

Solana: 高パフォーマンスなブロックチェーンを実現する 新しいアーキテクチャ v0.8.13

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概要

本文では Proof of History (PoH) による新たなブロックチェーンのアーキテクチャを提言する。PoH はトラストレスなネットワークにあって、一連のイベント発生タイミングの前後関係を記帳し、それを証明する仕組みである——この台帳は記帳済みの情報は変更不可能で、追記のみ可能なものである。PoH は Proof of Work (PoW) あるいは Proof of Stake (PoS) などの合意形成アルゴリズムと併用することで、Byzantine Fault Tolerant によるステートマシンの状態共有のオーバーヘッドを低減し、結果的に合意形成にかかる時間を短縮することができる。また PoH による時間管理の性能をより強固にする二つのアルゴリズムを紹介する。ひとつは任意のサイズに分断されたネットワークから復旧可能な PoS アルゴリズム、もうひとつは Proof of Replication (PoRep) を効率的にストリーミングするアルゴリズムである。PoRep と PoH の組み合わせは、時間（順序）とデータ保管を司る台帳の偽造に対する防衛手段となる。現代のハードウェア性能と 1Gbps のネットワーク環境が備えられていることを前提として、このプロトコルによる実装は最大 710,000TPS (transaction per-second) のスループットが実現可能であることを示す。

1 はじめに

ブロックチェーンは耐障害性を備える複製されたステートマシンの実装である。現在パブリックに利用可能なブロックチェーンの生成アルゴリズムは時間に依存しない、あるいはネットワーク参加者が正確な時間を管理できていることに期待しない [4, 5]。ネットワーク上の各ノードはローカル時間のみを参照し、他ノードのローカル時間をまったく意識しない。『信頼できる時間の基準がない』ということは、タイムスタンプをメッセージの承諾・拒否の判断に用いる場合に、すべてのノードがそのメッセージに対する判断を同じように下すとは限らないということになる。ここで紹介する PoH は、ネットワーク上の時間の基準となりえる台帳を提供する設計になっている。ここでいう時間とは、二つのイベントに挟まれた期間やメッセージの順序関係を指す。ネットワーク上のすべてのノードは、そのネットワークがトラストレスであるにも関わらず、PoH が生成した時間の基準に依拠できるようになると期待される。

2 本文の構成

本資料は次のような構成が取られている。セクション 3 ではシステム設計の全体像が描かれている。セクション 4 では Proof of History の詳細が語られている。セクション 5 では今回提案される Proof of Stake による合意形成アルゴリズムが示されている。セクション 6 では高速な Proof of Replication の仕組みが詳細に説明されている。セクション 7 ではシステムアーキテクチャとパフォーマンス上限に関する分析がなされている。セクション 7.5 では GPU 計算向きの高パフォーマンスなスマートコントラクト・エンジンについて詳しい考察がなされている。

3 ネットワークデザイン

図 1 に示されているように、システムノードは常に Leader として Proof of History の生成を担う。これはネットワーク全体で一貫性のある時間軸を提供する。スループットを最大化するため、他ノードが効率よく処理を進められるよう、Leader はユーザメッセージを並べて順序付けする。これは RAM（主記憶装置）に格納された状態に基づいてトランザクションを執行し、実行結果を署名付きで Verifier と呼ばれるノードに引き渡す。Verifier は各自が RAM 上に保持している状態から同じトランザクションを繰り返す、実



図1 ネットワーク上のトランザクションフロー

行結果を確認してそれに署名を付与する。この署名付きの計算結果は票となり、ネットワーク上の正史を選び出すための合意形成アルゴリズムに用いられる。

ネットワークが分断されていない状況下では、常に Leader はネットワーク上にひとつ存在する。各 Verifier ノードは Leader と同性能のハードウェアを備えるようにし、PoS に基づいて Leader として選出される可能性が与えられる。ここで挙げられた PoS のアルゴリズムはセクション 5.6 で詳しく説明する。

ネットワークの分断が発生してしまった場合、CAP 定理に基づく一貫性は可用性より優先される。大規模な分断が発生する状況を想定して、本資料は任意のサイズで分断された状態からネットワークを復旧させるメカニズムを説明する。詳細はセクション 5.12 を参照されたい。

4 Proof of History

Proof of History は任意の二つのイベントに挟まれた時間の経過を暗号学に検証できる方法を提供する。これには入力から出力を予測することが不可能な暗号学に安全な関数で計算することが求められる。一連の計算は単一コア上で行われ、前回計算のアウトプット

は今回計算のインプットとして使われる。関数が呼び出される度、その計算結果と呼び出し回数を記録する。ここまで行われた計算の入出力を分割して、外部マシンの複数コアに並列で再計算させることで、計算結果に対する正否の検証が行われる。データそのもの、あるいはデータのハッシュ値をシーケンスに加えることは、タイムスタンプに相当する情報をそのデータに付与することにあたる。つまりそれは状態、順序、データの記録が、次のハッシュ計算が開始された以前に完了していたことの証明に他ならないからだ。この設計は、複数のシーケンス生成者同士が互いのシーケンスに含まれる情報を提供し、その情報を計算のインプットとして混ぜ込み、同期を取ることができる平行スケーリングをサポートする。この平行スケーリングについてはセクション 4.4 で少し踏み込んだ議論を行う。

4.1 説明

システムは次のように設計される。実行前に計算結果を予測できない暗号学的ハッシュ関数 (例: sha256、ripemd など) を用いる。無作為に選ばれた値を初期入力値としてハッシュ計算を開始、今回の計算結果を次回計算の入力値として使う。今回計算も次回計算も実行するハッシュ関数は同じである。関数の呼び出し回数および計算結果は順次記録される。またここで登場した初期入力値は、当日のニューヨークタイムズ紙のヘッドラインなど、任意の文字列を選択して良い。

PoH シーケンス		
順番	計算内容	計算結果
1	sha256(" 無作為に選ばれた初期入力値")	hash1
2	sha256(hash1)	hash2
3	sha256(hash2)	hash3

図中の hashN は N 番目に行われたハッシュ計算の結果を表している。

ここで要求されるのは都度ハッシュ計算結果と順序番号を発行することに尽きる。

PoH Sequence

順番	計算内容	計算結果
1	sha256(” 無作為に選ばれた初期入力値”)	hash1
200	sha256(hash199)	hash200
300	sha256(hash299)	hash300

ハッシュ関数に強衝突耐性が備わっている限り、この一連のハッシュ値はシングルスレッドのみで計算可能である。これは 300 番目のハッシュ計算結果は、当該ハッシュ計算を 300 回繰り返すまで求まらないことから明らかである。この制約から 0 番目から 300 番目までの計算が終わるまでには、相応の時間が経過していることが分かる。

図 2 中にあるハッシュ値 62f51643c1 は 510144806912 番目に求められ、ハッシュ値 c43d862d88 は 510146904064 番目に求められたことを表している。既に説明した通り、510144806912 番目と 510146904064 番目の間にかかった計算時間の分だけ現実世界の時間も経過することがわかる。

