A Distributed Scalable Cross-chain State Channel Scheme Based on Recursive State Synchronization

Xinyu Liang, Ruiying Du, Jing Chen, Yu Zhang, Meng Jia, Shuangxi Cao, Yufeng Wei, Shixiong Yao

Abstract-As cross-chain technology continues to advance, the scale of cross-chain transactions is experiencing significant expansion. To improve scalability, researchers have turned to the study of cross-chain state channels. However, most of the existing schemes rely on trusted parties to support channel operations. To address this issue, we present Interpipe: a distributed cross-chain state channel scheme. Specifically, we propose a real-time crosschain synchronization scheme to ensure consistent operations between two blockchains to a cross-chain state channel. Moreover, we propose a batch transaction proof scheme based on recursive SNARK to meet the cross-chain verification needs of large-scale users. Based on the above designs, Interpipe offers protocols for opening, updating, closing, and disputing operations to crosschain state channels. Security analysis shows that Interpipe has consistency and resistance, and experimental results demonstrate that a cross-chain state channel can be nearly as efficient as an existing intra-chain state channel.

Index Terms—Blockchain, Cross-chain Technology, State Channel

I. INTRODUCTION

Blockchain [1] offers a secure and transparent way to record and verify transactions without the need for a central authority. In recent years, distributed trust systems centered around blockchains have been forming at an unprecedented pace. The application areas [2] of blockchain have expanded from the traditional cryptocurrency domain [1] [3] to various fields such as healthcare [4], supply chain [5], and cloud service [6]. However, while enriching the blockchain ecosystem, these blockchains are isolated from each other, hindering the flow of information and value. To solve the isolation problem, crosschain technology [7] enables different blockchain networks to communicate and interact with each other, which is invaluable for connecting the decentralized Web 3.0.

The existing cross-chain schemes can be classified into two categories, which are non-relay-based scheme and relaybased scheme. The non-relay-based scheme appeared in the early stage of cross-chain technology. It relies on external

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components to achieve cross-chain operations, such as decentralized exchanges [8] based on notaries, and atomic crosschain swaps [9] based on hashed time-lock contract [10]. However, non-relay-based schemes do not have the transfer of state information between blockchains, therefore limiting their functionality to relatively simple cross-chain operations. In a relay-based scheme [11] [12] [13] [14] [15] [16] [17], blockchains transfer their state information to each other by using a cluster of relay nodes. Based on the state information, a party of a blockchain can directly verify the transactions in another blockchain to support more complex cross-chain operations, leading to the emergence of cross-chain platforms such as Polkadot [15] and Cosmos [16]. With the number of users on the platform increasing, the daily cross-chain transactions have extended to a considerable scale, which will eventually exceed the blockchain throughput limit [18], resulting in a scalability issue.

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In previous intra-chain scenarios, the scalability issue can be solved by state channel [19] [20] [21] [22] [23] [24] [25] [26] [27]. In the most recent years, concerning the idea of state channel, researchers have begun to study the potential of cross-chain state channel between two blockchains, and move most cross-chain transactions into the channel for executions to share the blockchain throughput pressure. As far as we know, there are currently two papers [28] [29] that provide detailed designs. Specifically, Jia et al. propose cross-chain virtual payment channel [28] to achieve off-chain interactions between Ethereum and Bitcoin. Guo et al. propose Cross-Channel [29] to support cross-chain operations in both synchronous and asynchronous networks. However, these schemes rely on trusted parties to support channel operations, which are vulnerable in a distributed environment. To achieve a distributed cross-chain state channel, we are still facing two critical challenges.

- Consistent Operation: Two blockchains must synchronize their state information to ensure consistent operations within a cross-chain state channel. However, in most existing schemes, cross-chain synchronizations are non-real-time, leaving room for third parties or intermediaries to arbitrarily delay or interrupt the synchronization process. This can lead to situations where two blockchains have different operations within one cross-chain state channel, posing a security threat.
- Scalable Verification: Operations within cross-chain state channels require blockchain nodes to efficiently verify transactions on another blockchain. However, most of the existing schemes focus on verifying specific

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individual transactions. When the scale of the transactions becomes large, the cross-chain verifications will incur significant costs, which cannot satisfy the growing demands of users.

In this paper, we present Interpipe: a distributed crosschain state channel scheme. To ensure consistent operations, we introduce a real-time cross-chain synchronization scheme. Specifically, our approach involves the adoption of a state pulling strategy to retrieve the latest state from one blockchain and generate the corresponding state proof to be recorded in another blockchain. This process operates recursively in the background as the blockchain expands, a method we refer to as recursive state synchronization. As a result, two blockchains can synchronize their real-time state proofs with each other. Based on state synchronization, we achieve transaction synchronization. It enables the recording of one transaction ct into two blockchains, while maintaining their consistency based on the real-time state proofs of each other. In the subsequent discussion, ct is referred to as a cross-chain transaction. Subsequently, cross-chain transactions can be published on both blockchains to facilitate the operations of opening, updating, closing, and disputing within a cross-chain state channel.

To facilitate scalable verification, we propose a batch transaction proof scheme based on recursive SNARK. Specifically, within the system of blockchain \mathbf{P}_i , a prover aggregates every cross-chain transaction in \mathbf{P}_i into a one-way accumulator and binds this accumulator with the current state proof of \mathbf{P}_i using zk-SNARK. Notably, we leverage the recursively generated data structure of the blockchain to implement recursive SNARK, thereby reducing the computational cost of generating the state proof. On the other hand, within the blockchain system \mathbf{P}_j , a verifier first verifies the correctness of the accumulator based on the state proof of \mathbf{P}_i . Subsequently, each cross-chain transaction in \mathbf{P}_i can be efficiently verified based on the accumulator. Therefore, the batch proof system caters to the verification needs of any cross-chain transaction, meeting the large-scale requirements of users.

In general, we have the following contributions.

- Interpipe represents the first distributed cross-chain state channel scheme. To the best of our knowledge, existing cross-chain state channel schemes rely on trusted parties to support channel operations, which introduces security vulnerabilities.
- 2) To achieve consistent operations, we propose a real-time cross-chain synchronization scheme. This enables us to record one cross-chain transaction into two blockchains and ensure their consistency. Subsequently, we carry out operations of opening, updating, closing, and disputing within a cross-chain state channel.
- 3) To achieve scalable verification, we propose a batch transaction proof scheme based on recursive SNARK. This approach allows a verifier within a blockchain system to efficiently verify any cross-chain transaction in another blockchain.
- We conduct a security analysis of Interpipe. Additionally, we implement a proof-of-concept prototype and evaluate the performance of Interpipe.

This paper is organized as follows. In Section II, we review the existing works related to cross-chain scheme, state channel, and transaction verification. We describe the building blocks of our scheme in Section III, and give a description about the system model, threat model, and design goals in Section IV. We illustrate the batch transaction proof in Section V, and describe the details of Interpipe in Section VI. We analyze the security properties of our scheme in Section VII, and describe the implementation of our prototype in Section VIII. Finally, we conclude in Section IX.

II. RELATED WORK

A. Cross-chain Scheme

As illustrated in Fig. 1, the existing cross-chain schemes can be classified into two categories: non-relay-based schemes and relay-based schemes. In a non-relay-based scheme, two blockchains do not transfer their state information to each other but rely on external components to achieve cross-chain operations. For example, decentralized exchanges [8] use a notary committee as a third party to exchange users' tokens in one blockchain for tokens in another blockchain. Moreover, atomic cross-chain swaps [9] are achieved by using hashed time-lock contract [10]. However, as a non-relay-based scheme does not transfer blockchain state information, the scheme can only support simple cross-chain operations with a low security guarantee.

