Wrapless book $_{v.0.3}$ book

Rarimo Protocol

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Notation

Let \mathbb{G} be a cyclic group of prime order p written additively, $G \in \mathbb{G}$ is the group generator. We define $a \in \mathbb{F}_p$ as a scalar value and $A \in \mathbb{G}$ as a group element. In this paper, we are referring to the ECC group with secp256k1 curve and all parameters defined in its specification [3].

We define a hash function as $H_{alg} : \{0,1\}^* \to \{0,1\}^n$, where alg is the used algorithm (usually we will refer to SHA-256 with n = 256 and RIPEMD-160 with n = 160). Additionally, we use a separate hash function with the field element output $H_{alg_F} : \{0,1\}^* \to \mathbb{F}_p$ (Poseidon [6], for instance).

Let sigGen_{alg} : $(m, sk) \to \sigma$ be signature generation function and sigVer_{alg} : $(m, P, \sigma) \to \{0, 1\}$ a signature verification function, where alg is a algorithm used, $m \in \mathbb{B}^*$ is the message, $sk \in \mathbb{F}_p$ and $P = sk \cdot G \in \mathbb{G}$ is a signer's key pair.

We define the relation for the proof π as $\mathcal{R} = \{(w; x) \in \mathcal{W} \times \mathcal{X} : \phi_1(w, x), \phi_2(w, x), \dots, \phi_m(w, x)\}$, where w is a witness data, x is a public data and $\phi_1(w, x), \phi_2(w, x), \dots, \phi_m(w, x)$ the set of relations must be proven simultaneously.

We will use a short notation for Bitcoin transactions as:

$$\mathsf{TX}\{(\mathsf{id},\mathsf{i},\mathsf{proof})^{(n)};(\mathsf{aB},\mathsf{cond})^{(m)}\}$$

with *n* inputs and *m* outputs, where id is the reference to the previous transaction, i - a corresponding output's index, proof – the list of data which is needed for transaction spending, a - the number of coins in the output, cond – scriptPubKey conditions.

To visualize the transaction details, we will use the following notation:

Inputs	Outputs	Output Script
$\begin{array}{llllllllllllllllllllllllllllllllllll$	a_0 B	OP_DUP OP_HASH160 OP_PUSHBYTES_20 <addr_a> OP_EQUALVERIFY OP_CHECKSIG (P2PKH with Alice's address)</addr_a>
	b_0 B	OP_HASH160 OP_PUSHBYTES_20 <hash> OP_EQUAL (P2SH with conditions com- mited by the hash)</hash>

For detailed visualization of spending conditions in Bitcoin Script [10], we would show colored boxes like these:

scriptSig:	$\langle \sigma_{a} angle$	// Push a signatures on stack
scriptPubKey:	$\langle P_{a} \rangle$ OP_CHECKSIG	<pre>// Push a public key on stack // Bitcoin Script opcode</pre>

Where **scriptPubKey** is the previous output's spending condition (also mentioned above as cond) and **scriptSig** (also proof) are values (or script) that satisfy a spending condition from **scriptPubKey**, in the current transaction input.

Idea Block

In blocks like this, we will include some side notes that are required for a deeper understanding of the further conclusions.

Chapter 1

Introduction

Now, there is only one action people can take with bitcoins in a trustless manner: transfer. Bitcoin's programmability is limited, which does not allow us to launch popular DeFi protocols that operate with native BTC. Therefore, the popular approach is to wrap bitcoins and utilize them within the existing DeFi infrastructure. The problem is that the existing wrapping mechanisms are either centralized or federated with m-of-n trust assumptions.

One way to program BTC behavior is through DLC contracts [5]. This method relies on the oracle, which, signing different data, can define the coins' spending path. The primary drawback of this approach is that the oracle serves as the trusted entity. Despite the oracle's inability to steal funds, it can manipulate the decision acceptance in favor of one of the parties.

There is massive potential in BitVM2 technology [13]. Still, it requires some updates to Bitcoin, such as the addition of OP_CTV [8] + OP_CSFS [11] or OP_CAT [9], to achieve a more reliable security model (better than 1-of-n) and decrease the operating cost.

This paper aims to design a **Wrapless** – a lending protocol that enables the collateralization of BTC without requiring a trusted wrapping mechanism. This paper describes a solution that enables locking BTC in the "loan channel" and providing a loan on another blockchain platform, such that the loan's installment (which can be partial) results in unlocking the corresponding amount of BTC.

The advantage of the Wrapless is that it doesn't rely on any trusted party and represents a game between the borrower and lender, where cheating by any party is economically irrational. The most significant limitation we observe is that the solution is peer-to-peer and does not facilitate liquidity aggregation.

Chapter 2

Preliminaries

Before diving into the Wrapless protocol, we recommend reviewing the technologies it is based on. If you are familiar with them, you can skip this section.

2.1 Merkle Trees

2.1.1 Merkle Tree Construction

A *Merkle Tree* [1] is a complete binary tree built from a sequence of data blocks, where each leaf encodes the hash of a block and each internal node is computed as the hash of the concatenation of its children. This construction enables efficient inclusion proofs with logarithmic complexity.

In Bitcoin, Merkle trees are used to commit to the list of transactions in a block. The Merkle root is included in the block header, allowing Simplified Payment Verification (SPV) clients to verify transaction inclusion using short proofs, without the need to download the full block. The Merkle tree is constructed as follows:

```
Algorithm 1 Merkle Tree Construction
Require: Transactions x_1, \ldots, x_n
Ensure: Merkle root y
 1: L \leftarrow [\mathsf{H}(x_1), \mathsf{H}(x_2), \dots, \mathsf{H}(x_n)]
 2: while |L| > 1 do
         if |L| is odd then
 3:
             Append L[-1] to L
                                                                                        \triangleright Duplicate last element
 4:
 5:
         end if
         L \leftarrow [\mathsf{H}(L_{2i}||L_{2i+1}) \mid i = 0, \dots, |L|/2 - 1]
 6:
 7: end while
 8: return L[0]
```

The Merkle root y serves as a commitment to the entire set of transactions. A Merkle proof consists of $\log_2 n$ sibling hashes and is sufficient to recompute the path to the root. Given a transaction x_i , Merkle root y' and a proof π_i for the leaf index i, the verifier:

- 1. Computes $H(x_i)$.
- 2. Iteratively hashes with the siblings in π_i up to the root y.
- 3. Accepts if the result equals y'.

A classic Merkle tree construction supports *inclusion proofs*, but does not provide efficient non-inclusion proofs since the structure does not encode which leaves are assigned. For non-inclusion proofs, we can use the SMT construction described below.

2.1.2 Sparse Merkle Tree

A Sparse Merkle Tree (SMT) [14] is a fixed-depth binary tree used to commit to a large but sparsely populated key-value map efficiently. Unlike classical Merkle trees, SMTs allow for efficient proofs of both inclusion and non-inclusion. They are particularly useful for storing finalized blockchain state, such as account balances or rollup commitments, where only a small subset of the entire key space is populated.

We define a default value \perp representing empty leaves. The SMT is constructed by inserting known (k, v) pairs into an otherwise empty tree of depth k.

Algorithm 2 Sparse Merkle Tree Construction **Require:** Map $M : \mathcal{K} \to \mathcal{V}$, depth k **Ensure:** Root hash r1: Initialize all 2^k leaves to $h(\perp)$ 2: for each $(key, value) \in M$ do 3: $p \leftarrow \text{binary path of } key$ $h_p \leftarrow \mathsf{H}(value)$ 4: for i = k - 1 down to 0 do 5: Combine child hashes to compute parent 6: 7: end for 8: end for 9: return root r

Each proof consists of the k sibling hashes along the path from a leaf to the root. For non-inclusion, the proof shows that the leaf is unassigned and the hash chain is consistent with default values. Given a root r and a proof π for key k, the verifier:

- 1. Computes the binary path of k and the expected hash of its value (or default).
- 2. Hashes upward using the siblings in π to reconstruct the root.
- 3. Accepts if the result equals r.

Because every leaf is implicitly defined (either with real data or a default), SMTs enable efficient proofs of both *inclusion* and *non-inclusion*.

2.2 SPV Contract

The SPV (Simplified Payment Verification) node concept, initially proposed in the Bitcoin whitepaper [2], allows the verification of Bitcoin transactions without the need to maintain a full node. Instead of downloading the entire blockchain, the SPV node only synchronizes block headers and their corresponding Merkle roots. This SPV approach enables the verification of transaction inclusion by performing Merkle proof verification, which relies on the integrity of the Merkle root stored in the block header.

It is possible to launch the SPV node as a smart contract. This contract allows a trustless synchronization of the entire Bitcoin history to the required blockchain. Such a property is quite helpful for cross-chain applications.

2.2.1 Block Header Validation Rules

When the SPV node is syncing with the Bitcoin network, it receives the block headers and verifies them according to the set of rules:

- 1. Structure validity and existence of all fields:
 - i) Version (4 bytes), Previous block (32 bytes), Merkle Root (32 bytes), Timestamp (4 bytes), Bits (4 bytes), Nonce (4 bytes).
- 2. Previous block hash correctness:

- i) Verifies that the block, the header of which was received, is part of the mainchain and refers to the existing previous block.
- 3. Timestamp:
 - i) Verifies if the timestamp value exceeds the median value of the previous 11 blocks. Additionally, the node does not accept blocks with timestamps more than two hours in the future.
- 4. PoW verification:
 - i) The block's header double hash (SHA256) value must satisfy the defined difficulty parameter (must be less than the target value).
 - ii) The difficulty target parameter is changed every 2016 blocks to adjust the block mining time for the current network hash rate. It does so by summing up the total number of minutes miners took to mine the last 2,015 blocks and dividing this number by the protocol's desired goal of 20,160 minutes (2,016 blocks x 10 minutes). The ratio is then multiplied by the current difficulty level to produce the new difficulty level.
 - iii) If the correction factor is greater than 4 (or less than 1/4), then 4 or 1/4 is used instead to prevent abrupt changes.
- 5. Nonce validation:
 - i) The hash value of the concatenation of all previous parts of the header with the nonce value must be equal to the block hash value (satisfy difficulty target parameter).