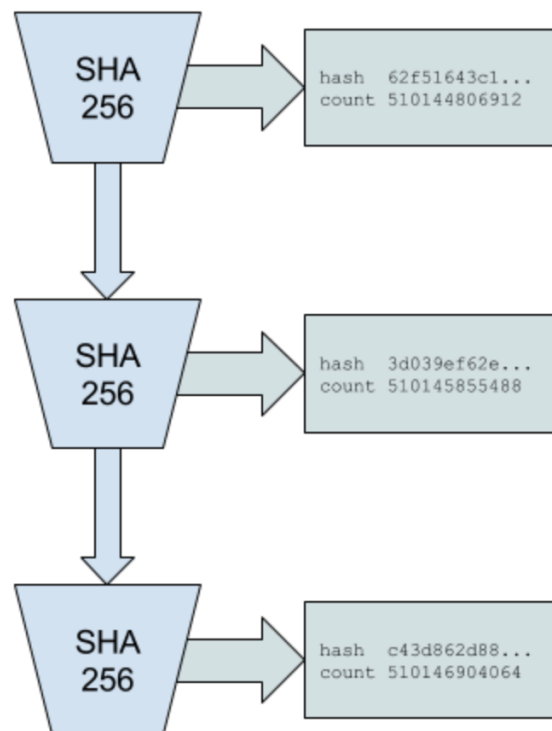


図 2 Proof of History シーケンス

4.2 イベントのタイムスタンプ

上述の通り、このハッシュ値のシーケンスは、あるデータがシーケンスに挿入される以前に、対象のデータが作成されていたことの記録として用いることができる。それはデータと現在の順序に弾き出されて来たハッシュ値に 'combine' 関数を適用することで、順序と値が組み合わされた計算結果が記録として残るためである。このとき任意のイベントデータが暗号的にユニークなハッシュ値に変換される。'combine' 関数は常に強衝突耐性を備え、単純に計算結果を積み重ねていくことができる。結果的に得られたハッシュ値はそのデータにとってのタイムスタンプとなる。それは以前のハッシュ値を基にして生成されたハッシュ値であるため、以前に記録されたデータよりも後に生成されていることが言えるからである。

PoH シーケンス

順番	計算内容	計算結果
1	sha256(" 無作為に選ばれた初期入力値")	hash1
200	sha256(hash199)	hash200
300	sha256(hash299)	hash300

例えば写真撮影など、なにか電子データが作成されるようなイベントが発生したとき、

PoH Sequence With Data

順番	計算内容	計算結果
1	sha256(" 無作為に選ばれた初期入力値")	hash1
200	sha256(hash199)	hash200
300	sha256(hash299)	hash300
336	sha256(append(hash335, 撮影データの sha256 値))	hash336

Hash336 は hash335 と撮影データの sha256 値を入力値として計算されている。こうして撮影データの sha256 値とその順番はシーケンスに記録される。つまり入力値さえ特定できていれば、誰でもこのシーケンスに対する変更内容を再現して検証することができるのだ。シーケンス上の各部分は並列で検証できることになるが、詳しくはセクション 4.3 で説明する。

POH シーケンス

順番	計算内容	計算結果
1	sha256(” 無作為に選ばれた初期入力値”)	hash1
200	sha256(hash199)	hash200
300	sha256(hash299)	hash300
336	sha256(append(hash335, 撮影データ 1 の sha256 値))	hash336
400	sha256(hash399)	hash400
500	sha256(hash499)	hash500
600	sha256(append(hash599, 撮影データ 2 の sha256 値))	hash600
700	sha256(hash699)	hash700

表 1 2つのイベントを挿入した PoH シーケンス

一連の計算はひとつずつ順番に行わざるを得ない仕組みから、ある情報がシーケンスに挿入されたタイミングは、それ以降に計算されたハッシュ計算が完了するより以前であることを明らかにできる。

表 1 のシーケンスから撮影データ 2 が hash600 の計算完了より以前に、撮影データ 1 が hash336 の計算完了より以前に作成されたことが分かる。ハッシュ値をシーケンスに書き込むことは、結果的に後続すべての計算結果に影響を与えることになる。シーケンスへ挿入したいデータに適用されるハッシュ関数が衝突耐性を備える限り、今後どのようなデータが追加されるか分かっていたとしても、未来のシーケンスを事前に予測することは不可能である。

シーケンスに挿入されるデータは無加工でも、メタデータ付きハッシュ値でも良い。

図 3 では入力値 cfd40df8...が Proof of History のシーケンスへ挿入されている。挿入された順番は 510145855488 で、その時点の状態は 3d039eef3 である。将来生成されるすべてのハッシュ値は、今回のシーケンスに対するデータ挿入により影響を受ける。その影響範囲を図中では色付きで表現している。

シーケンスを観察しているノードは、すべてのイベントが挿入された順序と、任意のふ

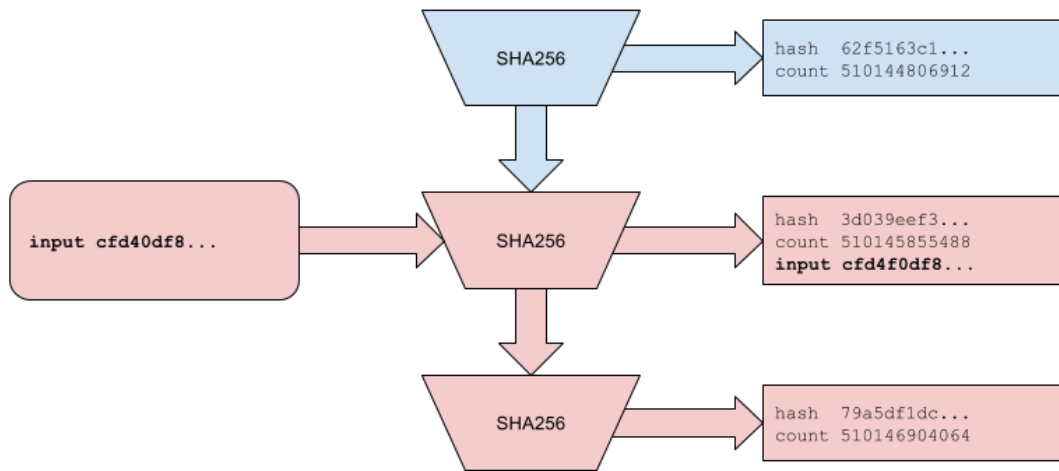


図3 Proof of History へのデータの挿入

たつの挿入時点の間で経過した時間を見積もることができる。

4.3 検証

検証時の計算はマルチコアで実行可能なので、生成時よりも圧倒的に短い時間で完了することができる。

コア 1		
順番	計算内容	計算結果
200	sha256(hash199)	hash200
300	sha256(hash299)	hash300
コア 2		
順番	計算内容	計算結果
300	sha256(hash299)	hash300
400	sha256(hash399)	hash400