In a relay-based scheme, two blockchains transfer their state information to each other by using a cluster of relay nodes. The relay-based scheme was first illustrated by Back et al. [11] in 2014. BTC Relay [12] is a representative implementation. It sends the Bitcoin block headers to the Ethereum smart contract, achieving cross-chain verification of Bitcoin transactions. Based on BTC Relay, Alexei et al. [13] propose XClaim. It achieves trustless cross-chain exchanges using cryptocurrencybacked assets and employs collateralization and punishments to enforce the correct behavior of participants. To further improve efficiency, Xie et al. [14] propose zkBridge. It introduces zk-SNARK to generate the state proof of blockchain. By this act, the state information can be compressed into a small proof to be transferred between blockchains, reducing the overhead of transmission and storage.

The early relay-based schemes mainly focus on the interaction between two blockchains, which is also called oneto-one framework. If a blockchain intends to interact with n blockchains, it has to establish n cross-chain connections, which is inefficient. To solve this problem, the relay nodes cluster begins to establish connections with multiple blockchains, called *parachains* (parallel blockchains). Besides, the relay nodes maintain a blockchain, called *relay chain*, by themselves to record the state information from every parachain. At the same time, relay chain is published to every parachain system. Subsequently, a parachain can obtain the states of other parachains by only accessing relay chain. Based on this relay-chain-parachain framework, a parachain only needs to establish one cross-chain connection with relay chain to interact with n parachains that also connect with relay chain, to improve efficiency.



Fig. 1: Categories of cross-chain schemes

The existing cross-chain platforms such as Polkadot [15] and Cosmos [16] are constructed following the relay-chainparachain framework. As mentioned in Section I, these platforms are required to support the cross-chain needs of largescale users with numerous cross-chain transactions per day. However, in previous cross-chain platforms, the cross-chain synchronizations between blockchains are non-real-time. It results that a blockchain cannot learn the latest states of another blockchain on the platform within a certain time limit, as the blockchain features a dynamically growing data structure with continuously updating states. To solve the problem, Liang et al. [17] propose a cross-chain state pulling scheme, called XPull. The relay nodes cluster will periodically pull the latest state information from parachains, and forward the state information to other parachain systems, which achieves real-time state transfer to ensure timeliness.

B. State Channel

In 2016, Joseph et al. proposed payment channel [19] to improve the scalability of Bitcoin. In the following works, the payment channel is beginning to develop in two directions, as shown in Fig. 2. The first direction is payment channel network [19], noted PCN. It enables the delivery of assets between two users U_1 and U_n by using a path of payment channels in PCN. In the following works, researchers have further improvements to payment channel network from various perspectives. For example, Giulio et al. [20] propose Fulgor to ensure privacy by using multi-hop hashed time-lock contract. Christoph et al. [21] propose the protocol AMCU for atomic multi-channel updates by jointly creating a multiple-input-multiple-output (MIMO) transaction. Lukas et al. [22] further propose Thora to refine atomicity, in which Thora is compatible with a number of cryptocurrencies having arbitrary payment channel topologies. Lukas et al. [23] propose Sleepy Channel, which does not require either of the channel users to be persistently online. Papadis et al. [24] propose single-hop scheduling (SHS), which provides a decision-making scheme for the users in payment channel network to maximize channel throughput.

The second direction is virtual payment channel [25]. Based on the current two channels, noted as (U_1, U_2) and (U_2, U_3) , the users U_1 and U_3 can establish a virtual payment channel (U_1, U_3) to have direct interaction. Next, virtual payment channel technology has derived the design of multi-party virtual channel (MPVC) [26]. It means that more than two users can interact within a channel, supporting more complex off-chain operations. Furthermore, Lukas et al. propose bitcoin-compatible virtual channel (BCVC) [27] to improve the compatibility. In the most recent work, Jia et al. propose a



Fig. 2: Categories of payment channel

scheme (CCVPC) [28] to achieve cross-chain virtual payment channel (U_1, U_3) , based on (U_1, U_2) and (U_2, U_3) in different blockchain systems. However, this design cannot resist the conspiracy attack of U_1 , U_2 , and U_3 , posing a security threat.

Moreover, with the extension of blockchain application scenarios from cryptocurrencies to other fields, the operations of transferring tokens within a channel have been generalized into a channel's state change [30], in which the previous "payment channel" has evolved into "state channel". Nowadays, state channels have been applied in various fields, such as log audit [31], data sharing [32], and video streaming [33].

C. Transaction Verification

The transaction verification schemes of blockchain can be classified into two categories. The first category is based on the well-known Merkle tree [34], applied by Bitcoin. Subsequently, researchers improve the Merkle tree and propose Merkle Patricia tree, applied by Ethereum [3]. It introduces prefix tree to enhance the efficiency of data storage and retrieval.

The second category is based on one-way accumulator. In 1993, Benaloh et al. [35] first constructed the accumulator based on the one-way hash function which satisfies a quasicommutative property. An accumulator allows a prover to hash the transactions in a blockchain into one short value, which supports efficient cross-chain transfer. Niko et al. [36] further generalize the definition of accumulators and construct a collision-free subtype. Jan et al. [37] propose dynamic accumulator that allows a prover to dynamically add and delete an element in the accumulator. In recent works, Boneh et al. [38] propose batching techniques for cryptographic accumulators, which achieve membership proof and non-membership proof of transactions in blockchain. As the accumulators are well compatible with zk-SNARK, the existing anonymous cryptocurrency schemes, such as Zcash [39] [40], adopt accumulators for transaction retrieval.

III. PRELIMINARY

A. Notation

To facilitate the understanding, we summarize the main notations in this paper in TABLE I.

B. Cross-chain State Transfer

The relay-chain-parachain framework is widely used in cross-chain platforms [15] [16] to meet the cross-chain needs of multiple blockchains.

TABLE I: Notations

Notation	Meaning		
R	relay chain		
\mathbf{P}_i	<i>i</i> -th parachain		
n	number of parachains on a cross-chain platform		
N^R	set of nodes which maintain relay chain		
N_i^P	set of nodes which maintain the <i>i</i> -th parachain		
$N_i^{R\sim}$	subset of N^R to interact with N^P_i		
π^i	zero knowledge proof of the state of \mathbf{P}_i		
A^i	accumulator for every cross-chain transaction in \mathbf{P}_i		
ct	cross-chain transaction		
$w^{ct,i}$	membership witness of ct in \mathbf{P}_i		

There are *n* parachains $\{\mathbf{P}_1, \ldots, \mathbf{P}_n\}$ and one relay chain \mathbf{R} in the framework. Each parachain \mathbf{P}_i $(i \in [n])$ is maintained by a set of parachain nodes N_i^P and the relay chain \mathbf{R} is maintained by a set of relay nodes N^R . Moreover, N^R are divided into *n* relay node groups $\{N_1^{R^{\sim}}, \ldots, N_n^{R^{\sim}}\}$ and $\forall \{i, j\} \subseteq \{1, \ldots, n\} \land i \neq j, N_i^{R^{\sim}} \cap N_j^{R^{\sim}} = \emptyset$. The relay node group N_i^R establish network connections with N_i^P to start the cross-chain state transfer, which includes two processes of state reception and state forwarding.

In the *state reception* process, the relay node groups $N_i^{R\sim}$ $(i \in [n])$ receive the state information of \mathbf{P}_i from N_i^P , and record the information into \mathbf{R} to be published to every entity on the cross-chain platform. In the *state forwarding* process, N_j^P $(j \in [n], i \neq j)$ extract the state information of \mathbf{P}_i from \mathbf{R} , and record the information into \mathbf{P}_j . Therefore, by only accessing \mathbf{P}_j , any entity in \mathbf{P}_j system can obtain the state information of \mathbf{P}_i , supporting cross-chain operations.

Furthermore, to ensure the timeliness of \mathbf{P}_i state information in \mathbf{R} , the relay node group $N_i^{R\sim}$ adopts a state pulling strategy [17]. $N_i^{R\sim}$ periodically send the state pulling instructions to N_i^P to pull the latest state information of \mathbf{P}_i , and subsequently record the state information into \mathbf{R} . Moreover, when an adversary has corrupted $N_i^{R\sim}$ to interrupt the state pulling, a new relay node group $N_i^{*R\sim}$ will be randomly selected from N^R based on distributed randomness [41] generated by N^R . $N_i^{*R\sim}$ will replace $N_i^{R\sim}$ to continue the state pulling, ensuring \mathbf{P}_j to record the real-time state information of \mathbf{P}_i .

