Pisa: Arbitration Outsourcing for State Channels

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ABSTRACT

State channels are a leading approach for improving the scalability of blockchains and cryptocurrencies. They allow a group of distrustful parties to optimistically execute an application-defined program amongst themselves, while the blockchain serves as a backstop in case of a dispute or abort. This effectively bypasses the congestion, fees and performance constraints of the underlying blockchain in the typical case. However, state channels introduce a new and undesirable assumption that a party must remain on-line and synchronised with the blockchain at all times to defend against *execution fork* attacks. An execution fork can revert a state channel's history, potentially causing financial damage to a party that is innocent except for having crashed. To provide security even to parties that may go off-line for an extended period of time, we present Pisa, the first protocol to propose an accountable third party who can be hired by parties to cancel execution forks on their behalf. To evaluate Pisa, we provide a proof-of-concept implementation for a simplified Sprites and we demonstrate that it is cost-efficient to deploy on the Ethereum network.

1 INTRODUCTION

Improving the scalability of cryptocurrencies and blockchains has emerged as an important open problem facing the nascent industry. Although cryptocurrencies have achieved record growth (a total market capitalisation of \$300bn as of April 2018), their ability to scale and increase transaction capacity is fundamentally at odds with their approach to security through wide replication [8]; in a typical cryptocurrency, every node processes every transaction. To highlight this tension, Ethereum has relaxed a throughput capacity limit imposed by Bitcoin [23], but as a result some peers lack the resources to verify new transactions in real-time [26].

Payment channels are a leading scalability approach that overcomes this tradeoff [4, 12, 17, 21, 25]. The main idea behind payment channels is optimism: the blockchain serves as a backstop or dispute handler, and in the typical case payments are carried out privately among small groups of parties via off-chain messages. Funds deposited in a payment channel are guaranteed to be secure, even if all other parties in the channel are malicious. This is because the honest party can rely on the blockchain to enforce payments and authorised withdrawals. While this scaling approach was originally proposed for payment applications, a generalization of the technique, called *state channels* [7, 12, 25], promises to bring scalability benefits to other smart contract applications as well, such as auctions and online games [2].

The security guarantees of state channels are ensured by the on-chain dispute handling mechanism. However, this mechanism also introduces a new failure mode, since it assumes each party remains on-line and synchronised with the blockchain at all times. To briefly explain the mechanism, each party in a state channel maintains a local view of the most recent channel state (e.g., account balances in the case of payment channels, and arbitrary application-defined state more generally), along with signatures from all other parties. If at least one other party aborts (or provides invalid data), an honest party must publish the most recent signed state to the blockchain to initiate the dispute process. To handle the case where a malicious party initiates a spurious dispute, other parties are given a fixed time period to submit a *newer* signed state to resolve the dispute. This is effective as long as honest parties remain online and responsive; a node that crashes or goes offline for a long period of time may miss the time window to participate in the dispute process. Worse, a malicious actor may exploit an offline party by reversing (or forking) collectively authorised states in the channel to their benefit (an "execution fork"). The global blockchain can ease the burden on parties by providing a longer grace period during which they can intervene, but this increases the time it takes to progress the program and thus introduces a trade-off between security and performance.

The hazard of execution fork attacks against offline parties is already known in the off-chain scaling community, who have proposed two mitigations thus far. Both existing approaches empower users to appoint a third party to help defend against execution forks on their behalf. The first proposal, called Monitor [10], is inefficient in that it requires the third party to consume $O(N)$ storage, where N is the number of off-chain transactions that have occurred within the state channel. The second proposal, called WatchTower [27], improves upon Monitor's efficiency, but cannot be deployed without consensus rule changes in the Bitcoin network, and cannot directly be adapted to generic state channels in Ethereum. As we explore in Section 3.2, the customer lacks any evidence that they have hired and paid a third party to watch the channel on their behalf. Thus both proposals suffer from the drawback that if the appointed third party fails, there is little to no recourse for the customer.

To overcome the above problems, we propose Pisa, which introduces a new accountable third party to watch generic state channel constructions. In Pisa, all appointments and payments between a customer and the accountable third party are performed using an off-chain payment channel. In return, the customer receives a signed receipt from the accountable third party, which constitutes evidence that they have agreed to defend the channel. This receipt can later be used to penalise the accountable third party if they fail to defend against an execution fork on the customer's behalf. Pisa improves on the efficiency of prior proposals, requiring only $O(1)$ storage from the accountable third paty, and for a two-party channel an appointment is approximately 162 bytes. Pisa is application-neutral, and can be used with any state channel program, since the accountable third party only receives a hash of the channel's state rather than the state itself. This also provides a privacy benefit, called state privacy, since the accountable third party does not learn any details about the off-chain interactions (e.g., payment metadata) except when a dispute is raised via the global blockchain.

To summarise, our contributions are as follows:

- We propose Pisa, the first application-agnostic state channel protocol that supports third-party monitoring for arbitrary applications.
- Pisa is also the first accountable third-party watching protocol that provides a customer with publicly verifiable cryptographic evidence in case the third-party fails, which can be used to penalise a faulty third-party.
- We provide a proof of concept implementation of Pisa for a simplified Sprites and experimentally demonstrate that it is cost-efficient to deploy on the Ethereum network.

2 BACKGROUND AND RELATED WORK

In this section, we present cryptographic primitives used throughout this paper, an overview of the blockchain, smart contracts and payment channels before discussing related work.

2.1 Cryptographic notation

Pisa and more generally state channels rely on cryptographic hash functions and digital signatures. We denote a hash computation as $h \leftarrow \mathsf{H}(\mathsf{msg})$ where H is the cryptographic hash function, msg is the pre-image and h is the resulting hash. For digital signatures, we denote signing as $\sigma_k \leftarrow \mathsf{Sign}(\mathsf{sk}_k, \mathsf{msg})$, where sk_k is the signer's secret key, msg is message to be signed and σ_k is the corresponding signature. Verification is denoted as $0/1 \leftarrow \mathsf{Sig.Verify}(\mathcal{P}, \mathsf{msg}, \sigma_k)$ where $\mathcal{P}$ is the party's corresponding public key and the algorithm returns 1 if the signature is authentic for msg.

2.2 Blockchains, accounts, and smart contracts

All parties independently compute their own pseudonymous identity called an external account, and this is simply the cryptographic hash of a public key. For readability, both external accounts and public keys are interchangeably denoted as $\mathcal{P}$. Once an account is associated with coins on the network, the party can digitally sign a transaction using their corresponding secret key sk. A transaction denotes the sender's account, receiver's account, the number of coins to transfer and a payload. In more expressive platforms like Ethereum, the payload stores bytecode which is used to deploy and instantiate a smart contract (i.e., a program) on the network, or contains instructions for executing a smart contract. The metric for size and computational complexity of this payload is called gas and the signer can set a gas price that they are willing to pay as a transaction fee.

All transactions are published and propagated throughout the peer-to-peer network. Each peer verifies whether the digital signature that authorises the transaction corresponds to an external account with a sufficient balance to cover the transaction's fee. Eventually the transaction should reach a group of peers called miners who collectively participate in a leader election every epoch. The first peer to solve a computationally difficult puzzle is elected as the epoch's leader and atomically creates a new block of transactions. This block is appended to a chain of previous blocks (which results in the name blockchain) and the miner is given a reward alongside the fees from each included transaction. Due to the probabilistic nature of the puzzle, two or more miners may propose a solution (i.e., a competing block) for any given epoch. All competing blocks are distinct forks based on the same parent block. The fork that emerges as the longest (and heaviest) chain is eventually considered the blockchain and only these transactions impact the network's state. The blockchain thus only provides eventual consistency and a transaction cannot be considered final until it is in the longest (and heaviest) chain.

Smart contracts are conceptually a third party that is trusted for correctness and availability but not for privacy [18]. We model a smart contract as a state machine and signed transactions carry commands cmd which execute the state transition from state_{i-1} to state_i. The contract's code alongside a transcript of all previous state transitions is recorded in the blockchain and transactions that perform state transitions are deterministically executed by all peers on the network. This deterministic execution implies that the contract cannot store secret values, but the honest execution of its protocol is guaranteed. As mentioned previously, a fee is associated with each state transition performed on the network and the cost of executing a smart contract increases when the blockchain is congested as users compete for the remaining space.

2.3 Payment channels

The concept of a payment channel emerged in Bitcoin to avoid executing all payments on the blockchain. A payment channel allows two parties to deposit coins and continuously re-distribute each party's share of this deposit amongst themselves. This reduces transaction fees paid by the channel's parties and also reduces congestion on the network as computation is performed locally instead of the global network. More generally, both parties are executing state transitions and authorising (i.e. digitally signing) every new state amongst themselves in such a way that only the most recently authorised state should be accepted into the blockchain.

It is crucial that parties can invalidate previous states to ensure the network only accepts the latest state. The simplest approach for state replacement is called replace-by-incentive [9], which emerged to support one-way payment channels. As well, the receiver's incentive is to only publish the state that sends them the most coins. The receiver can either sign the state and publish it to the network, or wait for a new state that increments their balance. This is considered safe as every state requires both parties to authorise it before the state can be accepted into the blockchain. There is also an expiry mechanism that eventually refunds the sender if there is no activity in the channel. However to extend payment channels to support bi-directional payments (i.e. sending coins back and forth), early constructions for state replacement in Bitcoin involved decrementing the channel's expiry time [9, 24]. This is undesirable as every change in payment direction brings the channel's expiry time closer to present time and ultimately restricts the total number of payments.

