Teechain: Scalable Blockchain Payments using Trusted Execution Environments

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ABSTRACT

Blockchain protocols such as Bitcoin are gaining traction for exchanging payments in a secure and decentralized manner. Their need to achieve consensus across a large number of participants, however, fundamentally limits their performance. We describe *Teechain*, a new off-chain payment protocol that utilizes trusted execution environments (TEEs) to perform secure, efficient and scalable fund transfers on top of a blockchain, with *asynchronous* blockchain access. Teechain introduces secure payment chains to route payments across multiple payment channels. Teechain mitigates failures of TEEs with two strategies: (i) backups to persistent storage and (ii) a novel variant of chain-replication. We evaluate an implementation of Teechain using Intel SGX as the TEE and the operational Bitcoin blockchain. Our prototype achieves orders of magnitude improvement in most metrics compared to existing implementations of payment channels: with replicated Teechain nodes in a trans-atlantic deployment, we measure a throughput of over $33,000$ transactions per second with 0.1 second latency.

1 INTRODUCTION

Blockchain protocols, first introduced by Nakamoto [29] and used to power the Bitcoin cryptocurrency, enable fund transfers over a trustless, decentralized, and global network. The robustness and security of blockchain protocols have attracted wide interest. A vibrant cryptocurrency community has emerged to develop hundreds of public, blockchain-based, cryptocurrencies. In addition, companies and organizations in the financial technology (FinTech) industry are looking to develop blockchain protocols, referred to as Distributed Ledger Technology, for bank-to-bank transactions.

The participants in a blockchain maintain a log of the systems' transactions and reach distributed consensus on their order with a high degree of replication to overcome node failure and attacks. While this approach is responsible for the security and reliability of blockchain protocols, it is also responsible for their greatest weakness: performance is limited by the rate and latency that it takes for nodes to reach consensus.

The increasing adoption of blockchain protocols for both cryptocurrencies and FinTech requires support for drastically higher performance. For cryptocurrencies in particular, adoption has grown rapidly and this raises a critical concern: can the technology that is currently limited to a handful of transactions per second (tx/sec), and takes minutes to process a transaction, achieve the performance required for credit card processing workloads, i.e. can blockchain based cryptocurrencies confirm transactions in seconds and accommodate throughput of tens of thousands of tx/sec [45]?

Payment channels [11, 16, 32] allow for efficient, trustless transfer of funds, in which parties perform transactions without having to impact the blockchain except when a channel is established or terminated. This decreases the delay of transaction confirmation, because only two entities are involved, and reduces the load on the blockchain, scaling throughput linearly with the number of channels. Yet existing proposals for payment channels have seen little adoption due to incompatability with current blockchain protocols, practical limitations and implementation complexity.

This paper presents **Teechain**, a novel payment channel and multi-hop payment protocol that supports practical, efficient and secure off-blockchain (off-chain) bilateral fund transfers, while only requiring asynchronous access to the underlying blockchain. To achieve this, Teechain combines the following techniques:

Asynchronous blockchain access. Existing solutions for payment channels [11, 32] require synchronous access to the blockchain: at any time, a user can settle the channel by removing their balance from the payment channel and creating a transaction to be placed on the blockchain. Each party can also settle the channel at a deprecated state using a previous capability. To prevent such attacks, existing solutions require users to monitor the blockchain continuously and react to misbehaviour, which places a burden on users.

Instead, Teechain is the first payment channel with asynchronous blockchain access. To achieve this, it departs from existing software-only solutions [11, 32] and leverages support for *trusted execution environments* (TEEs) in recent commodity CPUs [3, 19]. TEEs are a hardware security feature in which code and data in a trusted memory region are isolated and protected from the rest of the system. These guarantees are robust in the presence of an attacker who has full control of the hardware and has compromised privileged software, including the OS and the hypervisor.

Teechain uses collateral for funds in the form of on-blockchain *deposits* to secure payment commitments on its channels. The collateral is maintained by the TEEs, allowing users to dynamically move funds between different payment channels. Because the TEEs protect the internal channel state and release it only upon channel termination, they ensure that users cannot launch attacks by using stale state. In turn, this construction avoids the common attacks on payment channels, simplifies the protocol, and improves performance.

Support for payment chains. For *payment chains*, in which funds are transferred across a chain of channels, or hops, Teechain offers a new protocol for ensuring that either the payment completes successfully, or that all channels in the chain are settled consistently, either in pre-payment or post-payment state. This atomicity guarantee ensures that no coins are lost, double-spent or left in limbo despite failures along any of the nodes on a payment path.

Fault tolerance. Teechain provies a strong fault tolerance guarantee, based on two separate techniques targeting users with different performance demands. For low-frequency users, such as individuals, Teechain exploits TEE support for hardware *monotonic counters*, and uses them to persist state to stable storage, while preventing replay attacks; for high-frequency payments, such as exchanges, Teechain offers a novel variant of *chain replication* to achieve high performance and provide fault tolerance as long as at least one TEE in the chain is available.

The experimental evaluation of our Teechain prototype implementation shows that Teechain performs significantly better than prior protocols in a wide-area network (WAN) setting: channel bootstrapping and termination takes less than a second, rather than tens of minutes or hours with previous solutions; comparing against the Lightning Network (LN) implementation of payment channels [25], Teechain's channel latency is less than half that of LN with a backup node, and its throughput is over an order of magnitude higher, at $33,000$ tx/sec across the atlantic.

2 BACKGROUND AND MOTIVATION

We first introduce Bitcoin and explore its scalability challenges (§2.1). We then describe trusted execution environments as provided by recent commodity CPUs (§2.2).

2.1 Bitcoin

Bitcoin [29] is a digital cryptocurrency that allows users to keep and exchange funds. In Bitcoin, each user is identified by a public *Bitcoin address* that is associated with a public/private key pair that is kept by the user. Bitcoin users exchange funds by issuing public *Bitcoin transactions*, i.e. pieces of information conveying which funds are to be transferred between which Bitcoin addresses.

Technically, each transaction consists of *transaction inputs* and *transaction outputs*. Transaction inputs are *unspent transaction outputs* (UTXOs), i.e. outputs of previous transactions that have not yet been spent. As a consequence, valid transactions consume, or spend, existing UTXOs as inputs and create new UTXOs that can later be used in new transactions. To use an UTXO as a transaction input, i.e. to spend the UTXO, the spending user must meet a condition expressed as a *script* that is specified within each UTXO. Typically, this script specifies that the spender must present a signature that matches a certain Bitcoin address, thus proving ownership of the UTXO (this is often termed pay-to-public-key-hash or P2PKH). The scripting language allows for more complex scripts to be expressed, for example, offering primitives such as time locks [40] and m-of-n multisignature requirements [41]), but these are not required for our work. Teechain only requires P2PKH scripts.

Under the hood, Bitcoin is a distributed peer-to-peer network that executes a replicated state machine. Each peer, or *node*, in the network maintains and updates a copy of the Bitcoin *blockchain*, an append-only ledger that contains the entire history of all Bitcoin transactions ever published. In particular, all nodes maintain a copy of the Bitcoin blockchain and verify that all issued transactions are valid, i.e., only spend UTXOs and satisfy all scripts' conditions.

For technical reasons [4, 29] that are outside our focus, blockchain protocols have peculiar properties. Participating nodes in the network generate blocks at random intervals, on average, every 10 minutes, and the state of the blockchain can be undetermined for limited periods due to participants publishing conflicting blocks. Moreover, a transaction's placement in the blockchain is only guaranteed with finite probability, which can be made arbitrarily small by waiting sufficiently long; one hour is considered enough for most purposes.

Although the security properties of Bitcoin's blockchain protocol are not perfect [8, 15, 17, 30, 34], the operational blockchain has never been breached in practice. However, the properties mentioned above imply significant performance limitations. In particular, Bitcoin can process only a handful of transactions per second, and requires waiting 10's of minutes before providing meaningful guarantees of transaction confirmation.

It is possible to improve the performance of blockchain protocols by tuning the blockchain's parameters or using more advanced protocols [1, 13, 23, 31]. Several of these methods have been employed by other cryptocurrencies, however, they still require all nodes to process all transactions, limiting (i) throughput to that of the network's weakest node, and (ii) latency to the time required for all nodes to reach agreement.

2.2 Trusted Execution Environments

Recent commodity CPUs provide *trusted execution environments* (TEEs), i.e., isolated execution environments within which the CPU safeguards the confidentiality and integrity of code and data [3, 19]. TEEs provide a root of trust that allows for novel software deployment models: by only trusting the CPU, software can be securely deployed and run on remote systems.

While our protocol is general-purpose and can function on any TEE, our first implementation uses Intel's Software Guard Extensions (SGX) [18] that allow code to run in a trusted environment called an *enclave*.

Code and Memory Isolation. The SGX architecture divides the computing environment into *trusted* and *untrusted* parts, through cryptographically secured and unsecured code and memory regions. The CPU manages the strict isolation of these environments, ensuring that only trusted code accesses protected parts of the memory. The trusted environment has no direct I/O access, and a dedicated interface allows trusted code to call untrusted code and vice versa.

As long as the physical CPU is not breached, the confidentiality and integrity of trusted code and data are protected from attackers with physical access to the machine, including access to the memory, the system bus, BIOS, and peripherals.

Remote Attestation. TEEs typically provide remote attestation facilities [20, 22], which allow remote parties to verify that a certain piece of software is running within a genuine TEE. In SGX, the CPU (i) measures the trusted code being executed within the TEE and the corresponding trusted memory; (ii) cryptographically signs the computed values; and (iii) provides the measurements and signatures to the attesting party. The attestor can then verify the provided values, i.e., whether the signature is valid and whether the provided measurements correspond to a set of known values.

3 TEECHAIN OVERVIEW

3.1 Scenario

We consider a scenario in which several mutually distrusting parties use blockchain technology to exchange funds and make payments between each other. The parties, or *peers*, are connected via network communication links where not all peers can communicate with each other directly, e.g., some may reside behind firewalls or NATs. Many peers in the network may have long-lived financial relationships that require frequent interaction with high-throughput and low latency. For example, some peers may belong to currency exchanges or service providers who have a high degree of connectivity in the network and process many payments per second. Other peers in the network may require more infrequent interaction with a smaller degree of connectivity. For example, they may belong to individual consumers or customers who make only several purchases on a daily basis.

