx, tx'\) exists in that order before checkpointing. Thus the \(tx'\) referred by the checkpoint \(C\) will be a second occurrence and will be removed by ledger sanitization.

### 3.5 Contrast with FruitChains and Conflux

In terms of safety, the transaction inclusion from \(F_i\) has similarity to fruits in FruitChains [26] and DAG references in the pivot chain of Conflux [22]. However, we note that if the adversarial mining power is greater than 50%, the adversary can always beat honest nodes by creating a mainchain in Fruitchain and a conflicting pivot chain in Conflux, thus violating safety.

In terms of liveness, FruitChains has a chain quality of 1 - \(\beta\), which is ensured because all blocks created by honest miners are eventually included as fruits. This chain quality however is reduced to 0 for \(\beta > 0.5\). To understand this abrupt loss of chain quality, let us consider an attack by a 51% adversary. The adversary creates a longer blockchain, consisting of only adversarial blocks, and the adversarial blocks do not include references to fruits mined by honest miners. Since the longest blockchain is chosen to create the fruit ledger, it will not consist of any honest fruits, rendering the chain quality 0. Similar arguments can be made for a heavier pivot chain generated by adversaries in Conflux. This abrupt loss of chain quality for \(\beta > 0.5\) is depicted in Figure 1.

Note that implementing existing checkpointing designs like Casper to FruitChains will not will not improve chain quality since the adversarial majority can ensure that the main chain only contains blocks referring to no honest fruits; hence even the checkpointed ledger will not contain any honest fruits. Instead, Advocate
checkpoints all leaves of the block tree; this achieves optimal chain quality (Theorem 3) because the final ledger consists of all produced blocks, where the percentage of adversarial blocks is equal to the adversarial mining power (the lower bound).

4 ADVOCATE WITH BFT CHECKPOINTING

Although Advocate, as described above, satisfies the desired security properties, it assumes a single checkpointing node. This centralized design is problematic, especially in systems like distributed ledgers, whose main purpose is decentralization. In this section, we present Advocate with Byzantine Fault Tolerant (BFT) checkpointing, which extends the single checkpointing node with a committee of n nodes. Although this extension might seem trivial, there are certain fine points (for example running a BFT-SMR with external state validation) that need to be analyzed to establish equivalency. In contrast to other checkpointing protocols, Advocate -BFT allows multiple checkpointing candidates, since a candidate includes both the checkpointed block and the reference links, thus increasing the input space for the BFT committee nodes. The committee achieves consensus on the contents of the checkpoint certificate, which is then published on the main chain.

We present a design that optimizes transaction inclusion and confirmation latency. The adversary A controls up to f committee nodes, s.t. n ≥ 3f + 1, and a fraction β ∈ [0, 1) of the PoW mining power. Note that the BFT committee is independent from the committee of miners. Hence, it is possible for the committee of miners (i.e., a small community for novel PoW chains) to be in adversarial majority, whereas the BFT committee (consisting of well established and legally bound validators) is in honest supermajority.

4.1 Advocate-BFT

The committee nodes act as full nodes for the PoW main chain and run a separate SMR (BFT-based State Machine Replication) protocol; any generic BFT-SMR protocol should suffice. On receiving a valid PoW block, the committee node posts a transaction (Blockhash, Depth) on the SMR chain, which is finalized after some rounds as per the BFT-SMR’s rules.

The SMR chain announces a new checkpoint when a transaction containing a block with depth e more than the previous checkpoint is posted on the SMR chain. A checkpoint transaction tC_i = {H(B_i), M(R_i)} is posted on the SMR chain, where R_i consists of all the main chain blocks referenced on the SMR chain between the references for B_{i-1} and B_i, M(R_i) denotes it’s Merkle root and H(B_i) denotes hash of block B_i.

The checkpoint certificate C_i = {tC_i, R_i, w_i} consists of the checkpoint transaction tC_i = B_i, M(R_i), a witness w_i stating that it is finalized on the SMR chain, and the list of references R_i. C_i should be posted on the PoW chain before the depth of d(B_i) + c, where d(B_i) is the depth of checkpoint B_i.

The SMR chain’s block inclusion validity rules are as follows:

- Data availability: The block should be available.
- Block validity: The block should have valid PoW; note that full transaction validity is not required due to main chain’s ledger sanitization.
- No checkpoint conflict: The block should not be at a height of d(B_i) + e and extend a chain that does not contain B_i.