C. One-way Accumulator

An accumulator [35] [36] [38] enables one to encode a set into a short digest and prove that an element is in the set. Let D be the domain of an accumulator. An accumulator $\mathcal{ACC} = (Setup, Commit, Add, CreateMemWit, VerifyMem)$ consists of the following five algorithms.

- Setup(1^λ) → pp: Given a security parameter λ, this setup algorithm outputs a public parameter pp.
- Commit(pp, S) → A^S: Given the public parameter pp and a set S ⊆ D, this committing algorithm outputs an accumulator digest A^S to the set S.
- Add(A^S, ct) → A^{S∪{ct}}: Given an accumulator digest A^S to a set S and an element ct ∈ D \ S, this adding algorithm outputs a new accumulator digest A^{S∪{ct}} to the set S ∪ {ct}.

- CreateMemWit $(S, A^S, ct) \rightarrow w^{ct,S}$: Given a set S, an accumulator digest A^S to the set S, and an element $ct \in S$, this witness creation algorithm outputs the membership witness $w^{ct,S}$ of $ct \in S$.
- VerifyMem(A^S, ct, w^{ct,S}) → b: Given an accumulator digest A^S to a set S, an element ct, and a membership witness w^{ct,S}, this membership verification algorithm outputs a bit b ← 1 to indicate that w^{ct,S} is a valid witness for proving ct ∈ S; otherwise outputs b ← 0.

D. Zero-knowledge Proof

The zero-knowledge proof (ZKP) scheme [42] [14] enables one to prove a statement without exposing other information. The ZKP scheme ZKP = (Setup, Prove, Verify) consists of the following three algorithms.

- Setup(1^μ, R) → crs: Given a security parameter μ and a relationship R, this setup algorithm outputs a common reference string crs.
- Prove(crs, x, w) → π: Given a common reference string crs, a statement x, and a witness w, this proving algorithm outputs a proof π for the relationship R(x, w).
- Verify(crs, x, π) → b: Given a common reference string crs, the statement x, and the proof π, this verification algorithm outputs a bit 1/0 to indicate whether R(x, w) holds or not.

ZKP satisfies three properties. *Completeness*: if the witness being proved is true, the verifier will be convinced of this fact with high probability. *Soundness*: if the witness being proved is false, no cheating prover can convince the verifier that it is true, except with a negligible probability. *Zero-knowledge*: the proof does not reveal any information about the witness being proved, except for the fact that it is true.

IV. PROBLEM STATEMENT

A. System Model

Interpipe includes one relay chain \mathbf{R} , and two parachains \mathbf{P}_l and \mathbf{P}_r called left parachain and right parachain. \mathbf{P}_l and \mathbf{P}_r have established cross-chain connections with \mathbf{R} on a crosschain platform, following relay-chain-parachain framework. The state information of \mathbf{P}_l and \mathbf{P}_r is synchronized into each other in the following way (see Fig. 3): $(\mathbf{D} \ \mathbf{N}_l^{R^{\sim}})$ and $\mathbf{N}_r^{R^{\sim}}$ divided from \mathbf{N}_l^{R} pull the latest state information of \mathbf{P}_l and \mathbf{P}_r from \mathbf{N}_l^{P} and \mathbf{N}_r^{P} using state pulling strategy; $(\mathbf{D} \ \mathbf{N}_l^{R^{\sim}})$ and $\mathbf{N}_r^{R^{\sim}}$ generate the state proofs of \mathbf{P}_l and \mathbf{P}_r , and record the state proofs into \mathbf{R} ; (\mathbf{S}) as \mathbf{R} is public on the cross-chain platform, \mathbf{N}_r^{P} and \mathbf{N}_l^{P} extract the \mathbf{P}_l and \mathbf{P}_r state proofs from \mathbf{R} , and record them into \mathbf{P}_r and \mathbf{P}_l , achieving a synchronization.

There are two users Alice and Bob. On the one side, Alice belongs to \mathbf{P}_l system. She can access the network of N_l^P to obtain the full blockchain data of \mathbf{P}_l , or publish new transactions on \mathbf{P}_l via N_l^P . Since the state proof of \mathbf{P}_r has been recorded into \mathbf{P}_l , Alice can verify the state or transactions in both \mathbf{P}_l and \mathbf{P}_r by only accessing \mathbf{P}_l . In the same way, Bob belongs to \mathbf{P}_r system, and he can verify the state or transactions in both \mathbf{P}_l and \mathbf{P}_r by only accessing



Fig. 3: System model of Interpipe

 \mathbf{P}_r . Additionally, a communication connection is established between Alice and Bob to transmit signatures and membership witnesses of transactions. This communication connection is off-chain, which does not require the use of any blockchain network. Based on the above configurations, a cross-chain state channel is established between Alice and Bob.

It is worth noting that among the *n* parachains on the crosschain platform, any two parachains can establish cross-chain state channels in the same way as parachain \mathbf{P}_l and \mathbf{P}_r . For convenience, we specifically discuss a cross-chain state channel between \mathbf{P}_l and \mathbf{P}_r in the following content.

B. Threat Model

- *Hard fork*: Hard fork can occur in a blockchain to result in a split from the original chain and the creation of a new separate chain.
- *Denial-of-service attack*: With a sufficiently long period of time, an adversary can control every node in a relay node group to interrupt the information synchronization between parachains.
- *Replay attack*: An adversary can replay cross-chain transactions and state proofs, attempting to have duplicate operations to cross-chain state channel.
- *Counterfeiting*: An adversary can tamper the contents in cross-chain transactions and state proofs, attempting to synchronize false information between parachains.
- *Eclipse attack*: An adversary can create a fake network environment around a user, attempting to prevent the user from learning the new states of blockchains.
- Conspiracy attack: Alice and Bob can collude to publish different cross-chain transactions to \mathbf{P}_l and \mathbf{P}_r , attempting to create parachain data out of thin air.
- Noncooperation: One of Alice and Bob can refuse to cooperate with the other one, attempting to terminate the cross-chain transaction publication to P_l and P_r.

We assume the cryptographic primitives, including hash function and digital signature, of relay chain and parachains are secure. Moreover, the zero-knowledge proof algorithms can be deployed in distributed environment without trusted setup [42] [14].

As Interpipe establishes cross-chain state channels by the cooperation of three blockchains \mathbf{R} , \mathbf{P}_l , and \mathbf{P}_r , we assume the proportion of the corrupted consensus participators in each blockchain system is bounded by the threshold to ensure security. In the existing PoW [43] and PoS [44] protocol, it requires the proportion $\alpha < 1/3$.

Moreover, we assume that an adversary is mildly adaptive [44]. Specifically, for a group of honest nodes $\{node_1, \ldots, node_x\}$, the adversary cannot instantly corrupt every node in $\{node_1, \ldots, node_x\}$, and the corruption may only succeed after a sufficiently long period of time. Otherwise, the adversary possesses enough power to effortlessly control the majority of blockchain nodes, and overthrows the proportion $\alpha < 1/3$ or the security threshold in any node group.

Based on the above assumption, we can ensure persistence and liveness [45] of blockchain transactions. Moreover, we ensure a stable block time, as the block generation process is controlled by mining difficulty [46] in PoW consensus protocol or consensus slot [44] in PoS consensus protocol.

- Transaction persistence states that once a transaction goes more than k blocks deep into the blockchain of one honest consensus participator, it will be included in every honest participator's blockchain with overwhelming probability.
- *Transaction liveness* states that every transaction originating from an honest user will eventually end up at a depth of more than k blocks in an honest consensus participator's blockchain, and an adversary cannot perform a selective denial-of-service attack against the honest user.
- *Stable block time* states that the average time it takes for new blocks to be added to a blockchain remains consistent and predictable over an extended period.