例えば 4000 コアを備える GPU を使って計算する場合、検証者は生成されたシーケンスを 4000 に分割して、先頭から末尾までのハッシュ計算が正しく行われていたかを並列計算で確認できる。シーケンス生成にかかる計算時間を次のように計算できるとすると、

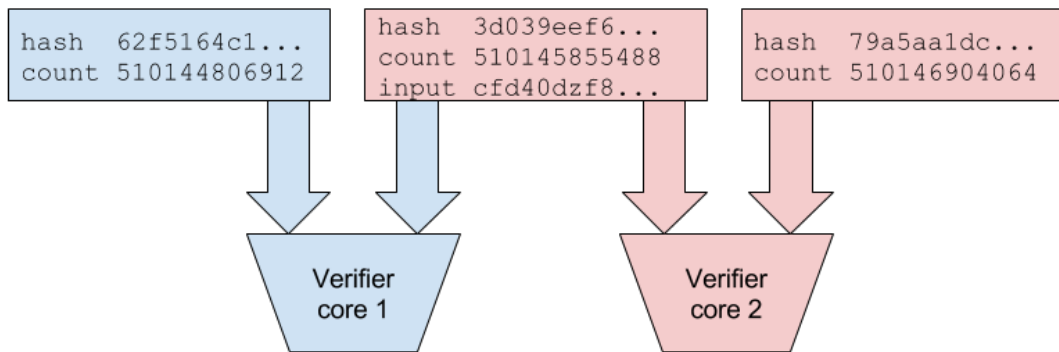


図 4 複数コアによる検証

$$\frac{\text{ハッシュ計算の総回数}}{\text{1 コアで処理される秒間ハッシュ計算回数}}$$

検証にかかる計算時間は、

$$\frac{\text{ハッシュ計算の総回数}}{(\text{1 コアで処理される秒間ハッシュ計算回数} * \text{検証に使えるコア数})}$$

図 4 では分割されたシーケンスを各コアが並列で検証している。すべてのインプットは順番と状態と併せて計算結果に記録され、検証者は同じ計算を繰り返すことでシーケンスを複製していく。赤色に染められたハッシュ値は、シーケンスがデータ挿入により変更されたことを指している。

4.4 平行スケーリング

複数の Proof of History 生成者同士でシーケンスの状態を共有することで、平行スケーリングの実現を可能とする。このスケーリングはシャーディングを使わずに果たせる。2つの生成者でスケーリングする場合、双方のシーケンスに記録されている全てのイベントの順序を分かるフルシーケンスを構築するためには、各生成者が導き出した計算結果が必要となる。

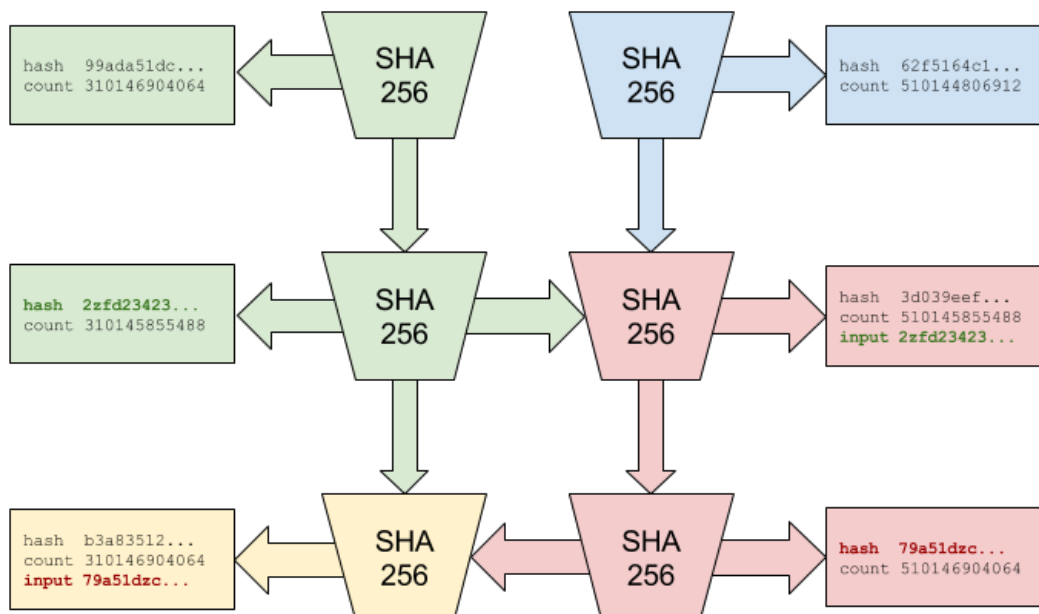


図5 同期する二つの生成者

PoH 生成者 A			PoH 生成者 B		
順番	計算内容	計算結果	順番	計算内容	計算結果
1	hash1a		1	hash1b	
2	hash2a	hash1b	2	hash2b	hash1a
3	hash3a		3	hash3b	
4	hash4a		4	hash4b	

図中のように生成者 A と B が参加している場合、A は B から直近の状態をデータパケット (hash1b) として受け取る。生成者 A が次に取る状態のハッシュ値は、生成者 B から提供された状態を含めて計算される。よって hash1b は hash3a より以前に計算済みであったことを示すことができる。この仕組みは、例えば 3 つ生成者が存在しているとき、 $A \leftrightarrow B \leftrightarrow C$ のように 1 組 (A と C) が直接同期を取っていないくても、弊害なく A、B、C 間のフルシーケンスを求めることが可能である。

定期的に同期することで、各生成者は外部のトラフィックを処理することが可能となり、システム全体として対処可能なイベント数を増幅させることができるようになる。ただしネットワークを通した同期であるため、生成者間で生じるレイテンシ分だけ時間の計測精度が犠牲となる。この同期中に発生するグローバルな順序決定の問題は、ハッシュ値順にするなどの事前に取り決めた方法で順序を決定づける。

図 5 は二つの生成者が出力した状態を共有し合い、互いのシーケンスに挿入している様子を表している。色の変化は同期によりシーケンスに影響を受けたことを表現している。同期時に共有されたハッシュ値は色付きの太字で表現されている。

この同期方法により、 $A \leftrightarrow B \leftrightarrow C$ のように直接同期していない生成者同士でも、三者間のイベント順序は矛盾なく決定することができる。

このようなスケーリング方法は可用性を犠牲にして成り立ってる。10 × 1 gbps のネットワーク環境の稼働率が 0.999 のとき、ネットワーク全体の稼働率は $0.999^{10} = 0.99$ となる。

4.5 一貫性

Users are expected to be able to enforce consistency of the generated sequence and make it resistant to attacks by inserting the last observed output of the sequence they consider valid into their input.