2.2.2 Transaction Inclusion Verification

For transaction verification, the SPV node requests the full node to return the proof of transaction inclusion in the block. As proof, in this case, the Merkle branch is being used, which must lead to the existing Merkle root, defined in one of the mainchain block headers. We will use the notation $\pi_{SPV}(TX)$ as an SPV proof that includes a block hash and an inclusion proof of transaction TX.

2.2.3 Reorganizations Management

When verifying the existence of a Bitcoin transaction, the SPV node must ensure that the block is included in the mainchain, which is the heaviest chain.

Finality in Bitcoin is probabilistic, which means the chain can always be reorganized. The SPV node must be able to switch to the alternative main chain if its total difficulty is greater.

2.2.4 Proposed SPV Contracts Architecture

The SPV contract serves as a storage for the Bitcoin block history. Similar to the SPV node, the SPV contract stores block headers provided by users and verifies their validity through a series of checks. Once a block header is successfully verified, it is stored within the contract, allowing other users to access the data with confidence in its correctness. The contract implements read methods to facilitate data retrieval, thereby ensuring a reliable source of verified Bitcoin transactions.

We propose the SPV contract architecture that allows for managing the depth parameter d – the length of the *confirmed* and *pending* chain:

- **Confirmed Chain**: the chain considered is final with a high probability. This chain can be reverted, but 1) random reorg can happen only in very rare cases (reorganization of the Bitcoin blockchain on the *n* last blocks); 2) the cost of the malicious reorg is very high.
- **Pending Chain**: consists of *n* last blocks that are not yet confirmed and have a higher probability of being replaced due to potential reorganization.

There are different mechanisms for processing confirmed and pending chains:

- Blocks of the confirmed chain represent the leaves of the Sparse Merkle Tree. Based on the root of SMT, it's possible to prove that some transactions are included in the confirmed chain (it's very helpful for privacy [12] and for the contract's storage compression).
- Blocks of the pending chain are stored in the form of a cache. It's possible to have several alternative blocks for the same height in the pending chain; some will be orphaned when the mainchain is defined.

Any user can propose a new block header to the SPV contract. The proposed block header undergoes validation to ensure that it:

- Has a valid structure
- References an existing previous block
- Satisfies the difficulty target

If all conditions are met, the block header is stored within the contract and becomes part of the mainchain if its total difficulty is the biggest.

As we mentioned, despite the high probability of blocks being confirmed, the possibility of chain reorganization persists. The SPV contract allows for updating the confirmed chain if a longer chain is presented, thereby ensuring consistency with the heaviest chain rule.

The SPV contract allows users to prove the existence of a transaction by providing $\pi_{SPV}(TX)$:

- $\bullet\,$ The transaction TX
- The block hash
- The Merkle branch leading to the root

Successful verification triggers predefined actions based on the provided proof.



2.2.5 Compressing of Bitcoin History with SNARKS

When we investigated the rationality of launching the SPV node, we found that synchronizing the entire chain from the genesis block is extremely expensive. An internal implementation of the SPV contract, which can be found here ¹, showed that the verification of one block header consumes around 130k gas.

 $^{^{1}} https://github.com/distributed-lab/spv-contracts/tree/master$

As of June 16, 2025, the cost of SPV synchronization on the Ethereum mainnet is approximately 775,300 USD.

We assume this cost can be reduced by replacing the verification of all blocks with a recursive proof up to a particular checkpoint (for example, having 900,000 blocks in total, we can prove 890,000 of them and then synchronize the remaining 10,000 as described above). In this case the contract initiator creates the proof $\pi_{\rm bh}$ for the following relation:

$$\begin{split} \mathcal{R}_{\mathsf{h}\mathsf{h}} &= \{\mathsf{header}^{n-1}; h_0, h_n : \\ &\forall i \in [1,n] : \\ &h_i \in \mathcal{H} \land \\ \mathsf{H}_{\mathsf{sha256}}(h_{i-1}) &= h_i.\mathsf{prev} \land \\ h_i.\mathsf{time} &\geq \mathsf{med}(\mathsf{h}_{i-11}, \dots, \mathsf{h}_{i-1}) \land \\ &\mathsf{H}_{\mathsf{sha256}}(h_i) < \mathsf{target}\} \end{split}$$

One project that tries to build an SPV STARK-based prover can be found here ². Our implementation of the PLONK-based SPV prover is currently in progress.

2.3 Payment Channels and Lightning Network

Payment channels [4] is a technology that allows counterparties to lock their funds and send instant payments within this channel without posting on-chain intermediate transactions. We will refer to the simplified payment channel construction to reuse it later for "loan channels" in Wrapless.

2.3.1 Funding Transaction

Assume we have two parties, Alice and Bob, who want to create a payment channel for sending funds between each other off-chain with $a\ddot{B}$ and $b\ddot{B}$ amounts respectively. For it, they cooperatively create what's so-called a "funding transaction" with the respective pair of keys:

$$sk_a \xleftarrow{R} \mathbb{F}_p, \quad \mathsf{P}_{\mathsf{a}} = sk_aG$$
$$sk_b \xleftarrow{R} \mathbb{F}_p, \quad \mathsf{P}_{\mathsf{b}} = sk_bG$$

To secure funds that can only be unlocked through mutual cooperation, payment channels utilize multisignatures. Depending on the version, this can be P2WSH or P2TR output. In case of P2WSH using ECDSA signatures and compressed public keys, the spending condition (scriptPubKey) and fulfilling witness (scriptSig) are:

scriptSig:	$\langle \sigma_a angle \; \langle \sigma_b angle$	// Push signatures to stack
scriptPubKey:	$\begin{array}{c} \langle 2 \rangle \\ \langle P_{a} \rangle \ \langle P_{b} \rangle \\ \langle 2 \rangle \\ \texttt{OP_CHECKMULTISIG} \end{array}$	 // 2 signatures are required // Alice's and Bob's public keys // Two public keys are to stack // Check keys and sigs from stack

In case of P2TR aggregated Schnorr signature and aggregated X-only public key are used:

$$\sigma_{\text{agg}} = \sigma_A \oplus \sigma_B \,, \mathsf{P}_{\text{agg}} = \mathsf{P}_{\mathsf{A}} \oplus \mathsf{P}_{\mathsf{B}} \tag{2.1}$$

Depending on protocol \oplus is some secure aggregation operation, but the most common approach can be found in the Musig2 [7] paper. The only thing we need to know, that σ_{agg} is a valid signature only for key P_{agg} , so we can check:

²https://github.com/ZeroSync/ZeroSync/tree/main

scriptSig:	$\langle \sigma_{ m agg} angle$
scriptPubKey:	$\langle P_{\mathrm{agg}} \rangle$ OP_CHECKSIG

Later on, we would mention it as multisig without specification of the underlying scheme. So, finally, the "funding transaction" is a transaction with one multisignature output, fulfilling amount $a\mathbf{B} + b\mathbf{B}$:

 $TX_{fund}{...;(aB + bB, multisig(P_a, P_b))}$

2.3.2 Commitment Transactions

Payments in channels are made through "commitment transactions". Each of the parties creates an asymmetric transaction that spends a multi-signature output from the $\mathsf{TX}_{\mathsf{fund}}$:

- local party spends their output after locktime, or it can be spent by counterparty if they sign it using the local party's revocation pubkey P^{rev}
- 2. the second output can be spent by the counterparty immediately

Let initial amounts $a_0 = a$, $b_0 = b$, N — number of blocks both of them agreed to lock funds for, $\mathsf{P}_{\mathsf{A}}^{\mathsf{rev}_0}$ and $\mathsf{P}_{\mathsf{B}}^{\mathsf{rev}_0}$ — Alice's and Bob's commitment revocation pubkeys. The commitment transactions for Alice and Bob are:

 $Alice's: \mathsf{TX}^{\mathsf{A}}_{\mathsf{comm}_0}\{(\mathsf{TX}_{\mathsf{fund}}, \mathsf{0}, (\sigma_{\mathsf{A}}, \sigma_{\mathsf{B}})); (a_0 \ \ \mathsf{B}, (\mathsf{addr}_{\mathsf{A}} \wedge \mathsf{LT}(N)) \lor (\mathsf{P}_{\mathsf{B}} \wedge \mathsf{P}^{\mathsf{rev}_0}_{\mathsf{A}})), (b_0 \ \ \mathsf{B}, \mathsf{addr}_{\mathsf{B}})\}$

Inputs	Outputs	Output Script
OP_0 < σ_A > < σ_B >	a₀₿	$\begin{array}{llllllllllllllllllllllllllllllllllll$
	b_0 B	OP_DUP OP_HASH160 OP_PUSHBYTES_20 <addr_b> OP_EQUALVERIFY OP_CHECKSIG (Bob can spend this output immediately)</addr_b>

 $\textbf{Bob's: } \mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_0}\{(\mathsf{TX}_{\mathsf{fund}}, \mathsf{0}, (\sigma_{\mathsf{A}}, \sigma_{\mathsf{B}})); (b_0 \ \ (\mathsf{addr}_{\mathsf{B}} \land \mathsf{LT}(N)) \lor (\mathsf{P}_{\mathsf{A}} \land \mathsf{P}^{\mathsf{rev}_0}_{\mathsf{B}})), (a_0 \ \ \mathsf{B}, \mathsf{addr}_{\mathsf{A}})\}$

Inputs	Outputs	Output Script
OP_0 < σ_A > < σ_B >	b₀₿	OP_IF <n> OP_CHECKLOCKTIMEVERIFY OP_DROP P_B OP_CHECKSIG OP_ELSE 2 P_A, P^{revo}_B OP_CHECKMULTISIG 2 OP_ENDIF (Bob can spend this output after N blocks have passed OR Alice can spend this output if she signs a transaction using Bob's revocation pubkey)</n>
	a_0 B	OP_DUP OP_HASH160 OP_PUSHBYTES_20 <addr_a> OP_EQUALVERIFY OP_CHECKSIG (Alice can spend this output immediately)</addr_a>

Index 0 means that this pair of transactions (and revocation pubkeys) is the first. When the first commitment transaction is created and parties exchange signatures, the $\mathsf{TX}_{\mathsf{fund}}$ can be sent, opening the channel.

