Transaction Finality through Ledger Checkpoints

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Abstract—Reversal of transactions due to blockchain ledger re-organization has become a major hindrance for public blockchain technologies adoption in real-world business and financial applications. Since a typical real-world product, service, or agreement cannot be backtracked; associated transactions in the blockchain ledger must also be final. This paper describes and analyzes the transaction finality solution for our proof of work (PoW) blockchain network, the Kona Blockchain Platform. Although designed for our specific platform, the ideas from the solution can be easily adapted to achieve transaction finality in existing public blockchain networks. This paper also discusses how this can be done. To the best of our knowledge, ours is the first solution for transaction finality for blockchain networks incentivised exclusively by PoW mining.

Index Terms—Computer Networks, peer-to-peer computing, distributed information systems

I. INTRODUCTION

Since the publication of Satoshi Nakamoto's 2008 seminal paper [26] that begot it, the blockchain technology has spurred a flurry of commercial activities. Initially the interest on blockchain technology was solely due to its prospect as a harbinger of alternative currency systems maintained by the masses. Blockchain based digital currencies, called *cryptocurrencies*, gained significant momentum in the wake of the 2008 global financial crisis [5]. Following the trail of Bitcoin [26], the first cryptocurrency, several cryptocurrencies [2] [17] [30] [4] [8] with their own blockchain networks appeared in the market.

Subsequently, Ethereum [31] demonstrated that a blockchain network can be utilized as a decentralized state machine that serves not only as a maintainer of a distributed ledger of cryptocurrency transactions but also a trusted computation engine for generic computer codes called *smart contracts*. The logic encoded in a smart contract can define the rules of interactions among mutually untrusted parties and subsequently enforces them during the contract execution, thus eliminating the chance of a dispute. The idea of enforcing business negotiations using a computer code was decades old [29] but did not get traction due to a central missing piece: there was no global computer whose execution result could be trusted. The discovery of the blockchain smart contract solved that problem and led to widespread interest in the technology from numerous application domains. Some

pundits even hail the blockchain technology as a revolution that can transform the global economy [7] [9].

From a technological standpoint, a blockchain system is a decentralized network of peers who maintain the state of a distributed ledger – *the blockchain* – by each executing/validating all the transactions sent to it. The current state of the ledger is updated by adding a block of transactions. Each block has a pointer to its previous block; hence forming a chain called the blockchain. In Nakamoto's proposal [26], a peer who wants to append a valid block in the blockchain has to solve a computational puzzle whose solution is difficult but verification is cheap. The solution of the puzzle becomes a part of the block the peer is trying to append in the blockchain. This serves as a *Proof of Work* (PoW) [10] of the peer to the rest of the network. Combined with the blockchain data structure, PoW provides a simple basis for concensus [11] among the network peers about the state of the ledger.

Users of a peer-to-peer network send transaction requests to arbitrary peers (or subset of peers). It is theoratically impossible to ensure that all transactions will reach all peers within a defined time interval given that even network connectivity among the peers cannot be guaranteed [19]. Consequently, a deterministic ordering of the requested transactions is also unacheivable. Given this problem, each peer of the blockchain network arbitrarily picks among the transactions it received from the users for processing and tries to add blocks in its local version of the chain using those transactions. Whenever it receives a valid blockchain from any of its network neighbors that is longer – i.e., has more work being done on it – than its own version, it accepts the longer chain as canonical and tries to redo its transactions in that longer chain.

Recent alternatives to PoW based consensus for public blockchain networks such as *Proof of Stake* (PoS) [3] or *Proof of Elapsed Time* (PoET) [15] work under the same principal. These protocols change the block construction process and the critera for deciding the best among candidate blockchains. The chance that a better blockchain will replace the current local chain of a peer remains regardless of their protocol differences. Consequently, the long term persistence of blockchain transactions is always a probabilistic guarantee. Currently, guaranteed permanence – commonly called *transaction finality* – in blockchain technology is available only under stringent trust and connectivity contraints among the network peers [16], [24]. These constraints are typically difficult to apply

in scalable, peer-to-peer, public networks.