PoH Sequence A			PoH Hidden Sequence B		
Index	Data	Output Hash	Index	Data	Output Hash
10		hash10a	10		hash10b
20	Event1	hash20a	20	Event3	hash20b
30	Event2	hash30a	30	Event2	hash30b
40	Event3	hash40a	40	Event1	hash40b

A malicious PoH generator could produce a second hidden sequence with the events in reverse order, if it has access to all the events at once, or is able to generate a faster hidden sequence.

To prevent this attack, each client-generated Event should contain within itself the latest hash that the client observed from what it considers to be a valid sequence. So when a client creates the "Event1" data, they should append the last hash they have observed.

PoH Sequence A

Index	Data	Output Hash
10		hash10a
20	Event1 = append(event1 data, hash10a)	hash20a
30	Event2 = append(event2 data, hash20a)	hash30a
40	Event3 = append(event3 data, hash30a)	hash40a

When the sequence is published, Event3 would be referencing hash30a, and if it's not in the sequence prior to this Event, the consumers of the sequence know that it's an invalid sequence. The partial reordering attack would then be limited to the number of hashes produced while the client has observed an event and when the event was entered. Clients should then be able to write software that does not assume the order is correct for the short period of hashes between the last observed and inserted hash.

To prevent a malicious PoH generator from rewriting the client Event hashes, the clients can submit a signature of the event data and the last observed hash instead of just the data.

PoH Sequence A

Index	Data	Output Hash
10		hash10a
20	Event1 = sign(append(event1 data, hash10a), Client Private Key)	hash20a
30	Event2 = sign(append(event2 data, hash20a), Client Private Key)	hash30a
40	Event3 = sign(append(event3 data, hash30a), Client Private Key)	hash40a

Verification of this data requires a signature verification, and a lookup of the hash in the sequence of hashes prior to this one.

Verify:

(Signature, PublicKey, hash30a, event3 data) = Event3

Verify(Signature, PublicKey, Event3)

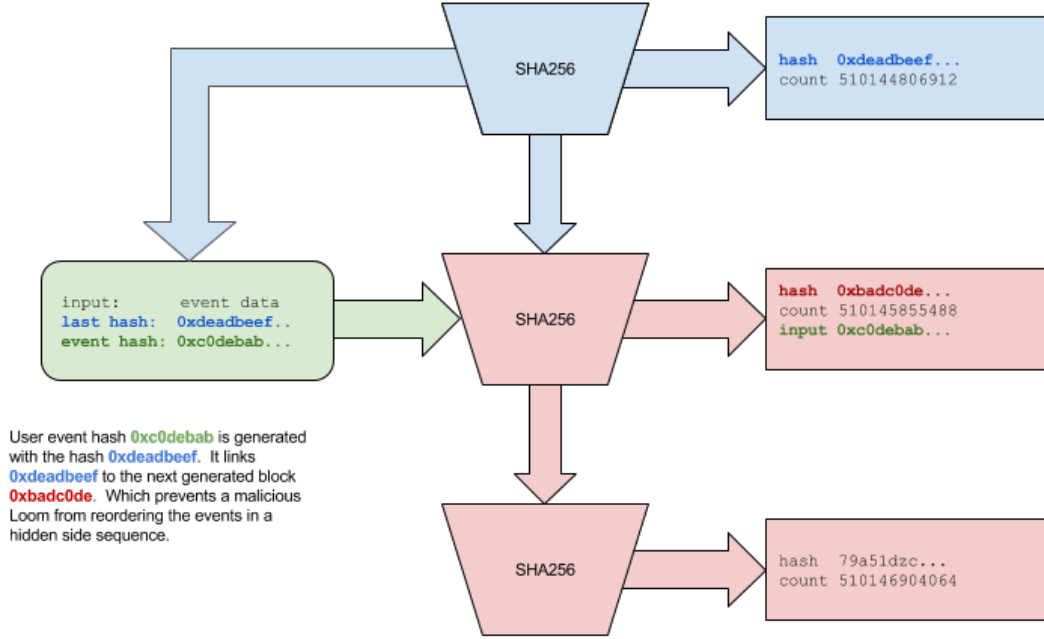


图 6 Input with a back reference.

Lookup(hash30a, PoHSequence)

In Figure 6, the user-supplied input is dependent on hash 0xdeadbeef... existing in the generated sequence sometime before it's inserted. The blue top left arrow indicates that the client is referencing a previously produced hash. The client's message is only valid in a sequence that contains the hash 0xdeadbeef.... The red color in the sequence indicates that the sequence has been modified by the clients data.

4.6 Overhead

4000 hashes per second would generate an additional 160 kilobytes of data, and would require access to a GPU with 4000 cores and roughly 0.25-0.75 milliseconds of time to verify.

4.7 Attacks

4.7.1 Reversal

Generating a reverse order would require an attacker to start the malicious sequence after the second event. This delay should allow any non malicious peer to peer nodes to communicate about the original order.

4.7.2 Speed

Having multiple generators may make deployment more resistant to attacks. One generator could be high bandwidth, and receive many events to mix into its sequence, another generator could be high speed low bandwidth that periodically mixes with the high bandwidth generator.

The high speed sequence would create a secondary sequence of data that an attacker would have to reverse.

4.7.3 Long Range Attacks

Long range attacks involve acquiring old discarded client Private Keys, and generating a falsified ledger [10]. Proof of History provides some protection against long range attacks. A malicious user that gains access to old private keys would have to recreate a historical record that takes as much time as the original one they are trying to forge. This would require access to a faster processor than the network is currently using, otherwise the attacker would never catch up in history length.

Additionally, a single source of time allows for construction of a simpler Proof of Replication (more on that in Section 6). Since the network is designed so that all participants in the network will rely on a single historical record of events.

PoRep and PoH together should provide a defense of both space and time against a forged ledger.

5 Proof of Stake Consensus

5.1 Description

This specific instance of Proof of Stake is designed for quick confirmation of the current sequence produced by the Proof of History generator, for voting and selecting the next Proof of History generator, and for punishing any misbehaving validators. This algorithm depends on messages eventually arriving to all participating nodes within a certain timeout.

5.2 Terminology

bonds Bonds are equivalent to a capital expense in Proof of Work. A miner buys hardware and electricity, and commits it to a single branch in a Proof of Work blockchain. A bond is coin that the validator commits as collateral while they are validating transactions.

slashing The proposed solution to the nothing at stake problem in Proof of Stake systems [7]. When a proof of voting for a different branch is published, that branch can destroy the validator's bond. This is an economic incentive designed to discourage validators from confirming multiple branches.

super majority A super majority is $\frac{2}{3}$ rd of the validators weighted by their bonds. A super majority vote indicates that the network has reached consensus, and at least $\frac{1}{3}$ rd of the network would have had to vote maliciously for this branch to be invalid. This would put the economic cost of an attack at $\frac{1}{3}$ rd of the market cap of the coin.

5.3 Bonding

A bonding transaction takes a amount of coin and moves it to a bonding account under the user's identity. Coins in the bonding account cannot be spent and have to remain in the account until the user removes them. The user can only remove stale coins that have timed out. Bonds are valid after super majority of the current stakeholders have confirmed the sequence.