The goal of Teechain is to allow for practical, secure, scalable and efficient bilateral off-chain transactions, thus overcoming the limitations of the underlying blockchain protocol.

3.2 Approach

The fundamental idea behind Teechain is to exploit trusted execution environments (TEEs) to enforce the correct operation of mutually distrusting parties during off-chain fund exchanges. In Teechain, TEEs form a distributed trusted third party. They arbitrate between participants in the Teechain network and are responsible for managing and maintaining the global state distribution of funds.

Technically, Teechain runs inside each party's TEE. Teechain then allows the participants to execute a protocol to construct bidirectional payment channels and to exchange payments in a peer-to-peer manner via those channels. To ensure the correct operation of these payment channels, the participant's TEEs remotely attest each other, thus providing guarantees that the other party is running genuine Teechain code within a genuine TEE.

Teechain further provides a protocol to route payments across multiple payment channels, thereby forming payment chains. This allows for payments between Teechain participants that do not share network communication links or payment channels. Such indirect payments reduce the amount of collateral required by the network, since nodes do not need to maintain collateral for a chain with each of their peers. It also poses a more practical deployment model, as senders and receivers of payments do not need to communicate directly with each other.

3.3 Threat Model and Assumptions

Our threat model assumes that multiple parties wish to exchange funds but mutually distrust each other. Each party is potentially malicious, i.e., they may attempt to steal funds, avoid making payments, and arbitrarily deviate from the protocol. In particular, parties may drop, send, record, modify, and replay arbitrary messages in the protocol. Either party may crash and stop responding entirely.

Fig. 1a shows the trust assumptions made by two parties in a Teechain payment channel. Each party trusts the cryptocurrency blockchain, its own environment, the local and remote TEEs, and the code that executes the Teechain protocol. The rest of the system, including the network channels and the other parties' software stacks (outside the TEE) and hardware are untrusted. For payments made across multiple payment channels, the same trust assumptions hold; Fig. 1b shows the trust assumptions for *Alice* routing a payment to *Carol* through *Bob*, trusting her own system and both *Bob* and *Carol*'s TEEs.

During protocol execution, any party may therefore access or modify any data in its non-TEE memory or stored on disk, view or modify its non-TEE application code, and control any aspect of its operating system and other privileged software and hardware.

We assume the TEE guarantees to hold and do not consider side-channel attacks [5, 35, 46] on the TEE. Such attacks and their mitigations [36, 43] are outside the scope of this work.

3.4 Protocol Overview

In the Teechain system, each participant operates her own TEE that executes the secure Teechain protocol.

3.4.1 Payment Channels. The Teechain protocol for payment channels works as follows:

(1) First, pairs of parties perform remote attestation and open bidirectional *payment channels*. Before a party may send funds over such a channel, it must provide a deposit in the form of a blockchain transaction output paid into a Bitcoin address owned by a Teechain TEE. For each channel, the TEE of each party acts as a trusted intermediary by holding its party's channel deposits.

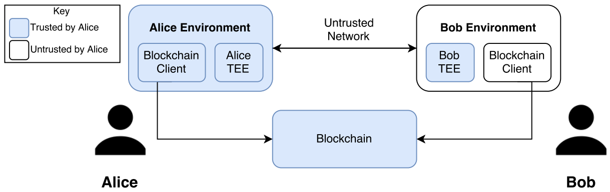
(2) While the channel is open, the TEEs securely maintain the channel state. Payments between the two parties may then be performed as long as the provided deposits are sufficient as collateral for the amounts transacted over the channel. The corresponding updates to the TEE-internal channel state are performed through a secure interface. Teechain maintains all channel balances and the deposits of all Teechain participants exclusively within TEEs.

(3) A Teechain participant may, at any point in time, issue the termination of any of their payment channels. This can be due to mutual agreement with its counterparty, or a unilateral decision to terminate the channel. The corresponding TEE will then close the channel in a secure manner. Only on termination does a TEE generate a transaction that can be placed onto the blockchain.

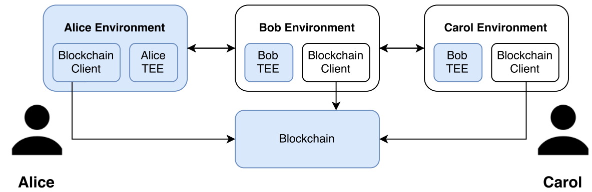
Fig. 1a shows the Teechain payment channel architecture. Both *Alice* and *Bob* run their TEE alongside a connection to the Bitcoin network. The connection to the Bitcoin network is only used to create or confirm a deposit, and to terminate a channel. We detail the payment channel protocol in §4.1.

3.4.2 Payment Routing. Teechain further allows to route payments across multiple payment channels. For this, we assume that the party initiating the payment has obtained a path to the receiving party through the network of open Teechain payment channels. To form a *payment chain* along this path, all involved parties lock the corresponding payment channels, committing not to use them for other payments. They then execute a protocol to reach consensus on the new balance for all of channels. After releasing all locks, the channels are again available for other payments.

If routing of the payment fails, e.g., due to node or network failures, Teechain ensures that all channels of the payment chain are



(a) Payment channel between Alice and Bob.



(b) Payment chain from Alice to Carol via Bob.

Figure 1: Teechain architecture. Entities trusted by Alice are shaded.

settled consistently either at their pre-payment state or at their post-payment state—depending on the stage that the protocol execution reached at time time of failure. We detail this protocol in §4.2.

4 TEECHAIN PROTOCOL

We describe the Teechain protocol. First, we outline the single channel protocol (§4.1), and then describe how to route payments across several payment channels (§4.2) and how to perform off-chain channel termination (§4.3). Finally, we describe how Teechain provides fault tolerance (§4.4). Pseudocode is in Appendix A and some practical aspects are discussed in Appendix B.

4.1 The Channel Protocol

The central idea behind the Teechain channel protocol is to establish bidirectional payment channels between pairs of Teechain participants and to exchange funds in a direct manner rather than placing transaction onto the blockchain for every single payment. To safeguard payment channels and payments as well as to prevent fraud by network participants, Teechain makes use of the confidentiality and integrity guarantees provided by TEEs.

To achieve this, each node participating in the protocol runs its own instance of the Teechain TEE (§4.1.1) and can generate and release blockchain deposits as collateral for channels (§4.1.2). Two nodes can then set up a secure network link (§4.1.3) and a payment channel (§4.1.4). Once the payment channel is set up, each of the parties associates deposits as collateral (§4.1.5) and they exchange payments. If the parties agree that a deposit is not necessary for their channel, they can release it, making it available for other channels (§4.1.7). At any time, either party can unilaterally terminate the channel by cashing out its fair portion of the channel's associated deposits (§4.1.8).

4.1.1 TEE Initialization. A participant *Alice* that wishes to participate in the Teechain protocol must set up a genuine Teechain TEE and be uniquely identifiable by all other participants to the end of sending and receiving payments. At setup, *Alice* thus first has its TEE generate a public/private key pair for the purpose of identification within the Teechain network. The public key is revealed to the participants in the network and uniquely identifies *Alice*'s TEE. The private key is securely held inside the TEE, inaccessible to the host *Alice* or any other parties in the system.

4.1.2 Deposit Creation and Release. To later perform payments to other Teechain participants, *Alice* must provide her TEE with deposits. Deposits will be securely held by the TEE and used to secure any of *Alice*'s payments. In a nutshell, *Alice* will only be able to send payments along Teechain channels as long as the sum of all of her payments does not exceed the combined sum of all of her deposits and received payments.

Technically, deposits are transaction outputs that (i) have been paid into a bitcoin address that is held by a Teechain TEE, meaning that the addresses' private keys are only known to the TEE, and that (ii) have been placed onto the blockchain. As a consequence, only the owning TEE is ever able to release those deposits again by generating a corresponding spending transaction.

To generate a deposit, *Alice* instructs her TEE to create a new Bitcoin address by issuing command **newAddr**. While the TEE maintains and safeguards the generated addresses' private key, the command returns the generated Bitcoin address a to *Alice*. *Alice* then (i) creates a transaction t with an output that sends money into the generated address a, (ii) places transaction t on the blockchain, and (iii) issues command **newDeposit** to provide to the TEE all output details of transaction t, i.e. the transaction ID, the output index and the deposit amount. The TEE verifies the transaction and the fact that it paid into the TEE-generated Bitcoin address and adds it as a free deposit to its deposit registry.

Alice may repeat this step of deposit creation at any time during protocol execution, thus being able to top up the deposits within her TEE. Because Bitcoin transactions can contain multiple outputs, *Alice* may further use a single Bitcoin transaction to create multiple Teechain deposits. We see in §4.1.5 why this is useful.

At any point in time *Alice* may issue command **releaseDeposit** to instruct the TEE to release a free deposit. For this, *Alice* provides the details of the deposit to be released as well as a designated target Bitcoin address. If the requested deposit is indeed free, the TEE creates and returns a transaction that transfers the corresponding deposit amount to the provided address. *Alice* can then reclaim the deposit by placing the transaction onto the blockchain. To prevent the user from reusing the same transaction output as a deposit again, the TEE will keep a copy within its deposit registry.

Note that this mechanism is robust against transaction malleability. The user *Alice* only provides the TEE with a transaction that is placed onto the blockchain. This means that, even if an external party was to maul the transaction and change its ID in the time between *Alice* constructing the transaction and it being placed on the blockchain, Teechain remains unaffected. This allows mauled Bitcoin transactions to still be used for depositing funds into a Teechain channel or to release funds back to the user.

4.1.3 Secure Link. For *Alice* and *Bob* to interact over a Teechain channel, both need to trust that their counterpart runs the unmodified Teechain code inside a genuine TEE. To this end, each party, *Alice* and *Bob*, uses the TEE remote attestation mechanism as follows. *Alice* and *Bob* both execute the **newNetworkChannel** command, which performs a remote attestation handshake between their TEEs. The outcome of this handshake is that (i) each party has verified that its counterpart runs Teechain inside a genuine TEE, and that (ii) the counterpart's public/private key pair (as presented in §4.1) was securely generated inside that TEE. The Teechain remote attestation handshake executes an authenticated Diffie-Hellman key exchange to create an AES-GCM-secured [12] network channel. Teechain ensures that any further interaction between the two TEEs: (i) is subject to the correct attestation of both TEEs, and (ii) happens over the secure established network channel.