However, the probabilistic permanence of transactions is a serious hindrance for blockchain technology adoption in modeling real-world business and financial interactions. This is because, unlike blockchain transactions, real-world consequences are typically irreversible or non-replayable. If a product is sold, it is sold. If a service is given, it is given. If an aggrement is signed, it is signed. Reversals of consequent payment transactions in the blockchain cannot nullify them. Hence, the transaction finality problem must be solved to realize blockchain technology's potential in documenting real-world interactions and for cryptocurrencies' acceptance in all kinds of payments.

This paper describes the transaction finality solution of the *Kona blockchain platform*: a blockchain solution supporting smart contracts with additional features needed for porting financial and business applications on a peer-to-peer blockchain network incentivised by PoW mining. Finality is achieved by periodically establishing network-wide consensus about *accepted, irreversible state* of the blockchain ledger we call a *checkpoint*. All transactions up to the latest checkpoint are final, thus, can be safely used for any real-world decision making. Transcations mined into blocks after the latest checkpoint are only probabilistically secure until they are included into the next checkpoint.

The checkpoint establishment process, we call *the checkpoint protocol*, neither compromises the PoW mining protocol nor does it necessitate any new network connectivity constraints among the mining peers. Miners' collaboration during checkpoint establishment is incentivised by a PoW mining based voting scheme. The only addition to the network is a *byzantine fault-tolerant* (BFT) [23] support service that disburses checkpoint ballots, seals checkpoint blocks, and does nothing else. The presence of the support service also ensures that a large group of new miners entering the network after a checkpoint cannot reverse a check-pointed state retroactively. We prove that under the current PoW incentive scheme, the addition of such a service is mandory for ensuring transaction finality in a peer-to-peer network. It can be proven that our checkpoint protocol is fair, non-exclusionary, and can only be interrupted by a successful DDoS attack [32] on the support service.

The paper provides a discussion of the design motives and a detailed analysis of the qualititative properties along with the description of the checkpoint protocol. In addition, the paper illustrates how a byzantine fault-tolerant support service can be realized and properly incentivised so that it cannot willfully bias or destabilize the checkpoint protocol. The rest the paper is organized as follows:

A. Paper Organization

Section II describes related work on transaction finality in blockchain technology; Section III analyses a PoW incentive scheme's impact on miner collaboration and consequent challenges in achieving transaction finality; Section IV then establishes the model for the check-pointing problem and elaborates on modeling objectives; Section V presents our checkpoint protocol; Section VI analyses how the protocol meets the objectives of Section IV; Section VII then touches on some implementation concerns, in particular, it describes how to implement a BFT support service and discusses what can be its alternative in existing public blockchain networks; Finally, Section VIII concludes the paper along with a discussion on future improvements to the protocol.

II. RELATED WORK

It has been theoretically proven that purely peer-to-peer blockchains are probabilistic state machines that cannot provide any finality guarantee [28]. The proof follows easily from the fact that malicious peers can reach 51% majority in a network and reverse all transactions. So any discussion of blockchain ledger stability assumes that the majority mining power is held by the honest peers. A more practical analysis [27] shows that assuming a bounded network delay and no message loss, a blockchain network achieves consistency (i.e., transaction finality) with probablity approaching 1. The problem is messages can be lost and the network delay bound cannot be predermined in practical peer-to-peer network even with majority honest peers. Hence, *probabilistic* transaction finality is the best that can be achieved without any new restriction on the blockchain network.