To overcome issues in early payment channel constructions such as requiring an expiry time and the restricted throughput, Poon and Dryja proposed replace-by-revocation [31] as a state replacement technique. Unlike replace-by-incentive, both parties have a copy of the channel's latest state and the state replacement requires both parties to authorise a new state before revoking the old state. Thus there is a set of revoked states, and only a single valid state. It also introduced the concept of a dispute period where one party can seek assistance from the global blockchain to close the channel based on an authorised state. The counter-party has a fixed time to detect whether this authorised state was previously revoked, and if so, the counter-party can submit evidence to the blockchain that the state was indeed revoked and in return they are sent all coins in channel. Otherwise the dispute period expires and both parties receive their share of the channel's deposit according to the accepted state. As we explore in the Section 3, a payment channel can be generalised for arbitrary protocols involving n parties and this dispute process can be used to enforce the protocol's progression (instead of simply closing the channel).

2.4 Related work

Probabilistic micropayments. To avoid processing all transactions on the blockchain, Pass and shelat [29], and Chiesa et al. [5] proposed using probabilistic payments. Every payment is a lottery and the receiver is only paid upon winning. The former relies on a trusted third party, or tying up more collateral than the largest possible payment. The latter adds support for privacy-preserving payments, and analyses the collateral requirements assuming a rational adversary. Probabilistic payments indeed reduce network congestion, though they increase the variance until the payee receives money, and they also have weaker expressibility (i.e. only supports payments) than a state channel.

Channels based on trusted hardware. Teechain [19] is an off-chain payment channel protocol for Bitcoin that utilizes the Intel SGX technology to produce the settlement transactions via SGX enclaves the run in the parties' computers, rather than by the parties directly. An accountable third party watching services are unnecessary with Teechain, since an enclave will only agree to produce a signed settlement message (to be sent to the blockchain) that deducts all the amounts that its operator paid to other parties. However, the Teechain protocol is risky even in the case that SGX is completely secure, because a party will lose all of her money if the SGX enclave stops running.[1] The risk can be overcome by allowing rollback (to an enclave backup image) in accord with monotonic hardware counters, but SGX does not have a secure implementation of hardware counters [22, 33]. Teechain proposes an extension where a party duplicates the secret data by using several computers that have SGX enclaves (these computers run continuously and communicate among each other via secure channels in order to backup the secret data). Still, the money will be lost if all of these computers crash at the same time.

Payment networks. Poon and Dryja proposed the concept of a payment (and collateral-based) network for Bitcoin. This allows multiple two-party channels to form a route and synchronise payments across the route using hashed time-locked contracts (HTLC) [24, 31]. Miller et al. proposed how to reduce the worst-case delay of HTLC to constant time for all channels in the route [25]. As well, Khalil et al. proposed REVIVE [17] that relies on this synchronisation technique to allow parties to re-balance their share of coins in a channel without interacting with the blockchain. In terms of privacy, Malavolta et al. proposed how to preserve the route's privacy [21] and, Green and Miers proposed BOLT [14] that allows two channels to transact via a single intermediary channel in a privacy-preserving manner. Instead of synchronising a single payment, Dziembowski et al. proposed Perun [11] that allows two parties to establish a route and conduct multiple payments without interacting with the intermediate channels. As mentioned earlier, Pisa is complementary to payment networks.

3 STATE CHANNELS

A state channel allows a group of mutually distrustful parties to execute an arbitrary application amongst themselves, while bootstrapping trust from the underlying blockchain. The blockchain (and in effect, the smart contract) is consulted only to open the channel, to store the latest authorised state if necessary and to resolve any disputes that occur. Our work builds on state channels to make them more robust in case some parties crash or go offline. Before proceeding to our main protocol, in this section we explain in detail the underlying state channel construction. We mostly follow the abstraction provided by Miller et al. [25][2].

A state channel for n participants $\mathcal{P} = \mathcal{P}_1, ..., \mathcal{P}_n$ is modeled as a state machine that proceeds logically in rounds, and is parameterized by an application-defined space of input commands cmd and a $\mathsf{Transition}$ function. In each round, the state channel receives an input cmd from one of the parties and applies the transition function

$$\mathsf{state_i} \leftarrow \mathsf{Transition}(\mathsf{state_{i-1}}, \mathsf{cmd}).$$

The main challenge in constructing a state channel is to ensure that the transition function is applied consistently, even in the case that one or more of the parties is malicious or aborts.

3.1 Generic state channel construction

At a high level, the state channel construction consists of an initialization routine to set up the channel, an off-chain protocol by which parties can collectively authorise new state transitions amongst themselves, and a smart-contract based dispute resolution process in case some party fails.

To initialize a state channel, one party must deploy a smart contract to the network and register all parties $\mathcal{P}$ in the contract to set it up. Notationally, we use `SC` to denote the unique identifier for the state channel contract, and use `SC.setup` (as one example)

[1]Even due to suspend or hiberation, see https://software.intel.com/en-us/node/708995.

[2]Alternative state channel abstractions include StCon by Bentov et al. [2] and Perun by Dziembowski et al. [11].

to denote a function call in this contract, with the function inputs omitted for readability.

Once established, all registered parties participate in an interactive protocol called AuthState to execute and authorise new state transitions. If all parties co-operate, then the contract SC is not involved and the state replacement is performed off-chain. To keep track of replaced states, a monotonic counter i is incremented for every state transition and the state associated with the largest i is considered the latest state (i.e. replace by monotonic counter). If one party fails to participate in AuthState, then the state replacement cannot be performed off-chain. Instead, another party in the channel must initiate the dispute process in SC to complete the state transition. To initiate, one party updates the contract with an authorised state (i.e. state_{i-1}) before triggering the dispute process. This provides a time period for each party to input a command. After this time period, SC selects one command (i.e. cmd is selected by the application's logic), executes it and stores state_i as the latest authorised state (alongside an incremented i). We now describe the construction in more detail.

Channel flags. A state channel has three flags $[\perp, \text{OK}, \text{DISPUTE}]$ where $\perp$ denotes the channel is not initialised, OK specifies the channel is open and all parties can collectively authorise new states, and DISPUTE signals that one party has triggered a dispute and the state transition from state_{i-1} to state_i must be authorised by the contract.

Channel establishment. One party is responsible for deploying the state channel contract to the blockchain using `SC.setup`. The channel must be initialised with a list of parties $\mathcal{P} = \mathcal{P}_1, ..., \mathcal{P}_n$ and a timer Δ_{settle} which specifies the minimum length of time for the dispute process. Once the channel establishment is complete, the channel's flag transitions $\perp \rightarrow \text{OK}$ and all parties can begin collectively signing (and authorising) every new state. The first state_1 is dependent on the channel's application.

State replacement. A state channel's integrity relies on all parties collectively invalidating previously authorised states to ensure SC always accepts the latest authorised state. In this construction, all parties collectively participate in an interactive protocol called AuthState (defined in Figure 4) that associates every new state_i with an incremented counter i. AuthState requires one party $\mathcal{P}_k$ to select a command cmd and locally execute the state transition.[3]

This party separately signs the command and the new state_i (alongside a newly incremented i). Both signatures $\sigma_k^{\text{cmd}}, \sigma_k^{\text{state}}$ and the values cmd, state_i, i are sent to all other parties. Each party must verify both signed messages and the state transition, according to:

$$0/1 \leftarrow \text{VerifyTransition}(\mathcal{P}_k, \text{cmd}, \sigma_k^{\text{cmd}}, \text{state}_{i-1}, i, \sigma_k^{\text{state}}, \text{SC})$$

Once satisfied, an honest party sends all other parties their signature for the new state (and its corresponding i). If an honest party does not receive a signature from all other parties before a local timeout, then the signed cmd (alongside state_{i-1}) is used to initiate the dispute process and complete the transition. To avoid the cost incurred by the on-chain state transition, all parties must exchange signatures for state_i before an honest party's local timeout.

[3]This transition function is available in SC and can be executed locally by the parties, but it is executed on the network only via the dispute process.

Dispute process. Any party within the channel can enforce a state transition on-chain via the dispute process. First, one party updates the contract using `SC.setstate` with the latest state_{i-1}, its corresponding counter (e.g. i-1) and a list of signatures $\Sigma_{\mathcal{P}}$. This allows the contract to verify that state_{i-1} was indeed authorised by all parties before accepting it. Second, one party initiates the dispute using `SC.triggerdispute` which transitions the channel's flag from OK to DISPUTE and establishes a deadline t_{settle}. Third, all parties can input a cmd to be considered for the state transition using `SC.input` before $\text{SC}.t_{\text{settle}}$. After the deadline has passed, the final step requires one party to notify the contract using `SC.resolve` which selects a single command from the list of commands, executes it and performs the state transition to state_i.