Teechain performs remote attestation inside each TEE. Specifically, for Intel SGX, remote attestation requires communication with a third party attestation service (IAS). While Teechain performs this communication outside the TEE, it verifies the attestation service's report and the corresponding signature inside the TEE.

Once remote attestation has been successfully completed, *Alice* and *Bob*'s TEEs share a secure network channel: *Alice*'s TEE can encrypt, sign and authenticate messages with *Bob*'s TEE, and vice-versa. Teechain ensures message freshness by using (i) nonces for message requests and acknowledgements (§4.1.5 and §4.1.7) and (ii) strict monotonic counters for payment messages (§4.1.6).

4.1.4 Teechain Payment Channel Initialization.

Teechain then uses the established secure communication channel to initialize a secure payment channel between *Alice* and *Bob*. For this, *Alice* and *Bob* provide their enclaves with the public key of the remote party as well as with their Bitcoin settlement addresees, i.e. addresses that will be paid into upon channel termination. *Alice* and *Bob*'s TEEs will then agree on a unique *channel ID* to identify the payment channel. In addition to this channel ID, the two TEEs also exchange the provided public keys and Bitcoin settlement addresses. The TEEs will then (i) associate the provided values with the channel, (ii) create an acknowledgement message confirming the details of the channel, (iii) sign it, (iv) encrypt it for the remote party, and (v) send it to the remote TEE. Upon receiving and verifying such an acknowledgement, the TEEs mark the channel open.

4.1.5 Deposit Association.

Before *Alice* or *Bob* may perform payments via the open payment channel, at least one of them must associate deposits, as described in §4.1.2, with the channel. By associating a TEE-owned deposit with a payment channel *Alice* commits this deposit as collateral for this channel. In particular, *Alice*'s TEE will ensure that the same funds will not be used as a collateral for any other channels. However, in order for a deposit to be associated with a payment channel, the remote party must first approve that deposit.

Deposit approval. Deposit approval requires the remote party to verify that a deposit has actually been placed onto the blockchain. This prevents a party from presenting their TEE with a valid transaction output without placing it on the blockchain.

If *Alice* wishes to have a deposit approved by *Bob*, she issues the command **approveMyDeposit**, providing the public key of *Bob*'s TEE and the transaction output she wants to have approved. *Alice*'s TEE then sends an approveMyDeposit request to *Bob*'s TEE. *Bob* verifies that the given transaction output has been placed onto the blockchain and allows his TEE to mark this deposit as approved and return an approvedDeposit message to *Alice*'s TEE. Upon success, *Alice*'s TEE marks the given deposit as approved by *Bob*.

Once a deposit has been approved by a remote TEE, it is granted the ability to be associated with any payment channel between the pair of TEEs. Note that each deposit must only be approved once for each pair of Teechain participants and that this step must not be repeated whenever the same deposit is reused by the same users. Similar to deposit creation and removal, deposit approval can be performed at any time during protocol execution in order to top up the amount of available deposits.

Deposit association. *Alice* may then associate any deposit approved by *Bob* with her payment channel using command **associateMyDeposit**. For this, she provides the to-be-associated channel ID and deposit. Her TEE asserts that the deposit is free and that it has been approved by *Bob*. If so, it considers the deposit value as part of the channel collateral, thereby increasing the balance of the channel by the deposit's value. It then locates the corresponding Bitcoin private key that can spend the transaction output, encrypts it for the payment channel, and forwards this as part of the signed deposit association message. By doing this, it allows *Bob*'s TEE to spend this transaction upon channel termination (see §4.1.8).

Upon receiving *Alice*'s deposit association commitment message, *Bob*'s TEE (i) asserts that the deposit has been approved by *Bob*, (ii) associates it with the payment channel with *Alice*, and (iii) acknowledges the deposit association to *Alice*'s TEE. In case *Bob*'s TEE declines the deposit, *Alice* dissociates the deposit from the channel (see §4.1.7).

Teechain allows *Alice* to associate multiple deposits with each channel, thus aggregating collateral. *Alice* can use this feature to minimize the unused collateral associated with individual channels by (i) providing her enclave with many small deposits rather, and (ii) associating channels with many deposits that are just large enough to cover her payments. Since a Bitcoin transaction may have multiple outputs (see §4.1.2), this approach does not increase the amount of transactions placed onto the blockchain.

4.1.6 Payment.

Now that deposits have been associated with payment channels, *Alice* and *Bob* may perform payments.

When making a payment to *Bob*, *Alice* commits not to settle the channel at a state prior to the payment. She achieves this by issuing command **pay**, providing a channel ID and the amount to be transferred. If her balance is sufficient to perform the payment, her TEE (i) decreases *Alice*'s channel balance, (ii) confirms the payment, and (iii) and sends a commitment confirmation message to *Bob*'s TEE. Upon receiving this commitment message *Bob*'s TEE increases *Bob*'s channel balance by the provided value.

To avoid replay attacks, Teechain appends a strict monotonically increasing counter to each payment message. Both TEEs remember the counter value and reject any messages not incrementing the value. This prevents old payment messages from being replayed.

4.1.7 Deposit Dissociation.

At any point in time may *Alice* dissociate deposits the values of which have not been transferred via the channel. This frees the deposit and makes it usable in other payment channels. Deposit removal removes the collateral from the channel, precluding her from payments that require such collateral.

To dissociate a deposit, *Alice* issues a **dissociateDeposit** command, providing a channel ID and the deposit to dissociate. Her TEE then verifies whether dissociation is permissible, i.e. whether the value of the dissociated deposit does not exceed her current channel balance. If this is the case, the TEE sends a corresponding dissociatedDeposit to *Bob*'s TEE. *Bob*'s TEE then also verifies whether the dissociation is permissible, and, upon success, dissociates the specified deposit. It also discards the Bitcoin private key that was used to spend the deposit, as it is no longer needed to settle the channel. Upon success, *Bob*'s TEE replies to *Alice*'s TEE with a dissociatedDepositAck confirmation message. *Alice*'s TEE will then free the deposit, thereby reducing *Alice*'s channel balance and making the deposit available for association with other channels.

Similar to deposit association, deposit dissociation may be performed at any point in time while the payment channel is open.

4.1.8 Payment Channel Settlement.

Either party may settle the channel according to its current state at any point in time. Depending on the parties' balances in the payment channel, the TEE will generate and return a settlement transaction that redistributes the current balances into the addresses given at channel setup.

To settle the channel, *Alice* issues command **settle**, providing the ID of the channel to be settled. If the balances of the parties in the channel are equivalent to their deposits, that is, equivalent to no payments having been made, the channel can be terminated without needing to touch the blockchain. The deposits can simply be disassociated from the channel. Any payment channel in this state is termed a *neutral* payment channel because neither party has a surplus or deficit of funds according to their deposits. Otherwise, a settlement transaction is generated that sends the balances of the parties to their settlement addresses using all the deposits currently associated with the channel, and the corresponding private keys to spend from those deposits.

While there is no guarantee that a terminating message will be received by the other endpoint in a channel, this does not affect safety of the channels, only liveness. Eventually the endpoint that still believes the channel to be alive will either have their connection timeout, or will not receive acknowledgements for requests they send, and so will assume the other party to be offline, thus terminating the channel on-chain.

Similarly, there is no guarantee that the two endpoints will generate equivalent settlement transactions. It is possible for both endpoints to see different final states as one may terminate before the other. However, the differences in states is always acceptable to both parties. If one party terminates early, they cannot receive any incoming payments, and thus cannot attain more funds than approved by the opposite party.

4.2 Payment Routing

We now describe a protocol to route payments across multiple Teechain payment channels, allowing for the formation of *Teechain payment chains*. The idea is to allow parties to exchange payments even if they do not share network links, e.g. such as a merchant and a customer of an online marketplace. A payment chain is thus composed of at least two payment channels and we use the term *chain* when referring to the entire path across which a payment is being routed (e.g. $A \rightarrow B \rightarrow C \rightarrow D$). The process of finding routes

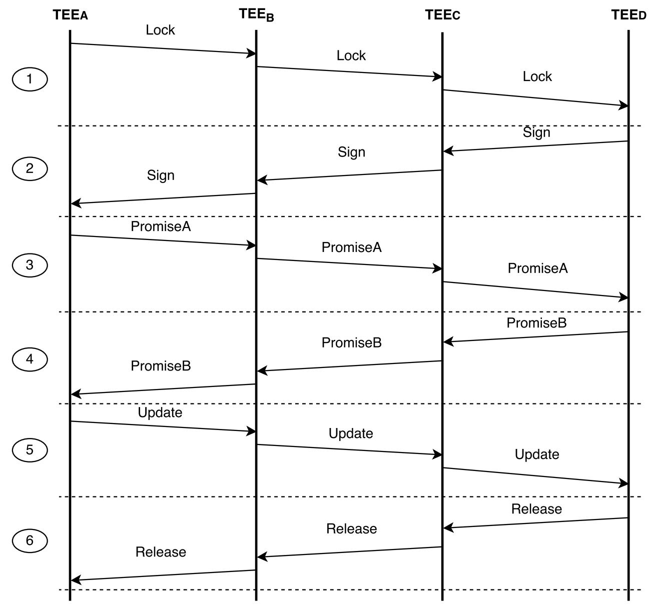


Figure 2: Chain Protocol Overview.

within the Teechain network is outside the scope of this work; we assume *Alice* to determine the path before initiating her payment.

For a node to trust the execution of the Teechain payment routing protocol, it must be sure that all nodes of the payment chain have been securely attested. Since Teechain remotely attests adjacent nodes inside the TEE (see §4.1.3), this trust relation is transitive: if *Alice*'s TEE attested that *Bob* is running genuine Teechain code inside a genuine TEE, then *Alice* can trust *Bob* to attest any other Teechain node prior to forming a payment channel. By transitivity, *Alice* can thus trust all nodes within the Teechain network.

For *Alice* to route a payment to *Dave* via *Bob* and *Carol*, she issues command **routePayment**, providing (i) the amount of money to be sent and (ii) the public keys of all nodes along the path. Payment routing across this path then proceeds in six stages as visualized in Fig. 2 and detailed in the following. During the protocol, each node passes through all of those six stages. At any time during payment routing, any party may settle on of the channels and eject from the protocol. The resulting settlement transaction will depend on the phase of the protocol that the settling TEE is in.