However, existing blockchain consensus protocols that claim to provide transaction finality impose restrictions on network participation that are difficult to realize in a peer-to-peer setting where participants can join and leave at any time. For example, the Ripple [16] protocol assumes that 80% neighbors of each honest peer are honest and malicious neigbors cannot intercept communications between honest peers. Similarly, the Stellar consensus protocol [24] assumes that the majority honest peers of the network form a connected sub-network that provides guaranteed message delivery. The Tendermint consensus protocol [12] also assumes $\frac{2}{3}$ majority of honest peers receives every message within a bounded time delay. Under this assumption, it provides a *PBFT* [14] solution decentralized for blockchain technology domain. The central issue with all these protocols is that they assume a gossip communication protocol [6] can be utilized as a mean to implement a reliable broadcast primitive [21] in a peer-to-peer network. This assumption is not theoretically valid. Hence these protocols suffer stagnation when broadcast fails.

The forerunner of the *business blockchain movement*, Hyperledger, provides transaction finality for two of its blockchain solutions: *Iroha* [25] and *Fabric* [20]. Both assume there is a BFT ordering service that orders and reliably delivers messages to all network peers. The network is definitely not peer-to-peer in either case and so far no convincing BFT solution for a distributed ordering service has been proposed.

None of the aforementioned protocols work on a network incentivised by PoW mining. The only notable transaction finality solution for PoW blockchain networks is Ethereum's Casper [13]. Casper assigns validator nodes (based on deposit of stakes) among the mining population for regularly voting on

alternative blockchain versions. The version receiving $\frac{2}{3}$ majority of votes is called a finalized checkpoint, thus irreversible. Since the underlying networking characteristics remain the same, $\frac{2}{3}$ validator nodes may fail to communicate, consequently to collaborate, for establishing a voting consensus. Thus, in the worst case no checkpoint can be finalized.

A major difference between ours and existing transaction finality solutions is that we do not assume the existence of any reliable broadcast primitive in the underlying peer-to-peer network. Still, we periodically establish checkpoints in the blockchain ledger. In addition, although we employ voting for reaching consensus about a checkpoint like others, our voting process is also governed by a PoW incentive unlike any.

III. AN ANALYSIS OF POW INCENTIVE

From a technical perspective, Nakamoto's Bitcoin [26] took the world by storm because it shows for the first time that a highly secure distributed system can be built from laissez-faire collaboration of a network of mutually-distrusted autonomous peers. Even continuous network connectivity among the peers are not required and the network-wide connection topology remains dynamic. He deemed a PoW for block mining is necessary to thwart traditional networking attacks such as the Sybil Attack [18] on such a system. To successfully alter a shared blockchain ledger of honest miners, an attacker has to surpass their combined mining power to construct an alternative chain that is longer; then offer it to them for synchronization. The effort becomes more futile as the population of honest peers increases.

The strength of information security in a blockchain network is proportional to the mining capacity of its honest peers. Therefore, from its inception, keeping honest peers interested in network participation is a central concern in blockchain technology. Nakamoto's ingeneous idea was to make participation in block mining process an economic activity [22] by rewarding a block miner for his/her PoW in terms of transaction fees and a block reward. This is the crux of the PoW incentive scheme.

PoW incentive makes honest behavior the rational behavior [26] in a blockchain network governed by economic principles. This particular feat is the source of its resilience. So far no alternative to PoW incentive is proven to be equally scalable, secure, and censorship-resistant. Consequently, the largest and most-powerful blockchain networks are still PoW networks despite widespread scrutiny of PoW mining's power consumption cost [1]. Hence, transaction finality solutions should also target PoW mining based blockchain networks.

In the PoW incentive scheme, all miner activities including computation and communication are governed by rational behavior of maximizing ecomoic gain. As a result, in such a network a consensus about an irreversible ledger state (i.e., transaction finality) cannot be established without halting the mining process, as explained in the following lemma:

Lemma III.1. *Transaction finality is unachievable without halting block mining in a PoW blockchain network.*

Proof. Since there is no benefit for a peer in throwing away its local blockchain ledger version and accepting a neighbor's blockchain that has the same amount of PoW being done on it, information about alternative equally good blockchain versions will not spreed in the network. Consequently, at any instance of time there might be as many equally good blockchain ledger versions as the number of miners. In addition, a peer cannot accurately estimate the number of currently active peers in the network. Consequently, it cannot determine if its local version of the blockchain ledger is accepted by the majority.