5.4 Voting

It is anticipated that the Proof of History generator will be able to publish a signature of the state at a predefined period. Each bonded identity must confirm that signature by publishing their own signed signature of the state. The vote is a simple yes vote, without a no.

If super majority of the bonded identities have voted within a timeout, then this branch would be accepted as valid.

5.5 Unbonding

Missing N number of votes marks the coins as stale and no longer eligible for voting. The user can issue an unbonding transaction to remove them.

N is a dynamic value based on the ratio of stale to active votes. N increases as the number of stale votes increases. In an event of a large network partition, this allows the larger branch to recover faster than the smaller branch.

5.6 Elections

Election for a new PoH generator occur when the PoH generator failure is detected. The validator with the largest voting power, or highest public key address if there is a tie is picked as the new PoH generator.

A super majority of confirmations are required on the new sequence. If the new leader fails before a super majority confirmations are available, the next highest validator is selected, and a new set of confirmations is required.

To switch votes, a validator needs to vote at a higher PoH sequence counter, and the new vote needs to contain the votes it wants to switch. Otherwise the second vote will be slashable. Vote switching is expected to be designed so that it can only occur at a height that does not have a super majority.

Once a PoH generator is established, a Secondary can be elected to take over the transactional processing duties. If a Secondary exists, it will be considered as the next leader during a Primary failure.

The platform is designed so that the Secondary becomes Primary and lower rank

generators are promoted if an exception is detected or on a predefined schedule.

5.7 Election Triggers

5.7.1 Forked Proof of History generator

PoH generators are designed with an identity that signs the generated sequence. A fork can only occur in case the PoH generator's identity has been compromised. A fork is detected because two different historical records have been published on the same PoH identity.

5.7.2 Runtime Exceptions

A hardware failure or a bug, or a intentional error in the PoH generator could cause it to generate an invalid state and publish a signature of the state that does not match the local validator's result. Validators will publish the correct signature via gossip and this event would trigger a new round of elections. Any validators who accept an invalid state will have their bonds slashed.

5.7.3 Network Timeouts

A network timeout would trigger an election.

5.8 Slashing

Slashing occurs when a validator votes two separate sequences. A proof of malicious vote will remove the bonded coins from circulation and add them to the mining pool.

A vote that includes a previous vote on a contending sequence is not eligible as proof of malicious voting. Instead of slashing the bonds, this vote removes the currently cast vote on the contending sequence.

Slashing also occurs if a vote is cast for an invalid hash generated by the PoH generator. The generator is expected to randomly generate an invalid state, which would trigger a fallback to Secondary.

5.9 Secondary Elections

Secondary and lower ranked Proof of History generators can be proposed and approved. A proposal is cast on the primary generator's sequence. The proposal contains a timeout, if the motion is approved by a super majority of the vote before the timeout, the Secondary is considered elected, and will take over duties as scheduled. Primary can do a soft handover to Secondary by inserting a message into the generated sequence indicating that a handover will occur, or inserting an invalid state and forcing the network to fallback to Secondary.

If a Secondary is elected, and the primary fails, the Secondary will be considered as the first fallback during an election.

5.10 Availability

CAP systems that deal with partitions have to pick Consistency or Availability. Our approach eventually picks Availability, but because we have an objective measure of time, Consistency is picked with reasonable human timeouts.

Proof of Stake verifiers lock up some amount of coin in a “stake”, which allows them to vote for a particular set of transactions. Locking up coin is a transaction that is entered into a PoH stream, just like any other transaction. To vote, a PoS verifier has to sign the hash of the state, as it was computed after processing all the transactions to a specific position in the PoH ledger. This vote is also entered as a transaction into the PoH stream. Looking at the PoH ledger, we can then infer how much time passed between each vote, and if a partition occurs, for how long each verifier has been unavailable.

To deal with partitions with reasonable human timeframes, we propose a dynamic approach to “unstake” unavailable verifiers. When the number of verifiers is high and above $\frac{2}{3}$, the “unstaking” process can be fast. The number of hashes that must be generated into the ledger is low before the unavailable verifiers stake is fully unstaked and they are no longer counted for consensus. When the number of verifiers is below $\frac{2}{3}$ but above $\frac{1}{2}$, the unstaking timer is slower, requiring a larger number of hashes to be generated before the missing verifiers are unstaked. In a large partition, like a

partition that is missing $\frac{1}{2}$ or more of the verifiers, the unstaking process is very very slow. Transactions can still be entered into the stream, and verifiers can still vote, but full $\frac{2}{3}$ rds consensus will not be achieved until a very large amount of hashes have been generated and the unavailable verifiers have been unstaked. The difference in time for a network to regain liveness allows us as customers of the network human timeframes to pick a partition that we want to continue using.

5.11 Recovery

In the system we propose, the ledger can be fully recovered from any failure. That means, anyone in the world can pick any random spot in the ledger and create a valid fork by appending newly generated hashes and transactions. If all the verifiers are missing from this fork, it would take a very very long time for any additional bonds to become valid and for this branch to achieve $\frac{2}{3}$ rds super majority consensus. So full recovery with zero available validators would require a very large amount of hashes to be appended to the ledger, and only after all the unavailable validators have been unstaked will any new bonds be able to validate the ledger.

5.12 Finality

PoH allows verifiers of the network to observe what happened in the past with some degree of certainty of the time of those events. As the PoH generator is producing a stream of messages, all the verifiers are required to submit their signatures of the state within 500ms. This number can be reduced further depending on network conditions. Since each verification is entered into the stream, everyone in the network can validate that every verifier submitted their votes within the required timeout without actually observing the voting directly.

5.13 Attacks

5.13.1 Tragedy of Commons

The PoS verifiers simply confirm the state hash generated by the PoH generator. There is an economic incentive for them to do no work and simply approve every generated state hash. To avoid this condition, the PoH generator should inject an

invalid hash at a random interval. Any voters for this hash should be slashed. When the hash is generated, the network should immediately promote the Secondary elected PoH generator.

Each verifier is required to respond within a small timeout - 500ms for example. The timeout should be set low enough that a malicious verifier has a low probability of observing another verifiers vote and getting their votes into the stream fast enough.

5.13.2 Collusion with the PoH generator

A verifier that is colluding with the PoH generator would know in advance when the invalid hash is going to be produced and not vote for it. This scenario is really no different than the PoH identity having a larger verifier stake. The PoH generator still has to do all the work to produce the state hash.

5.13.3 Censorship

Censorship or denial of service could occur when a $\frac{1}{3}$ rd of the bond holders refuse to validate any sequences with new bonds. The protocol can defend against this form of attack by dynamically adjusting how fast bonds become stale. In the event of a denial of service, the larger partition will be designed to fork and censor the Byzantine bond holders. The larger network will recover as the Byzantine bonds become stale with time. The smaller Byzantine partition would not be able to move forward for a longer period of time.