(1) ***locked*: Obtaining locks.** The goal of the first stage is to lock the states of all payment channels in the payment chain. For this, the payment initiator's TEE starts by sending a lock message along the set of nodes involved in the payment chain. For each node, Teechain ensures that (i) the payment channel has sufficient funds to route the payment (see §4.1) and that (ii) the payment channel is currently idle, i.e. that no other payments are currently being made along that channel. If this is the case for all involved channels, Teechain locks the corresponding channel for payment routing.

Starting from the second node in the chain, the nodes further compose the chain settlement transaction chainSettleTx—a single Bitcoin transaction that settles the state of all channels in the payment chain according to the post-payment state. That is, the state of the channels after the payment has been successfully routed along the chain. To compose this settlement transaction, each node adds the input and output transactions that are required to settle the channel associated with that node. Upon reaching the last node of the chain, the settlement transaction has been composed and all nodes are locked to perform the payment routing.

(2) ***signed*: Signing the settlement transaction.** The last node then starts the second phase, the goal of which is to have the settlement transaction chainSettleTx signed by all nodes. The last node starts by signing chainSettleTx and sending a corresponding sign message along the chain towards the payment initiator. Eventually the initiator will receive and sign the settlement transaction chainSettleTx, thus (i) obtaining the settlement transaction *signedChainSettleTx* that was signed by all nodes within the payment chain and (ii) starting the third phase of the protocol.

(3) ***promiseA*: Promise to not settle pre-payment.** The third phase obtains a promise from all nodes to not settle their channel's pre-payment state, i.e. the state of the channel before the payment to be routed has been settled. The purpose of this phase is to distribute the signed transaction *signedChainSettleTx* to all nodes in the chain, allowing them to ensure that should they eject from the protocol after this point, they can do so without violating consistency with the rest of the nodes. Specifically, each node promises to (i) only eject from the protocol by placing the signed settlement transaction *signedChainSettleTx* onto the blockchain, and to (ii) only settle its individual channel in the pre-payment state if another node has placed a transaction settling its local channel in the pre-payment state. We call this phase promiseA. As with the earlier phases, the promise transitively propagates through the payment chain: starting from the initiator, each node makes the above promise to its successor node. The involved nodes' TEEs will enforce the promise upon ejection of a node. Once the last node committed to this promise, it starts the fourth phase.

(4) ***promiseB*: Promise to correctly settle post-payment.** Once all nodes promised to not settle their pre-payment channel state, they update their internal channel balances to reflect the post-payment state, i.e. the channels' states after the payment to be routed has been performed. Further, all nodes promise to (i) only eject from the protocol by placing settlement transaction *signedChainSettleTx* onto the blockchain, and to (ii) only settle their individual channels in the post-payment state iff another node has placed a transaction settling its local channel in the post-payment state. We call this stage promiseB. Yet again, this promise is propagated through all nodes of the payment chain.

Once this phase completed, the initiator node knows that all nodes in the chain have updated their channel state to the post-payment state and can only eject from the protocol by placing settlement transaction *signedChainSettleTx* onto the blockchain.

(5) update: State Update. Starting from the initiator node, each node then deletes their copy of *signedChainSettleTx* and undoes the promiseB commitment. This allows each node to settle their own channel in the post-payment state. Once this phase is complete, the last node knows that all nodes in the chain have updated their channels to the post-payment channel state and deleted *signedChainSettleTx*.

(6) Lock release. Going backward along the chain, each node that is notified by its successor releases the channel lock with that node for other uses, such as routing additional payments, and switches back to the idle state. This completes the payment routing.

Discussion. Locking payment channels along the payment chain is necessary to prevent interference with other payments. Note, however, that any pair of Teechain participants may open multiple payment channels along a single network channel. Therefore, while payment routing is in progress, *Alice* and *Bob* may thus open additional payment channels as detailed in §4.1.4 to avoid contention, and either exchange payments directly or route other payments in parallel.

§5.2 analyses how the Teechain payment routing protocol always achieves agreement across all nodes of the payment chain.

4.3 Off-chain Channel Termination

Payment channels can be terminated either *on-chain*, by placing a settlement transaction on the blockchain, or *off-chain*, i.e. without placing any transaction on the blockchain. In Teechain, terminating channels off-chain comes with the benefit that the funds become available immediately and can be used for future payments. In addition, off-chain termination reduces the amount of transactions that must be placed onto the blockchain as well as the amount of collateral that needs to be held in the Teechain network.

Teechain is able to terminate channels off-chain if two nodes of the Teechain network share at least two *payment paths*, i.e. either payment channels or payment chains. In such a case, Teechain achieves off-chain channel termination by (i) merging the states of multiple payment paths into one single payment path and (ii) dissociating all possible deposits wherever possible. We hereby exploit two features of the Teechain network: (i) the ability to create 'payment cycles', more than one payment path between two nodes; and (ii) the ability to close *neutral* payment channels (see §4.1.8) off-chain by simply disassociating all deposits.

Fig. 3 illustrates merging of two payment paths between *Alice* and *Bob*: path 1 (p_1) is a direct payment channel between *Alice* and *Bob* ($A \to B$), while path 2 (p_2) is a payment chain between *Alice* and *Bob* via *Carol* and *Dave* ($B \to D \to C \to A$). Together p_1 and p_2 form a cycle in the Teechain network.

If *Alice* wishes to close p_1 off-chain, she can do so by moving any fund deficit, or surplus, from p_1 to p_2, assuming that there are sufficient funds in the payment path p_2 to allow the surplus/deficit to be routed (see §4.2). This shifting of funds turns payment path p_1 into a neutral payment channel, that can then be terminated off-chain as described in §4.1.8. For example, if *Alice* has a surplus of X bitcoins in p_1, i.e.*Bob* sent her X bitcoins and she made no payments back, she can set p_1 to a neutral state by sending X bitcoins to herself through the cycle of p_1 followed by p_2 (i.e. $A \to B \to D \to C \to A$). She can then terminate the payment channel $A \to B$ off-chain.

4.4 Fault Tolerance

Teechain provides strong security guarantees by having TEEs manage and maintain all funds held in the network. Despite the advantages this provides, this makes Teechain sensitive to TEE crash failures: in case of a TEE crash, any funds held are permanently lost because only the TEE contains the private keys to spend those funds. To avoid such permanent loss of funds, Teechain offers two fault tolerance strategies depending on the deployment scenario:

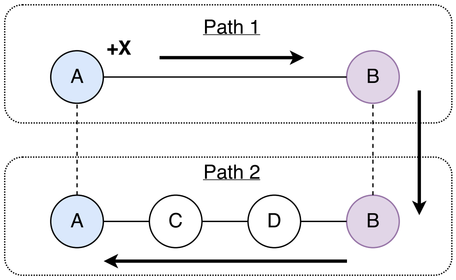


Figure 3: Settling a balance off-chain by moving the difference from one channel path to another.

If Teechain is deployed in an end user environment, where payments happen infrequently, i.e. in the order of magnitude of a dozen payments per minute, Teechain achieves fault tolerance against TEE failures by persisting the TEE internal state to disk as detailed in §4.4.1. In case of a TEE failure, the persisted state can then be restored and appropriate funds made re-accessible.

If Teechain is deployed in an environment with the goal of achieveing high-frequency and low-latency transactions, persisting to disk is not an option due to the current limitations of available TEE hardware monotonic counters. We argue then that it is reasonable to deploy multiple TEEs in independent failure domains, i.e. data centers. Teechain then achieves fault tolerance by replicating the TEE internal state to multiple TEE replica in different failure domains as detailed in §4.4.2. The locked funds can then be reliably retrieved as long as at least one replica survives.

4.4.1 Persistent Storage.

When persisting the TEE's state to disk, Teechain must take special care to avoid rollback attacks [26, 38]: upon TEE failure and subsequent state recovery, an attacker might present the TEE with a stale state with the goal to, e.g., revoke previous payments. Teechain thus uses (i) hardware monotonic counters [21] and (ii) secure data sealing [2] whenever persisting the TEE's state: encryption and digital signatures ensure the confidentiality and integrity of the persisted data, while hardware monotonic counters prevent rollback attacks. The end user may further use RAID technology or auto-backup solutions such as Dropbox to resist disk failures.

Concretely, Teechain persists the TEE's state as follows. Whenever a payment is to be sent or whenever a payment is received, Teechain first increments the hardware monotonic counter and waits for the TEE's state to be securely written to disk. Only after receiving a corresponding acknowledgement will Teechain send the payment to the remote TEE or reflect the incoming payment within the local TEE. This prevents users from rolling back any payments by crashing their TEE. With current monotonic counter implementations, which throttle monotonic counter increments to approx. 10 per second [26, 38], this fault tolerance strategy is able to scale up to 10tx/sec—a value that we reckon sufficient for end users and most small businesses.

4.4.2 TEE State Replication: Backup Chains.

The above fault tolerance strategy does not scale in the presence of high-frequency and low-latency transactions. Teechain thus also provides a fault tolerance strategy that avoids hardware monotonic counters and instead replicates the *primary* TEE's state to remote TEEs, i.e. *backup* Teechain instances that are ideally located in different failure domains. The role of a backup is to replicate the state of the primary, offering the ability to settle any channels or release deposits, should the primary fail.

Teechain organizes backup nodes in the form of chains: for each Teechain TEE—either primary or backup—, the user is able to dynamically add or remove a single backup TEE at runtime. Upon adding a backup, Teechain will perform a remote attestation procedure as described in §4.1.3. It then achieves fault tolerance as follows. Whenever a primary TEE sends an outgoing payment or receives an incoming payment, it first contacts its backup TEE to replicate the new state. This backup may, in turn, first contact its own backup for the same matter. This continues all the way to a TEE that doesn't have a backup. After receiving a state update acknowledgement from its backup, the primary knows that all backups have been updated and can then proceed to either send the payment or process an incoming one.

In addition, Teechain also offers the ability to perform asynchronous state replication to backup nodes on incoming payments. In the case that a Teechain node receives many incoming payments, the rate at which Teechain state is replicated to backup nodes can be configured by each user, allowing them to maintain a bounded amount of money that is not replicated. This trades off fault-tolerance for the benefit of improved latencies when processing incoming payments. Note however, that this is doesn't affect the safety of the protocol; any attempted rollback attack here could only lose money.

5 SECURITY

We first discuss how Teechain mitigates potential attacks (§5.1) and then analyze the chain and channel protocols (§5.2).