There is a danger that one party triggers a dispute based on a previously authorised state_{i-1} which has already been replaced off-chain by state_i. If the dispute is successful, then the contract enforces the transition to a forked state'_i which may be different to state_i. We call this an *execution fork* as state'_i cannot be replaced by state_i once it is accepted by the contract. For example, if the application was a payment channel, state_i may represent sending coins from Alice to Bob, but state'_i represents a withdrawal that sends Alice her coins. Thus her coins are no longer available to facilitate the payment if state_i replaced state'_i. Preventing an execution fork requires one party to settle the dispute before $\text{SC}.t_{\text{settle}}$ by updating the contract with the competing state_i (alongside i and the corresponding list of signatures) using `SC.setstate`. If state_i is accepted, then the contract's flag transitions from DISPUTE to OK and the dispute is settled. This introduces a new assumption that each party must remain on-line and synchronised with the blockchain in order to detect (and settle) execution forks. To get around this, we evaluate solutions proposed in the community for payment channels which allows any party to outsource the responsibility of preventing an execution fork (and settling the dispute process) to a third party called the Monitor.

3.2 Monitor solution

Dryja proposed the concept of a Monitor for replace-by-revocation channels in Bitcoin. This is a third party agent who is appointed by a customer to settle disputes (and prevent execution forks) on their behalf [10]. Briefly, the customer signs a new transaction that rewards both the customer and the Monitor if it is used to settle a dispute. This transaction (and the customer's signature) is encrypted using a secret key that is only revealed if the counter-party publishes a previously invalidated transaction.[4] When a customer appoints the Monitor to watch a channel on their behalf, the customer sends the Monitor this encrypted transaction. Once a dispute is detected in the customer's channel, the Monitor must try to decrypt this encrypted transaction. If the decryption is successful, then the Monitor confirms that the transaction contains the expected payment before settling the dispute.

Only the transaction which settles a dispute is revealed and all intermediary transactions remain are hidden. As well, more than

[4]In a replace-by-revocation channel, each party has a transaction that only they can broadcast. The unique identifier of the counterparty's transaction is used as the encryption key.

one Monitor can be appointed to watch the channel and the counterparty is unaware of any appointment. However due to the nature of replace-by-revocation channels as presented in Section 2.3, the Monitor is required to store every encrypted transaction received from the customer and this employs a storage requirement of $O(N)$ for the Monitor per customer. To put this into perspective, Dryja claimed that for 10k channels, and 1 million payments per channel, the Monitor will need to store around 1TB of transactions [10].

On the other hand, the Monitor protocol relies on a bonus payment as the Monitor is rewarded only upon successfully settling a dispute. This reward policy is also under consideration by Raiden [6]. We call this the *double-deposit approach* as the channel must allocate coins for use in the channel and the bonus payment. This introduces an unfair reward policy as only a single Monitor can receive the payment and this results in a race condition as all appointed Monitors must compete to settle the dispute.[5] This is problematic in the context of a state channel as the deposit must be sufficient to support multiple disputes (as opposed to a single dispute that closes the payment channel). There is also no cryptographic evidence if the Monitor aborts and fails to settle a dispute on the customer's behalf. Thus, there is no mechanism for the customer to seek recourse or to publicly prove the Monitor's wrongdoing.

A second proposal by Osuntokun [16, 27] called WatchTower reduces the third party's storage requirement to $O(1)$, but this proposal cannot be deployed without a new consensus rule to update Bitcoin Script.[6] This new rule essentially allows Bitcoin to support the replace-by-monotonic-counter approach presented in Section 3.1, but the implementation detail is tailored to work with Bitcoin script. In terms of payment, it proposes paying the WatchTower via the off-chain payment network for every appointment as opposed to relying on the double-deposit approach. However the customer is not provided with evidence that the WatchTower was appointed to settle disputes on their behalf and thus there is no deterrence mechanism. Finally since WatchTower is designed for payment channels, it only considers settling a single dispute to close the channel as opposed to multiple disputes which is necessary to enforce a smart contract's progression.

4 PISA PROTOCOL

To overcome the above issues, we propose Pisa and the first accountable third party watching service. Pisa has three components and it is designed for resolving disputes in the generic state channel construction presented in Section 3.1.

The first component is *publicly verifiable appointments* as the customer has a ratified signed receipt of appointment from the accountable third party. As well, due to how state channels are designed in Ethereum, the accountable third party will have a storage requirement of $O(1)$. The second component is *fair (and real-time) rewards* as the accountable third party is paid for every new appointment using a one-way payment channel (or alternatively the accountable third party can be paid using a payment network). The third component is *customer recourse* as the ratified signed receipt can be used to prove the accountable third party's failed to settle a dispute on the customer's behalf and as a result the accountable third party's large security deposit is forfeited.

In the rest of this section, we present the goals and requirements before providing an overview of Pisa. Afterwards we highlight the modifications required to the generic state channel construction presented in Section 3.1 and the new Pisa contract to facilitate the appointments from customers.

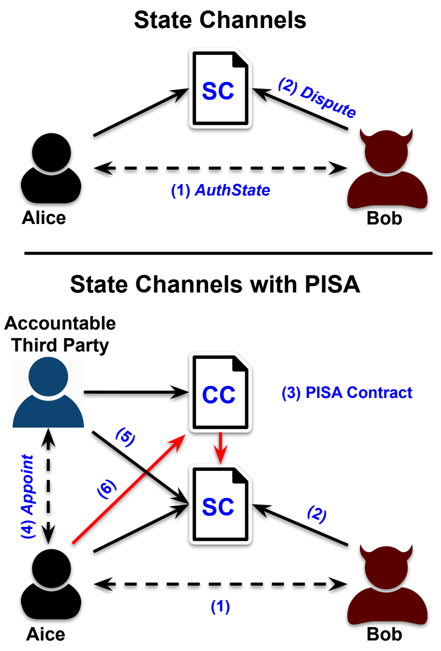

Figure 1: System Overview. In ordinary channels (top), parties communicate off-chain to authorize state transitions (1) through *AuthState* (Figure 4), but can raise a dispute on-chain (2) in case of abort. With Pisa (bottom), the interaction between channel participants, (1) and (2), remains unchanged, but A runs *Appoint* (Figure 3) to delegate to an accountable third party, (4), who can submit a hashed state on A's behalf if A crashes (5). Pisa further guarantees that if the accountable third party fails, A obtains a publicly verifiable receipt and can penalize them through an on-chain recourse (6).

4.1 Protocol goals

We present a list of protocol goals for Pisa which focus on the privacy of intermediate states, fairness for the customer and accountable third party, and practical requirements that ensure Pisa can be deployed.

State privacy. We extend value privacy from [21] such that the accountable third party does not learn any information about the state. As well, there is a single (and unavoidable) case when state

[5]In Ethereum, the deposit can be split between all Monitors that respond to settle the dispute, but this increases the number of on-chain transactions and does not provide the Monitor with a fixed reward.
[6]A new opcode called OP_CHECKSIGFROMSTACK that can verify a signed message and parse its message.

privacy may be breached. If there is a dispute in the state channel, then the accountable third party may be required to broadcast the state hash to SC in order to resolve the dispute. Afterwards one of the parties in the channel may reveal the state (pre-image of the hash) in order to execute a command. In this case, the accountable third party, like all other observers of the blockchain, will learn the state.

Fair exchange. An honest customer can review the signed receipt of appointment before deciding whether to pay the accountable third party in order to ratify it. On the other hand, an honest accountable third party is always paid once they ratify a signed receipt for the customer.

Non-frameability. A malicious customer or a full collusion of the state channel's parties cannot produce evidence that causes an honest accountable third party to lose their security deposit.

Recourse as a financial deterrent. [7] A accountable third party is considered rational and only colludes against the customer if their payout is greater than the loss of their security deposit. An honest customer should always be able to seek recourse and prove the accountable third party's wrongdoing.

Efficiency requirements. The accountable third party stores only information associated with the latest state, meaning its storage requirement is $O(1)$ per customer. The accountable third party should be paid using the one-way (and off-chain) payment channel.

4.2 Overview of Pisa

Figure 1 presents a high-level overview of the system and Figure 2 presents the high-level interaction in Pisa between three parties: two arbitrary parties in the state channel, and the accountable third party (and, implicitly, the contracts via interaction with the network). Initially, the accountable third party sets up the Pisa contract CC, stores a large security deposit and publicly advertises their service. At some point, all parties establish a state channel and begin collectively authorising new states amongst themselves using the AuthState algorithm presented in Figure 4. If a party wishes to go offline for an extended period of time, but wants to ensure that previously invalidated states are not accepted by CC, they may decide to appoint a accountable third party to watch the state channel on their behalf.

We call this party the customer, who must deposit coins into the accountable third party's contract to set up a one-way payment channel. Afterwards the customer can outsource the job of monitoring the state channel using the Appoint algorithm in Figure 3. The accountable third party receives a hash of the state which we denote as $\mathsf{hstate_i}$ (alongside its counter i and signatures from all parties $\Sigma_{\mathcal{P}}$), the state channel contract's identifier SC and a payment for watching the channel. In return the customer is provided a signed receipt of appointment that specifies the monitoring time period.