The algorithm would work as follows. A majority of the network would elect a new Leader. The Leader would then censor the Byzantine bond holders from participating. Proof of History generator would have to continue generating a sequence, to prove the passage of time, until enough Byzantine bonds have become stale so the bigger network has a super majority. The rate at which bonds become stale would be dynamically based on what percentage of bonds are active. So the Byzantine minority fork of the network would have to wait much longer than the majority fork to recover a super majority. Once a super majority has been established, slashing could be used to permanently punish the Byzantine bond holders.

5.13.4 Long Range Attacks

PoH provides a natural defense against long range attacks. Recovering the ledger from any point in the past would require the attacker to overtake the valid ledger in time by outpacing the speed of the PoH generator.

The consensus protocol provides a second layer of defense, as any attack would have to take longer then the time it takes to unstake all the valid validators. It also creates an availability “gap” in the history of the ledger. When comparing two ledgers of the same height, the one with the smallest maximum partition can be objectively considered as valid.

5.13.5 ASIC Attacks

Two opportunities for an ASIC attacks exist in this protocol - during partition, and cheating timeouts in Finality.

For ASIC attacks during Partitions, the Rate at which bonds are unstaked is non-linear, and for networks with large partitions the rate is orders of magnitude slower then expected gains from an ASIC attack.

For ASIC attacks during Finality, the vulnerability allows for byzantine validators who have a bonded stake wait for confirmations from other nodes and inject their votes with a collaborating PoH generator. The PoH generator can then use its faster ASIC to generate 500ms worth of hashes in less time, and allow for network communication between PoH generator and the collaborating nodes. But, if the PoH generator is also byzantine, there is no reason why the byzantine generator wouldn't have communicated the exact counter when they expect to insert the failure. This scenario is no different than a PoH generator and all the collaborators sharing the same identity and having a single combined stake and only using 1 set of hardware.

6 Streaming Proof of Replication

6.1 Description

Filecoin proposed a version of Proof of Replication [6]. The goal of this version is to have fast and streaming verifications of Proof of Replication, which are enabled by

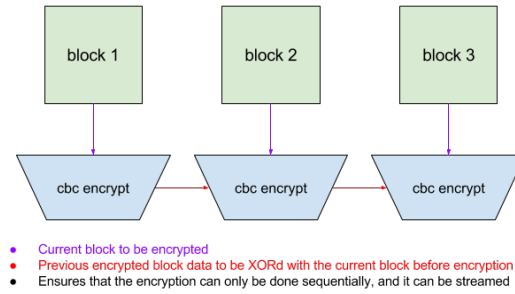


图 7 Sequential CBC encryption

keeping track of time in Proof of History generated sequence. Replication is not used as a consensus algorithm, but is a useful tool to account for the cost of storing the blockchain history or state at a high availability.

6.2 Algorithm

As shown in Figure 7 CBC encryption encrypts each block of data in sequence, using the previously encrypted block to XOR the input data.

Each replication identity generates a key by signing a hash that has been generated Proof of History sequence. This ties the key to a replicator's identity, and to a specific Proof of History sequence. Only specific hashes can be selected. (See Section 6.5 on Hash Selection)

The data set is fully encrypted block by block. Then to generate a proof, the key is used to seed a pseudorandom number generator that selects a random 32 bytes from each block.

A merkle hash is computed with the selected PoH hash prepended to the each slice.

The root is published, along with the key, and the selected hash that was generated. The replication node is required to publish another proof in N hashes as they are generated by Proof of History generator, where N is approximately $\frac{1}{2}$ the time it takes to encrypt the data. The Proof of History generator will publish specific hashes

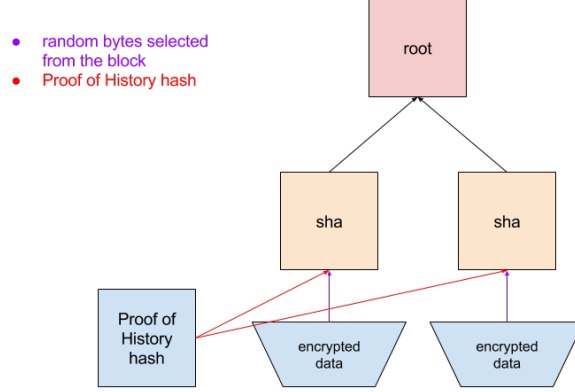


图 8 Fast Proof of Replication

for Proof of Replication at a predefined periods. The replicator node must select the next published hash for generating the proof. Again, the hash is signed, and random slices are selected from the blocks to create the merkle root.

After a period of N proofs, the data is re-encrypted with a new CBC key.

6.3 Verification

With N cores, each core can stream encryption for each identity. Total space required is $2blocks * Ncores$, since the previous encrypted block is necessary to generate the next one. Each core can then be used to generate all the proofs that derived from the current encrypted block.

Total time to verify proofs is expected to be equal to the time it takes to encrypt. The proofs themselves consume few random bytes from the block, so the amount of data to hash is significantly lower than the encrypted block size. The number of replication identities that can be verified at the same time is equal to the number of available cores. Modern GPUs have 3500+ cores available to them, albeit at $\frac{1}{2}$ - $\frac{1}{3}$ the clock speed of a CPU.

6.4 Key Rotation

Without key rotation the same encrypted replication can generate cheap proofs for multiple Proof of History sequences. Keys are rotated periodically and each replication is re-encrypted with a new key that is tied to a unique Proof of History sequence.

Rotation needs to be slow enough that it's practical to verify replication proofs on GPU hardware, which is slower per core than CPUs.

6.5 Hash Selection

Proof of History generator publishes a hash to be used by the entire network for encrypting Proofs of Replication, and for using as the pseudorandom number generator for byte selection in fast proofs.

Hash is published at a periodic counter that is roughly equal to $\frac{1}{2}$ the time it takes to encrypt the data set. Each replication identity must use the same hash, and use the signed result of the hash as the seed for byte selection, or the encryption key.

The period that each replicator must provide a proof must be smaller than the encryption time. Otherwise the replicator can stream the encryption and delete it for each proof.

A malicious generator could inject data into the sequence prior to this hash to generate a specific hash. This attack is discussed more in [5.13.2](#).

6.6 Proof Validation

The Proof of History node is not expected to validate the submitted Proof of Replication proofs. It is expected to keep track of number of pending and verified proofs submitted by the replicator's identity. A proof is expected to be verified when the replicator is able to sign the proof by a super majority of the validators in the network.

The verifications are collected by the replicator via p2p gossip network, and submitted as one packet that contains a super majority of the validators in the network. This packet verifies all the proofs prior to a specific hash generated by the Proof of History sequence, and can contain multiple replicator identities at once.

6.7 Attacks

6.7.1 Spam

A malicious user could create many replicator identities and spam the network with bad proofs. To facilitate faster verification, nodes are required to provide the encrypted data and the entire merkle tree to the rest of the network when they request verification.