Evidently, the BFT checkpointing service realizes in a distributed manner the checkpointing node of Section 3. Specifically, the BFT service collects all leaves which are not checkpointed, including the main chain and uncle blocks, and issues a certificate which references them. Assuming the BFT protocol is secure (safe and live), the committee will i) issue a certificate which ii) references all non-checkpointed blocks, so the analysis of Section 3 also applies here.

Main chain behavior The main chain miners act as light nodes for the SMR chain. They include C_i in the main chain as soon as tC_i is finalized on the SMR chain. We assume that the main chain nodes are connected to at least one honest SMR chain node, to get the references from M(R_i). The mining behavior and validity rules including the c constraint on checkpoint inclusion remain the same as described in Section 3.

Latency To compute the latency for a transaction, let τ_m be the time until a block B containing the transaction is mined. Also let τ_f be the time until a transaction containing the hash of B is posted on the SMR chain and τ_c be the time until that transaction is finalized on the SMR chain. The total time until an honest transaction is considered for checkpointing is τ = τ_m + τ_f. Observe that the value τ_f is not affected by the adversarial mining fraction. Finally, the transaction is confirmed when the next checkpoint is posted on the SMR chain, i.e., after time τ_c until the checkpoint is finalized. Therefore, the overall latency of a transaction is τ = τ_f + τ_c. We note that, the parameter c depends on the BFT latency, i.e., ΔBFT.

4.2 BFT integration

We abstract the BFT functionality F_{BFT} and show equivalence with the checkpointing service F_{cps} described in Section 3.

BFT-SMR service F_{BFT}

F_{BFT} is a part of a network of P replicas participating in BFT-SMR. F_{BFT} takes an input I_{BFT} and outputs O_{BFT} after a delay bounded by ΔBFT. F_{BFT} may take no input and still output O_{BFT} depending on the state S_{BFT} and I_{BFT}; an input received by some replica. F_{BFT} checks validity of I_{BFT} and/or I_{BFT} with respect to S_{BFT} stored locally using V_{BFT}. A message from one replica implementing F_{BFT} to another takes a maximum delay of Δ.

We now establish an equivalence between F_{BFT} and F_{cps}. inputValue in F_{cps} is equivalent to I_{BFT} in F_{BFT}, while commitDecision is equivalent to O_{BFT}. However, a major difference is that the delay between the two is ΔBFT in F_{BFT} and Δcps in F_{cps}, s.t. ΔBFT / Δcps > 1. Note that ΔBFT is dependent on the liveness parameter u of the BFT protocol. A further major deviation regards to the implementation of V_{BFT}, which corresponds to the isInputValid and inputValidity messages in F_{cps}. Since the state is not in the same module and the input may be indirectly received from a different replica, the data needed for validating I_{BFT} may not be available to f_advocate, thus returning inputValidity may take unknown time. This is resolved via a unified network functionality N_{uni} (Figure 4) to which each BFT replica connects.
5 ADVOCATE: CHECKPOINTING FOR PARALLEL-POW CHAINS

Many emerging PoW blockchains rely on a “parallel-chain” architecture for scaling, where multiple chains run in parallel and are aggregated. Two successful parallel-chain architectures are Prism [4] and OHIE [34]. Although these two protocols are significantly different from each other, we demonstrate the generalizability of Advocate; we extend Advocate to both these settings by proposing a meta-protocol Advocate-PC for integrating Advocate to parallel-chain architectures. For simplicity, we design Advocate-PC using a single (honest) checkpointing node, which can be readily extended to a BFT federation as described in Section 4.

5.1 Advocate-PC: Meta-protocol

Consider M parallel chains, with mining power sortition across them. A block is labelled as \(B_{m,j,f}\) if it belongs to branch \(f\) of chain \(m\) and has rank \(j\). \(B_{m,j,f}\) is a function of parent of \(B_{m,j,f}\). The rank \(R(B_{m,j,f}) = j\) of a block is determined by the parallel-chain protocol’s specifics and is deterministic when a block is mined. We highlight the first important meta-principle:

**Rank criterion:** Blocks mined by honest miners have monotonically increasing rank within a chain.

Block ranks are used to determine epoch intervals with a checkpointing epoch spanning blocks with a rank-difference of \(e\). We denote a chain as *payload-carrying*, denoted by \(Y(i) = 1\) if its blocks are designed to carry a transaction payload. We set one chain (chain 0) as a *base-chain*, which may or may not be payload-carrying.