C. Design Goals

- Consistency: Parachain \mathbf{P}_l and \mathbf{P}_r can synchronize the real-time state proofs of each other. A cross-chain transaction *ct* can be recorded into both \mathbf{P}_l and \mathbf{P}_r , with their consistency being kept.
- *Resistance*: It is hard for an adversary to interrupt the cross-chain synchronization between \mathbf{P}_l and \mathbf{P}_r . Resistance relies only on the security guarantees in \mathbf{R} , \mathbf{P}_l , and \mathbf{P}_r systems.
- *Liveness*: Any two users respectively located in \mathbf{P}_l and \mathbf{P}_r systems can have opening, updating, closing, and disputing to a cross-chain state channel.
- *Efficiency*: Any user in **R**, **P**_l, and **P**_r systems can have cross-chain verification to the state and transactions in **R**, **P**_l and **P**_r with low storage and computation overhead.

V. BATCH TRANSACTION PROOF

Batch transaction proof enables verifiers in \mathbf{P}_l or \mathbf{P}_r system to have verification to any cross-chain transaction in \mathbf{P}_r or \mathbf{P}_l with low storage and computation overhead. This scheme has three processes, which are initialization, recursive proving, and verification.

Initialization: The initialization is executed when relay chain **R** and parachains \mathbf{P}_i $(i \in [n])$ first establish crosschain connections on cross-chain platform. Specifically, the blockchain protocols of relay chain and parachains including data structure, encryption algorithm, and consensus mechanism are published to every entity on the cross-chain platform. Second, the identity information including public keys and blockchain addresses of blockchain nodes N^R , N_i^P $(i \in [n])$ are also published on the cross-chain platform, which will be used as the public statement x to verify new blocks and state proofs following the scheme in [42]. Moreover, the blockchain nodes generate public parameter $pp \leftarrow \mathcal{ACC}.\text{Setup}(1^{\lambda})$ and $crs \leftarrow \mathcal{ZKP}.\text{Setup}(1^{\mu}, R)$ for accumulator and zero knowledge proof in distributed environment.

Then, the group $N_l^{R^{\sim}}$ is divided from relay node set N^R to establish cross-chain connections with N_l^P , and pull the data of \mathbf{P}_l from N_l^P . $N_l^{R^{\sim}}$ generate the initial accumulator A_0^l , which can be the generator without adding elements. Moreover, $N_l^{R^{\sim}}$ generate the zero knowledge proof π_0^l of \mathbf{P}_l , which can be achieved by the existing scheme [14]. The tuple (A_0^l, π_0^l) is called the initial state proof of \mathbf{P}_l .

Noted, in the following content, we only illustrate the batch transaction proof of \mathbf{P}_l for convenience, while the proof of \mathbf{P}_r is generated by the same method of \mathbf{P}_l .

Recursive proving: Recursive proving is executed in rounds, which are a continuous series of time intervals with fixed length. The proving process in the *u*-th round includes three steps, which are updating accumulator, generating proof of new block, and updating state proof. The proof generation process is shown in Fig. 4.

① Updating accumulator. In the *u*-th round, there are multiple new \mathbf{P}_l blocks generated, noted as \mathbf{B}_u^l . The relay node group $N_l^{R\sim}$ pull \mathbf{B}_u^l from N_l^P , extract all cross-chain transactions \mathbf{T}_u^l from \mathbf{B}_u^l , and add \mathbf{T}_u^l into accumulator A_{u-1}^l to generate $A_u^l \leftarrow \mathcal{ACC}$.Add $(A_{u-1}^l, \mathbf{T}_u^l)$, where A_{u-1}^l is the accumulator in the (*u*-1)-th round. Noted, the ordinary intrachain transactions in \mathbf{B}_u^l which do not need to be cross-chain synchronized will not be extracted or added into the accumulator.

⁽²⁾ Generating proof of new blocks. $N_l^{R\sim}$ generate the zeroknowledge proof $\pi_u^{*r} \leftarrow \mathcal{ZKP}$. Prove $(crs, x, A_{u-1}^l, A_u^l, \mathbf{B}_u^l)$. The witness to be proved includes the following.

- There is a set of new parachain blocks \mathbf{B}_{u}^{l} . Every block in \mathbf{B}_{u}^{l} has the correct format with valid proof of work (in PoW protocol) or proof of stake (in PoS protocol). Every block in \mathbf{B}_{u}^{l} has a valid hash pointer pointing to the last block.
- Every cross-chain transaction in \mathbf{B}_{u}^{l} has been correctly included in the Merkle tree of the block in \mathbf{B}_{u}^{l} .
- Every cross-chain transaction in \mathbf{B}_{u}^{l} has been added in A_{u-1}^{l} to output A_{u}^{l} .

The above witness will be transformed into arithmetic circuits to be substituted into the proof process of zk-SNARK to output the proof π_u^{*r} .

③ Updating state proof. We have a recursive proof by using the recursive SNARK in Nova [42] to further generate



Fig. 4: Recursive proof of parachain

 $\pi_u^l \leftarrow \mathcal{ZKP}.$ Prove $(crs, x, \pi_{u-1}^l, \pi_u^{*l})$, in which π_{u-1}^l is the proof generated in the (u-1)-th round. By this step, the zero knowledge proof of \mathbf{P}_l is updated from π_{u-1}^l to π_u^l . Subsequently, we call (π_u^l, A_u^l) as the state proof of \mathbf{P}_l in the *u*-th round. More importantly, to obtain π_u^l , the prover only needs to calculate the arithmetic circuits in the new blocks \mathbf{B}_u^l and the proof π_{u-1}^l in the last round. The old blocks \mathbf{B}_x^l (0 < x < u) generated in the previous rounds do not need to be recalculated, as the witness of \mathbf{B}_x^l have been proved by π_{u-1}^l . Because the number of new blocks in a round is relatively small, the calculation to the arithmetic circuits can be completed in a short time.

Verification: On the side of \mathbf{P}_r , without accessing the original data of \mathbf{P}_l , verifiers will confirm the correctness of (π_u^l, A_u^l) by \mathcal{ZKP} . Verify $(crs, x, A_{u-1}^l, A_u^l, \pi_u^l)$. Specifically, there is a valid parachain \mathbf{P}_l , and every cross-chain transaction in \mathbf{P}_l has been added into A_u^l . The identities of the verifiers are \mathbf{P}_r node set \mathbf{N}_r^P and any user in \mathbf{P}_r system including Alice.

Based on A_u^l , verifiers in \mathbf{P}_r system can further verify that a certain cross-chain transaction ct has been recorded in \mathbf{P}_l . This requires a prover connecting with \mathbf{P}_l system to create the membership witness $w_u^{ct,l}$ of ct in A_u^l , where $w_u^{ct,l} \leftarrow \mathcal{ACC}$.CreateMemWit $(\mathbf{P}_l, A_u^l, ct)$, and send $w_u^{ct,l}$ to the verifiers. Based on $w_u^{ct,l}$, the verifiers have verification by \mathcal{ACC} .VerifyMem $(A_u^l, ct, w_u^{ct,l})$ to confirm that ct has been added into A_u^l , and consequently, ct has been recorded in \mathbf{P}_l .

By the above method, verifiers first need to have one verification to (π_u^l, A_u^l) to confirm the correctness of A_u^l . Then, based on A_u^l , the verifiers can verify any cross-chain transactions in \mathbf{P}_l . Each verification of a cross-chain transaction only requires one calculation of \mathcal{ACC} .VerifyMem $(A_u^l, ct, w_u^{ct,l})$, which can satisfy the demands of scalable cross-chain transaction verification.