After each payment, balances and revocation pubkeys are changed. For example, if Alice wants to send p to Bob through this channel, she constructs a new pair of commitment transactions:

$$\begin{aligned} \mathsf{TX}^{\mathsf{A}}_{\mathsf{comm}_1}\{(\mathsf{TX}_{\mathsf{fund}}, 0, (\dots, \dots)); (a_1 \ B, (\mathsf{addr}_{\mathsf{A}} \land \mathsf{LT}(N)) \lor (\mathsf{P}_{\mathsf{B}} \land \mathsf{P}^{\mathsf{rev}_1}_{\mathsf{A}})), (b_1 \ B, \mathsf{addr}_{\mathsf{B}})\} \\ \mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_1}\{(\mathsf{TX}_{\mathsf{fund}}, 0, (\dots, \dots)); (b_1 \ B, (\mathsf{addr}_{\mathsf{B}} \land \mathsf{LT}(N)) \lor (\mathsf{P}_{\mathsf{A}} \land \mathsf{P}^{\mathsf{rev}_1}_{\mathsf{B}})), (a_1 \ B, \mathsf{addr}_{\mathsf{A}})\} \end{aligned}$$

where $a_1 = a_0 - p$ and $b_1 = b_0 + p$. Alice sends signature $\sigma_A(\mathsf{TX}^A_{\mathsf{comm}_1})$ through commitment_signed message and Bob must respond with revoke_and_ack that includes per_commitment_secret, which is a secret that was used in the creation of $\mathsf{P}^{\mathsf{rev}_0}_{\mathsf{B}}$ and next_per_commitment_point for next revocation pubkey $\mathsf{P}^{\mathsf{rev}_2}_{\mathsf{B}}$. Then Bob sends $\sigma_{\mathsf{B}}(\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_1})$ and Alice reveals her revocation keys.

The revocation public key is created as follows:

$$\mathsf{P}^{\mathsf{rev}_i}_{\mathsf{A}} = \mathsf{Q}^{\mathsf{rev}} \cdot \mathsf{Sha256}(\mathsf{Q}^{\mathsf{rev}}||\mathsf{C}^{\mathsf{rev}_i}_{\mathsf{A}}) + \mathsf{C}^{\mathsf{rev}_i}_{\mathsf{A}} \cdot \mathsf{Sha256}(\mathsf{Q}^{\mathsf{rev}}||\mathsf{Q}^{\mathsf{rev}})$$

where Q^{rev} — revocation basepoint from open_channel or accept_channel messages, $C_A^{rev_i}$ — per commitment point from open_channel and accept_channel or revoke_ack (depending on the number of the commitment tx and party).

2.3.3 HTLC Payments

While direct balance updates work for simple payments within a channel, the Lightning Network primarily uses **Hashed Timelock Contracts (HTLCs)** for payments, especially for routed payments across multiple channels. However, even in a direct channel between Alice and Bob, HTLCs are the standard mechanism.

An HTLC is a conditional payment output in a Bitcoin transaction. It allows funds to be locked such that they can be claimed under specific conditions involving a cryptographic hash and a time limit. Specifically, an HTLC output can be spent in one of two ways:

- By the recipient (e.g., Bob): If they can provide the preimage (secret) R such that its hash H = Hash(R) matches the hash specified in the HTLC script, before a specified timeout (cltv_expiry).
- 2. By the sender (e.g., Alice): If the recipient fails to provide the preimage before the timeout expires.

When Alice wants to send a payment to Bob using an HTLC, the process involves modifying the commitment transactions. Alice generates a secret preimage R and computes its hash H. She then proposes adding an HTLC to Bob via an update_add_htlc message. This message contains the payment amount, the hash H, and the timeout cltv_expiry.

If Bob accepts the HTLC, both parties update their commitment transactions to reflect this pending payment. The new commitment transactions will include an additional output representing the HTLC. For instance, Alice's updated commitment transaction $(\mathsf{TX}^{\mathsf{A}}_{\mathsf{comm'}})$ might look like this (simplified):

Inputs	Outputs	Output Script	
$multisig(P_{a},P_{b})$	$a_0 - h \mathbf{B}$	Alice can spend after N blocks OR Bob can spend using Alice's revocation key $P^{rev'}_{A}$.	
	b_0 B	Bob can spend immediately.	
	h₿	Bob claims with preimage R (where $Hash(R) = H$) before cltv_expiry OR Alice claims after timeout (cltv_expiry).	

Similarly, Bob's commitment transaction $(\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm'}})$ will have a corresponding HTLC output structure, viewed from his perspective (Received HTLC):

Inputs	Outputs	Output Script	
$\mathrm{multiSig}\;(P_{a}+P_{b})$	b_0 B	Bob can spend this output after N blocks have passed OR Alice can spend this output using Bob's revocation key $P_{B}^{rev'}$.	
	$a_0 - h$ B	Alice can spend this output immediately.	
	h₿	Bob claims with preimage R (where Hash $(R) = H$) before cltv_expiry OR Alice claims after timeout (cltv_expiry). (HTLC Received by Bob)	

These new commitment transactions $(\mathsf{TX}^{\mathsf{A}}_{\mathsf{comm'}}, \mathsf{TX}^{\mathsf{B}}_{\mathsf{comm'}})$ are signed and exchanged, following a process similar to that for simple balance updates, which effectively adds the HTLC to the channel state.

To complete the payment, Bob reveals the preimage R to Alice by sending an update_fulfill_htlc message before the timeout. Upon receiving R, Alice can verify that $\mathsf{Hash}(R) = H$. Knowing R allows Bob to definitively claim the HTLC output if the commitment transaction were ever broadcast. More importantly, in the off-chain context, receiving the update_fulfill_htlc signals to Alice that the payment is successful. Both parties then update their commitment transactions again to remove the fulfilled HTLC and adjust their main balances accordingly, again using commitment_signed and revoke_and_ack to finalize the state change.

If Bob fails to provide the preimage before the cltv_expiry, Alice can send an update_fail_htlc message, and both parties update their commitment transactions to remove the expired HTLC, returning the funds to Alice's balance.

2.3.4 Closing Channel

Closing a payment channel can occur in two primary ways: cooperatively (mutual close) or unilaterally (force close).

Mutual Close

This is the preferred method where both parties agree to close the channel.

- 1. Alice and Bob agree on the final channel balances, say $a_k \ddot{\mathbb{B}}$ for Alice and $b_k \ddot{\mathbb{B}}$ for Bob.
- 2. They cooperatively construct a single "closing transaction" (TX_{close}) that spends the funding transaction output (TX_{fund}) .
- 3. This transaction has outputs directly paying $a_k \mathbf{B}$ to Alice's final address (addr_A) and $b_k \mathbf{B}$ to Bob's final address (addr_B), minus transaction fees.

$$\mathsf{TX}_{\mathsf{close}}\{(\mathsf{TX}_{\mathsf{fund}}, \mathsf{0}, (\sigma_{\mathsf{A}}, \sigma_{\mathsf{B}})); (a_k \ \ \mathsf{B}, \mathsf{addr}_{\mathsf{A}}), (b_k \ \ \mathsf{B}, \mathsf{addr}_{\mathsf{B}})\}$$

- 4. Both parties sign this transaction using the keys associated with the funding multi-signature $(\mathsf{P}_a,\mathsf{P}_b).$
- 5. Once signed by both, the transaction is broadcast to the Bitcoin network. The funds become available to each party after the transaction is confirmed. This method is fast and efficient, as it involves no time locks.

Force Close

If one party becomes unresponsive or uncooperative, the other party can unilaterally close the channel by broadcasting their latest valid commitment transaction.

Assume Alice decides to force close using her latest commitment transaction, $\mathsf{TX}^{\mathsf{A}}_{\mathsf{comm}_k}$. This transaction reflects the agreed-upon state k, including Alice's main balance, Bob's main balance, and any active HTLCs. She broadcasts this transaction to the Bitcoin network.

- 1. Bob's direct output (to_remote, representing his main balance $b_k \ddot{B}$) can be spent by Bob immediately once $\mathsf{TX}^{\mathsf{A}}_{\mathsf{comm}_k}$ confirms.
- 2. Alice's direct output (to_local, representing her main balance $a_k \beta$) is encumbered by a time lock (to_self_delay, denoted as N blocks in the previous section). Alice can only spend these funds after the time lock expires.
- 3. **Revocation:** This time lock (N) on Alice's to_local output provides a window for Bob to contest the closure if Alice broadcast an outdated commitment transaction (e.g., $\mathsf{TX}^{\mathsf{A}}_{\mathsf{comm}_j}$ where j < k). If Bob possesses the revocation secret corresponding to state j (which Alice would have revealed when moving to state j + 1), Bob can use the revocation path within the to_local script to immediately claim Alice's funds $(a_j \not B)$. This acts as a strong deterrent against attempting to cheat by broadcasting old states.
- 4. Handling In-flight HTLCs: If there were active HTLCs at state k, TX^A_{commk} will contain corresponding HTLC outputs. These outputs are resolved on-chain via second-level transactions after TX^A_{commk} confirms:
 - HTLCs Offered by Alice: An output exists for each HTLC Alice offered.
 - Success Case: Bob can spend this output by creating a second-level transaction that reveals the preimage R before the HTLC's timeout (cltv_expiry).
 - Timeout Case: Alice can spend this output via a second-level transaction after the cltv_expiry has passed.
 - HTLCs Received by Alice: An output exists for each HTLC Alice received.
 - Success Case: Alice can spend this output via a second-level transaction that reveals the preimage R (if she knows it) before the HTLC's timeout (cltv_expiry).
 - Timeout Case: Bob can spend this output via a second-level transaction after the cltv_expiry has passed.
 - *Revocation for HTLCs:* Importantly, similar to the to_local output, these HTLC outputs also have a revocation path. If Alice broadcasts an outdated $\mathsf{TX}^{\mathsf{A}}_{\mathsf{comm}}$, Bob can use the corresponding revocation key to claim these HTLC outputs immediately via a second-level transaction, regardless of the preimage or timeouts.
- 5. If Alice broadcasts the correct, latest state $\mathsf{TX}^{\mathsf{A}}_{\mathsf{comm}_k}$, Bob cannot use the revocation path on any output. Alice can spend her to_local output after the time lock N expires. The HTLC outputs are resolved on-chain as described above (success or timeout path) via second-level transactions initiated by the party entitled to the funds under those conditions.