Since a rational miner can convincingly neither deduce if its own attempt to established a network-wide consensus about irrefutable blockchain ledger state will be successful nor deduce whether it will be worthwhile to throw away its own equally good local ledger state in response to a request from a neighbor, the only rational behavior is to keep lengthening its own local ledger version. In the worst case, all miners will emulate the same behavior and the only consented state will be the genesis state and no transaction can ever be declared final. Hence halting block mining is essential for forcing a ledger state consensus. $\square$

At what state of the blockchain ledger the next checkpoint consensus should be attempted must be known to all network peers beforehand since otherwise they will not know when to halt in the absence of a reliable broadcast mechanism. A simple way to achieve this is to make checkpoints periodical to the length of the blockchain or the total amount of PoW. Another alternative is to decide the next checkpoint time as part of the consensus establishement for the current checkpoint.

An important property of transaction finality in a PoW mining based blockchain network is that given it is a requirement, the rational behavior is to halt and establish a checkpoint at intended time before attempting further progress in advancing the blockchain. This is explained in the following lemma:

Lemma III.2. *The only rational behavior is to collaborate on a checkpoint consensus when a miner's local blockchain ledger approaches the checkpoint state.*

Proof. Without loss of generality, assume that checkpoints are set at intervals periodic to the length of the blockchain ledger. Now contrary to the proposition, assume a miner whose local blockchain ledger has reached the checkpoint length did not attempt a checkpoint consensus and keeps mining new blocks.

Since the rule is to set checkpoints at specific lengths of the blockchain, all blockchain ledger versions that are at least as long as the next checkpoint length are PoW-wise equal for the lagging behind peers regardless of their actual length. Except for the fact that it is rational for a lagging behind peer to accept the ledger version that keeps most of its own mined blocks intact. Since it can happen that the shortest chain that crossed the next checkpoint length is the chain that maximises the profits of the majority miners, the shortest chain can win the next checkpoint.

Since all blocks in the loosing chains after the checkpoint length will be dropped, it is not rational for a miner to keep

mining blocks after its ledger reaches the checkpoint length without knowing that its own chain maximises the profit of majority lagging behind miners. Which it cannot do without attempting a checkpoint consensus. Thus a contradiction. $\square$

Lemma III.1 and III.2 suggest that a reasonable strategy to acheive transaction finality in a PoW mining based blockchain network is to periodically alternate between a block mining and a checkpoint protocols. However, the checkpoint protocol should be designed with care to avoid scalability and fairness issues during its execution and to avoid introducing security, and censorship issues in the block mining process during the protocol switching.

IV. PROBLEM MODELING

From the discussion of Section III, we understand that the goal of the checkpoint protocol is to achieve a network-wide consensus about an irreversible and unique state of the blockchain ledger at deterministic intervals. We also understand that at the end of a checkpoint interval, there might be many miners holding different blockchain ledgers that are valid candidates to be the next checkpoint and many who are lagging behind. If we call the formers, *Front-runners*, the qualitative goal of the checkpoint protocol should be as follows:

> **Fairly select** a single ledger version from the front-runners **without censoring** the lagging behind miners and ensure **unaffected progression** of PoW block mining after the selection.

Our approach to the aforementioned highlighted objectives is to establish each checkpoint based on a 51% majority voting by the currently active network peers on the chains of the front-runners who reached the checkpoint candidacy state the earliest. The evidence of checkpoint selection is included in the winning chain as a checkpoint block and the proceeds for mining the checkpoint block is distributed to the peers voted to support it. Here a balot is casted for a candidate by solving PoW puzzles on its chain state.