5.1 Attacks and Mitigation Strategies

We proceed by discussing how Teechain secures any assets and resources within the Teechain network. While we exploit the security guarantees of TEEs (see §2.2), attackers may still drop, send, record, modify, and replay arbitrary messages at any time during protocol execution. They may further try to misuse any information available to them outside of the TEE, e.g. persistently stored backups of the TEE-internal state. Note that any external adversary, such as an attacker who has compromised the network, has fewer privileges than any legitimate Teechain participant and can thus be subsumed by a malicious Teechain participant.

Remote Attestation and Transitive Trust. As detailed in §4.1.3 and §4.2, Teechain attests remote TEEs before setting up any payment channels. By performing remote attestation inside the TEE, Teechain ensures that all TEEs of the Teechain network run genuine Teechain code within genuine TEEs. With this, Teechain achieves transitive trust relationships and precludes bad backup chains or colluding parties across payment chains.

Data and Message Confidentiality and Integrity. Teechain protects the confidentiality and integrity of any sensitive data by only ever maintaining it in the clear inside the TEEs. This data includes Bitcoin addresses, their associated public and private keys, payments between Teechain participants, channel balances, as well as any other parts of the TEE-internal state. When any sensitive data, such as payment information, must be communicated between TEEs, it is only ever communicated over the secure communication channels established during remote attestation. Teechain further uses cryptographic signatures to verify the integrity of messages.

Payment Message Freshness. Teechain protects all point-to-point payments in a channel (§4.1) against replay attacks by enriching each message with a fresh value obtained from a TEE-internal strictly monotonic counter. To protect payments across chains (§4.2), the payment initiator securely generates a nonce for each protocol round-trip. This nonce is then used by all TEEs along the payment chain and verified upon receiving responses. Teechain protects any other messages between two TEEs in the same manner, i.e. by including nonces whenever messages require acknowledgements.

Security of Deposits and Payments. Teechain safeguards from TEE crashes by providing two different fault tolerance strategies (§4.4). Due to the volatile nature of TEEs, accidental crashes might result in the indefinite loss of funds. By exploiting hardware monotonic counters in persistent storage, and chain replication, users are able to recover crashed states, obtain settlement transactions for open payment channels, and release all unused deposits.

Freshness of Persistent TEE State Backups. Teechain prevents attackers from replaying stale backups that have been created as part of Teechain's fault tolerance strategy (§4.4.1). Whenever a Teechain TEE stores the TEE-internal state to stable storage, it protects the content using encryption, a cryptographic signature, as well as a monotonic counter beimg maintained by the TEE hardware. Upon restoring a backed up state, the TEE verifies that the backup's counter value corresponds to the current value of its monotonic hardware counter, thus ensuring that only the most recent state is being loaded.

Honesty of TEE Backup Replica. Attackers may try to misuse state replica (§4.4.2), i.e. backup TEEs, to obtain, e.g., settlement transactions while spending the same funds on a payment channel from within the primary TEE. Teechain prevents such attacks by requiring the backup TEEs' acknowledgements before triggering any TEE-internal state change. As a consequence, and because also backup TEEs are remotely attested, any such attacks will result in state violations either within the primary or within the backup TEE—thus being unable to spend the same funds more than once.

Reliance on Host System. Even though TEEs provide security guarantees, the correct functional operation of Teechain relies on services provided by the untrusted hardware, operating system, and network. For example, at any point in time the operating system might provide incorrect results through system calls, decide not to further execute the Teechain TEE, or not to deliver network messages in either direction. While the security of Teechain is not affected by any such malicious behaviour, single Teechain instances might be subject to denial of service attacks. The fault tolerance provided by Teechain ensures that no funds can be stolen in the presence of such attacks. In case the Teechain TEE is provided with meaningless system call results or network messages, the most secure mitigation strategy is to immediately terminate any open payment channels.

5.2 Protocol Analysis

We discuss here the security of the channel (§5.2.1) and chain protocols (§5.2.2).

5.2.1 Channel. We discuss the security of the channel protocol, showing that, at any point of the execution, a participant Alice with a channel with Bob can claim at least her channel balance with asynchronous access to the underlying blockchain.

The balance on the channel is backed by deposit transactions placed by the parties. For every deposit associated with the channel at a given time, Alice either created it or has approved it, given the commitment from Bob. Moreover, Alice did not approve the dissociation of the deposit. Therefore, Bob's enclave has not issued a transaction that spends the deposit before association, and has not done so since, as the deposit is still associated to the channel.

For every payment made to Bob, Alice deducts the amount from the channel balance, and for every payment received from Bob, Alice increments the balance by that amount. At that time, Alice can generate a transaction that terminates the channel, send it to the blockchain and have it eventually (due to asynchrony) placed in the blockchain, unless Bob has already placed a transaction that spends the deposits. It remains to show that in this latter case Alice receives at least the amount she expects according to her record of the balance. And indeed, for every payment made from Bob, Alice is guaranteed that his enclave updated its record of the balance with that amount. Bob might not have delivered all of Alice's payments to his enclave, but that only distorts his balance record in Alice's favor.

5.2.2 Chain. We now discuss the security of the chain payment protocol, showing that it settles all channels of the payment chain consistently. More precisely, we show that for every finite execution of the Teechain payment routing protocol (see §4.2 and Fig. 2), every node p either (i) agrees with both its neighbours on the new state, or (ii) settles on the network such that both its channels with both its neighbours are consistently settled in either pre-payment or post-payment state of the entire chain.

Stage: idle. At any given point in time, if p is in stage idle then all other nodes of the chain are either in stage idle or locked. In both cases, p and all other nodes can only obtain the pre-payment local settlement transactions from their enclave, which will subsequently stop the protocol and not produce any other payments or transactions.

Stage: locked. If p is in stage locked, all other nodes are either (i) some in stage idle and some in stage locked, or (ii) some in stage locked and some in stage signed. In both cases, all nodes can only settle their local chains at the pre-payment state (Alg. 4, line 58). If only one node does so, p can settle the other side by calling **eject**. The node can also do so voluntarily if it suspects that the other nodes prevent progress.

Stage: signed. If p is in stage signed, all other nodes are either (i) some in stage locked and some in stage signed, or (ii) some in stage signed and some in stage promiseA.

Case (i). If a node in the locked stage ejects, it settles its local channels in the pre-payment state. It will subsequently block the behavior of the protocol and no node will reach the promiseA stage. Node p can then eject as well (observing the settlement of one of its channels or voluntarily), resulting in a pre-payment settlement of its local channels (Alg. 4, line 58). If a node at the signed stage ejects, it also settles a local channel at the pre-payment state, and the conclusion is as before for p.

Case (ii). A node in the promiseA stage might choose to eject with the global post-payment settlement transaction. In this case, both of p's channels will also be settled in the post-payment state.

Stage: promiseA. If p is in stage promiseA, all other nodes are either (i) some in stage signed and some in stage promiseA, or (ii) some in stage promiseA and some in stage promiseB.

Case (i). Any of the nodes in stage signed can choose to eject by settling any of the chain channels in the pre-payment state. In this case, node p can call eject, present its enclave with the single-channel settling transaction, obtain settlement transactions for both its channels, and settle them at the pre-payment state. Node p can also voluntarily eject and obtain the chain settlement transaction. Placing this transaction in the blockchain will only fail if one of the channels was already settled, in which case node p can present its enclave with the channel settlement transaction and obtain settlement transactions for its channels as above.

Case (ii). Any nodes in the promiseA stage and promiseB stage can eject and settle the chain at post-payment state. If nodes have reached promiseB, then all nodes passed stage signed, therefore none can generate local settlements.

Stage: promiseB. If p is in stage promiseB, all other nodes are either (i) some in stage promiseA and some in stage promiseB, or (ii) some in stage promiseB and some in stage update.

Case (i). Any nodes in the promiseA stage and promiseB stage can eject and settle the chain at post-payment state. None can generate local settlements.

Case (ii). Nodes in update have updated their channels and can only settle their local channels at post-payment state. Node p can present its enclave with the single-channel settling transaction, obtain settlement transactions for both its channels, and terminate its channels.

Stage: update. If p is in stage update, all other nodes are either (i) some in stage promiseB and some in stage update, or (ii) some in stage update and some in stage idle.

Case (i). Nodes in the promiseB stage can only voluntarily settle the entire chain. Nodes in stage update can settle their local channels at post-payment, and node p can do the same.

Case (ii). Nodes in the update and idle can only settle their local channels at post-payment, and node p can do the same.

Stage: idle. Finally, when node p returns to the idle stage, all other nodes are either all idle, or some are in stage promiseB. In both cases, the nodes can only settle their local channels at the post-payment state.

6 PERFORMANCE EVALUATION

We implement Teechain and evaluate its performance in a realistic environment with nodes in the US and in Europe. We compare Teechain against the open-source Lightning Network implementation [25], one of the most mature implementations of off-chain payment channels. We discuss the implementation in §6.1, our experimental setup in §6.2 and performance measurements in §6.3.

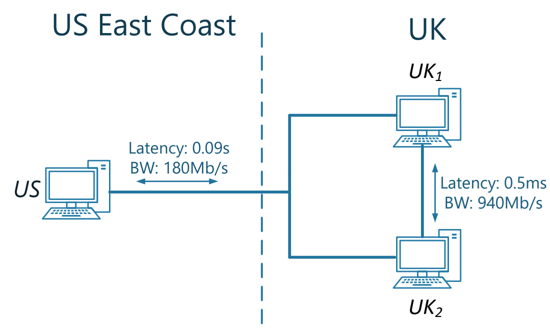


Figure 4: Average latency and bandwidth between the machines used to evaluate performance.

6.1 Teechain Implementation

We implement Teechain on Intel SGX. Intel SGX provides secure TEEs offering both execution integrity and confidentiality against an attacker on the same machine, even one with physical access. We use the Intel SGX SDK v1.7 [18] for Linux and port a subset of Bitcoin Core [39] to an Intel SGX enclave. Only several features of Bitcoin core are required: (i) Bitcoin address generation; (ii) transaction creation; (iii) transaction signing; and (iv) signature verification. Teechain consists of 77,000 lines of trusted C/C++ code inside the enclave, and 5,000 lines of untrusted code. We deactivate hyper-threading and compile the applications using GCC 5.4.0 with -O2 optimizations for all experiments.