Force closes are less desirable as they require waiting for time locks (both to_self_delay on the main output and potentially cltv_expiry on HTLC outputs) and involve broadcasting the more complex commitment transaction. Resolving HTLCs on-chain requires additional second-level transactions, potentially leading to higher transaction fees and significantly slower fund recovery compared to a mutual close.

2.4 Collateral Debt Position

A Collateral Debt Position (CDP) is a financial construct that enables the use of an asset as collateral to secure a loan for another asset. Typically, CDP is utilized for pledging volatile assets, such as Bitcoin and Ethereum, and securing a loan in stablecoins with a predictable interest rate. This allows for two major gains:

- Getting a stable coin loan without selling a volatile asset, the user keeps a long position with the borrower's collateral asset
- If the user does not sell a volatile asset, there are no taxes for income to pay from getting a loan

The significant risk for the user is the potential for borrower liquidation when the price of the collateral asset falls to the minimum borrower collateralization ratio, after which position liquidation occurs, and the user retains the loan but loses the collateral to the liquidator.

Let Alice be a borrower and Bob be a lender. Alice pledges BTC as collateral; Bob provides a stablecoin loan to Alice. If Alice fully repays the loan, she can withdraw the collateral. If the borrower's collateralization ratio falls below the minimum level, any third party appointed as a liquidator can repay the loan and seize the borrower's collateral for their own use.

2.4.1 Loan Origination

Borrower Collateralization Ratio (BCR) is calculated as:

$$\mathsf{BCR} = \frac{\mathsf{BCAA} * \mathsf{OP}}{\mathsf{LA}}$$

where BCAA is the borrower's collateral asset amount, OP is the oracle price, and LA is the loan amount. The protocol defines a minimum BCR (MBCR) value after which CDP liquidation could be initiated.

- 1. The loan origination process begins with Alice locking collateral in the CDP position contract. Alice also makes a loan request for a specific loan amount. If the loan is not originated, Alice can claim the collateral asset back at her address.
- 2. Alice initiates a loan origination transaction with the following rules applied:
 - The maximum loan amount (MLA) is calculated as: MLA = BCAA * OP/MBCR
 - An additional fee for loan origination might be applied
 - An additional interest rate for the loan might be applied

If LA < MLA, the borrower can withdraw part of the collateral asset until LA = MLA.



Figure 2.1: Loan origination via CDP

2.4.2 Borrower Liquidation Scenario

In case the oracle price leads to BCAA * OP/MBCR < OLA (outstanding loan amount), the borrower liquidation process is triggered.

Bob or any other third party called a liquidator can initiate a transaction in which:

- Liquidator repays the full amount of a loan in stablecoin plus accrued interest rate and fees (if any) outstanding
- Liquidator receives full borrower collateral asset

To avoid borrower liquidation, Alice should do either or both until BCR is restored to a minimal level equal to or higher than MBCR:

- 1. Partially repay the loan
- 2. Add borrower collateral

2.4.3 Loan Repayment and CDP Closure

When Alice is ready to close the CDP position, the protocol requires:

- 1. Alice repays the full amount of a loan in stable coin plus accrued interest rate and fees (if any) to Bob
- 2. Alice claims back the borrower's collateral asset

Partial loan repayment is also possible. In this case, Alice can withdraw the borrower collateral until the LA < MLA based on the new collateral asset value.



Figure 2.2: Loan repayment and CDP closure

Chapter 3

Wrapless Protocol

3.1 Construction and properties

Wrapless is an analog of the CDP protocol that operates with native BTC. The primary features of the Wrapless protocol are trustlessness (through two-sided overcollateralization) and bidirectional liquidation.

- 1. **Trustlessness**. The parties create a cross-chain contract in a way that, if one of them manipulates, the other receives an economic advantage. The lender is protected by the collateral, the value of which exceeds the loan amount. The borrower is protected by the security deposit, which, together with the loan, exceeds the collateral value.
- 2. Bidirectional liquidation. Existing CDP protocols are designed in a manner that assumes possible borrower liquidation when the price of the collateral asset falls to the minimum borrower collateralization ratio. However, at the same time, the borrower does not receive any advantage (except for decreasing the liquidation risk) if the collateral asset's value increases. The first version of Wrapless had a significant drawback that allowed the lender to seize the collateral at any point in time, particularly when its value increased substantially. We fixed this by creating the liquidation construction that works in both ways.

Assume that Alice wants to lend USD from Bob on an EVM-based chain in exchange for her B on the Bitcoin network. We can informally describe the protocol as follows:

- **Agreement On Loan Details:** Bob and Alice must agree on the details of the future loan. It's possible to perform this procedure entirely off-chain or to create an order-based market in the form of a smart contract.
- **Loan Channel Establishment:** After details are agreed, Bob locks his (b+c) USD on the loan contract and initiates the creation of a Lightning Network channel with Alice. Alice funds the channel with $a\ddot{B}$ on Bob's side and 0 on Alice's side. Alice broadcasts the funding transaction and provides SPV proof to the loan contract, marking the beginning of the lending process. Alice then receives b on the EVM-based chain. If Alice doesn't submit a funding transaction to the Bitcoin network, Bob can return all deposited funds after the locktime T_0 .
- **Loan Installment:** Alice sends $\frac{b(1+k)}{N}$ \$ back to the loan contract to initiate an installment. In response, Bob must accept the installment and send $\frac{a}{N}$ \$ to Alice through the loan channel. Both parties exchange signatures for their respective commitment transactions and submit them (excluding their signatures) to the loan contract. If both signatures are valid, the installment is considered finalized.
- Loan Completion: In case of a dispute (e.g., one party fails to submit the required signature for the commitment transaction either in the lightning channel or later to the loan contract) or upon successful repayment of all N installments, the loan process concludes. The loan channel is closed, and the final commitment or closing transaction is submitted to the loan contract. Bob retains any remaining BTC; depending on how the loan channel was closed, one of the parties receives the security deposit.

Liquidation: If the BTC price is changed and leads to the situation when one party is motivated to close the channel, an additional timeframe is opened. Depending on the direction in which the price moves, the borrower or liquidator must fund the channel or security deposit within this timeframe. If this funding has not been completed, the channel will be closed without penalty to the party responsible.

Below, we provide a more detailed explanation of the protocol flow, and from now on, Alice is the **borrower** B and Bob is the **lender** L.

3.2 Agreement On Loan Details

Before the loan process begins, the lender and borrower should agree on the details. As we shortly mentioned, this can be done in on-chain and off-chain ways. Initially, let's define the parameters that need to be agreed upon between counterparties (later we will use S as a notation for the set of all parameters below):

- $a{:}$ collateral amount in $\ddot{\mathbb{B}}$
- $b{:}$ loan amount in USD
- k: interest rate

c: security deposit in USD provided by the lender. It can be unlocked by the borrower if their counterparty tries to cheat. If the entire lending process has been successful, the lender returns the security deposit.

N: number of installments

 T_0 : the time point before which the borrower must open the loan channel

 $T_1 \ldots T_N$: installment deadlines

 $\mathsf{lnid}_\mathsf{B},\mathsf{lnid}_\mathsf{L}\colon \mathsf{lightning} \ \mathsf{node} \ \mathsf{IDs} \ (\mathsf{the} \ \mathsf{hash} \ \mathsf{of} \ \mathsf{secp256k1} \ \mathsf{public} \ \mathsf{key} \ \mathsf{used} \ \mathsf{for} \ \mathsf{discovering} \ \mathsf{and} \ \mathsf{routing} \ \mathsf{in} \ \mathsf{Lightning} \ \mathsf{Network})$

 P_B, P_L : the borrower's and lender's public keys

 $TX_{fund}\{(TX_B, *, -); (aB, multisig(P_B, P_L))\}$: funding transaction for the loan channel (you can find it doesn't include signatures, they should be collected after forming the commitment transactions)

 $\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm0}}, \mathsf{TX}^{\mathsf{L}}_{\mathsf{comm0}}$: initial commitment transactions, formed as:

$$\begin{aligned} \mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_0}\{(\mathsf{TX}_{\mathsf{fund}}, 0, (-, -)); (0\ddot{\mathbb{B}}, (\mathsf{addr}_{\mathsf{B}} \wedge \mathsf{LT}_{\mathsf{B}}) \lor (\mathsf{P}_{\mathsf{L}} \wedge \mathsf{P}^{\mathsf{rev}_0}_{\mathsf{B}})), (a\ddot{\mathbb{B}}, \mathsf{addr}_{\mathsf{L}}) \} \\ \mathsf{TX}^{\mathsf{L}}_{\mathsf{comm}_0}\{(\mathsf{TX}_{\mathsf{fund}}, 0, (-, -)); (a\ddot{\mathbb{B}}, (\mathsf{addr}_{\mathsf{L}} \wedge \mathsf{LT}_{\mathsf{L}}) \lor (\mathsf{P}_{\mathsf{B}} \wedge \mathsf{P}^{\mathsf{rev}_0}_{\mathsf{I}})), (0\ddot{\mathbb{B}}, \mathsf{addr}_{\mathsf{B}}) \} \end{aligned}$$

 $\sigma_{L_b} \leftarrow \mathsf{sigGen}_{\mathsf{ecdsa}}(\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_0},\mathsf{sk}_{\mathsf{L}}) \text{ and } \sigma_{B_l} \leftarrow \mathsf{sigGen}_{\mathsf{ecdsa}}(\mathsf{TX}^{\mathsf{L}}_{\mathsf{comm}_0},\mathsf{sk}_{\mathsf{B}}): \text{ signatures for initial commitment transactions}$

 \mathcal{O} : an oracle instance that returns the ratio between \ddot{B} and USD and can initiate liquidation event. This oracle can be a service or a decentralized protocol, such as Uniswap [15]. Oracle cannot help one of the parties win the loan game we create, but rather signals a change in the price of collateral.