Assume there are total N active peers in the blockchain network and the current state of the local blockchain ledger version of peer i is represented as follows:

$$BS_i(h, l, t, c) = i^{th} \ peer's \ state, \ where$$
$$h = current \ header \ block \ hash$$
$$l = length \ of \ the \ blockchain$$
$$t = header \ block \ mining \ time$$
$$c = last \ checkpoint \ block \ hash$$

Further, let $BS_i^h, BS_i^l, BS_i^t, BS_i^c$ denote the individual attributes of ith peer's state and $BS_i^h(n), BS_i^t(n)$ refer to the header block hash and mining time when the ledger length was n. In addition, let $\Lambda(h)$ returns the length of the blockchain ledger and $\mathcal{T}(h)$ the time when the block with hash h was mined by anyone. Finally, let C denotes the set of checkpoints. Then the objective of our checkpoint protocol is to maintain

the following invariants as true for all currently active network peers:

$$BS_i^c = BS_j^c, \ \forall i \neq j \ \& \ i.j \in N \quad (1)$$

$$\mathcal{T}(c) = \{\min_{i \in N}(\mathcal{T}(BS_i^h(l))) \mid l = \Lambda(c)\}, \ \forall c \in C \quad (2)$$

$$\frac{\sum_i^N \{1 \mid BS_i^h(l) = c, \ l = \Lambda(c)\}}{N} \geq .51, \ \forall c \in C \quad (3)$$

Invariant 1 says that all active network peers advance their ledger versions from a common check-pointed state, Invariant 2 ensures that each checkpoint is selected among the ledger versions that receached the checkpoint candidacy state the earliest, finally, Invariant 3 dictates that the candidate ledger version that gains 51% majority support (i.e., synchronized by the majority) becomes the checkpoint.

A prerequisite to maintaining these invariant is to determine the value of N: the number of active peers in the network. In a purely peer-to-peer blockchain network no peer has an accurate estimate of the size of the currently active peer population. Thus we introduce a set of *support service* nodes for active network population estimation. Addresses of these nodes are known to the mining peers. Support service nodes form a distributed population status estimation service. Each mining peer exchanges periodic heartbeat messages with random support nodes. To be considered currently active and eligible for participation in the upcoming checkpoint consensus protocol, a peer must have exchanged a heartbeat with some support node within a defined time window, we call the *keep-alive time interval*. Assume the timestamp of latest heartbeat message of Peer i is H_i^t, the keep-alive time interval is Δ, and the network time of the distributed support service is Υ. Then the rule for estimating N is as follows:

$$N = \sum_{i=0}^{i=\infty} 1 \mid \Upsilon - H_i^t \leq \Delta \quad (4)$$

The support service also seals the checkpoint block by signing it once a majority consensus about the winning ledger version is reached. This seal is needed to ensure that even if the entire population of the active mining peers is replaced, new peers cannot revert a check-pointed state. A sealed checkpoint block is a 7-tuple of the form $\langle \zeta_h, \zeta_c, \zeta_t, \zeta_e, \zeta_v, \zeta_i \rangle$ with the following interpretation:

$\zeta_h = the \ block \ hash \ of \ the \ checkpointed \ ledger \ state$

$\zeta_c = the \ current \ checkpoint \ interval \ counter$

$\zeta_t = the \ timestamp \ of \ the \ checkpoint \ block$

$\zeta_e = evidence \ that \ the \ estimation \ of \ N \ is \ accurate$

$\zeta_v = evidence \ that \ majority \ supported \ the \ checkpoint$

$\zeta_i = next \ checkpoint \ interval \ length$

ζ_c and ζ_t ensure that the support service cannot regress to an earlier state of the blockchain and resume checkpoint sealing from there, and ζ_i makes provision for dynamic adjustments of the checkpoint interval.

Note that all attributes of Peer i's ledger state are self-evident except for BS_i^t: the mining time of the header block.

The peers of a blockchain network are only loosely time-synchronized and a mining peer can advance its clock (within a limit) to gain advantage in the checkpoint selection process. To tackle arbitrary adjustments of the block mining time, BS_i^t is derived from Peer i's heartbeat message timing with support nodes. Assume that, heartbeat message sequence is $1 \cdots M$.

V. Checkpoint Algorithm

VI. Fitness Analysis

VII. Implementation Concerns

VIII. Conclusion

A. Future Work

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