As mentioned previously, once the customer is offline, all other parties may collude to perform an execution fork. In this case there are two outcomes. First, the accountable third party may settle a dispute by publishing $\mathsf{hstate_i}$ and the counter i alongside the list of signatures $\Sigma_{\mathcal{P}}$ on behalf of the customer. In this case the correct state hash will be accepted and the execution fork cancelled. Otherwise, the accountable third party may fail to respond during the dispute process. In this case, the Pisa contract empowers the customer to seek recourse after they come back on-line using both the signed receipt and a record of the dispute in the state channel. If the recourse is successful, then the Pisa contract forfeits the accountable third party's large deposit.

4.3 Protocol assumptions

We present a list of assumptions for the smart contracts and the threat model.

Smart contracts. We assume a smart contract is a trusted third party that maintains public state. All contracts and payment channels have a unique identifier on the blockchain. The underlying blockchain cannot be compromised and honest parties can always interact with the contracts within a designated grace period.

Threat model. We assume the adversary can control the order of messages, but all messages must be delivered within a designated grace period. The adversary can either corrupt all parties in the channel, $n-1$ parties in the channel and the accountable third party, the accountable third party's customer, or just the accountable third party. However the adversary cannot forge messages from non-corrupted parties.[8] If the accountable third party is corrupted, then we must assume the adversary is rational and only colludes with other parties in the customer's state channel if the payout is more than the accountable third party's security deposit. We assume there is an authenticated and secure end-to-end communication channel for parties within the state channel to prevent eavesdropping by an honest-but-curious accountable third party. This also implies there is no collusion between the accountable third party and a party in the channel, since otherwise it is trivial to eavesdrop on all states.

4.4 State channel modifications

We focus on modifications to the generic state channel construction presented in Section 3.1 and the interaction between parties in the channel to support authorising $\mathsf{hstate_i}$ instead of $\mathsf{state_i}$.

Modifications to the state channel contract. Figure 5 highlights several modifications to the state channel construction. SC.setstate accepts $\mathsf{hstate_i} = H(\mathsf{state_i}||\mathsf{r_i})$ as the latest state if it is authorised by all parties in the channel (instead of $\mathsf{state_i}$). The $\mathsf{state_i}$ (alongside the blinding nonce $\mathsf{r_i}$) is only revealed if one party triggers a dispute and resolves it using SC.resolve. Both modifications allows the accountable third party to settle disputes by publishing $\mathsf{hstate_i}$ (alongside a list of signatures from all parties in the channel) and this is further explored in Section 4.5. A third modification requires the contract to record the start time $\mathsf{t_{start}}$, settle time $\mathsf{t_{settle}}$ and the new state round stateRound for every successful dispute that performs a state transition using SC.resolve. This evidence is stored

[7] Another way look at this security property is that PISA provides a financial guarantee that it will always broadcast the latest agreed state it has received from the customer. If PISA fails to protect the customer, then there is publicly verifiable evidence that can be used by the customer to seek recourse and thus slash PISA's security deposit.

[8] This implies the digital signature scheme used in Pisa is unforgeable under chosen message attacks (EUF-CMA) which is proven for Schnorr signatures [30]. However for the digital signature algorithm (DSA) such as ECDSA which is used in Ethereum, this is proven using non-standard assumptions [34].

Party K	**Party N**	**Accountable third party**

All parties have a secret key sk and have access to SC, CC *via the network.*
AuthState() *is defined in Figure 4 and* Appoint() *is defined in Figure 3.*

$\texttt{SC.setup}(\mathcal{P}, \Delta_{\text{settle}})$

Multiple states are authorised between $\mathcal{P}_k,\ldots,\mathcal{P}_n$

$\text{AuthState}(\mathcal{P}_k, \mathcal{P}_n, \text{state}_{i-1})$

Party K	Party N	Accountable third party
$\text{hstate}_i, i, \Sigma_{\mathcal{P}}, \text{state}_i, r_i \leftarrow \mathcal{P}_k$	$\text{hstate}_i, i, \Sigma_{\mathcal{P}}, \text{state}_i, r_i \leftarrow \mathcal{P}_n$	

$\text{Appoint}(\Sigma_{\mathcal{P}}, (\text{hstate}_i, i), \text{coins})$

Party K	Party N	Accountable third party
	$\text{receipt}, s_i, \sigma_C \leftarrow \mathcal{P}_n$	$\text{pay}, \sigma_n \leftarrow C$

Party N goes off-line

$\texttt{SC.setstate}(\text{hstate}_{i-1}, i-1, \Sigma_{\mathcal{P}})$
$\sigma_k \leftarrow \text{Sign}(sk_k, (\text{dispute}, \text{hstate}_{i-1}, i-1, \texttt{SC}))$
$\texttt{SC.triggerdispute}(\sigma_k)$

We present two protocol outcomes based on whether the accountable third party is honest or colludes with $\mathcal{P}_k$

Outcome 1: *Accountable third party resolves dispute on behalf of* $\mathcal{P}_n$

$\texttt{SC.setstate}(\text{hstate}_i, i, \Sigma_{\mathcal{P}})$

Outcome 2: *Accountable third party colludes with* $\mathcal{P}_k$ *and afterwards* $\mathcal{P}_n$ *seeks recourse.*

Party K:

```
Selects a cmd
$\sigma_k^{\text{cmd}} \leftarrow \text{Sign}(sk_k, (\text{cmd}, \text{hstate}_{i-1}, i-1, \texttt{SC}))$
$\texttt{SC.input}(\text{cmd}, \sigma_k^{\text{cmd}})$
$\text{Wait}(\texttt{SC.}t_{\text{settle}})$
$\texttt{SC.resolve}(\text{state}_{i-1}, r_{i-1})$
```

Party N:

```
*Party N returns online*
$b \leftarrow \text{SeekRecourse}(\text{receipt})$
if $b = 0$, abort
$\texttt{CC.recourse}(\text{receipt}.t_{\text{start}}, \text{receipt}.t_{\text{expire}}, \text{receipt}.\texttt{SC},$
        $\text{receipt}.i, \text{receipt}.h_i, s_i, \text{receipt}.\sigma_C)$
```

Figure 2: High level interaction for authorising states and if the customer needs to seek recourse.

for later use by the customer to demonstrate the accountable third party's failure to settle a dispute on their behalf.

Exchanging collectively authorised state hashes. Figure 4 presents AuthState which is an interactive protocol between all parties to authorise a new state. To initiate a state transition, the initiator $\mathcal{P}_k$ signs a command cmd and separately signs the tuple (hstate_i, i, SC). All other parties $\mathcal{P}_2, \ldots, \mathcal{P}_n$ must verify the state transition upon receiving both signed messages:

```
$\text{VerifyTransition}(\mathcal{P}_k, \text{cmd}, \sigma_k^{\text{cmd}}, r_i, i, \text{hstate}_i, \sigma_k^{\text{hstate}_i}, r_{i-1}, \text{state}_{i-1}, \texttt{SC})$
if $\mathcal{P}_k \notin \texttt{SC}.\Sigma_{\mathcal{P}}$ return 0
$\text{state}_i \leftarrow \text{Transition}(\text{state}_{i-1}, \text{cmd})$
if $\text{hstate}_i \neq H(\text{state}_i || r_i)$ return 0
set $\text{hstate}_{i-1} := H(\text{state}_{i-1} || r_{i-1})$
return $\text{Sig.Verify}(\mathcal{P}_k, (\text{cmd}, \text{hstate}_{i-1}, i-1, \texttt{SC}), \sigma_k^{\text{cmd}}) \wedge$
$\text{Sig.Verify}(\mathcal{P}_k, (\text{hstate}_i, i, \texttt{SC}), \sigma_k^{\text{hstate}})$
```

Briefly, VerifyTransition checks if state_i is indeed a valid transition from state_{i-1} using the command cmd and if this transition was authorised by the signer. Then it checks if state_i, r_i correspond to hstate_i and that the signer has indeed authorised hstate_i (alongside the incremented i). If an honest party does not receive a signature from all other parties before `LocalTimeout()`, then they can enforce this state transition via the dispute process. To enforce, an honest party updates the contract with the previously authorised hstate_{i-1} using `SC.setstate` before initiating a dispute using `SC.triggerdispute`. This provides a grace period for all parties to input a command (including the initiator's signed cmd) before $\texttt{SC.}t_{\text{settle}}$. Once the dispute's deadline has passed, any party can call `SC.resolve`. This reveals state_i, selects one cmd from the list of inputs (i.e. determined to the application's logic) and performs the state transition on-chain.

4.5 Pisa contract

The Pisa contract CC allows a customer to hire the accountable third party to monitor their state channel. All payments are performed using a one-way (and off-chain) payment channel and the accountable third party is paid for every new hstate_i they are appointed to publish on the customer's behalf. Each payment incorporates a fair exchange protocol to ratify a signed receipt of appointment for the customer after the accountable third party is paid for accepting this task. The signed receipt alongside a list of recorded disputes in SC can later be used in CC to prove the accountable third party's wrongdoing if they did not settle a dispute to prevent an execution fork. In the following, we provide an overview of the Pisa contract which is presented in Figure 6. As before, we denote the contract as CC and interaction with the contract is denoted as a function e.g. CC.setup with the parameters omitted for readability.