The Proof of Replication that is designed in this paper allows for cheap verification of any additional proofs, as they take no additional space. But each identity would consume 1 core of encryption time. The replication target should be set to a maximum size of readily available cores. Modern GPUs ship with 3500+ cores.

6.7.2 Partial Erasure

A replicator node could attempt to partially erase some of the data to avoid storing the entire state. The number of proofs and the randomness of the seed should make this attack difficult.

For example, a user storing 1 terabyte of data erases a single byte from each 1 megabyte block. A single proof that samples 1 byte out of every megabyte would have a likelihood of collision with any erased byte $1 - (1 - 1/1,000,000)^{1,000,000} = 0.63$. After 5 proofs the likelihood is 0.99.

6.7.3 Collusion with PoH generator

The signed hash is expected to be used to seed the sample. If a replicator could select a specific hash in advance then the replicator could erase all bytes that are not going to be sampled.

A replicator identity that is colluding with the Proof of History generator could inject a specific transaction at the end of the sequence before the predefined hash for random byte selection is generated. With enough cores, an attacker could generate a hash that is preferable to the replicator's identity.

This attack could only benefit a single replicator identity. Since all the identities have to use the same exact hash that is cryptographically signed with ECDSA (or equivalent), the resulting signature is unique for each replicator identity, and collision

resistant. A single replicator identity would only have marginal gains.

6.7.4 Denial of Service

The cost of adding an additional replicator identity is expected to be equal to the cost of storage. The cost of adding extra computational capacity to verify all the replicator identities is expected to be equal to the cost of a CPU or GPU core per replication identity.

This creates an opportunity for a denial of service attack on the network by creating a large number of valid replicator identities.

To limit this attack, the consensus protocol chosen for the network can select a replication target, and award the replication proofs that meet the desired characteristics, like availability on the network, bandwidth, geolocation etc...

6.7.5 Tragedy of Commons

The PoS verifiers could simply confirm PoRep without doing any work. The economic incentives should be lined up with the PoS verifiers to do work, like by splitting the mining payout between the PoS verifiers and the PoRep replication nodes.

To further avoid this scenario, the PoRep verifiers can submit false proofs a small percentage of the time. They can prove the proof is false by providing the function that generated the false data. Any PoS verifier that confirmed a false proof would be slashed.

7 System Architecture

7.1 Components

7.1.1 Leader, Proof of History generator

The Leader is an elected Proof of History generator. It consumes arbitrary user transactions and outputs a Proof of History sequence of all the transactions that guarantees a unique global order in the system. After each batch of transactions the Leader outputs a signature of the state that is the result of running the transactions in that order. This signature is signed with the identity of the Leader.

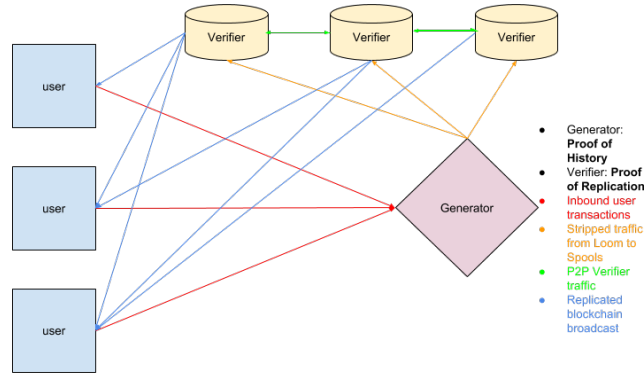


图 9 System Architecture

7.1.2 State

A naive hash table indexed by the user's address. Each cell contains the full user's address and the memory required for this computation. For example Transaction table contains:

0	31	63	95	127	159	191	223	255
Ripemd of Users Public Key				Account		unused		

For a total of 32 bytes.

Proof of Stake bond's table contains:

0	31	63	95	127	159	191	223	255
Ripemd of Users Public Key						Bond		
Last Vote								
unused								

For a total of 64 bytes.

7.1.3 Verifier, State Replication

The Verifier nodes replicate the blockchain state and provide high availability of the blockchain state. The replication target is selected by the consensus algorithm,

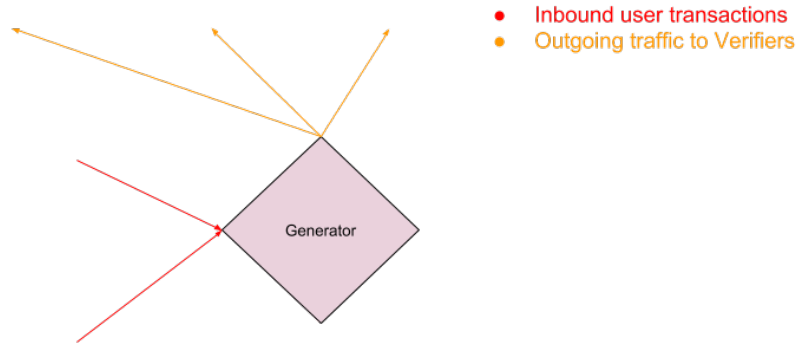


图 10 Generator network limits

and the validators in the consensus algorithm select and vote the Proof of Replication nodes they approve of based on off-chain defined criteria.

The network could be configured with a minimum Proof of Stake bond size, and a requirement for a single replicator identity per bond.

7.1.4 Validators

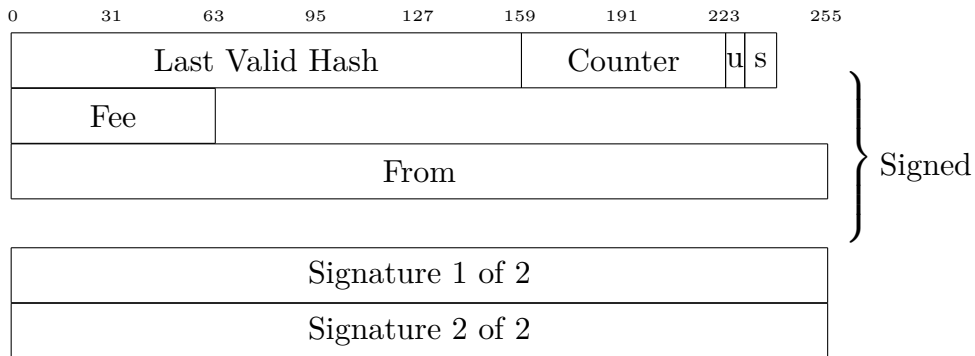
These nodes are consuming bandwidth from Verifiers. They are virtual nodes, and can run on the same machines as the Verifiers or the Leader, or on separate machines that are specific to the consensus algorithm configured for this network.