**Checkpointing party behavior.**

- Upon receiving Block \(B_{0,j,f}\) at rank \(R(\hat{C}_{i-1}) + e\), where \(\hat{C}_{i-1}\) is the latest checkpointed base-chain block, it creates a new checkpoint certificate \(C_i\), the block \(B_{0,j,f}\) is the checkpointed block \(\hat{C}_i\).

- The certificate \(C_i = \{R(\hat{C}_i), R_i, B_i\}\) defines: (a) a vector of \(M-1\) parallel-chain blocks \(B_i\), i.e., one tip block from each parallel chain except the base-chain, (b) the reference list \(R_i\) of all payload-carrying blocks not referenced by any checkpoint until Rank \(R(\hat{C}_i)\), (c) a reference \(R(\hat{C}_i)\) to the checkpointed base-chain block \(\hat{C}_i\).

**Validity rules.**

- All chains extend the latest checkpoint;
- A base-chain block is invalid if it extends the chain past rank \(R(\hat{C}_i) + c\) and does not contain \(\hat{C}_i\);
- A non base-chain is invalid if none of it’s blocks refer to the base-chain block containing the certificate \(C_i\) by rank \(R(\hat{C}_i) + c\);
- A non base-chain tip block \(B_{m,j,f}\) is valid for inclusion in \(B_i\) only if chain \(m\) has referred to \(\hat{C}_{i-1}\).

The ledger creation rules are similar to Advocate; the checkpoint certificate brings in all the referred blocks \(R_i\) in the respective payload-carrying chain’s ledger.

Advocate-OHIE: We observe that rank in OHIE satisfies the rank criterion and thus can be treated as \(R\). The meta-protocol can be integrated into OHIE by setting the chain 0 as base chain and
assigning its protocol defined rank with the Advocate rank \( R \). A similar extension of the rank criterion works for ledger combiner as well.

**Advocate-Prism**: We observe that Prism’s proposer levels follow the Rank criterion since honest miners always mine blocks with increasing proposer levels. We can integrate Advocate-PC by setting the proposer chain as the base-chain and assigning proposer level as Advocate rank \( R \).

# 6 IMPLEMENTATION AND EVALUATION

We implement Advocate on a codebase in Rust and compare its performance with various existing checkpointing techniques. To test the performance of Advocate to the limit, we integrate Advocate-Prism along with its high performance implementation of Prism written in Rust [33]. We evaluate the performance of Advocate comparing with various other checkpointing protocols. The code is available at [1].

## 6.1 Comparison baselines

We implement two other checkpointing protocols as baselines to compare performance metrics of Advocate. We briefly describe these baselines and their integration with Prism below.

**Stochastic-checkpointing**: Derived from [15], the checkpoint certificates referring to a single Block-hash(checkpoint) are introduced in the ledger. The certificates add randomness at every epoch, ensuring the adversary cannot implement a front-running attack described in [15]. Stochastic-checkpointing is implemented by modifying the Advocate \( F_{gps} \) to generate checkpoint without references.

**Nakamoto-checkpointing**: Derived from the off-chain checkpoints published by Nakamoto in the early days of bitcoin (checkpointing via GitHub). The checkpoints certificates are posted off-chain and consist of a block’s hash. The full node codebase recognizes these checkpoints and only considers chains extending these checkpoints as valid. Nakamoto-checkpointing is implemented by modifying code for Stochastic-checkpointing not to include the certificate on chain.

**Experimental setup**: We run Advocate and Advocate-Prism experiments on c5.9large and c4.4xlarge AWS instances respectively. We run our experiments with \( \beta \geq 0.5 \) with private mining attack where the adversary mines a private chain and broadcast private blocks in bursts of epoch length. Our evaluation answers the following questions:

1. How do performance and security metrics of Advocate compare to state-of-the-art checkpointing and finality gadgets?
2. How does the performance of Advocate react to a slow checkpointing service?
3. How does Advocate perform with large epoch sizes?
4. How does Advocate integrate with very high throughput PoW blockchains, e.g., Prism? How is the performance overhead?