Contract flags. There are four flags ($\perp$, OK, CHEATED, CLOSED). The flag $\perp$ specifies that the contract is not initialised. To transition $\perp \rightarrow$ OK, the accountable third party must invoke SC.setup to set a list of timers and store a large security deposit. Customers can open payment channels while the contract's flag = OK by storing a deposit using SC.deposit. To withdraw the security deposit, the accountable third party must initiate a closing period SC.stopmonitoring which transitions from OK $\rightarrow$ CLOSED. It also enforces a time period (e.g. Δ_{withdraw}) for customers to seek recourse. The accountable third party withdraws their deposit using SC.withdraw when this time period has expired and if all payment channels are closed. Crucially the contract can transition from any flag to CHEATED if the customer can prove the accountable third party's wrongdoing using SC.recourse.

Contract establishment. To transition from $\perp \rightarrow$ OK requires the accountable third party to set the contract's timers Δ_{settle}, Δ_{withdraw} and store a large security deposit using CC.setup. The first timer Δ_{settle} is used to determine the minimum time period for the accountable third party to respond and settle the customer's payment channel. The second timer Δ_{withdraw} is used to determine the minimum time period the accountable third party must wait before their security deposit can be withdrawn. Both timers cannot be retrospectively changed.

Customer's one-way payment channel. The accountable third party's contract maintains a list of one-way payment channels. Each payment channel has four flags ($\perp$, OK, DISPUTE, CLOSED). Flag $\perp$ implies the one-way payment channel has never existed and CLOSED implies the channel was previously opened. To open the channel and transition from $\perp \rightarrow$ OK or CLOSED $\rightarrow$ OK requires the customer to deposit coins using CC.deposit. For readability, we assume SC represents a new instance of the payment channel and it always has a unique identifier if it is closed and re-opened.

Due to the nature of a one-way payment channel, every new payment signed by the customer increments the number of coins sent to the accountable third party and only the accountable third party can mutually sign the final payment to close the channel using CC.setstate. However the customer can signal their desire to close the channel by initiating the dispute using CC.triggerdispute. The accountable third party must respond using CC.setstate to settle the dispute and redeem their share of the customer's deposit. Otherwise, after the grace period, the customer can return their full deposit using CC.resolve.

Fair exchange of signed receipt. Figure 3 presents our fair exchange protocol which provides the customer with a ratified signed receipt once the payment is accepted by the accountable third party. To initiate the fair exchange, the customer sends the authorised hstate (alongside all signatures $\Sigma_{\mathcal{P}}$), the channel identifier SC and the expected minimum time period for this appointment Δ_{expire}. We assume that the appointment time period Δ_{expire} chosen by the customer is larger than the payment channel's settlement time period CC.Δ_{settle}. This ensures the accountable third party must watch the channel for a reasonable period of time if the signed receipt's ratification is enforced on-chain by the customer. As well, the mutually agreed price for each appointment is omitted, but can be fixed or variable. Upon receiving a new appointment request, the accountable third party must locally verify whether they can settle a dispute on behalf of the customer using:

```
VerifyAppointment($\Sigma_{\mathcal{P}}$, SC, i, hstate, $\Delta_{\text{min}}$)
if i $\leq$ SC.stateRound return 0
if SC.$\Delta_{\text{settle}} \leq \Delta_{\text{min}}$ return 0
if SC.flag $\neq$ OK return 0
return Sig.Verify(SC.$\mathcal{P}$, (hstate, i, SC), $\Sigma_{\mathcal{P}}$)
```

Briefly this checks whether the authorised hstate_i was signed by all parties in SC and the dispute period in the customer's state channel is reasonable (i.e. greater than a minimum bound Δ_{min}). If the accountable third party is satisfied they can settle a dispute in the channel, then the accountable third party sends a signed receipt to the customer which includes the start time t_{start}, expiry time t_{expire}, the channel identifier SC and a conditional transfer hash h_i. This receipt is not yet ratified and cannot be used for recourse until the accountable third party reveals the corresponding pre-image s_i of h_i. The customer must verify the signed receipt can later be used, if necessary, to prove the accountable third party's wrong doing and it is indeed valid for CC after it is ratified:

```
VerifyReceipt(receipt, SC, CC, i, $\Delta_{\text{fresh}}$, $\Delta_{\text{expire}}$)
if receipt.SC $\neq$ SC return 0
if receipt.CC $\neq$ CC return 0
if CurTime() $-$ receipt.$t_{\text{start}} < \Delta_{\text{fresh}}$ return 0
if receipt.$t_{\text{expire}}$ $-$ receipt.$t_{\text{start}} < \Delta_{\text{expire}}$ return 0
if receipt.i $\neq$ i return 0
return Sig.Verify(C, (receipt.$t_{\text{start}}$, receipt.$t_{\text{expire}}$, SC,
                CC, i, receipt.$h_i$), receipt.$\sigma_C$)
```

Briefly this checks whether the signed receipt's appointment start time receipt.t_{start} is close to present time Δ_{fresh} and its expiry time receipt.t_{expire} is in the future by at least Δ_{expire}. As well, the customer must check the receipt.i corresponds to the expected the counter for hstate_i and the receipt references both the customer's channel SC and the accountable third party's channel CC. Once satisfied, the customer initiates a conditional transfer which increases the number of coins sent to the accountable third party by an agreed price and this transfer is only valid if s_i is revealed. The accountable third party must locally verify the conditional transfer:

```
VerifyPayment(pay, coins, receipt.$h_i$, CC)
if pay.coins $\neq$ coins return 0
if pay.$h_i$ $\neq$ receipt.$h_i$ return 0
if pay.CC $\neq$ CC return 0
if pay.coins $\leq$ CC.ID[$\mathcal{P}_k$].balance[9] return 0
return Sig.Verify($\mathcal{P}_k$, (pay.$h_i$, pay.coins, pay.CC), pay.$\sigma_k$)
```

[9]The ID[$\mathcal{P}_k$].balance refers to the customer's current "off-chain" balance in the one-way payment channel.

```
Customer                                                    Accountable third party
Both parties have a signing key sk, the appointment cost coins and can access SC, CC via the network.
Customer has $\mathsf{hstate}_i, i, \Delta_{fresh}, \Delta_{settle}$ and the accountable third party has $\Delta_{min}$.

$\sigma_k \leftarrow \mathsf{Sign}(sk_k, (\mathsf{coins}, \mathtt{CC}))$
$\mathtt{CC.deposit}(\mathsf{coins}, \sigma_k)$

$\xrightarrow{\mathsf{hstate}_i,\ i,\ \mathtt{SC},\ \Sigma_{\mathcal{P}},\ \Delta_{expire}}$
                                                            $b \leftarrow \mathsf{VerifyAppointment}(\Sigma_{\mathcal{P}}, \mathtt{SC}, i, \mathsf{hstate}_i, \Delta_{min})$
                                                            if b=0, abort
                                                            $s_i \xleftarrow{r} R, h_i \leftarrow H(s_i)$
                                                            $t_{start} \leftarrow \mathsf{CurTime}(), t_{expire} \leftarrow t_{start} + \Delta_{expire}$
                                                            $\sigma_C \leftarrow \mathsf{Sign}(sk_C, (t_{start}, t_{expire}, \mathtt{SC}, \mathtt{CC}, i, h_i))$
                                                            $\mathsf{receipt} \leftarrow (\sigma_C, t_{start}, t_{expire}, \mathtt{SC}, \mathtt{CC}, i, h_i)$

                                                            $\xleftarrow{\mathsf{receipt}}$
$b \leftarrow \mathsf{VerifyReceipt}(\mathsf{receipt}, \mathtt{SC}, \mathtt{CC}, i, \Delta_{fresh}, \Delta_{expire})$
if b=0, abort
$\sigma_k \leftarrow \mathsf{Sign}(sk_k, (\mathsf{receipt}.h_i, \mathsf{coins}, \mathtt{CC}))$
$\mathsf{pay} \leftarrow (\sigma_k, \mathsf{receipt}.h_i, \mathsf{coins})$

$\xrightarrow{\mathsf{pay}}$
                                                            $b \leftarrow \mathsf{VerifyPayment}(\mathsf{pay}, \mathsf{coins}, \mathsf{receipt}.h_i, \mathtt{CC})$
                                                            if b=0 return 0

We present three protocol outcomes based on depending on the accountable third party's response.
-----------------------------------------------------------------------------------------------------
Outcome 1: Accountable third party accepts payment within a timely manner

$b \leftarrow h_i = H(s_i)$                                 $\xleftarrow{s_i}$
if b=0, move to outcome 2 or 3
-----------------------------------------------------------------------------------------------------
Outcome 2: Accountable third party does not reveal $s_i$ privately to the customer, but redeems on-chain

LocalTimeout()
$\sigma_k \leftarrow \mathsf{Sign}(sk_k, (\mathsf{close}, \mathtt{CC}))$
$\mathtt{CC.triggerdispute}(\sigma_k)$
                                                            $\sigma_C \leftarrow \mathsf{Sign}(sk_C, (h_i, \mathsf{coins}, \mathtt{CC}))$
                                                            $\mathtt{CC.setstate}(h_i, \mathsf{coins}, s_i, \mathsf{pay}.\sigma_k, \sigma_C)$
-----------------------------------------------------------------------------------------------------
Outcome 3: Accountable third party does not reveal $s_i$ privately to the customer, no on-chain redemption

LocalTimeout()
$\sigma_k \leftarrow \mathsf{Sign}(sk_k, (\mathsf{close}, \mathtt{CC}))$
$\mathtt{CC.triggerdispute}(\sigma_k)$
$\mathsf{Wait}(\mathtt{CC}.t_{settle})$
$\mathtt{CC.resolve}(\mathcal{P}_k)$
```

Figure 3: Appoint: A fair exchange protocol that ensures the Monitor is paid upon validating the customer's receipt.