 LR_B and LR_L : the liquidation ratio parameters

If all these details are agreed upon off-chain, the lender can initialize the contract by calling createLoanOffer(S) method and providing the loan and security deposit (see Section 3.3).



Figure 3.1: Off-chain agreement

However, in practice, we can have a model where the order-matching mechanism exists on-chain; lenders initially define the loan conditions, and borrowers can select an option they are interested in:

- 1. The lender defines the set of parameters $\mathcal{L} = \{min_a, max_a, \mathsf{BCR}, k, c, N, \Delta t, \mathsf{Inid}_\mathsf{L}, \mathsf{P}_\mathsf{L}, \mathcal{O}, \mathsf{LR}_B, \mathsf{LR}_L\},\$ where min_a, max_a - minimal and maximum acceptable collateral value, Δt - installment period. The lender can offer various options \mathcal{L}^* depending on the relationship between the parameters.
- 2. The borrower selects the option \mathcal{L}_i from the list of available ones and provides their set of parameters by requestLoan(\mathcal{B}), $\mathcal{B} = \{a, T_0, \mathsf{Inid}_{\mathsf{B}}, \mathsf{P}_{\mathsf{B}}, \mathsf{TX}_{\mathsf{fund}}, \mathsf{TX}_{\mathsf{comm}_0}^{\mathsf{B}}\}$
- 3. If the lender agrees to provide the loan, they confirm it by calling $acceptLoan(TX_{comm0}^{L}, \sigma_{L_b})$. Additionally, the lender locks (b + c) USD (details explained in Section 3.3).
- 4. A final borrower's confirmation (method finalize($\sigma_{B_l}, \pi_{SPV}(\mathsf{TX}_{\mathsf{fund}})$)). Installment deadlines are calculated as $T_i = T_0 + i \cdot \Delta t, i \in [1, N]$.



Figure 3.2: Borrower places order on Loan Smart Contract, creating an Order

Therefore, we can see that all parameters can be agreed upon in both ways: on-chain and off-chain. With the on-chain agreement process, it makes sense to wrap all functions with the minimum reasonable fee to protect each user from DoS of the counterparty.

On usage of the lender's public key

The lender's public key P_L is required for the borrower to verify the validity of $\mathsf{TX}_{\mathsf{fund}}$ during channel establishment, as well as for the loan contract to verify its validity. Assume we have keys:

$$sk_{L} \xleftarrow{R} \mathbb{F}_{p}, \quad \mathsf{P}_{\mathsf{L}} = sk_{L}G$$
$$sk_{B} \xleftarrow{R} \mathbb{F}_{p}, \quad \mathsf{P}_{\mathsf{B}} = sk_{B}G$$

where sk_L and sk_B – are the lender's and borrower's secret keys, respectively, that they set in the loan contract. So that borrower, after receiving the open_channel ^a message, can compare P_L to the received key in funding_pubkey field of the message thus make sure that its the same lender, that accepted order. For the loan contract, the importance comes from examining the provided funding transactions. Loan constructs P2WSH redeem script^b:

redeemScript:

OP_2 $\left< \mathsf{P}_{\mathsf{L}} \right> \left< \mathsf{P}_{\mathsf{B}} \right>$ OP_2 OP_CHECKMULTISIG

hashes it h = Sha256(redeemScript) and finally constructs scriptPubKey that it can compare to one in TX_{fund}:

scriptPubKey:

OP_O $\langle h \rangle$

 $^{a} https://github.com/lightning/bolts/blob/ccfa38ed4f592c3711156bb4ded77f44ec01101d/02-peer-protocol.md\#the-open_channel-message$

 $^b \rm https://github.com/bitcoin/bips/blob/9a56d3544 eac1f949a747c251810f7a440d63fb9/bip-0141.mediawiki#witness-program$

3.3 Loan request acceptance and channel establishment

When all details are agreed, the lender locks (b+c) USD on the loan contract. The loan b, can be taken by the borrower, but only if they open a loan channel on Bitcoin. A security deposit c is being controlled by the loan contract.

Idea Block

There may be a concern that the lender needs to freeze the security deposit, c, before the loan is paid off. It creates an overcollateralization from the lender's side. However, 1) the lender can unlock the security deposit partially after covering the part of the loan by the borrower; 2) these funds can actually be used as liquidity for other protocols. Therefore, the deposit plays a crucial role in the security of the lending process, and at the same time, can serve as a source of additional income.

Therefore, the single option for the borrower to take a loan is to send $\mathsf{TX}_{\mathsf{fund}}$, which was previously agreed upon (the loan contract knows the specific Bitcoin transaction that must be sent).

 $\mathsf{TX}_{\mathsf{fund}}\{(\mathsf{TX}_\mathsf{B},*,\sigma_\mathsf{B});(\mathsf{a}\ddot{\mathbb{B}},\mathsf{multisig}(\mathsf{P}_\mathsf{B},\mathsf{P}_\mathsf{L}))\}$

If the borrower sent $\mathsf{TX}_{\mathsf{fund}}$, they can provide $\pi_{\mathsf{SPV}}(\mathsf{TX}_{\mathsf{fund}})$ to the loan contract before T_0 (Figure 3.3). If the borrower does not open the channel (or fails to prove it before T_0), it means the lender can reclaim all (b + c) USD (it's the reason why we proposed having a minimal, reasonable fee and an on-chain agreement for the loan). openChannel($\mathsf{TX}_{\mathsf{fund}}, \pi_{\mathsf{SPV}}$) needs to be called to receive the loan.



Figure 3.3: A loan channel creation

The loan contract verifies the validity of $\pi_{SPV}(TX_{fund})$ by invoking the appropriate method of the SPV contract, which maintains a complete record of the Bitcoin blockchain history. If the proof is correct, the borrower can take a loan of *b*. Finally, LT_B , LT_L are locktimes for outputs to the local party for Alice and Bob in all commitment transactions, required for checks in further steps.

3.3.1 Closing the Loan Channel Instantly

After the channel is established, it can be closed at any point in time. It makes no sense for the borrower to initiate it because they will lose the collateral. However, a reasonable question is why the lender does not close the channel to receive the collateral, whose value exceeds the amount of the provided loan.

We cannot influence the lender's decision to close the channel. Still, we can create conditions that make these attempts economically irrational — specifically, by allowing the borrower to take a security deposit of c in the case the lender closes the channel.

So, assume the channel was created and a loan was taken (no loan installments have been paid yet):

- $\mathsf{TX}_{\mathsf{fund}}$ was confirmed on-chain, $\mathsf{TX}_{\mathsf{comm0}}^{\mathsf{B}}, \mathsf{TX}_{\mathsf{comm0}}^{\mathsf{L}}$ exist, each of them can be signed and propagated to the Bitcoin network
- The borrower has already received b, the lender controls a, c is locked

There are several possible scenarios at this stage, so we define corresponding rules for them that the protocol must follow:

1. The borrower closes the channel by co-signing and publishing the $\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_{n}}$:

 $\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_{\mathsf{B}}}\{(\mathsf{TX}_{\mathsf{fund}}, \mathsf{0}, (\sigma_{\mathsf{L}_{\mathsf{b}}}, \sigma_{\mathsf{B}_{\mathsf{b}}})); (0\overset{\mathsf{B}}{\oplus}, (\mathsf{addr}_{\mathsf{B}} \land \mathsf{LT}_{\mathsf{B}}) \lor (\mathsf{P}_{\mathsf{L}} \land \mathsf{P}^{\mathsf{rev}_{\mathsf{0}}}_{\mathsf{B}})), (a\overset{\mathsf{B}}{\oplus}, \mathsf{addr}_{\mathsf{L}})\}$

- (a) The borrower receives $0\ddot{B}$
- (b) The lender can take $a\ddot{B}$ instantly
- (c) The lender waits for $\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_0}$ confirmation and provides $\pi_{\mathsf{SPV}}(\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_0})$ to the loan contract (as a proof that the borrower initiated the channel close). This proof allows them to claim c USD.
- 2. The lender closes the channel by co-signing and publishing the TX^L_{comm}:

$$\mathsf{TX}_{\mathsf{comm}}^{\mathsf{L}}\{(\mathsf{TX}_{\mathsf{fund}}, \mathsf{0}, (\sigma_{\mathsf{L}_{\mathsf{I}}}, \sigma_{\mathsf{B}_{\mathsf{I}}})); (a\ddot{\mathbb{B}}, (\mathsf{addr}_{\mathsf{L}} \land \mathsf{LT}_{\mathsf{L}}) \lor (\mathsf{P}_{\mathsf{B}} \land \mathsf{P}_{\mathsf{L}}^{\mathsf{rev}_{\mathsf{0}}})), (0\ddot{\mathbb{B}}, \mathsf{addr}_{\mathsf{B}})\}$$

- (a) The borrower receives 0B
- (b) The lender can take $a \ddot{\mathbb{B}}$ after locktime LT_{L}
- (c) The borrower waits for $\mathsf{TX}^{\mathsf{L}}_{\mathsf{comm}_0}$ confirmation and provides $\pi_{\mathsf{SPV}}(\mathsf{TX}^{\mathsf{L}}_{\mathsf{comm}_0})$ to the loan contract (as a proof that the lender initiated the channel close). This proof allows them to take the security deposit.
- 3. Parties close the channel cooperatively using the transaction $\mathsf{TX}_{\mathsf{close}}$:

$$\mathsf{TX}_{\mathsf{close}}\{(\mathsf{TX}_{\mathsf{fund}}, 0, (\sigma_L, \sigma_B)); (e \ B, \mathsf{addr}_{\mathsf{L}}), ((a-e) \ B, \mathsf{addr}_{\mathsf{B}})\}$$

- (a) The borrower receives (a e)B instantly
- (b) The lender receives $e \mathbf{B}$ instantly
- (c) The lender waits for TX_{close} confirmation and provides $\pi_{SPV}(TX_{close})$ to the loan contract. By default, we presume that the lender can take the security deposit; however, it is possible to organize conditions under which the security deposit is distributed between counterparties based on their agreement.
- 4. Parties continue working by paying loan installments and creating new commitment transactions in the channel.