**Performance metrics**: We use three metrics defined below to measure performance:

- **Fractional Goodput (FG)**: Let Goodput (\( G \)) be the number of honest transactions confirmed per unit time and optimal throughput (\( T \)) be the maximum throughput in the absence of an adversary. We define fractional goodput as \( G / T \).
- **Ledger Inclusion latency (IL)**: for an honest party \( P \) is the time taken (measure in means of block arrival time \( \Delta_A \) between transaction generation and inclusion in the ledger of \( P \).
- **Honest block wastage (HW)**: Fraction of honest blocks that are not part of the ledger.

The performance metrics are tabulated in Tables 1, 2, 3 for a variety of experimental settings: varying adversary mining power, BFT network latency (\( \Delta_{gt} \)), epoch size. Each experiment was conducted over a range of 50-100 epochs. We make the following more broad observations from the data:

1. We observe that Advocate is far superior to its competitors in all settings and metrics
2. Advocate takes a lesser hit on performance as compared to its competitors if the checkpointing service is slow
3. IL of Advocate increases linearly with epoch length with minimal drop in its FG

**Prism** The Prism full-stack implementation can achieve a throughput of 70K tx/s; coupled with Advocate an optimized implementation should achieve a throughput of \((1 - \beta) \cdot 70K\) tx/s. However, checkpointing adds to the validity rules, leading to loss of throughput. Our implementation of Advocate-Prism aims to develop a proof-of-concept, s.t. checkpointing can be integrated into high throughput parallel chains without much expense of throughput. To this end, we design an adversary \( A \) for Prism who censors honest transaction blocks. For such an adversary \( A \) with \( \beta = 0.7 \), our full-stack implementation of Advocate-Prism (with UTXO at the application layer and p2p networking at the networking layer) can achieve a goodput of 8200 tx/s with a confirmation latency of 120s. While 8200 tx/s with a 70% adversary is much higher than any existing protocol can achieve, we believe it can be further improved by optimizing interaction between ledger manager and integrated checkpointing module, a direction which will be explored in future research.

# 7 ACKNOWLEDGEMENTS

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\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\textbf{Parameters} & $e = 5$, $\Delta_{\text{BF}} = 0$ & $e = 5$, $\Delta_{\text{BF}} = 2$ & $e = 10$, $\Delta_{\text{BF}} = 0$ \\
\hline
\textbf{Metrics} & FG & IL & HW & FG & IL & HW \\
\hline
Nakamoto-cp & 0.148 & 67.14 & 0.7032 & - & - & - \\
\hline
Stochastic-cp & 0.323 & 6.688 & 0.3539 & 0.204 & 13.76 & 0.594 \\
\hline
Advocate & 0.588 & 3.611 & 0 & 0.514 & 2.546 & 0 \\
\hline
\end{tabular}
\caption{Advocate evaluation for $\beta = 0.5$}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\textbf{Parameters} & $e = 5$, $\Delta_{\text{BF}} = 0$ & $e = 5$, $\Delta_{\text{BF}} = 2$ & $e = 10$, $\Delta_{\text{BF}} = 0$ \\
\hline
\textbf{Metrics} & FG & IL & HW & FG & IL & HW \\
\hline
Nakamoto-cp & 0 & $\infty$ & 1 & - & - & - \\
\hline
Stochastic-cp & 0.101 & 43.11 & 0.696 & 0.033 & 24.43 & 0.9 \\
\hline
Advocate & 0.389 & 3.491 & 0 & 0.330 & 3.217 & 0 \\
\hline
\end{tabular}
\caption{Advocate evaluation for $\beta = 0.67$}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\textbf{Parameters} & $e = 5$, $\Delta_{\text{BF}} = 0$ & $e = 5$, $\Delta_{\text{BF}} = 2$ & $e = 10$, $\Delta_{\text{BF}} = 0$ \\
\hline
\textbf{Metrics} & FG & IL & HW & FG & IL & HW \\
\hline
Nakamoto-cp & 0 & $\infty$ & 1 & - & - & - \\
\hline
Stochastic-cp & 0 & $\infty$ & 1 & 0 & $\infty$ & 1 \\
\hline
Advocate & 0.102 & 2.849 & 0 & 0.072 & 4.319 & 0.278 \\
\hline
\end{tabular}
\caption{Advocate evaluation for $\beta = 0.9$}
\end{table}