Briefly this checks if the payment is transferring the agreed price, if the conditional transfer hash h_i corresponds to receipt.h_i and if the customer has a sufficient balance in the off-chain and one-way payment channel to cover the payment. If satisfied, the accountable third party sends the customer s_i which ratifies the signed receipt and completes the payment. Otherwise if the customer does not receive s_i before a local timeout, then the customer initiates a dispute using `CC.triggerdispute` to enforce the receipt's ratification within the time period CC.Δ_{settle}. To claim the payment (and ratify the signed receipt), the accountable third party must reveal the conditional transfer and the corresponding s_i using `CC.setstate`. This settles the dispute and returns both parties their share of the deposit. If the dispute expires and s_i is not revealed, then customer's

Party K **Party N**

Each party has a signing key sk, a local copy of the previously authorised state
$\mathsf{hstate}_{i-1}, \mathsf{state}_{i-1}, \mathsf{r}_{i-1}, \mathsf{i}-1, \Sigma_{\mathcal{P}}$ *and can access* SC *via the network*

Party K:

Selects a cmd
$\mathsf{state}_i \leftarrow \mathsf{Transition}(\mathsf{state}_{i-1}, \mathsf{cmd})$
$\mathsf{r}_i \xleftarrow{r} R$
$\mathsf{i} \leftarrow \mathsf{i}+1$
$\mathsf{hstate}_i \leftarrow \mathsf{H}(\mathsf{state}_i || \mathsf{r}_i)$
$\sigma_k^{\mathsf{hstate}} \leftarrow \mathsf{Sign}(\mathsf{sk}_k, (\mathsf{hstate}_i, \mathsf{i}, \mathsf{SC}))$
$\sigma_k^{cmd} \leftarrow \mathsf{Sign}(\mathsf{sk}_k, (\mathsf{cmd}, \mathsf{hstate}_{i-1}, \mathsf{i}-1, \mathsf{SC}))$

$\xrightarrow{(\mathsf{hstate}_i, \mathsf{i}, \sigma_k^{\mathsf{hstate}}), (\mathsf{cmd}, \sigma_k^{\mathsf{cmd}}), \mathsf{state}_i, \mathsf{r}_i}$

Party N:

$b \leftarrow \mathsf{VerifyTransition}(\mathcal{P}_k, \mathsf{cmd}, \sigma_k^{\mathsf{cmd}}, \mathsf{r}_i, \mathsf{i}, \mathsf{hstate}_i,$
$\sigma_k^{\mathsf{hstate}_i}, \mathsf{state}_{i-1}, \mathsf{r}_{i-1}, \mathsf{SC})$
if b=0, abort

We present two protocol outcomes based on Party N's response.

Outcome 1: *$\mathcal{P}_n$ co-operates and authorises the state transition*

Party N:

$\sigma_n \leftarrow \mathsf{Sign}(sk_n, (\mathsf{hstate}_i, \mathsf{i}, \mathsf{SC}))$

$\xleftarrow{\sigma_n}$

Party K:

$b \leftarrow \mathsf{Sig.Verify}(\mathcal{P}_n, (\mathsf{hstate}_i, \mathsf{i}, \mathsf{SC}), \sigma_n)$
if b=0, abort

Outcome 2: *$\mathcal{P}_n$ aborts and does not authorise the state transition*

Party K:

LocalTimeout()
$\mathsf{SC.setstate}(\mathsf{hstate}_{i-1}, \mathsf{i}-1, \Sigma_{\mathcal{P}})$

$\sigma_k \leftarrow \mathsf{Sign}(sk_k, (\mathsf{dispute}, \mathsf{hstate}_{i-1}, \mathsf{i}-1, \mathsf{SC}))$
$\mathsf{SC.triggerdispute}(\sigma_k)$
$\mathsf{SC.input}(\mathsf{cmd}, \sigma_k^{cmd})$

$\mathsf{Wait}(\mathsf{SC.t}_{\mathsf{settle}})$
$\mathsf{SC.resolve}(\mathsf{state}_{i-1}, \mathsf{r}_{i-1})$

Figure 4: AuthState: Two (out of N) parties authorising a state.

full deposit is returned using CC.resolve and the signed receipt is never ratified.

Seeking Recourse. The customer can check whether the accountable third party failed to settle a dispute on their behalf:

```
SeekRecourse(receipt)
SC := receipt.SC
for k in SC.disputelist.length
  if SC.disputelist[k].$t_{start}$ > receipt.$t_{start}$ ∧
    receipt.$t_{expire}$ > SC.disputelist[k].$t_{expire}$ ∧
    receipt.i ≥ SC.disputelist[k].stateRound
      return 1
return 0
```

Briefly this checks whether there was a successful dispute while the accountable third party was expected to monitor the channel. If there is a dispute such that receipt.i ≥ SC.stateRound, then an execution fork was performed. The customer can seek recourse by calling CC.recourse with the signed receipt. This requires CC to fetch the list of disputes recorded in SC and verify there is a recorded dispute between receipt.start and receipt.expire. If there is a dispute which satisfies receipt.i ≥ SC.stateRound, then the accountable third party's contract is marked as cheating CC.flag = CHEATED. This forfeits the accountable third party's security deposit and allows all customers to immediately close remaining payment channels and withdraw their deposit.

Closing contract. The accountable third party can signal its desire to stop accepting new customers using CC.stopmonitoring which transitions the flag from OK ⟶ CLOSED. The large security deposit can be returned when all payment channels are closed and the grace period $\Delta_{\mathsf{withdraw}}$ has expired. It is crucial the expiry time for a customer's signed receipt is never greater than the withdrawal time such that $t_{\mathsf{withdraw}} > t_{\mathsf{expire}}$ otherwise the accountable third party's deposit can be returned before the receipt expires.

5 SECURITY ANALYSIS

We focus on the protocol's goals outlined in Section 4.1 based on the assumptions presented in Section 4.3.

5.1 State Privacy

Our goal is to protect the privacy of all intermediary states the accountable third party is appointed to publish if there is a dispute and we consider a malicious accountable third party who cannot corrupt parties in SC. The accountable third party receives hstate_i during the interactive Appoint protocol and the pre-image of hstate_i includes a nonce r_i such that $H(\mathsf{state}_i || r_i)$. This nonce prevents the accountable third party simply brute-forcing hstate_i to learn state_i and thus we rely on the pre-image resistance property of a cryptographic hash function. There are two situations when the nonce r_i is revealed. First r_i is revealed during the interactive AuthState protocol, but we previously assumed a malicious accountable third party cannot eavesdrop on this communication channel. Second r_i is globally revealed (alongside state_i) in SC to complete the dispute process by `SC.resolve`. As mentioned in the state privacy goal, the accountable third party learns if a globally revealed state_i corresponds to a hstate_i in which they were appointed to publish.

5.2 Fair Exchange

We consider the case of a malicious customer. After receiving a signed receipt from the accountable third party, the customer can propose a malformed conditional transfer which is not applicable for CC by including a different hash than supplied by the accountable third party such that $\mathsf{pay}.h_i \neq \mathsf{receipt}.h_i$ or reference a different contract such that $\mathsf{pay}.\mathsf{CC} \neq \mathsf{CC}$. As well, the customer can propose a conditional transfer which underpays the accountable third party, but can be redeemed using `CC.setstate`. The accountable third party locally runs VerifyPayment to check the above conditions to ensure the conditional transfer is well-formed, fulfills the payment and can be accepted by `CC.setstate`. Otherwise the accountable third party does not reveal s_i and the signed receipt is not ratified.

Next we consider the case of a malicious accountable third party. Once the accountable third party has received pay, the accountable third party can simply not reveal s_i and wait until $\mathsf{receipt}.t_{expire}$ for the signed receipt to expire. To prevent stalling, the customer performs a local time-out before triggering the dispute process in CC and Figure 3 illustrates two outcomes for the fair exchange. The accountable third party can mutually sign pay and reveal s_i before $\mathsf{CC}.t_{settle}$ in order to claim the payment. By claiming the payment in CC, however, the signed receipt is atomically ratified as s_i is publicly revealed. Otherwise the customer is fully refunded via the dispute process and the accountable third party can no longer accept the payment. It is crucial the receipt's expiry time $\mathsf{receipt}.t_{expire}$ is significantly greater than $\mathsf{CC}.t_{settle}$ to ensure the receipt can be ratified via the dispute process. As mentioned previously we assumed the customer has chosen a Δ_{expire} which is significantly greater than $\mathsf{CC}.\Delta_{settle}$.