	Borrower closes	Lender closes	Cooperative	Normal flow
Lender	(a+c)	a	up to agreement	$b \cdot (1+k) + c$
Borrower	b	b+c		a

3.4 Loan Installment

After a channel is established and registered on the loan smart contract, the borrower must follow the installment conditions, paying fractions of the loan until the corresponding deadlines, $T_1, ..., T_N$.

The payment $i \in [1, N]$ is made by the payInstallment(...) method, providing $\frac{b(1+k)}{N}$ USD to the contract. Additionally, the borrower needs to attach the $\mathsf{TX}_{\mathsf{comm}_i}^{\mathsf{B}}$ with the new BTC distribution in the channel:

$$\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm}_{\mathsf{i}}} = \{(\mathsf{TX}_{\mathsf{fund}}, 0, (-, -)); (\frac{a \cdot i}{N} \dot{\mathsf{B}}, (\mathsf{addr}_{\mathsf{B}} \wedge \mathsf{LT}_{\mathsf{B}}) \vee (\mathsf{P}^{\mathsf{rev}_{\mathsf{i}}}_{\mathsf{B}} \wedge \mathsf{P}_{\mathsf{L}}), (a - \frac{a \cdot i}{N} \dot{\mathsf{B}}, \mathsf{addr}_{\mathsf{L}}))\}$$

This action forces the lender to accept the installment using the takeInstallment(...) method. This method requires providing the signature $\sigma_{L_{bi}} \leftarrow sigGen_{ecdsa}(\mathsf{TX}^{\mathsf{B}}_{comm_i}, \mathsf{sk}_{\mathsf{L}})$ and the transaction $\mathsf{TX}^{\mathsf{L}}_{comm_i}$, formed as:

$$\mathsf{TX}^{\mathsf{L}}_{\mathsf{comm}_{\mathsf{i}}} = \{(\mathsf{TX}_{\mathsf{fund}}, 0, (-, -)); (a - \frac{a \cdot i}{N} \ddot{\mathsf{B}}, (\mathsf{addr}_{\mathsf{L}} \wedge \mathsf{LT}_{\mathsf{L}}) \lor (\mathsf{P}^{\mathsf{rev}_{\mathsf{i}}}_{\mathsf{L}} \wedge \mathsf{P}_{\mathsf{B}}), (\frac{a \cdot i}{N} \ddot{\mathsf{B}}, \mathsf{addr}_{\mathsf{B}}))\}$$

The next step requires the borrower to provide the signature $\sigma_{B_{li}} \leftarrow sigGen_{ecdsa}(TX_{comm_i}^L, sk_B)$ and the secret used for the previous $TX_{comm_{i-1}}^B$. Finally, the lender must respond with the secret committed to $TX_{comm_{i-1}}^L$.



Figure 3.4: Installment-and-commitment protocol: on-chain calls and off-chain handshake

The last installment must lead to the creation of the $\mathsf{TX}_{\mathsf{close}}$ Bitcoin transaction where the borrower takes all collateral from the channel.

$$\mathsf{TX}_{\mathsf{close}}\{(\mathsf{TX}_{\mathsf{fund}}, 0, (\sigma_L, \sigma_B)); (0\ddot{\mathsf{B}}, \mathsf{addr}_{\mathsf{L}}), (a\ddot{\mathsf{B}}, \mathsf{addr}_{\mathsf{B}})\}$$

3.4.1 Dispute Resolution

The protocol incorporates mechanisms to handle scenarios where either party attempts to deviate from the agreed-upon rules or fails to fulfill their obligations.

- 1. Borrower fails to pay installment: If the borrower does not call payInstallment(...) before the corresponding deadline T_i , the lender can initiate a channel closure procedure by broadcasting the latest, mutually signed commitment transaction $\mathsf{TX}_{\mathsf{comm}_{i-1}}^{\mathsf{L}}$ to the network. Then, the lender can take the security deposit the loan contract releases it if the borrower fails to make the installment payment.
- 2. Lender attempts to publish outdated channel state: The construction of the lightning channel protects against this case. If the lender attempts to close the channel with one of the previous commitment transactions, they provide the lender with the ability to withdraw all funds from the channel. We can also cover it with the ability to take the security deposit by the borrower; in this case, the borrower extracts the maximum value: (a + b + c).
- 3. Lender fails to cooperate after installment payment: If the borrower pays the installment via payInstallment(...), but the lender doesn't accept it (doesn't provide the necessary signature ($\sigma_L(TX^B_{comm_i})$) for the updated commitment transaction in the channel or fails to register it (takeInstallment(...)) with the loan contract) within a specified timeframe, the borrower can initiate a dispute. The dispute involves closing the channel with the latest state and retaining the security deposit by the borrower.
- 4. Submitting incorrect data to loan contract: If either party submits an invalid signature or an incorrectly constructed commitment transaction/revocation key, the loan contract's verification checks will fail and the transaction will be rejected. Such actions can be subject to penalties, such as forfeiture of the security deposit after a dispute period (like in the previous example).

These mechanisms aim to ensure that rational actors are incentivized to follow the protocol honestly, as attempting to cheat typically results in a financial loss greater than any potential gain. The security deposit held in the loan contract plays a crucial role in penalizing malicious behavior and compensating the honest party.

3.5 Liquidation

The latest and most interesting part we want to cover is the case where the collateral price is changed. We can show initial loan agreement details schematically, in Figure 3.5:



Figure 3.5: Initial loan parameters

We need to protect both parties in situations where changes in collateral prices can motivate the counterparty to act dishonestly:

1. If the collateral price goes down and creates an undercollateralized loan, the borrower stops paying installments, and the lender loses

2. If the collateral price goes up and exceeds the loan and security deposit, the lender closes the channel, and the borrower loses the collateral

Let's assume we have an oracle instance \mathcal{O} integrated with the loan contract. This oracle provides the current exchange rate r between USD and BTC on a regular basis (1 $\mathring{B} = r$ USD).

3.5.1 Borrower's position liquidation

If the oracle provided r, which is $r \cdot a = \mathsf{LR}_B$, it triggers the liquidation event because if the collateral prices continue going down, it will lead to an uncollateralized loan.



Figure 3.6: Funding the channel to cancel the liquidation

The liquidation process consists of two stages. The first stage includes the timeframe during which the borrower can fund the channel and cancel the liquidation, thereby increasing the collateral value above LR_B .

If the borrower fails to fund the channel within the designated timeframe, the lender can close the channel without incurring a penalty.

3.5.2 Lender's position liquidation

In this case, we assume the oracle provides r, such that $r \cdot a = \mathsf{LR}_L$. We need to initiate the liquidation event before the collateral price exceeds (b + c), as this would render the lender economically motivated to close the channel.



Figure 3.7: Funding the security deposit to cancel the liquidation

The liquidation procedure is also divided into two stages: 1 - the period when the lender can increase the security deposit (moving LR_L value up), and 2 - final liquidation if the lender didn't do that (in this case, the borrower can close the channel and take the security deposit).

Chapter 4

SPV contract specification

addBlockHeader(block_header_raw)

Purpose: This function enables the addition of a new Bitcoin block header to the SPV contract's internal block header chain, allowing for simplified payment verification.

Internal steps:

- 1. Initial Parameter Parsing and Validation: The function first parses the provided blockHeaderRaw input and performs several initial checks:
 - ensuring that the length of blockHeaderRaw is exactly 80 bytes.
 - verifying that a block with the same hash has not been previously added to the contract's chain.
 - confirming that the prevBlockHash extracted from blockHeaderRaw is already present within the contract's block tree.
- 2. Block Metadata Determination: Following initial validation, the contract determines essential metadata for the new block, including its height, target, and medianTime.
- 3. Block Content Validation: A validation of the block's content is then performed. This includes:
 - verifying that the block's target (difficulty) aligns with the network's current expected target.
 - ensuring that $blockHash \leq blockTarget$, confirming it meets the proof-of-work requirement.
 - checking that the $\texttt{blockTime} \geq \texttt{medianTime},$ preventing timestamp manipulation.
- 4. Block Addition to Chain: Upon successful validation, the block is added to the contract's internal block header chain. This process can result in one of three outcomes: the new block extends the main chain, becomes an alternative (fork) block, or triggers a reorganization of the main chain.
- 5. Event Emission: A BlockHeaderAdded(block_height, block_hash) event is emitted.

addBlockHeaderBatch(block_header_raw_arr)

Purpose: This function facilitates the addition of a batch (array) of Bitcoin block headers to the SPV contract's internal chain, enabling more efficient synchronization.

- 1. Batch Processing and Initial Validation: The function iterates through each blockHeaderRaw element within the blockHeaderRawArr. For each individual block header, it performs initial parsing and validations analogous to those in addBlockHeader:
 - ensuring that the length of blockHeaderRaw is exactly 80 bytes.
 - verifying that a block with the same hash has not been previously added.
 - confirming that the prevBlockHash extracted from blockHeaderRaw is already present within the contract's block tree.
- 2. Block Metadata Determination: For each block, its height, target, and medianTime are determined.