7.2 Network Limits

Leader is expected to be able to take incoming user packets, orders them the most efficient way possible, and sequences them into a Proof of History sequence that is published to downstream Verifiers. Efficiency is based on memory access patterns of the transactions, so the transactions are ordered to minimize faults and to maximize

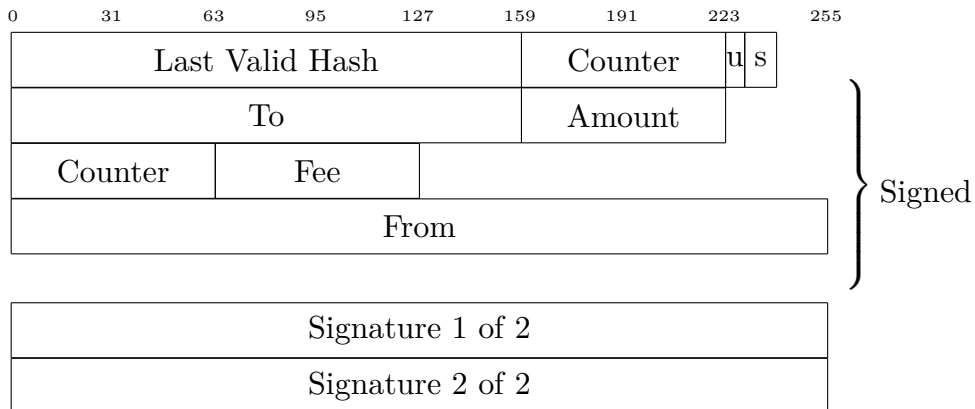
prefetching.

Incoming packet format:



Size $20 + 8 + 16 + 8 + 32 + 3232 = 148$ bytes.

The minimal payload that can be supported would be 1 destination account. With payload:

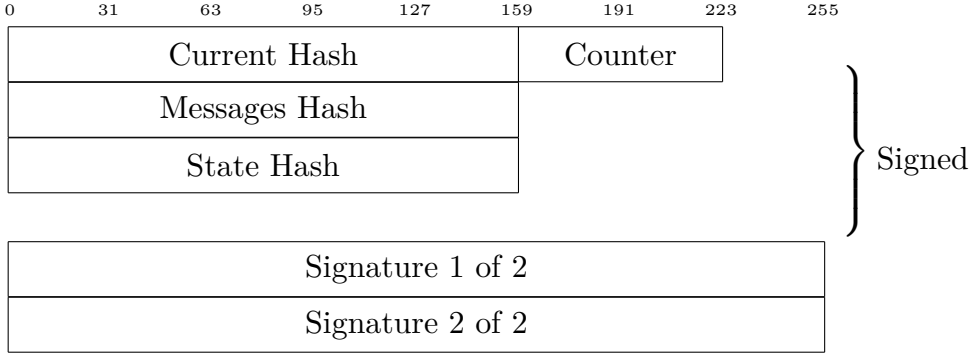


With payload the minimum size: 176 bytes

The Proof of History sequence packet contains the current hash, counter, and the hash of all the new messages added to the PoH sequence and the state signature after

processing all the messages. This packet is sent once every N messages are broadcast.

Proof of History packet:



Minimum size of the output packet is: 132 bytes

On a 1gbps network connection the maximum number of transactions possible is 1 gigabit per second / 176 bytes = 710k tps max. Some loss 1 – 4% is expected due to Ethernet framing. The spare capacity over the target amount for the network can be used to increase availability by coding the output with Reed-Solomon codes and striping it to the available downstream Verifiers.

7.3 Computational Limits

Each transaction requires a digest verification. This operation does not use any memory outside of the transaction message itself and can be parallelized independently. Thus throughput is expected to be limited by the number of cores available on the system.

GPU based ECDSA verification servers have had experimental results of 900k operations per second [9].

7.4 Memory Limits

A naive implementation of the state as a 50% full hashtable with 32 byte entries for each account, would theoretically fit 10 billion accounts into 640GB. Steady state random access to this table is measured at $1.1 * 10^7$ writes or reads per second.

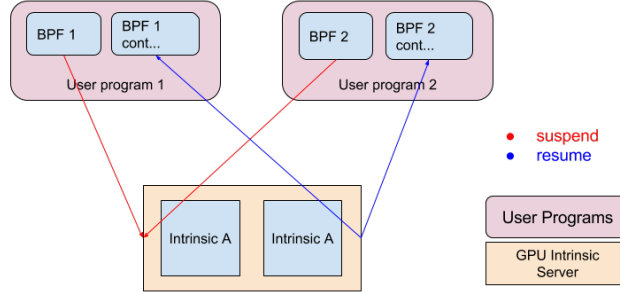


图 11 Executing BPF programs.

Based on 2 reads and two writes per transaction, memory throughput can handle 2.75m transactions per second. This was measured on an Amazon Web Services 1TB x1.16xlarge instance.

7.5 High Performance Smart Contracts

Smart contracts are a generalized form of transactions. These are programs that run on each node and modify the state. This design leverages extended Berkeley Packet Filter bytecode as fast and easy to analyze and JIT bytecode as the smart contracts language.

One of its main advantages is a zero cost Foreign Function Interface. Intrinsic, or functions that are implemented on the platform directly, are callable by programs. Calling the intrinsic suspends that program and schedules the intrinsic on a high performance server. Intrinsic are batched together to execute in parallel on the GPU.

In the above example, two different user programs call the same intrinsic. Each program is suspended until the batch execution of the intrinsic is complete. An example intrinsic is ECDSA verification. Batching these calls to execute on the GPU can increase throughput by thousands of times.

This trampoline requires no native operating system thread context switches, since

the BPF bytecode has a well defined context for all the memory that it is using.

eBPF backend has been included in LLVM since 2015, so any LLVM frontend language can be used to write smart contracts. It's been in the Linux kernel since 2015, and the first iterations of the bytecode have been around since 1992. A single pass can check eBPF for correctness, ascertain its runtime and memory requirements and convert it to x86 instructions.

参考文献

- [1] Liskov, Practical use of Clocks
<http://www.dainf.cefetpr.br/~tacla/SDII/PracticalUseOfClocks.pdf>
- [2] Google Spanner TrueTime consistency
<https://cloud.google.com/spanner/docs/true-time-external-consistency>
- [3] Solving Agreement with Ordering Oracles
<http://www.inf.usi.ch/faculty/pedone/Paper/2002/2002EDCCb.pdf>
- [4] Tendermint: Consensus without Mining
<https://tendermint.com/static/docs/tendermint.pdf>
- [5] Hedera: A Governing Council & Public Hashgraph Network
<https://s3.amazonaws.com/hedera-hashgraph/hh-whitepaper-v1.0-180313.pdf>
- [6] Filecoin, proof of replication,
<https://filecoin.io/proof-of-replication.pdf>
- [7] Slasher, A punitive Proof of Stake algorithm
<https://blog.ethereum.org/2014/01/15/slasher-a-punitive-proof-of-stake-algorithm/>
- [8] BitShares Delegated Proof of Stake
<https://github.com/BitShares/bitshares/wiki/Delegated-Proof-of-Stake>
- [9] An Efficient Elliptic Curve Cryptography Signature Server With GPU Acceleration
<http://ieeexplore.ieee.org/document/7555336/>
- [10] Casper the Friendly Finality Gadget

<https://arxiv.org/pdf/1710.09437.pdf>