Finally we consider whether the accountable third party can steal the customer's deposit from the one-way payment channel. The nature of a replace-by-incentive and one-way channel, however, is that all payments must be authorised by both the sender and receiver. Therefore the accountable third party cannot independently authorise a payment which steals the customer's full deposit.

5.3 Non-frameability

We consider if all parties in the SC collude to appoint the accountable third party and later prevent the accountable third party settling a dispute using `SC.setstate`. If successful, this records a dispute in SC and alongside the corresponding signed receipt, the colluding parties can satisfy `CC.recourse`. The accountable third party receives $\mathsf{hstate}_i, i, \Sigma_{\mathcal{P}}$ from the customer which is necessary to settle any future dispute and this is verified using VerifyAppointment. To interfere with the dispute process, the cartel must modify the state of SC such that $\mathsf{hstate}_i, i, \Sigma_{\mathcal{P}}$ is no longer valid for settling a dispute. The cartel can use `SC.setstate` to update the contract such that $\mathsf{SC.stateRound} \geq \mathsf{receipt}.i$, but this does not record a dispute in the channel and it also implies the accountable third party is no longer required to settle a dispute. The contract will always accept hstate_i as it is simply a random string of bytes. The only option for the adversary is to register a new party to SC such that the accountable third party will not have a signature from the newly registered party to settle a future dispute. Parties can only be registered using `SC.resolve` after the dispute process is complete as this is the only time the state is revealed and a registration command can be processed. The accountable third party can settle a malicious registration if it results in an execution fork and thus parties cannot register a new party to interfere with $\Sigma_{\mathcal{P}}$.

5.4 Recourse as a financial deterrent

In the fair exchange analysis, it was shown the customer pays for a signed receipt only if it is indeed valid and can be used to seek recourse. However if the customer is off-line, then a malicious accountable third party can collude with the channel's remaining $n-1$ parties simply by not settling a dispute and permitting an execution fork in the state channel. The accountable third party should thus be deterred both from invalidating the customer's signed receipt, and from receiving a payout that is greater than the loss of the security deposit.

The former follows on from the fair-exchange analysis as the customer already has the corresponding s_i and the signed receipt is ratified. To re-iterate, a receipt contains the monotonic counter i, the start and expire time of the appointment t_{start}, t_{expire}, the receipt hash h_i and of course both contracts SC, CC. The timestamp for any execution forks (or disputes) is enforced by SC and thus the signed receipt is always valid between t_{start} and t_{expire}. The only remaining option to invalidate the signed receipt is to record a larger counter $\mathsf{SC.stateRound}$ in the contract. However, the dispute process strictly increments the counter by one and thus setting a dispute based on a previously authorised state (i.e. to perform an execution fork) will always have a counter which is less than (or equal to) the receipt. Since the other $n-1$ parties require the customer's assistance to authorise a new hstate_i with a larger counter than the receipt's counter, the safety of the customer is therefore guaranteed.

The latter deters a dishonest accountable third party if the outstanding potential payout for cheating is less than the pre-agreed collateral backing. The accountable third party's potential pay-off

	State Privacy	Verifiable Job	Storage	Fair Exchange	Signed Receipt	Financial Deterrent	Fork-free
Monitor	✓	×	$O(N)$	◖	◖	×	✓
WatchTower	✓	✓	$O(1)$	◖	◖	×	×
Pisa	✓	✓	$O(1)$	✓	✓	✓	✓

Table 1: Comparison of arbitration outsourcing protocols. Notation ✓ has property, × does not have property, ◖ not proposed in original protocol but we believe it is compatible.

for cheating is not easily measurable, since a single customer can appoint the accountable third party to watch two or more channels, and an appointment is publicly disclosed only if there is a dispute via the global blockchain (or the customer seeks recourse). In an extended version of this paper, we extend Pisa to reserve coins from the security deposit for each customer, parametrized according to a leveraged ratio for discounted service fees. This extension of explicit coin allocation can be used to compensate customers for their loss if the accountable third party cheats, making the service more attractive relative to burning of the security deposit. However, compensation can also be less secure than burning in several respects. In particular, it may allow the accountable third party to minimise the loss of their security deposit by compensating a Sybil account.

5.5 Efficiency requirements

We consider if all parties in SC collude to outsource multiple appointments to the accountable third party for a single state channel such that the storage requirement is not $O(1)$. The algorithm VerifyAppointment run by the accountable third party ensures the counter i is incremented for every new appointment. Furthermore `SC.setstate` will settle the dispute as long as the corresponding counter i for $\mathsf{hstate}_\mathsf{i}$ is the largest received so far. Thus the accountable third party only needs to store the $\mathsf{hstate}_\mathsf{i}$ (alongside a valid signature for all parties in SC) which is associated with the largest monotonic counter i, although the accountable third party is required to keep track of the designated time period for each appointment which can potentially require $O(N)$ storage. The accountable third party's local policy can dictate the number of unique time periods stored and whether each new appointment simply extends the expiry time.

6 PROOF OF CONCEPT IMPLEMENTATION

We present a proof of concept implementation for Pisa based on a simplified version of Sprites [25] to evaluate whether it is gas-efficient to deploy. In the following, we provide a high-level overview of the experiment before evaluating its cost.

Our experiment involves three contracts.[10] Both the state channel contract and the PISA contract are implemented as illustrated in Figure 5 and 6. The third contract is a simplified version of Sprites which stores the full state and it has the `transition` function. This function can only be called by the state channel contract and it is the only function that can modify the state (i.e. execute a state transition). Separating the state channel and the `transition` function into distinct contracts is beneficial as the accountable third party is only required to audit the state channel contract[11]. In terms of functionality, simplified Sprites only supports withdrawing coins or sending payments.

Table 1 presents the cost of our experiments for Pisa on a private Ethereum network. Steps 1-3 highlight the one-time costs for creating each contract.

For the Pisa contract, the customer creates a payment channel in step 4 using a single transaction. The customer can uncooperatively close the payment channel via the dispute process in steps 5-6 which requires 3 transactions. Intermediary (and off-chain) payments between the customer and accountable third party do not incur any cost. Every appointment (and payment) requires three rounds of communication between the customer and accountable third party. The accountable third party can close the channel with a mutually authorised payment in step 7 and this requires a single transaction. If the accountable third party aborts and fails to settle a dispute on the customer's behalf, then step 8 represents the customer seeking recourse and proving the accountable third party's wrongdoing using a ratified signed receipt. Submiting this proof to the Pisa contract requires a single transaction.

For the state channel contract, step 9 represents updating the contract with the latest authorised state hash. This requires a single transaction and the gas cost is constant for any party, including when the accountable third party settles a dispute on the customer's behalf. Steps 10-12 represents a successful dispute and requires a single transaction to trigger the dispute, up to $O(n)$ transactions for submitting commands, where n is the number of parties in the channel, and a single transaction to resolve the dispute. When the dispute is resolved, the `transition` function is invoked in the simplified Sprites contract.

7 DISCUSSION AND FUTURE WORK

Comparison of arbitration outsourcing protocols. Table 1 presents a comparsion of Monitor, WatchTower and Pisa. All protocols achieve state privacy which hides the customer's outsourced state from the third party unless there is a dispute. However in the Monitor protocol, the third party cannot verify if an appointment received from the customer can be used to settle a dispute. Furthermore, a Monitor must store all received appointments $O(N)$ from the customer for every update in their payment channel. WatchTower achieves $O(1)$ storage by proposing a new consensus rule (i.e. it is not fork-free) to allow payment channels in Bitcoin to support replace by monotonic counter (i.e. the state replacement technique proposed from Sprites [25]). Pisa is the first protocol to propose an

[10]Code: https://github.com/PISAresearch/pisa

[11]In practice, this allows all state channels to have the same bytecode regardless of their application and thus it is straight-forward audit in real-time.

Step	Command	Cost (gas)	Cost ($)
	Create Contracts		
1	Accountable third party contract	1,609,613	2.53
2	State contract	1,892,135	2.97
3	Sprites contract	869,280	1.37
	Appoint accountable third party		
4	Customer opens payment channel (`CC.deposit`)	65,504	0.10
5	Customer signals payment channel closure (`CC.triggerdispute`)	48,763	0.08
6	Customer is refunded (`CC.resolve`)	37,290	0.06
7	Accountable third party closes payment channel (`CC.setstate`)	103,794	0.16
8	Customer seeks recourse (`CC.recourse`)	51,892	0.08
	State Channel Dispute Process		
9	Party set collectively authorised state (`SC.setstate`)	90,130	0.14
10	Party initiates dispute process (`SC.triggerdispute`)	78,667	0.12
11	Party submits a command (`SC.input`)	140,275	0.22
12	Party resolves dispute and state transition is executed on-chain (`SC.resolve`)	149,494	0.23

Table 2: Cost of Pisa for simplified Sprites. We have approximated the cost in USD ($) using the conversion rate of 1 ether = $785.31 and the gas price of 2 Gwei which reflects the real world costs in May 2018.

accountable third party as the customer is provided with a cryptographic (and publicly verifiable) warrant that the third party was hired, a financial deterrent is enforced to deter cheating by the third party and the customer can pursue recourse if wrongdoing is detected. On hindsight, our fair exchange protocol to ratify a signed receipt upon paying the third party is compatible with both WatchTower and Monitor. Thus, the contributions within Pisa are beneficial for Bitcoin and Ethereum channel networks.