VI. INTERPIPE

In this section, we first have an illustration of crosschain synchronization (see Section VI-A), which enables two parachains \mathbf{P}_l and \mathbf{P}_r to have consistent operations. Based on cross-chain synchronization, we provide designs for the cross-



Fig. 5: One round of state synchronization

chain state channel operations of opening, updating, closing, and disputing (see Section VI-B).

A. Cross-chain Synchronization

Cross-chain synchronization has two parts, which are state synchronization and transaction synchronization. First, state synchronization is the underlying design. It is recursively executed in rounds, enabling two parachains to keep real-time records of the state proofs of each other. Based on the realtime state proofs, we achieve transaction synchronization. It means that users can record one cross-chain transaction ct into the two parachains \mathbf{P}_l and \mathbf{P}_r , and keep their consistency.

1) State synchronization: First, state synchronization follows the initialization of batch transaction proof to generate the initial state proof (A_0^l, π_0^l) of \mathbf{P}_l (see line 2-11 in Protocol 1). Then, $\mathbf{N}_l^{R^{\sim}}$ record (A_0^l, π_0^l) into \mathbf{R} to start state synchronization. Because \mathbf{P}_l continues to grow over time, the \mathbf{P}_l state keeps updating. To keep the real-time \mathbf{P}_l state proof synchronized into \mathbf{P}_r , the state synchronization repeats at regular time intervals called rounds (see line 12-17 in Protocol 1). In the *u*-th round, the state information of \mathbf{P}_l and \mathbf{P}_r will be transferred and recorded into each other based on cross-chain state transfer [15] [16] with two processes of state reception and state forwarding. In the following content, we further design the two processes, and illustrate the information transfer from \mathbf{P}_l to \mathbf{P}_r , where the information transfer from \mathbf{P}_r to \mathbf{P}_l follows the same way.

In state reception process (see line 18-25 in Protocol 1), N_l^P transfer the state information of \mathbf{P}_l to $N_l^{R\sim}$. The state information is in the form of newly generated \mathbf{P}_l blocks in the *u*-th round, noted as \mathbf{B}_u^l . Then, $N_l^{R\sim}$ extract all cross-chain transactions \mathbf{T}_u^l which need to be cross-chain synchronized from \mathbf{B}_u^l , and add \mathbf{T}_u^l into A_{u-1}^l to generate A_u^l , where A_{u-1}^l is the accumualtor in the (*u*-1)-th round. Next, $N_l^{R\sim}$ generate the zero-knowledge proof π_u^l of the current \mathbf{P}_l by recursive proving (see Section V), where A_u^l is binded with π_u^l to have (π_u^l, A_u^l) as the state proof of \mathbf{P}_l . Then, $N_l^{R\sim}$ will record (π_u^l, A_u^l) into relay chain \mathbf{R} to be published on cross-chain platform.

Moreover, in the *u*-th round, $N_l^{R^{\sim}}$ use state pulling strategy [17] to pull \mathbf{B}_u^l from N_l^P . Therefore, every time there are new blocks generated in \mathbf{P}_l , the new blocks will be obtained by $N_l^{R^{\sim}}$ within a certain number of rounds. Subsequently, the time between the moment in which new blocks are generated and the moment in which new state proof is recorded into \mathbf{P}_r

Prototol 1. State Synchronization

StateSynchronization 1 // Initialization 2 N^R , N^P_i $(i \in [n])$: publish blockchain protocols 3 and identity information $\mathbb{N}^{R}, \mathbb{N}^{P}_{i} \ (i \in [n]) : \mathcal{ZKP}.\mathsf{Setup}, \mathcal{ACC}.\mathsf{Setup}, u \leftarrow 1$ 4 for $i \leftarrow l, r$ do 5 $\mathbf{N}^R \to \mathbf{N}^{R \sim}$: \mathbf{N}^{R} divide groups 6 $N_i^{R\sim} \Leftrightarrow N_i^{P}$: $N_i^{R\sim}$ establish connections with N_i^P 7 $\begin{array}{l} \mathbf{N}_{i}^{R} \Leftrightarrow \mathbf{N}_{i}^{*} \quad : \ \mathbf{N}_{i} \quad \text{estatistic connection} \\ \mathbf{N}_{i}^{R} & \leftarrow \mathbf{N}_{i}^{P} \quad : \ \mathbf{N}_{i}^{R} & \text{pull } \mathbf{P}_{i} \ \text{from } \mathbf{N}_{i}^{P} \end{array}$ 8 $N_i^{R^{-}} \leftarrow N_i^{R^{-}}$ is the initial accumulator A_i^{i} 9 $\begin{array}{l} \mathbf{N}_{i}^{R} \sim : \mathcal{ZKP}. \mathsf{Prove}(crs, x, \mathbf{P}_{i}, A_{0}^{i}) \rightarrow \pi_{0}^{\breve{i}} \\ \mathbf{N}_{i}^{R} \sim : \mathbf{N}_{i}^{R} \sim \operatorname{record} \left(\pi_{0}^{i}, A_{0}^{i}\right) \text{ into } \mathbf{R} \end{array}$ 10 11 // Synchronization in rounds 12 13 for true do

for $i \leftarrow l, r$ do $\begin{bmatrix} N_i^{R} \sim : N_i^{R} \sim \text{have StateReception} \\ N_j^{P} : N_j^{P} \text{ have StateForwarding} \\ N^{R} : \text{Round number } u \text{ increases by one} \end{bmatrix}$

18 StateReception

14

15

16

17

```
for i \leftarrow l r do
19
                                \Leftarrow \mathbf{N}_{i}^{P}
                                               : N_i^{R\sim} pull the new parachain blocks \mathbf{B}_u^i
20
                                                   generated in the u-th round from N_i^P
                      \mathbf{N}^{R\sim}_i : \mathbf{N}^{R\sim}_i extract all cross-chain trans \mathbf{T}^i_u from \mathbf{B}^i_u
21
                      \mathbf{N}_{i}^{{^{l}\!\!R}\sim}\ : \mathcal{\dot{ACC}}.\mathsf{Add}(A_{u-1}^{i},\mathbf{T}_{u}^{i}) \to A_{u}^{i}
22
                      \mathbf{N}_{i}^{R\sim} : \mathcal{ZKP}.\mathsf{Prove}(crs, x, A_{u-1}^{i}, A_{u}^{i}, \mathbf{B}_{u}^{i}) \rightarrow \pi_{u}^{*i}
23
                     24
                      \mathbf{N}_{i}^{^{l}\!R\sim}~:\mathbf{N}_{i}^{R\sim}~\mathrm{record}~(\pi_{u}^{i},A_{u}^{i}) into \mathbf{R}
25
26 StateForwarding
```

 $\begin{array}{cccc} \textbf{27} & \quad \textbf{for} \ i \leftarrow l, r \ and \ j \leftarrow r, l \ \textbf{do} \\ \textbf{28} & \quad \begin{matrix} \mathbf{N}_j^P &: \mathbf{N}_j^P \ \text{extract} \ (\pi_u^i, A_u^i) \ \text{from} \ \textbf{R} \\ \textbf{N}_j^P &: \mathcal{ZKP}. \text{Verify}(crs, x, \pi_u^i, A_u^i) \\ \textbf{N}_j^P &: \mathbf{N}_j^P \ \text{record} \ (\pi_u^i, A_u^i) \ \text{into} \ \textbf{P}_j \end{array}$

will not exceed a certain limit, which ensures the timeliness of state synchronization.

In state forwarding process (see line 26-30 in Protocol 1), **R** is published to \mathbf{P}_r system to reach consensus among \mathbf{N}_r^P . Then, \mathbf{N}_r^P extract (π_u^l, A_u^l) from **R**, verify the correctness of (π_u^l, A_u^l) , and record (π_u^l, A_u^l) into \mathbf{P}_r . We say that the \mathbf{P}_l state proof (π_u^l, A_u^l) is synchronized into \mathbf{P}_r . Furthermore, based on (π_u^l, A_u^l) , \mathbf{P}_r system can verify that a certain crosschain transaction *ct* has been recorded into \mathbf{P}_l , with the help of a prover in \mathbf{P}_l system to provide the membership witness $w_u^{ct,l}$ of *ct*.