For fault tolerance, Teechain uses both chain replication and persistent storage as described in §4.4.1. Since at the time of writing the Intel SGX SDK for Linux does not provide hardware monotonic counter support [18], we emulate it by waiting 100ms —the latency reported in microbenchmarks of the Windows SDK [26, 38].

6.2 Experimental Setup

We evaluate the performance of Teechain on three SGX-enabled machines, two in the UK and one on the US East Coast (Fig. 4). The two machines in the UK (UK_1 and UK_2) each consist of an Intel Xeon E3-1280 v5 with 64GB memory. The machine in the US (*US*), operates an Intel i7-6700K with 32GB memory. All machines run Ubuntu 16.04.2 LTS. UK_1 and UK_2 are in the same cluster, and are connected by a network link with an average round trip time (RTT) of 0.5ms and a bandwidth of 1Gb/sec. Communication between the US and the UK machines is done via SSH-tunnelling, across a network with an average measured latency of about 90ms (RTT) and an average bandwidth of 170MB/sec from the UK to the US and 200MB/sec from the US to the UK.

We compare Teechain with the Lightning Network Daemon (LND) [25], an implementation of a Lightning Network node. We communication with the LND node via its *gRPC* interface.

Blockchain synchronization. We measure the performance of off-chain payment channels, i.e. without access to the blockchain.

Measuring blockchain access times is orthogonal to our approach. In addition, blockchain write latencies depend on parameters inherent to the blockchain implementation, e.g. tens of minutes for Bitcoin; read latencies depend on individual implementations, e.g. operating an in-memory store of the blockchain, or contacting an external API. In Teechain, access to the blockchain is only required to create deposits or settle channels. Sending, receiving and routing of payments, as well as the creation of payment channels and chains do not require blockchain access.

For LND we avoid access to the public operational blockchain by using a private blockchain that resides in the local memory of each machine and that is not connected to the operational one. LND requires asynchronously checking the blockchain to ensure that no previously invalidated state has been pushed. However, these accesses do not interfere with payments. Nevertheless, we minimize these additional overheads as much as possible by running a BTCD [6] Bitcoin blockchain client locally at each node, thus operating a privately shared and minimal blockchain.

6.3 Performance

To evaluate the performance of Teechain, we measure throughput and latency of payment channels and payment chains. To understand the performance impact of fault tolerance, we further perform experiments where Teechain nodes use either persistent storage or chain replication.

We define *throughput* to be the maximum number of transactions sent on a channel or a chain per second. To measure the throughput, we send x payments to the counterparty and measure the time Δ_t from the initiation of the first payment until the receipt of the x-th acknowledgement. We vary the number of payments and the slope of the linear regression of x over Δ_t is the throughput. We define *latency* to be the time measured from the moment a payment is issued until the acknowledgement for that payment is received.

6.3.1 Payment channel performance. When comparing the performance of the Lightning Network to Teechain, there are three notable differences that need to be taken into account. First, payments in the Lightning Network protocol (LN) require two round trips in order to complete, as opposed to Teechain that requires only one. Second, in LN a payment cannot be sent until the previous payment has been completed, as opposed to Teechain, where payments can be sent concurrently. Finally, the LND implementation batches payment orders at the sender's side and sends a single payment that summarises the funds exchanged in the batch. The batch is sent after every ten payment orders or at an interval of 50ms—whatever happens first.

To test the throughput and latency of Teechain and LND, we construct a payment channel between *US* and UK_2 and measure the performance. We repeat each experiment 10–20 times. The results are shown in Tab. 1.

On a channel between UK_1 and *US* without fault tolerance, Teechain achieves an average throughput of 111, 000tx/sec, and a latency of 86ms. The measured latency is similar to the raw channel's latency, as only one single message is needed per payment. This represents two orders of magnitude throughput improvement compared to LND (1, 000tx/sec) and over 4*x* better latency (387ms for LND), due to the limitations of LN listed above.

Single Channel	Throughput (txs)		Latency (ms	± stddev)
Lightning Network	1,000	(R^2 = 0.972)	387	± 31
Teechain				
No fault tolerance	111,000	(R^2 = 0.973)	86	± 4.4
Chain replication	33,000	(R^2 = 0.910)	123	± 1.2
Persistent storage	9.9	(R^2 = 1.00)	185	± 0.3
Remote attestation and channel creation	N/A		2,010	± 420

Table 1: Throughput and latency of a single payment channel.

Adding chain replica for fault tolerance, we evaluate a payment channel from UK_1 to *US*, while using UK_2 as a backup node for UK_1. We further set up a payment channel between UK_1 and UK_2, using *US* as a backup for UK_1. In both cases, the average latency is 123ms due to the additional communication with the backup nodes; we achieve an average throughput of 33, 000tx/sec.

To evaluate the effect of persistent storage for fault tolerance, we activate the functionality on both UK_1 and *US* and send transactions from UK_1 to *US*. As expected, performance is capped by the hardware counter's latency of 100ms per update, resulting in a throughput of about 10tx/sec and a latency increase of around 100ms when compared with the results without fault tolerance.

Lastly, we measure the time that it takes to create a secure network link and payment channel between UK_1 and *US*. Our measurements show that this takes around two seconds as a result of performing a Diffie-Hellman key exchange, contacting the IAS for remote attestation and initializing the payment channel state.

6.3.2 Payment chain performance. Next, we measure the latency for a three-step payment chain: $UK_1 \rightarrow US \rightarrow UK_2$. Results are reported in Tab. 2. In this measurement, LND outperforms Teechain: while Teechain takes 2.28sec to perform the payment, LND takes 0.91sec.

The reason is that Teechain requires three round trips between UK_1 and UK_2 in order to complete a payment (see §4.2), while LN requires only 1.5 round trips.

When all nodes in the chain employ persistent storage for fault tolerance, latency increases as a function of the number of times each node must update its monotonic counters. In this case, UK_1 and UK_2 both increment their monotonic counters three times, once for every two stages of the routing protocol because they are nodes on the edges of the chain. The *US* increments its monotonic counter six times. This increases the latency by around 0.9sec, resulting in a total payment latency of 3.5sec.

We observe similar results when employing backup replica for fault tolerance. The latency becomes a function of the additional RTTs, as each node must wait for its replica to acknowledge the state updates. In this experiment, we use the *US* to act as backup for the UK_1 and UK_2 and vice versa. We observe the additional latencies across the Atlantic when replicating state. Since the RTT is slightly less than the 100ms required by the hardware counters, the observed overall latency is slightly smaller.

Two Channels (Chain)	Latency (sec ± stddev)	
Lightning Network	0.91	± 0.115
Teechain		
No fault tolerance	2.28	± 0.10
Chain replication	3.3	± 0.15
Persistent storage	3.5	± 0.11
$UK_1 \rightarrow UK_2$ with chain replication	0.22	± 0.05

Table 2: Throughput and latency of a payment chain.

When routing payments across payment chains, Teechain is predominantly bound by the network latencies between nodes. The total time to route a payment increases linearly with the nodes in the payment chain. The overheads of our implementation are minimal when compared to those of the network. To compare these cost we also routed payments between the two UK machines having minimal network latencies. We assigned both machines two backup replica each, themselves and the other machine, resulting in six Teechain nodes overall. We routed a payment across two channels, back and forth between the machines. The time to route the payment was 0.22sec—only 10 % of the time taken to route the payment across the Atlantic. In fact, we found that routing a payment across 10 channels back and forth between the two machines took only 0.41sec. Comparing these to the results across the Atlantic presented above, network latencies far outweigh those of the implementation.

7 RELATED WORK

Direct payments were first proposed by Chaum [10] to achieve privacy in ecash. However, early ecash guarantees are significantly weaker than those offered by payment channels. Mainly, cheating is enforced in retrospect through external punishment mechanisms.

Several proposals address the performance issues of the Bitcoin network and blockchain protocols, from the GHOST protocol and alternatives to the chain structure [24, 37, 42], to alternative block generation techniques [14, 23, 31]. Others [7, 27, 28] build on classical consensus protocols [9] or operate in permissioned settings. While they all improve on the Nakamoto blockchain performance, none can reach the performance offered by direct channels that do not require global system consensus for each transaction.

Unidirectional Bitcoin *micropayment channels* were first informally discussed by Hearn and Spilman [16]. These could not be deployed directly as they required changes to the Bitcoin protocol, unlike Teechain. Alternative proposals for unidirectional micropayment channels have been made to avoid these changes. However, all unidirectional payment channels only operate in a single direction and suffer from channel exhaustion.

Decker and Wattenhofer [11] were the first to realize duplex micropayment channels (DMC), improving the exhaustion limit. In DMC, two parties form a pair of channels, one in each direction, and re-balance them as needed, that is, when the credit in one direction is depleted but after there have been transactions in the opposite direction. However, the number of resets possible is limited at channel construction, depending on the time allotted for the refund timeout and the bound on the time to place a transaction on the blockchain. Therefore, the lifetimes of DMC payment channels are bounded and the total amount that can be sent on the channel in one direction is capped by the deposit amount times the maximal number of resets. DMC also requires changes to Bitcoin.

In Teechain, payment channel lifetimes are unbounded and there is no limit on the total amount moving in any direction. Additionally, Teechain places at most two transactions on the blockchain per payment channel. This is in contrast to DMC, which makes terminating transactions available after every individual payment. On disagreement, DMC places $1 + d + 2$ transactions on the blockchain, where d represents the invalidation tree's active branch.

Lightning Network (LN) [32] allows for unlimited reuse of its channels. Two parties form a series of transaction structures, in which each update invalidates the previous one. If a party tries to settle the channel on the blockchain with an invalidated state, its counterpart sees this transaction on the blockchain and can redirect all the deposited amount to itself. In this protocol, payments happen in a serial fashion, one at a time. Updating the balance takes about four message exchanges (from deciding on the new value to sending transaction signatures in a certain order). During these exchanges, no payments can be reliably made. In Teechain, a payment is done with a single message, and payments in both directions can be made concurrently. On disagreement, the Lightning Network places four transactions in the blockchain, while Teechain places only two.

Informal proposals have been sketched to deploy LN on the Bitcoin network without changes to the Bitcoin protocol [33]. However, these come with various limitations: a channel can only be funded by a single party and parties need to monitor the blockchain to react to invalidated states. This is not the case for Teechain, however, as both parties can deposit into a Teechain channel, and neither party ever controls a transaction that reflects an old state.