- 3. Block Content Validation: For each block, a comprehensive validation of its content is performed, identical to the checks in addBlockHeader with the next optimizations:
 - For subsequent blocks within the blockHeaderRawArr, the prevBlockHash can be directly validated against the hash of the immediately preceding block within the same input array, reducing the need for storage reads.
 - If the batch contains more than 11 block headers, the medianTime for blocks from the 12th onwards can be computed using the timestamps of the preceding blocks within the provided blockHeaderRawArr, rather than requiring reads from the contract's storage.
- 4. Batch Block Addition to Chain: Upon successful validation, each block in the array is added to the contract's internal block header chain. Similar to single block additions, this may extend the main chain, create alternative chains, or trigger reorganizations.
- 5. Event Emission: For each successfully added block header, a BlockHeaderAdded (block_height, block_hash) event is emitted.

validateBlockHash(block_hash)

Purpose: This view function provides information about a given Bitcoin block header, specifically whether it resides on the SPV contract's recognized main chain and its number of confirmations.

Parameters:

- blockHash: The hash of the Bitcoin block header to query.

Returns:

- (bool is_in_main_chain, uint256 confirmations): A boolean indicating if the block is part of the main chain, and an unsigned integer representing its confirmation count.

Internal steps:

- 1. Block Height Retrieval: The function first retrieves the height of the block corresponding to the provided blockHash from the contract's storage.
- 2. Main Chain Check: It then verifies if the provided blockHash is indeed part of the SPV contract's currently recognized main chain.
- 3. Confirmation Count Calculation: The number of confirmations is determined by calculating the difference between the current height of the main chain and the height of the queried block. If blockHash is not found in the main chain, its confirmation count is set to zero (0).
- 4. Value Return: Finally, the function returns the determined is_in_main_chain status and the calculated confirmations count.

$verifyTx(block_hash, TX, \pi_{SPV}(TX))$

Purpose: This view function verifies the inclusion of a specific Bitcoin TX within a blockHash using a provided $\pi_{SPV}(TX)$.

Parameters:

- * blockHash: The hash of the Bitcoin block where the transaction is expected to be included.
- * TX: The raw bytes of the Bitcoin transaction.
- * $\pi_{\mathsf{SPV}}(TX)$: The Merkle proof demonstrating the transaction's inclusion in the block.

Returns:

* bool: true if the transaction is successfully verified as part of the block's Merkle tree, false otherwise.

- 1. MR Calculation: The function first computes a calculatedMerkleRoot by processing the provided TX and $\pi_{SPV}(TX)$.
- 2. Block MR Retrieval: It then retrieves the canonical blockMerkleRoot associated with the given blockHash from the contract's stored block headers.

3. Return: Finally, the function compares the calculatedMerkleRoot with the blockMerkleRoot. The boolean result of this comparison is returned, indicating whether the transaction's inclusion in the block is valid.

Chapter 5

Loan contract specification

createLoanOffer(S)

Purpose: This function facilitates the creation of a new loan offer by a lender.

Internal Steps:

•

- 1. **Parameter Validation:** The function validates all input parameters, specifically:
 - ensuring that $a_min \le a_max$.
 - confirming the correct order of liquidation ratios: $LR_B \leq CR \leq LR_L$.
 - verifying that periods N, IP, IRP are all strictly positive values.
 - ensuring that the lender's associated key P_L and node ID Inid_L are non-zero.
 - validating the installment response period (IRP) by checking that $4 \times IRP \leq IP$.
- 2. **State Persistence:** The function initializes and stores the following key parameters within the contract's storage, forming the immutable state of the loan offer:

$\texttt{min_collateral_amount} = a_min,$	$\texttt{security_deposit} = c,$
$max_collateral_amount = a_max,$	$\texttt{interest_rate} = k,$
$\texttt{collateralization_ratio} = CR,$	$\texttt{installments_count} = N,$
${\tt installment_period} = IP,$	$\texttt{response_penalty} = RP,$
$\verb"installment_response_period" = IRP,$	$\texttt{lender_key} = P_L,$
$\texttt{first_installment_deadline} = T_0,$	$\mathtt{lnid}_{-}\mathtt{l} = lnid_L,$
$\texttt{oracle} = \mathcal{O},$	$lr_b = LR_B,$
$lr_l = LR_L.$	

- 3. Lender Penalty Deposit: The lender is required to transfer an amount of USD, equivalent to the specified responsePenalty, to the contract. This transfer serves as a commitment associated with the offer.
- 4. **Event Emission:** An LoanOfferCreated(offer_id) event is emitted.

requestLoan(B)

Purpose: This function allows a **borrower** to formally request a loan against an existing, available loan offer.

- 1. **Parameter Validation:** The function first validates all provided input parameters. This includes:
 - ensuring that the Node ID Inid_B and public key or address P_B are non-zero.
 - confirming that the loan offer identified by **positionId** currently holds an *Offered* status.
 - verifying that the $a_min \le a \le a_max$ established by the offer.
 - checking that the remaining time until the T_0 is at least $2 \times IRP$.
- 2. Offer State Update: Upon successful validation, the internal state of the loan offer associated with positionId is updated. This involves changing its status to *Requested* and incorporating relevant borrower details.
- 3. **Borrower Penalty Deposit:** The **borrower** is required to transfer an amount of **USD** tokens, equivalent to the specified *RP*, to the contract. This transfer serves as a commitment associated with the loan request.
- 4. **Event Emission:** A LoanRequested(offer_id) event is emitted.

checkRequest(B)

Purpose: view-only validation of borrower's submitted parameters.

Internal Steps:

- 1. verify format and scripts of TX_fund and TX_commOB
- 2. check consistency with on-chain $\{a, b, c, k\}$

acceptLoan(offer_id, $TX_{comm0}^{L}, \sigma_{L_b}$)

Purpose: This function allows the **lender** to accept a loan request, thereby finalizing the loan offer and proceeding with the fund transfer.

Internal Steps:

- 1. **Parameter Validation:** The function first validates all provided input parameters. This includes:
 - ensuring that the loan offer identified by **positionId** currently holds a *Requested* status.
 - confirming that the transaction sender (msg.sender) is indeed the original creator of the loan offer (i.e., the lender associated with positionId).
 - checking that the remaining time until the T_0 is at least one *IRP*.
 - verify σ_{L_b} over $\mathsf{TX}_{\mathsf{comm0}}^{\mathsf{B}}$ recovers P_L .
- 2. Offer State Update: Upon successful validation, the provided σ_{L_b} and $\mathsf{TX}^{\mathsf{B}}_{\mathsf{comm0}}$ are stored within the offer's state. Subsequently, the status of the loan offer associated with positionId is updated to "Accepted".
- 3. **Loan Amount Calculation and Transfer:** The actual *b* is calculated as follows: $b = \frac{a \times BTC_price}{CR}$. The b + c is then transferred from the lender to the contract.
- 4. **Event Emission:** A LoanAccepted(offer_id) event is emitted.

openChannel(offer_id, σ_{B_l} , $\pi_{SPV}TX_fund$))

Purpose: This function enables the **borrower** to finalize the loan offer, confirming the on-chain collateralization.

- 1. **Parameter Validation:** The function first validates all provided input parameters. This includes:
 - ensuring that the loan offer identified by positionId currently holds an *Accepted* status.
 - confirming that the transaction sender (msg.sender) is indeed the borrower associated with positionId.
 - verifying that this function call occurs before the T_0 .
 - utilizing an SPV (Simplified Payment Verification) contract to verify $\pi_{SPV}(TX_fund)$, confirming that the required collateral transaction has been successfully recorded on the BTC network.
- 2. Offer State Update: Upon successful validation, the provided σ_{B_l} is stored within the offer's state. Subsequently, the status of the loan offer associated with positionId is updated to *Opened*.
- 3. **Fund Transfer:** The contract transfers the total amount b + RP to the borrower's address.
- 4. **Event Emission:** A ChannelOpened(offer_id) event is emitted.

payInstallment(offer_id, $TX^B_comm_i$)

Purpose: This function enables the borrower to make a scheduled repayment for an active loan installment.

Internal Steps:

- 1. **Parameter Validation:** The function first validates all provided input parameters. This includes:
 - ensuring that the loan offer identified by **positionId** currently holds an *Opened* status.
 - confirming that the transaction sender (msg.sender) is indeed the borrower associated with positionId.
 - verifying that there are no outstanding or unfinished previous installments for this loan.
 - checking that the remaining time until the deadline of the current installment is at least $3 \times IRP$.
- 2. **Installment State Update:** The function marks the current installment as paid and stores the provided $TX^B_comm_i$ within the offer's state. Subsequently, the status of the current installment is updated to *PaidInstallment*.
- 3. Installment Amount Transfer: The borrower is required to transfer the calculated installmentAmount to the contract. The installmentAmount is determined by the following formula:

$$\texttt{installmentAmount} = \frac{b}{N} + (b \times k)$$

4. **Event Emission:** An InstallmentPaid(offer_id, installment_id) event is emitted.

takeInstallment(offer_id, $\sigma_{L_{bi}}$, TX^{L} _comm_i)

Purpose: This function allows the **lender** to claim the principal and interest of a successfully paid installment.

- 1. **Parameter Validation:** The function first validates all provided input parameters. This includes:
 - ensuring that the loan offer identified by **positionId** currently holds an *Opened* status.
 - confirming that the msg.sender is indeed the lender associated with positionId.
 - verifying that the status of the current installment is *PaidInstallment*.
 - checking that the remaining time until the current installment's deadline is at least $2 \times IRP$.
- 2. Installment State Update: The function updates the status of the current installment to *TookInstallment* and stores the provided $\sigma_{L_{bi}}$ and $TX^{L}_comm_{i}$ within the offer's state.
- 3. **Event Emission:** An InstallmentAccepted(offer_id, installment_id) event is emitted.

revealRevocationKeyBorrower(offer_id, σ_{B_l} , PRK_b)

Purpose: This function enables the **borrower** to disclose their borrowerPrevRevocationKey (PRK_b) for the current installment, an essential step in the loan's lifecycle.