Fig. 6: Transaction synchronization

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Using the same method of state reception and state forwarding, (π^r_u, A^r_u) is generated by $\mathbf{N}^{R\sim}_r$ to be recorded into **R**, and then (π_u^r, A_u^r) is extracted by N_l^P to be recorded into \mathbf{P}_l . Therefore, in the same round, \mathbf{P}_l and \mathbf{P}_r have their state proofs synchronized to each other. Fig. 5 shows one round of state synchronization.

2) Transaction synchronization: Based on state synchronization, we further achieve transaction synchronization to record one cross-chain transaction ct into two parachains \mathbf{P}_{l} and \mathbf{P}_r , and keep their consistency. Classified by the initiator, transaction synchronization can be divided into two categories, which are unilaterally initiated transaction synchronization (UITS) and jointly initiated transaction synchronization (JITS).

UITS: UITS is initiated by any single party belonging to \mathbf{P}_l system or \mathbf{P}_r system. For example, if Bob in \mathbf{P}_r system wants to unilaterally record ct into \mathbf{P}_l and \mathbf{P}_r , he needs to go through the following steps.

- 1) In the *u*-th round of state synchronization, Bob attaches a UITS label to ct, and publishes ct to N_r^P . Then, N_r^P record *ct* into \mathbf{P}_r . (see line 3-5 in Protocol 2)
- 2) In the (u+1)-th round of state synchronization, $N_r^{R\sim}$ additionally generate the membership witness $w_n^{ct,r}$ of ct in \mathbf{P}_r . ct and $w_u^{ct,r}$ will be recorded into \mathbf{R} . Then, ct and $w_{u}^{ct,r}$ are extracted by \mathbf{N}_{l}^{P} to be recorded into \mathbf{P}_l . Subsequently, by verifying ct, $w_u^{ct,r}$, and (π_u^r, A_u^r) , \mathbf{P}_l system will confirm that *ct* has been recorded in \mathbf{P}_r . (see line 6-12 in Protocol 2)
- 3) In the (u+2)-th round of state synchronization, $N_l^{R\sim}$ additionally generate the membership witness $w_{u+1}^{ct,l}$ of ct in \mathbf{P}_l . $w_{u+1}^{ct,l}$ will be recorded into \mathbf{R} , Then, $w_{u+1}^{ct,l}$ is extracted by N_r^P to be recorded into \mathbf{P}_r . Subsequently, by verifying $w_{u+1}^{ct,l}$ and (π_{u+1}^l, A_{u+1}^l) , \mathbf{P}_r system will confirm that *ct* has been recorded in P_1 . (see line 13-19 in Protocol 2)

It is worth noting that Alice does not participate in UITS with Bob, but she can monitor that ct is recorded in \mathbf{P}_l , as \mathbf{P}_l is public to the members in \mathbf{P}_l system. The monitoring will

Prototol 2. Transaction Synchronization

1 UITS 2 $|| i \leftarrow l \text{ or } r || j \leftarrow r \text{ or } l || U^i \leftarrow \text{Alice or Bob}$ // u-th round $U^i \Rightarrow \mathbf{N}^P_i : U^i$ publishes ct to \mathbf{N}^P_i : N_i^P record ct into \mathbf{P}_i^P N_i^P // (u+1)-th round : $\mathbf{N}_i^{R\sim}$ extract ct from \mathbf{P}_i \mathbf{N}^{R} $N^{R\sim}$: \mathcal{ACC} .CreateMemWit $(\mathbf{P}_i, A_u^i, ct) \rightarrow w_u^{ct,i}$ $\mathbf{N}_{\pm}^{R\sim}$: $\mathbf{N}_{i}^{R\sim}$ record $(ct, w_{u}^{ct,i})$ into \mathbf{R} : N_i^P extract $(ct, w_u^{ct,i})$ from **R** N_{a}^{F} N_{i}^{P} : \mathcal{ACC} .VerifyMem $(A_u^i, ct, w_u^{ct,i})$ N^{F} : N_i^P record $(ct, w_u^{ct,i})$ into \mathbf{P}_i // (u+2)-th round \mathbf{N}^{R} : $N_i^{R\sim}$ extract *ct* from \mathbf{P}_j N^{R} : \mathcal{ACC} .CreateMemWit $(\mathbf{P}_j, A_{u+1}^j, ct) \rightarrow w_{u+1}^{ct,j}$ 15 N^{R} : $N_j^{R\sim}$ record $w_{u+1}^{ct,j}$ into \mathbf{R} : N_i^P extract $w_{u+1}^{ct,j}$ from \mathbf{R} N^{P} 17 $\mathbf{N}_{\dot{\cdot}}^{P}$: \mathcal{ACC} . Verify $\mathsf{Mem}(A_{u+1}^j, ct, w_{u+1}^{ct, j})$ 18 : N_i^P record $w_{u+1}^{ct,j}$ into \mathbf{P}_i N_{i}^{P} 20 JITS $/\!/ \ U^l \leftarrow \text{Alice} \quad /\!/ \ U^r \leftarrow \text{Bob}$ // v-th round

```
21
22
                \begin{array}{l} U^l \ / \ U^r \Rightarrow \mathbf{N}_l^P \ / \ \mathbf{N}_r^P &: U^l \ / \ U^r \ \text{publish} \ ct \ \text{to} \ \mathbf{N}_l^P \ / \ \mathbf{N}_r^P \\ \mathbf{N}_l^P \ / \ \mathbf{N}_r^P &: \mathbf{N}_l^P \ / \ \mathbf{N}_r^P \ \text{record} \ ct \ \text{into} \ \mathbf{P}_l \ / \ \mathbf{P}_r \end{array} 
23
24
                // (v+1)-th round
25
                U^l \ / \ U^r
                                       : \mathcal{ACC}.CreateMemWit(\mathbf{P}_l, A_v^l, ct) \rightarrow w_v^{ct,l} /
26
                                           \mathcal{ACC}.CreateMemWit(\mathbf{P}_r, A_v^r, ct) \rightarrow w_v^{ct, r}
                                       : U^l and U^r exchange w_v^{ct,l} and w_v^{ct,r}
                U^l \Leftrightarrow U^r
27
                U^l / U^r
                                       : U^l / U^r publish w_v^{ct,r} / w_v^{ct,l} to N_l^P / N_r^P
28
                                      : \mathcal{ACC}.\mathsf{VerifyMem}(A_v^r, ct, w_v^{ct,r}) /
                N_{l}^{P} / N_{r}^{P}
29
                                           \mathcal{ACC}.\mathsf{VerifyMem}(A_v^{\tilde{l}}, ct, w_v^{ct, l})
                                      : N_l^P / N_r^P record w_v^{ct,r} / w_v^{ct,l} into P_l / P_r
               N_l^P / N_r^P
30
```

enable Alice to learn the malicious behavior of Bob when he publishes an outdated transaction by UITS. This feature will be applied in the disputing operation to cross-chain state channel (see Section VI-B).

JITS: If Alice and Bob intend to jointly record ct into \mathbf{P}_l and \mathbf{P}_r by using JITS, they need to go through the following steps. To facilitate the description, the roles on both sides of the slash "/" will perform the operation simultaneously in the following content.

- 1) In the *v*-th round of state synchronization, Alice / Bob attaches a JITS label to *ct*, and publishes *ct* to N_l^P / N_r^P . Then, N_l^P / N_r^P records *ct* into $\mathbf{P}_l / \mathbf{P}_r$. (see line 22-24 in Protocol 2)
- 2) In the (v+1)-th round of state synchronization, Alice / Bob generates the membership witness w_v^{ct,l} / w_v^{ct,r} of ct in P_l / P_r, and sends the membership witness to Bob / Alice. Then, Alice / Bob publishes w_v^{ct,r} / w_v^{ct,l} to N_l^P / N_r^P. N_l^P / N_r^P verify the correctness of w_v^{ct,r} / w_v^{ct,l}, and record it into P_l / P_r. P_l system / P_r system will confirm that ct has been recorded in P_r / P_l. (see line 25-30 in Protocol 2)

Fig. 6 shows the process of UITS and JITS.