While Towncrier [47] was the first approach to use TEEs in the context of blockchains, its goal was to provide authenticated data feeds for smart contracts. As far as we are aware, Teechain is the first system to use TEEs to secure payment channels. In a public presentation [blinded] we presented preliminary results, however, without achieving asynchronous blockchain access, channel bootstrapping without blockchain access, and payment chains.

Van Renesse and Schneider [44] introduced chain replication achieving high availability and throughput for strong-consistency storage. Their solution allows read-access from any replica, making it resilient to failure of all but one server. While Teechain shares the goals of providing high throughput and availability in face of such failures, it also uses the structure of the chain to maintain security guarantees. As in storage chain replication reads, any server in the chain can be accessed to unilaterally terminate the payment channel. However, in Teechain such an operation, by design, irrevocably breaks the replication chain, as the operator now holds the capability to settle the channel at its current balance.

8 CONCLUSION

We presented Teechain, a TEE-based protocol for payment channels and chains with only asynchronous access to an underlying blockchain. We achieve Teechain's guarantees with a novel distributed protocol that separates each party's state between its TEE-protected environment and its unprotected environment.

Unlike previous solutions, Teechain can be directly deployed to the operational Bitcoin blockchain. Moreover, although our experiments were specific to the Bitcoin blockchain and to Intel SGX, the protocol is trivially adoptable to other blockchains and Intel SGX can be replaced with alternate TEE implementations.

Beyond the novelty of its asynchronous channel and chain protocols, Teechain provides quantitative improvements over existing solutions with orders of magnitude performance gains compared to the popular Lightning Network payment-channel implementation.

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A PSEUDOCODE

The single-chain pseudocode is shown in Algs. 1 and 2, and the pseudocode for chain payments is shown in Algs. 3 and 4

B PRACTICAL CONSIDERATIONS

Scalability of channel locks. The Teechain payment routing protocol makes use of channel locks. Locks do not prevent a party from settling their channels but rather from performing parallel payments on the same channel. This is necessary because a failure during the routing protocol requires all deposits to be spent upon channel termination. Attempting to lock only the in-flight payment by spending only part of the deposit and returning the rest to the TEE cannot be performed automatically due to the transaction malleability problem; it would require both parties in the payment channel to check the blockchain and provide their TEEs with the transaction IDs of the transactions that returned change to the TEEs.

To avoid this, Teechain takes an alternate approach: during payment routing it allows TEEs to create an arbitrary number of payment channels between any two Teechain nodes—as long as unused outputs to open additional channels are available. As a consequence, Teechain supports parallel payments between two nodes. In combination with the possibility to use multiple outputs of a single setup transaction on different channels, Teechain can dynamically create additional payment channels without the need for user intervention.

For example, assume *Alice* and *Bob* share an open payment channel, and that they have already approved a set of deposits for one another. Using any free and approved deposits, the two TEEs can create as many payment channels between the two TEEs as required in order to maintain an open and unlocked payment channel between the two parties at all times. This approach prevents bottlenecks at commonly used payment paths and can support the demand of routing payments concurrently across *Alice* and *Bob* concurrently. Once multiple payments have been successfully routed, Teechain can 'merge' all channels sharing the same endpoints and unlock any unused deposits.

This approach motivates an exponential distribution in the size of transaction outputs that are to be used as channel deposits (i.e. 2^x, $x \in \mathbb{N}$). The idea then is to use for each payment to be routed, the smallest unused output satisfying the request, thus locking as little funds as possible.

Reduced channel collateral and blockchain transactions. Teechain is able to reduce the collateral on payment channels by dynamically moving funds between channels as well as to and from the free deposit registry. This allows Teechain to operate with as little funds as possible. This approach is also facilitated by the use of single blockchain transactions with multiple outputs, whereby each output can be used as a separate fund. Note, however, that there is a trade-off between transaction output granularity and the space required on the blockchain: the smaller the transaction outputs, the more flexibility there is for associating funds with channels and reducing collateral; but, more outputs require more space on the blockchain.

Algorithm 1: Teechain Single-Channel Trusted Execution (1/2)

$(myPubKey, myPrivKey) \leftarrow$ generate public/private key pair for TEE
$\forall pubKey : networkChannel_{AESKey}(pubKey) = \perp$ (Stores the AES symmetric encryption key for each network channel)
$\forall channelID : channel_{theirPubKey}(channelID) = \perp$ (Stores the public key of the other TEE for each payment channel)
$\forall channelID : channel_{isOpen}(channelID) = False$
$\forall tx : allDeposits(tx) = \perp$ (Stores the transaction output of every deposit)
$\forall tx : freeDeposits(tx) = \perp$ (Stores the deposits that are not associated with any channelID)
$\forall pubKey : approvedDeposits(pubKey) = \perp$ (Stores the deposits that have been approved by a remote party)
$\forall btcAddress : bitcoinPrivateKeys(btcAddress) = \perp$ (Stores the Bitcoin private keys for each Bitcoin address)
$\forall channelID : channel_{myDeposits}(channelID) = \perp$
$\forall channelID : channel_{theirDeposits}(channelID) = \perp$
$\forall channelID : channel_{myBalance}(channelID) = \perp$
$\forall channelID : channel_{theirBalance}(channelID) = \perp$
$\forall channelID : channel_{myAddress}(channelID) = \perp$ (Stores my Bitcoin settlement address for the channel)
$\forall channelID : channel_{theirAddress}(channelID) = \perp$ (Stores their Bitcoin settlement address for the channel)

on newNetworkChannel(*theirPubKey*)
  assert $networkChannel_{AESKey}(theirPubKey) = \perp$
  $networkChannel_{AESKey}(theirPubKey) \leftarrow$
    perform remote attestation handshake and authenticated Diffie-Hellman using theirPubKey and generate symmetric AES encryption key (AESKey)

on newPaymentChannel(*channelID*, *theirPubKey*, *myAddr*, *theirAddr*)
  assert $channel_{theirPubKey}(channelID) = \perp$
  $channel_{theirPubKey}(channelID) \leftarrow theirPubKey$
  $channel_{myAddress}(channelID) \leftarrow myAddr$
  $channel_{theirAddress}(channelID) \leftarrow theirAddr$
  $channel_{myBalance}(channelID) \leftarrow 0$
  $channel_{theirBalance}(channelID) \leftarrow 0$
  $channel_{isOpen}(channelID) \leftarrow$ False
  return (NEWCHANNELACK, *channelID*, *myAddr*, *theirAddr*) signed using *myPrivKey* .

on receive (NEWCHANNELACK, *channelID*, *theirAddr*, *myAddr*) signed by private key for $channel_{theirPubKey}$ (*channelID*)
  assert $channel_{isOpen}(channelID) =$ False
  assert $channel_{myAddress}(channelID) = myAddr$
  assert $channel_{theirAddress}(channelID) = theirAddr$
  $channel_{isOpen}(channelID) \leftarrow$ True

on newAddr()
  (btcAddress,btcPrivateKey) $\leftarrow$ generate new Bitcoin address and private key
  $bitcoinPrivateKeys(btcAddress) \leftarrow btcPrivateKey$
  return *btcAddress*

on newDeposit(*txo*, *btcAddress*)
  assert *bitcoinPrivateKeys*(*btcAddress*) exists
  assert $txo \notin allDeposits$ (can't add same deposit twice)
  assert $txo.btcAddress == btcAddress$ (verify that txo is a transaction output sent to *btcAddress*)
  $allDeposits \leftarrow allDeposits \cup \{txo\}$
  $freeDeposits \leftarrow freeDeposits \cup \{txo\}$

on releaseDeposit(*txo*, *btcTargetAddress*)
  assert $txo \in freeDeposits$ (verify deposit is free)
  assert *bitcoinPrivateKeys*(*txo.btcAddress*) exists
  $tx \leftarrow$ generate transaction spending *txo* into *btcTargetAddress* using *bitcoinPrivateKeys*(*txo.btcAddress*)
  $freeDeposits \leftarrow freeDeposits \setminus \{txo\}$
  return *tx*

on approveMyDeposit(*theirPubKey*, *txo*)
  assert $networkChannel_{AESKey}(theirPubKey)$ exists (Verify a network channel exists between our TEE and the given TEE public key)
  assert $txo \in freeDeposits$
  assert $txo \notin approvedDeposits(theirPubKey)$ (Given deposit has not already been approved by the remote party)
  return (approveMyDeposit, *myPubKey*, *txo*) signed using *myPrivKey* (Alice sends this to Bob)

Algorithm 2: Teechain Single-Channel Trusted Execution (2/2)

on receive (approveMyDeposit, *theirPubKey*, *txo*) signed by corresponding *theirPrivKey* for given *theirPubKey*
    assert $networkChannel_{AESKey}(theirPubKey)$ exists (Verify a network channel exists between our TEE and the given TEE public key)
    assert $txo \notin approvedDeposits(theirPubKey)$ (Given deposit has not already been approved)
    Bob must verify that *txo* is indeed in the blockchain
    $approvedDeposits(theirPubKey) \leftarrow approvedDeposits(theirPubKey) \cup \{txo\}$
    return (approvedDeposit, *myPubKey*, *txo*) signed using *myPrivKey* (Bob sends this to Alice)

on receive(approvedDeposit, *theirPubKey*, *txo*)) signed by corresponding *theirPrivKey* for given *theirPubKey*
    assert $networkChannel_{AESKey}(theirPubKey)$ exists (Verify a network channel exists between our TEE and the given TEE public key)
    assert $txo \in freeDeposits$ (Given deposit is indeed free)
    assert $txo \notin approvedDeposits(theirPubKey)$ (Given deposit has not already been approved by the remote party)
    $approvedDeposits(theirPubKey) \leftarrow approvedDeposits(theirPubKey) \cup \{txo\}$

on associateMyDeposit(*channelID*, *txo*)
    assert $channel_{isOpen}(channelID)$ = True (Channel is open)
    assert $txo \in approvedDeposits(channel_{theirPubKey}(channelID))$ (Given deposit has been approved by the remote TEE)
    assert $txo \in freeDeposits$ (Given deposit is indeed free)
    $freeDeposits \leftarrow freeDeposits \setminus \{txo\}$
    $channel_{myDeposits}(channelID) \leftarrow channel_{myDeposits}(channelID) \cup \{txo\}$
    $channel_{myBalance}(channelID) \leftarrow channel_{myBalance}(channelID) + txo.amount$
    $theirPubKey \leftarrow channel_{theirPubKey}(channelID)$
    $encDepositPrivKey \leftarrow bitcoinPrivateKeys(txo.btcAddress)$ encrypted under $networkChannel_{AESKey}(theirPubKey)$ (Encrypt private key to spend txo)
    return (associatedDeposit, *txo*, *encDepositPrivKey*) signed using *myPrivKey* (Alice sends this to Bob)