Internal Steps:

- 1. **Parameter Validation:** The function first validates all provided input parameters. This includes:
 - ensuring that the loan offer identified by positionId currently holds an *Opened* status.
 - confirming that the msg.sender is indeed the borrower associated with positionId.
 - verifying that the status of the current installment is *TookInstallment*.
 - checking that the remaining time until the current installment's deadline is at least *IRP*.
- 2. **Installment State Update:** The function updates the status of the current installment to *BorrowerRevocationKey* and stores the provided σ_{B_l} and *PRK*_b within the offer's state.
- 3. **Event Emission:** A BorrowerRevocationKeyRevealed(offer_id, installment_id) event is emitted.

revealRevocationKeyLender(offer_id, PRK_l)

Purpose: This function enables the **lender** to disclose PRK_l , which is the final step to formally complete the current installment and potentially the entire loan.

- 1. **Parameter Validation:** The function first validates all provided input parameters. This includes:
 - ensuring that the loan offer identified by positionId currently holds an *Opened* status.
 - confirming that the msg.sender is indeed the lender associated with positionId.
 - verifying that the status of the current installment is *BorrowerRevocation-Key*.

- checking that this function call occurs before the deadline of the current installment.
- 2. Installment and Offer State Update: The function updates the status of the current installment to *LenderRevocationKey* and stores the provided PRK_l within the offer's state. If this particular installment is determined to be the final one in the loan sequence, the overall status of the loan offer is then updated to *Successful*.
- 3. **Fund Transfer:** The contract transfers the installmentAmount to the lender's address.
- 4. **Event Emission:** A LenderRevocationKeyRevealed(offer_id, installment_id) event is emitted.

Chapter 6

A single-sided liquidity aggregation

WIP

6.1 Staker Registration & TSS Recomposition

We can extend the basic loan-channel construction by introducing a dynamic set of *stakers* who jointly manage the *liquidity pool* via a threshold signature. Let:

- \mathcal{A} : active staker list, $|\mathcal{A}| \leq N$.
- *stake*_{min}: minimum stake amount for participation.
- Δ : base increment for computing stake levels.
- $coef_k$: coefficient for the k-th staker such that $stake_k = stake_{\min} + coef_k \cdot \Delta$.
- T_0 : global timelock after which new stakers may no longer join.
- t_{epoch} : duration of one epoch for join/leave requests.
- Δt : duration of the TSS recomposition window at each epoch's end.

During each epoch:

- i) Collect join/leave requests; maintain a waiting list sorted descending by stake.
- ii) While $|\mathcal{A}| < N$, move the highest waiting candidate into \mathcal{A} (locking their stake).
- iii) If $|\mathcal{A}| = N$ and new candidates exist, compare the smallest $stake_i$ in \mathcal{A} with the highest in the waiting list; if the new stake is larger, evict the least staker and promote the candidate.

At the end of each epoch, the contract initiates a TSS recomposition round over \mathcal{A} :

- i) Sort \mathcal{A} by decreasing stake.
- ii) Request each staker to participate in the TSS DKG and signing process.
- iii) If a staker fails to respond within Δt :
 - Identify the non-responder and move them to the waiting list (unlocking their funds).
 - Promote the top waiting candidate into \mathcal{A} (locking their stake).
 - Recompute all weights

$$w_i = \frac{stake_i}{\sum_{j \in \mathcal{A}} stake_j}, \quad i = 1, \dots, |\mathcal{A}|,$$

and rerun the DKG until a full set of N participants completes.

iv) When N responsive stakers produce the TSS key, finalize the new aggregate key and record the weights.

6.2 Loan Acceptance & Channel Creation

When the borrower decides to take a loan (before T_0), they open a Lightning-style channel. The funding outputs to the $n = |\mathcal{A}|$ stakers are split according to their stakes:

$$\begin{aligned} \mathsf{TX}^B_{\operatorname{comm}_0} &: \{ (\mathsf{TX}_{\mathsf{fund}}, 0, (-, -)); \ (0\ddot{\mathbb{B}}, (addr_B \wedge LT_B) \lor (P_{\operatorname{agg}} \wedge P_B^{\operatorname{rev}_0})), \\ & (a_1\ddot{\mathbb{B}}, addr_{L_1}), \dots, (a_n\ddot{\mathbb{B}}, addr_{L_n}) \}, \\ \mathsf{TX}^L_{\operatorname{comm}_0} &: \{ (\mathsf{TX}_{\mathsf{fund}}, 0, (-, -)); \ (a_1\ddot{\mathbb{B}}, (addr_{L_1} \wedge LT_{L_1}) \lor (P_B \wedge P_{L_1}^{\operatorname{rev}_0})), \\ & \dots, \ (a_n\ddot{\mathbb{B}}, (addr_{L_n} \wedge LT_{L_n}) \lor (P_B \wedge P_{L_n}^{\operatorname{rev}_0})), \ (0\ddot{\mathbb{B}}, addr_B) \}, \end{aligned}$$

where each

$$a_i = \frac{stake_i}{\sum_{j \in \mathcal{A}} stake_j} \cdot a, \quad i = 1, \dots, n,$$

and a_i is decremented proportionally with each borrower repayment.

6.3 Staker Participation Penalty Mechanism

Each staker $i \in \mathcal{A}$ maintains a failure counter $f_i \in \mathbb{N}$, initially zero. At every TSS recomposition or signing epoch:

- 1. On timely valid response, set $f_i \leftarrow 0$.
- 2. Otherwise, $f_i \leftarrow f_i + 1$:
 - If $f_i = 1$, fine 10% of their stake: $stake_i \leftarrow 0.9 stake_i$.
 - If $f_i \geq 2$, remove *i* from \mathcal{A} and forfeit remaining $stake_i$.

```
Algorithm 3 Enforcing Participation Penalties
```

```
Require: Active set \mathcal{A} with \{stake_i, f_i\}
 1: for all i \in \mathcal{A} do
         if valid response from i then
 2:
 3:
              f_i \leftarrow 0
         else
 4:
              f_i \leftarrow f_i + 1
 5:
              if f_i = 1 then
 6:
 7:
                  stake_i \leftarrow 0.9 \times stake_i
 8:
              else if f_i \geq 2 then
                  remove i; forfeit stake_i
 9:
              end if
10:
         end if
11:
12: end for
```

 \triangleright 10% fine

6.4 Multi-Borrower Support

To accommodate sequential borrowers B_1, B_2, \ldots , the same LoanContract stores a mapping of channel states per borrower. Upon borrower B_j drawing amount b_j :

for each
$$i \in \mathcal{A}$$
: $stake_i \leftarrow stake_i - \frac{stake_i}{\sum_{k \in \mathcal{A}} stake_k} \cdot b_j$,

then:

- i) Remove all i with $stake_i < stake_{\min}$ (unlock their funds).
- ii) At epoch end, accept new stakers as usual using the updated $stake_i$ values.

iii) Recompose the TSS key using the epoch procedure over the updated \mathcal{A} .

In the base protocol, the loan contract provides a single registerChannel entry point:

registerChannel $(TX_{fund}, \pi_{SPV}, LT_B, LT_L)$

which locks (b + c) USD and records one borrower's channel. To allow multiple borrowers B_1, B_2, \ldots to draw sequential loans from the same contract, we simply generalize:

- Internally maintain a list (or mapping) of $ChannelState_j$ for each borrower B_j .
- The same registerChannel function appends a new *ChannelState_j* rather than blocking further calls.
- All funding TX, SPV proof, locktimes, principal b_j , deposit c_j are stored under j.

No separate contract is required: one LoanContract can safely host all sequential borrowers, provided it enforces that each $\sum_j b_j \leq \Sigma$ (the total available USD) and manages each channel's lifecycle independently.

6.4.1 On-chain Call Flow for Borrower B_i

- 1. requestLoan $(B_j, a_j, T0_j, TX_{fund}^j, TX_{comm0}^j)$: borrower B_j pays no on-chain value; they register their pre-agreed funding and initial commitment TXs.
- 2. acceptLoan(σ_L^j, c_j): lender confirms by providing the signed channel commitment and locking $(b_j + c_j)$ USD.
- 3. finalizeLoan($\sigma_B^j, \pi_{SPV}(TX_{fund}^j)$): borrower proves funding on Bitcoin and receives b_j USD.

Each of these calls reads/writes only that borrower's $ChannelState_j$, so multiple borrowers can coexist.

6.5 Signer Identification during TSS Key Generation

To precisely identify non-responders (malicious or offline) during the TSS DKG for public key creation, we record each phase's contributions. Let \mathcal{M} be the set of identified non-responders.

Algorithm 4 Identifying Malicious Stakers in TSS DKG

Require: Active set \mathcal{A}	
1: $\mathcal{M} \leftarrow \emptyset$	\triangleright Initialize malicious set
2: for all $i \in \mathcal{A}$ do	
3: if commitment _i not received or invalid then	
4: $\mathcal{M} \leftarrow \mathcal{M} \cup \{i\}$; remove <i>i</i> from \mathcal{A}	
5: else	
6: record valid commitment _{i}	
7: end if	
8: end for	
9: for all $i \in \mathcal{A}$ do	
10: if share _{i} not received or fails verification then	
11: $\mathcal{M} \leftarrow \mathcal{M} \cup \{i\}$; remove <i>i</i> from \mathcal{A}	
12: $else$	
13: record valid share _{i}	
14: end if	
15: end for	
16: for all $i \in \mathcal{M}$ do	
17: move i to waiting list, take fine	
18: promote top candidate into \mathcal{A} ; lock their stake	
19: recompute weights and rerun DKG until $ \mathcal{A} = N$	
20: end for	
21: Finalize TSS public key over remaining \mathcal{A}	

Chapter 7

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