Comparison: We have a comparison between UITS and JITS. For the same points, UITS and JITS have the same result. Specifically, one cross-chain transaction ct is recorded into two parachains \mathbf{P}_l and \mathbf{P}_r , and \mathbf{P}_l and \mathbf{P}_r confirm the recording of ct in each other.

For the different points, JITS does not need relay chain **R** to record ct, $w^{ct,l}$, and $w^{ct,r}$. For a cross-chain platform with numerous users, there will be a mass of ct, $w^{ct,l}$, and $w^{ct,r}$ generated per day, which may occupy the throughput of **R**. If the users use JITS to have transaction synchronization, JITS will greatly reduce the throughput pressure of **R**, which is more efficient than UITS.

However, compared with UITS, the prerequisite of JITS is more stringent. JITS requires Alice and Bob to cooperate to publish ct, $w^{ct,l}$ and $w^{ct,r}$. If one of Alice and Bob refuses to cooperate, \mathbf{P}_l and \mathbf{P}_r have to enable \mathbf{R} again to accomplish transaction synchronization, in which JITS degrades to UITS. (see Section VII-G)

B. Cross-chain State Channel

1) Opening operation: By using JITS, Alice and Bob jointly publish an opening transaction ct^{open} to \mathbf{P}_l and \mathbf{P}_r to achieve an opening operation. ct^{open} will lock a part of Alice's and Bob's data in \mathbf{P}_l and \mathbf{P}_r , and move the data into the cross-chain state channel as its initial state. The data can be tokens, assets, or private records of Alice and Bob. Then, the data can be processed in the channel without touching blockchains. Technically, it is also feasible to record ct^{open} to \mathbf{P}_l and \mathbf{P}_r by using UITS. However, we suppose that Alice and Bob are cooperative at the beginning of the cross-chain state channel. Therefore, only the ct^{open} published by JITS can open a cross-chain state channel. (see line 1-4 in Protocol 3)

2) Updating operation: Updating operation includes two steps. Alice and Bob first draft an updating transaction ct_m^{update} , and exchange the signatures of ct_m^{update} . Second, Alice and Bob draft a punishment transaction pct_{m-1}^{update} to invalidate ct_{m-1}^{update} , and exchange the signatures of pct_{m-1}^{update}

Prototol 3. Channel Operation

 $\begin{array}{c|c} & \textbf{1} \quad \textit{Opening} \\ & \textbf{2} & \texttt{I} \mid U^l \leftarrow \text{Alice} \quad \texttt{I} \mid U^r \leftarrow \text{Bob} \\ & \textbf{3} & U^l \Leftrightarrow U^r \quad : \text{Cosign} \rightarrow ct^{open} \\ & \textbf{4} & U^l \Leftrightarrow U^r \quad : \texttt{JITS}(ct^{open}) \end{array}$

5 Updating

6 | // $U^l \leftarrow Alice$ // $U^r \leftarrow Bob$

$$U^l \Leftrightarrow U^r : U^l$$
 and U^r exchange signatures of ct_m^{update}

```
U^l \Leftrightarrow U^r : U^l \text{ and } U^r \text{ exchange signatures of } pct_{m-1}^{update}
```

```
9 Closing
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10
           if Joint closing then
                 /\!/ \ U^l \leftarrow \text{Alice} \quad /\!/ \ U^r \leftarrow \text{Bob}
11
                  U^l \Leftrightarrow U^r \ : \mathsf{Cosign} \to ct^{close}
12
                  U^l \Leftrightarrow U^r : JITS(ct^{close})
13
14
           else
                 // U^i \leftarrow Alice \text{ or Bob}
15
                  U^i : UITS(ct_m^{update})
16
                  U^i : U^i waits for \Delta t
17
                  U^i : UITS(cct_m^{update})
18
19 Disputing
           // U^j \leftarrow \text{Bob or Alice}
20
           repeat
21
            U^j : U^j \text{ monitors } \mathbf{P}_i
22
           until ct_x^{update} (0 < x < m) is recorded in \mathbf{P}_j
23
           U^j: UITS(pct_r^{update})
24
```

(see line 5-8 in Protocol 3). The two steps are consistent with the existing intra-chain state channel [19]. We do not have further illustrations.

3) Closing operation: There are two categories of closing operations, which are joint closing and unilateral closing. In joint closing, Alice and Bob will publish closing transaction ct^{close} to \mathbf{P}_l and \mathbf{P}_r by using JITS. According to the state in ct^{close} , Alice's and Bob's data in the channel will be returned back to their accounts in \mathbf{P}_l and \mathbf{P}_r . Then, the cross-chain state channel is closed.

In unilateral closing, we assume that Bob attempts to unilaterally close the channel. He will publish the latest updating transaction ct_m^{update} to \mathbf{P}_l and \mathbf{P}_r by using UITS. After a waiting time of Δt , Bob will publish the confirmation transaction cct_m^{update} of ct_m^{update} to \mathbf{P}_l and \mathbf{P}_r by using UITS. cct_m^{update} will return the data of Alice and Bob in ct_m^{update} back to their accounts in \mathbf{P}_l and \mathbf{P}_r . Then, the cross-chain state channel is closed. (see line 9-18 in Protocol 3)

Noted, if Bob publish cct_m^{update} within the waiting time of Δt , cct_m^{update} is invalid. Besides, if Alice notices that Bob has published ct_m^{update} by UITS, she can also publish cct_m^{update} by using UITS, and cct_m^{update} takes effect immediately without waiting a time of Δt .

4) Disputing operation: In the process that Bob unilaterally closes the cross-chain state channel, there may be a malicious behavior that Bob publishes outdated transaction ct_x^{update} (0 < x < m) to \mathbf{P}_l and \mathbf{P}_r , attempting to deny the latest transaction ct_m^{update} . For example, when ct_x^{update} contains more tokens for Bob, compared with ct_m^{update} , Bob may choose to close the channel by ct_x^{update} instead of ct_m^{update} , attempting to get more tokens back to his account. In this condition, a dispute

occurs.

If Bob has the malicious behavior, ct_x^{update} will be crosschain transferred within a certain number of state synchronization rounds by UITS. Alice needs to remain online in \mathbf{P}_l system to monitor whether a ct_x^{update} is recorded into \mathbf{P}_l . If yes, Alice will have UITS to publish pct_x^{update} to \mathbf{P}_l and \mathbf{P}_r within the time of $\Delta t. pct_x^{update}$ rejects ct_x^{update} in \mathbf{P}_l and \mathbf{P}_r , and closes the channel in the most favorable channel state for Alice, such as returning all the tokens in the channel to Alice's account, as a punishment to Bob. (see line 19-24 in Protocol 3)

VII. SECURITY ANALYSIS

This section offers an informal security analysis to support the designs presented in Sections VI and V. We will explore attack vectors, potential impacts, and ways to mitigate them.

A. Hard Fork

A hard fork is a non-backward-compatible upgrade to a blockchain network that fundamentally changes its protocol, resulting in a split from the original chain and the creation of a new separate chain.

1) Hard fork in parachain: When a hard fork occurs in left parachain \mathbf{P}_l to create two separate parachains \mathbf{P}_l^* and \mathbf{P}_l^{**} . Bob in the \mathbf{P}_r system may attempt to establish two crosschain state channels to \mathbf{P}_l^* and \mathbf{P}_l^{**} by only publishing one cross-chain transaction *ct*. Consequently, Bob's data in \mathbf{P}_r can be used twice. (Alice may also have the same attempt when \mathbf{P}_r has a hard fork.) To solve the problem, \mathbf{N}^R need to select the main chain in \mathbf{P}_l^* and \mathbf{P}_l^{**} . For example, it follows the chain with the most accumulated proof-of-work. Relay chain \mathbf{R} only has cross-chain synchronization with the main chain. Subsequently, Bob can only establish a cross-chain state channel with Alice's account in one of \mathbf{P}_l^* and \mathbf{P}_l^{**} .