on associateTheirDeposit(*channelID*, *txo*, *encDepositPrivKey*) signed by private key for $channel_{theirPubKey}$ (*channelID*)
    assert $channel_{isOpen}(channelID)$ = True (Channel is open)
    assert $txo \in approvedDeposits(channel_{theirPubKey}(channelID))$ (Given deposit has been approved by the remote TEE)
    $channel_{theirDeposits}(channelID) \leftarrow channel_{theirDeposits}(channelID) \cup \{txo\}$
    $channel_{theirBalance}(channelID) \leftarrow channel_{theirBalance}(channelID) + txo.amount$
    $theirPubKey \leftarrow channel_{theirPubKey}(channelID)$
    $depositPrivKey \leftarrow encDepositPrivKey$ decrypted under $networkChannel_{AESKey}(theirPubKey)$ (Decrypt private key to spend txo)
    $bitcoinPrivateKeys(txo.btcAddress) \leftarrow depositPrivKey$ (Store deposit private key for settlement)
on pay(*channelID*, *amount*)
    assert $channel_{myBalance}(channelID) \geq amount$
    $channel_{myBalance}(channelID) \leftarrow channel_{myBalance}(channelID) - amount$
    $channel_{theirBalance}(channelID) \leftarrow channel_{theirBalance}(channelID) + amount$
    return (paid, *channelID*, *amount*) signed using *myPrivKey*

on receive(paid, *channelID*, *amount*) signed by $channel_{theirPubKey}$ (*channelID*)
    $channel_{myBalance}(channelID) \leftarrow channel_{myBalance}(channelID) + amount$
    $channel_{theirBalance}(channelID) \leftarrow channel_{theirBalance}(channelID) - amount$

on dissociateDeposit(*channelID*, *txo*)
    assert $txo \in channel_{myDeposits}(channelID)$
    assert $channel_{myBalance}(channelID) \geq txo.amount$
    return (dissociatedDeposit, *channelID*, *txo*) signed using *myPrivKey* (Alice sends this to Bob)

on receive (dissociatedDeposit, *channelID*, *txo*) signed by private key for $channel_{theirPubKey}$ (*channelID*)
    assert $txo \in channel_{theirDeposits}(channelID)$
    assert $channel_{theirBalance}(channelID) \geq txo.amount$ (Deposit not used by Bob)
    $channel_{theirDeposits}(channelID) \leftarrow channel_{theirDeposits}(channelID) \setminus \{txo\}$
    $channel_{theirBalance}(channelID) \leftarrow channel_{theirBalance}(channelID) - txo$
    return (dissociatedDepositAck, *txo*) signed by *myPrivKey*

on receive (dissociatedDepositAck, *channelID*, *txo*) signed by private key for $channel_{theirPubKey}$ (*channelID*)
    $channel_{myDeposits}(pubKey) \leftarrow channel_{myDeposits}(pubKey) \setminus \{txo\}$
    $channel_{myBalance}(channelID) \leftarrow channel_{myBalance}(channelID) - txo.amount$
    $freeDeposits \leftarrow freeDeposits \cup \{txo\}$
    $bitcoinPrivateKeys(txo.btcAddress) \leftarrow \perp$ (Discard private key for transaction output)

on settle(*channelID*)
    if $channel_{myBalance}$ (*channelID*) and $channel_{theirBalance}$ (*channelID*) equals the sum of all deposit amounts respectively:
        Disassociate all deposits and close channel.
    otherwise $txSettle \leftarrow$ generate transaction spending:
        $channel_{myBalance}$ (*channelID*) into $channel_{myAddress}$ (*channelID*) and
        $channel_{theirBalance}$ (*channelID*) into $channel_{theirAddress}$ (*channelID*) using
        $channel_{myDeposits}(channelID)$, $channel_{theirDeposits}(channelID)$ & *bitcoinPrivateKeys(all deposits in channelID)*
    reset all corresponding *channelID* state.

Algorithm 3: Teechain Trusted Execution at node p_i (1/2)

signedChainSettleTx ← ⊥

on routePayment ($p_2, \ldots, p_n$, *amount*)
    assert $channel_{stage}(id(\langle p_1, p_2\rangle))$ = idle
    assert $channel_{myBalance}(id(\langle p_1, p_2\rangle)) \geq amount$
    send (lock, $(p_1, \ldots, p_n)$, chainSettleTx()) encrypted and signed for p_2

on receive (lock, $(p_1, \ldots, p_n)$, chainSettleTx($\langle p_1, p_2\rangle, \ldots, \langle p_{i-2}, p_{i-1}\rangle$)), encrypted and signed by p_{i-1}
    assert $channel_{stage}(id(\langle p_i, p_{i+1}\rangle))$ = idle
    if $i < n$ **then**
        $channel_{stage}(id(\langle p_i, p_{i+1}\rangle))$ ← locked
        send (lock, $(p_1, \ldots, p_n)$, chainSettleTx($\langle p_1, p_2\rangle, \ldots, \langle p_{i-1}, p_i\rangle$)) encrypted and signed for p_{i+1}
    else ($i == n$)
        $channel_{stage}(id(\langle p_{n-1}, p_n\rangle))$ ← signed
        send (sign, chainSettleTx($\langle p_1, p_2\rangle, \ldots, \langle p_{n-1}, \underline{p_n}\rangle$)) encrypted and signed for p_{n-1}

on receive (sign, chainSettleTx($\langle p_1, p_2\rangle, \ldots, \langle p_{i-1}, p_i\rangle, \langle p_i, \underline{p_{i+1}}\rangle, \ldots, \langle \underline{p_{n-1}}, \underline{p_n}\rangle$)), encrypted and signed by p_{i+1}
    assert $channel_{stage}(id(\langle p_i, p_{i+1}\rangle))$ = locked
    if $i > 1$ **then**
        $channel_{stage}(id(\langle p_i, p_{i+1}\rangle))$ ← signed
        send (sign, chainSettleTx($\langle p_1, p_2\rangle, \ldots, \langle p_{i-1}, \underline{p_i}\rangle, \langle \underline{p_i}, \underline{p_{i+1}}\rangle, \ldots, \langle \underline{p_{n-1}}, \underline{p_n}\rangle$)) encrypted and signed for p_{i-1}
    else ($i == 1$)
        signedChainSettleTx ← chainSettleTx($\langle \underline{p_1}, \underline{p_2}\rangle, \ldots, \langle \underline{p_{n-1}}, \underline{p_n}\rangle$)
        $channel_{stage}(id(\langle p_1, p_2\rangle))$ ← promiseA
        send (promiseA, *signedChainSettleTx*) encrypted and signed for p_2

on receive (promiseA, *signedTx*) encrypted and signed by p_{i-1}
    assert $channel_{stage}(id(\langle p_i, p_{i+1}\rangle))$ = signed
    signedChainSettleTx ← *signedTx*
    if $i < n$ **then**
        $channel_{stage}(id(\langle p_i, p_{i+1}\rangle))$ ← promiseA
        send (promiseA, *signedChainSettleTx*) encrypted and signed for p_{i+1}.
    else ($i == n$)
        $channel_{stage}(id(\langle p_{n-1}, p_n\rangle))$ ← promiseB
        send (promiseB) encrypted and signed for p_{n-1}

Algorithm 4: Teechain Trusted Execution at node p_i (2/2)

on receive (promiseB) encrypted and signed by p_{i+1}
  assert $channel_{stage}(id(\langle p_i, p_{i+1}\rangle))$ = promiseA
  if $i > 1$ **then**
    $channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) \leftarrow$ promiseB
    send (promiseB) encrypted and signed for p_{i-1}
  else ($i == 1$)
    signedChainSettleTx $\leftarrow \perp$
    $channel_{stage}(id(\langle p_1, p_2\rangle)) \leftarrow$ update
    send (update) encrypted and signed for p_2

on receive (update) encrypted and signed by p_{i-1}
  assert $channel_{stage}(id(\langle p_i, p_{i+1}\rangle))$ = promiseB
  if $i < n$ **then**
    signedChainSettleTx $\leftarrow \perp$
    $channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) \leftarrow$ update
    send (update) encrypted and signed for p_{i+1}.
  else ($i == n$)
    $channel_{stage}(id(\langle p_{n-1}, p_n\rangle)) \leftarrow$ idle
    send (release) encrypted and signed for p_{n-1}

on receive (release) encrypted and signed by p_{i-1}
  assert $channel_{stage}(id(\langle p_i, p_{i+1}\rangle))$ = update
  $channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) \leftarrow$ idle
  if $i > 1$ **then**
    send (release) encrypted and signed for p_{i-1}.

on eject
  if $channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) = locked \lor channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) = signed$ **then**
    $channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) \leftarrow$ terminated
    return pre-payment settlements for channels $\langle p_{i-1}, p_i\rangle$ and $\langle p_i, p_{i+1}\rangle$ (or just one if at end of chain)
  else if $channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) = promiseA$ **then**
    $channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) \leftarrow$ terminated
    if pre-payment transaction for any channel in the chain **then**
      return pre-payment settlements for channels $\langle p_{i-1}, p_i\rangle$ and $\langle p_i, p_{i+1}\rangle$ (or just one if at end of chain)
    else if post-payment transaction for any channel in the chain **then**
      return post-payment settlements for channels $\langle p_{i-1}, p_i\rangle$ and $\langle p_i, p_{i+1}\rangle$ (or just one if at end of chain)
    else
      return chainSettleTx
  else if $channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) = promiseB$ **then**
    $channel_{stage}(id(\langle p_i, p_{i+1}\rangle)) \leftarrow$ terminated
    if post-payment transaction for any channel in the chain **then**
      return post-payment settlements for channels $\langle p_{i-1}, p_i\rangle$ and $\langle p_i, p_{i+1}\rangle$ (or just one if at end of chain)
    else
      return chainSettleTx
  return local post-payment settlements