Persistent dispute evidence. The Ethereum community are seeking proposals to charge rental fees [35] and expire instantiated contracts (alongside stored data). This is problematic for Pisa as the state channel contract cannot be immediately destroyed if there is a dispute in order to preserve evidence and prove the accountable third party's wrongdoing. In an extended version of this paper, we present another approach using a new contract called the dispute registry. This contract is responsible for storing disputes on behalf of all other contracts and periodically clearing dispute records (e.g. after one week). Otherwise, Ethereum could make the event-logs recorded in the transaction receipt accessible via the Ethereum Virtual Machine and the event-logs could be used as the indisputable evidence.

Customer crash recovery. It was reported in March 2018 [3] that one party tried to close a replace-by-revocation channel using a previous (and revoked) state, but the counter-party was on-line. Due to the nature of a replace-by-revocation channel, the counter-party was awarded all coins in the channel. At the time, it was implied that this was an attempt to reverse payments and steal the counter-party's coins. However it later emerged that the party had allegedly crashed and lost a copy of the latest state. As a result, their wallet software used the revoked state to close the channel. One desirable feature for an accountable third party is to support crash recovery by storing an encryption of the state which can later be retrieved and decrypted by the customer. In an extended version of this paper, we propose how to encrypt the state such that it is gas-efficient and compatible with the Ethereum network.

8 CONCLUSION

In this paper, we proposed Pisa to help address a new (and undesirable) security assumption for state channels by allowing a customer to appoint an accountable third party to monitor a state channel on their behalf. Pisa is designed to support any application built using a state channel and it is the first protocol that allows the customer to seek recourse if the accountable third party's fails to settle a dispute on their behalf. To evaluate Pisa, we provided a proof of concept implementation for Sprites to demonstrate that it is cost-efficient to deploy in practice. We hope Pisa provides a new step towards the realisation of state channels as a practical scaling solution for cryptocurrencies.

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Modified generic state channel contract

```
flag := $\bot$
stateRound := 0
state, hstate := $\varepsilon$
$\mathcal{P}$, disputelist, cmdlist := $\emptyset$
$t_{settle}, t_{start}, \Delta_{settle}$ := 0

function setup($\mathcal{P}, \Delta_{settle}$):
    discard if flag $\neq \bot$
    set $\Delta_{settle} := \Delta_{settle}$, $\mathcal{P} := \mathcal{P}$, flag := OK
    EventSetup($\mathcal{P}, \Delta_{settle}$)
function setstate(hstate$_i$, i, $\Sigma_{\mathcal{P}}$):
    discard if i $\leq$ stateRound
    if Sig.Verify($\mathcal{P}$, (hstate$_i$, i, this), $\Sigma_{\mathcal{P}}$)
        set stateRound := i
        set hstate := hstate$_i$
        set cmdlist := $\emptyset$; flag := OK
        EventEvidence(stateRound, hstate$_i$)
function triggerdispute($\sigma_k$):
    discard if flag $\neq$ OK
    discard if $\mathcal{P}_k \notin \mathcal{P}$
    if Sig.Verify($\mathcal{P}_k$, (dispute, hstate, stateRound, this), $\sigma_k$)
        set flag := DISPUTE
        set $t_{start}$ := CurTime()
        set $t_{settle} := t_{start} + \Delta_{settle}$
        EventDispute($t_{settle}$)
function input(cmd, $\sigma_k$):
    discard if flag $\neq$ DISPUTE
    discard if $\mathcal{P}_k \notin \mathcal{P}$
    if Sig.Verify($\mathcal{P}_k$, (cmd, hstate$_i$, stateRound, this), $\sigma_k$)
        set cmdlist[$\mathcal{P}_k$] := cmd
        EventInput(cmd, $\mathcal{P}_k$)
function resolve(state$_i$, r$_i$):
    discard if CurTime() $\leq t_{settle}$
    discard if hstate $\neq H$(state$_i$, r$_i$)
    if flag = DISPUTE
        set state := transition(state$_i$, cmdlist)
        set $\mathcal{P}$ := state.$\mathcal{P}$
        set cmdlist := $\emptyset$; flag := OK
        add (stateRound, $t_{start}, t_{settle}$) to disputelist
        set stateRound := stateRound + 1
        EventResolve(stateRound)
function transition(state, cmdlist) internal:
    // Implement application logic.
    // Only executable by the contract on the network.
    // Locally executed by parties to verify a transition.
```

Figure 5: Modifications to the state channel construction from Sprites

```
PISA contract
flag := ⊥
IDC := ∅
$\Delta_{settle}, \Delta_{withdraw}, t_{withdraw} := 0$
deposit, profit := 0

function setup(coins, $\sigma_C$, $\Delta_{withdraw}$, $\Delta_{settle}$,):
    discard if flag ≠ ⊥
    if Sig.Verify(C, coins, $\sigma_C$)
        set C := C, deposit := coins
        set $\Delta_{withdraw} := \Delta_{withdraw}$, $\Delta_{settle} := \Delta_{settle}$, flag := OK
    EventSetup()
function deposit(coins, $\sigma_k$):
    discard if flag ≠ OK
    discard if ID[$\mathcal{P}_k$].flag = DISPUTE
    if Sig.Verify($\mathcal{P}_k$, (coins, this), $\sigma_k$)
        if ID[$\mathcal{P}_k$].flag = CLOSED
            set ID[$\mathcal{P}_k$].flag := OK
        set ID[$\mathcal{P}_k$].deposit += coins
    EventDeposit($\mathcal{P}_k$, coins)
function setstate($h_i$, coins, $s_i$, $\sigma_k$, $\sigma_C$):
    discard if flag = CHEATED
    discard if coins > ID[$\mathcal{P}_k$].deposit
    discard if $h_i \neq H(s_i)$.
    if Sig.Verify(C, ($h_i$, coins, , this[a]), $\sigma_C$)
    ∧ Sig.Verify($\mathcal{P}_k$, ($h_i$, coins, this), $\sigma_k$)
        set profit += coins
        send ID[$\mathcal{P}_k$].deposit − coins to $\mathcal{P}_k$
        set ID[$\mathcal{P}_k$].flag := CLOSED
        set ID[$\mathcal{P}_k$].deposit := 0
        set ID[$\mathcal{P}_k$].$t_{settle}$ := 0
        EventEvidence($\mathcal{P}_k$)
function triggerdispute($\sigma_k$):
    if ID[$\mathcal{P}_k$].flag = OK ∧
        Sig.Verify($\mathcal{P}_k$, (close, this), $\sigma_k$)
        set ID[$\mathcal{P}_k$].flag := DISPUTE
        set ID[$\mathcal{P}_k$].$t_{settle}$ := CurTime() + $\Delta_{settle}$
        EventDispute($\mathcal{P}_k$, ID[$\mathcal{P}_k$].$t_{settle}$)
function resolve($\mathcal{P}_k$):
    if flag = CHEATED ∨
    (ID[$\mathcal{P}_k$].$t_{settle}$ ≤ CurTime() ∧ ID[$\mathcal{P}_k$].flag = DISPUTE)
        send ID[$\mathcal{P}_k$].deposit coins to $\mathcal{P}_k$
        set ID[$\mathcal{P}_k$].flag := CLOSED
        set ID[$\mathcal{P}_k$].deposit := 0
        set ID[$\mathcal{P}_k$].$t_{settle}$ := 0
        EventResolve($\mathcal{P}_k$)
```

[a]For readability, we assume this is a unique identifier for the contract and a new instance of the payment channel (e.g. to prevent replay-attacks of previously signed messages, a counter may be incremented for every new deposit or when the channel is settled)

```
PISA contract (continued)
function stopmonitoring($\sigma_C$):
    discard if flag = CHEATED
    if Sig.Verify(C, (stop, this), $\sigma_C$)
        set flag := CLOSED
        set $t_{withdraw}$ := CurTime() + $\Delta_{withdraw}$
        EventClose($t_{withdraw}$)
function withdraw($\sigma_C$):
    discard if flag = CHEATED
    if Sig.Verify(C, (withdraw, this), $\sigma_C$)
        if ID.length = 0 ∧ CurTime() > $t_{withdraw}$ ∧ flag = CLOSED
            set profit += deposit, deposit := 0
        send profit to C
        set profit := 0
        EventWithdraw()
function recourse($t_{start}$, $t_{expire}$, SC, i, $h_i$, $s_i$, $\sigma_C$):
    discard if flag = CHEATED
    discard if $h_i \neq H(s_i)$
    set chan := lookup(SC)
    if Sig.Verify(C, ($t_{start}$, $t_{expire}$, SC, this, i, $h_i$), $\sigma_C$)
        for $k$ in chan.disputelist.length
            if chan.disputelist[k].$t_{start}$ > $t_{start}$
            ∧ $t_{expire}$ > chan.disputelist[k].$t_{expire}$
            ∧ i ≥ chan.disputelist[k].stateRound
                set flag := CHEATED
                EventForfeit()
```

Figure 6: PISA contract