2) Hard fork in relay chain: There is another possibility that a hard fork occurs in relay chain \mathbf{R} to create \mathbf{R}^* and \mathbf{R}^{**} . The original cross-chain platform maintained by N^R is divided into two platforms respectively maintained by N^{*R} and N^{**R} . Surprisingly, the relay chain hard fork has little impact on cross-chain state channel. Because relay chain is only an intermediary to transfer parachain state information, and it does not generate new information. If N^{*R} or N^{**R} have sufficiently large scale to ensure the security of \mathbf{R}^* system or \mathbf{R}^{**} system with $\alpha < 1/3$, the cross-chain synchronization can continue to support the operations in cross-chain state channel.

B. Denial-of-service Attack

The existing cross-chain platform divides the relay node cluster N^R into n relay node groups $N_i^{R\sim}$. This division was intended to reduce communication and calculation overhead, as $N_i^{R\sim}$ only needs to process information from one parachain. However, this design also reduces the number of nodes in each $N_i^{R\sim}$, making it vulnerable to potential attacks. An adversary may attempt to take control of every node in $N_i^{R\sim}$. The corrupted nodes may deny to pull the parachain state or generate state proof. Consequently, relay chain **R** cannot receive

the real-time state information of a parachain \mathbf{P}_i , which in turn affects the other parachains, causing a synchronization interruption.

To address the denial-of-service attack, N^R adopt the random scheduling mechanism in XPull [17] (see Section III-B) to randomly select a new group $N_i^{*R\sim}$ to replace $N_i^{R\sim}$. There is a high possibility that $N_i^{*R\sim}$ contains a portion of normal nodes to continue the cross-chain synchronization. To break the random scheduling mechanism, the adversary needs to control the majority of relay nodes N^R . We assume it is hard to achieve. Moreover, if the adversary attempts to regain control of N_i^{*R} , another random scheduling can be executed to respond to it. We assume that the adversary is mildly adaptive [44], i.e. the adversary cannot instantly corrupt every node in N_i^{*R} , and the corruption may only succeed after a sufficiently long period of time. Therefore, between each random scheduling, there is a time interval in which N_i^{*R} includes at least one normal relay node to have cross-chain synchronization. Therefore, the interruption is only temporary, and the cross-chain synchronization can continue.

C. Replay Attack

Without adequate protection, a malicious party may attempt to replay cross-chain transactions. Specifically, the party publishes duplicate opening transaction ct^{open} to open two crosschain state channels without permission; the party publishes duplicate updating transaction ct^{update}_{m} or closing transaction ct^{close} to close the channel, attempting to return duplicate data to its account. A simple method to solve the problem is to add a unique identifier to each cross-chain transaction to prevent duplication.

D. Counterfeiting

A node in N_i^P may submit tampered parachain blocks to $N_i^{R\sim}$, and a corrupted $N_i^{R\sim}$ may generate counterfeit zero-knowledge proofs of the parachain state, attempting to synchronize the false state proofs into other blockchains. However, when \mathbf{P}_i first established a cross-chain connection with relay chain \mathbf{R} , the parachain protocols and parachain node identities were made public to the cross-chain platform. Based on the tamper-proof property of blockchain, the tampered blocks or state proofs violate the parachain protocol or parachain node signature, which can be easily detected. Moreover, we assume the proportion of corrupted parachain nodes have $\alpha < 1/3$. Therefore, the adversary does not process enough hash rate (in PoW) or stake (in PoS) to create a replica of parachain, and consequently, the counterfeiting is hard to achieve.

E. Eclipse Attack

Bob may unilaterally close the cross-chain state channel by publishing an outdated updating transaction ct_x^{update} , attempting to deny the latest updating transaction ct_m^{update} (0 < x < m) (see Section VI-B). At the same time, an adversary may create a fake network environment around Alice to prevent her from learning the publication of ct_x^{update} through accessing

 \mathbf{P}_l , attempting to let Alice miss the opportunity to solve the dispute. For this problem, Alice needs to keep updating her local state of \mathbf{P}_l by receiving new \mathbf{P}_l blocks. If the new blocks cannot be received, she needs to find new P2P connections to ensure that at least one honest node of \mathbf{P}_l can provide the service to prevent eclipse attacks.

F. Conspiracy Attack

Alice and Bob having a cross-chain state channel may attempt to collude to create blockchain data out of thin air. For example, between parachain \mathbf{P}_l and \mathbf{P}_r , Alice and Bob each contribute 50 tokens to open a cross-chain state channel, noted (50, 50), which includes 100 tokens in total. Next, Alice and Bob attempt to publish ct_x^{update} to \mathbf{P}_l to close the channel in a state of (100, 0), by which Alice has 100 tokens returned to her account in \mathbf{P}_l . Then, Alice and Bob attempt to publish ct_u^{update} to \mathbf{P}_r to close the channel in a state of (0, 100), by which Bob has 100 tokens returned to his account in \mathbf{P}_r . Finally, Alice and Bob have 200 tokens in total, with 100 tokens created out of thin air. The timeliness of cross-chain synchronization ensures that \mathbf{P}_l and \mathbf{P}_r learn the real-time states of each other. When a cross-chain transaction ct is recorded in one of \mathbf{P}_l and \mathbf{P}_r , ct will be definitely recorded in the other one. Therefore, the ct_x^{update} and ct_u^{update} closing the same channel can be detected to conflict, and they will be refused by both \mathbf{P}_l and \mathbf{P}_r , in which the conspiracy attack is hard to succeed.

G. Noncooperation

The noncooperation may occur during JITS, in which one of Alice and Bob refuses to cooperate with the other one. For example, Alice may refuse to publish ct to \mathbf{P}_l , send the membership witness $w^{ct,l}$ to Bob, nor publish $w^{ct,r}$ to \mathbf{P}_l . In these conditions, $\mathbf{N}_l^{R\sim}$ or $\mathbf{N}_r^{R\sim}$ will detect that \mathbf{P}_l or \mathbf{P}_r has only recorded ct without recording ct membership witness in the other parachain. If the problem persists for a long enough time, $\mathbf{N}_l^{R\sim}$ or $\mathbf{N}_r^{R\sim}$ will switch to UITS to have the synchronization of ct, using relay chain \mathbf{R} to transfer ct and its membership witnesses. Therefore, the noncooperation can only degrade JITS to UITS. The transaction synchronization can still be finished.

VIII. EXPERIMENT AND EVALUATION

A. Implementation

We develop a prototype implementation of Interpipe. The main process is written in Golang, Rust, and C++. In addition, the recursive proof algorithm utilizes Nova [42], and the hash algorithm adopts SHA-256. The blockchains, including a relay chain and two parachains, are based on Ouroboros consensus protocol [44]. We adjust the consensus slot to keep the block generation rate at 18 seconds per block. The system of relay chain **R** includes 120 relay nodes, denoted as N^R. They are implemented with Intel Xeon Platinum 8280 @2.7GHz, 256GB DDR4 ECC DIMMs, and Windows Server operation system. In the initialization phase of relay chain system, two groups N_l^{R~} and N_r^{R~}, each including 8 nodes, are randomly selected from N^R using a distributed randomness beacon based

on Drand [47]. The system of two parachains \mathbf{P}_l and \mathbf{P}_r respectively include 100 parachain nodes, denoted as N_l^P and N_r^P . They are deployed on two hosts with Intel Core i9-13900K @3.0GHz, 64G DDRS 5200MHz XMP, and Windows operation system. Then, we deploy Protocol 1, 2, and 3 to Interpipe.

In each round of state synchronization, the state proofs of \mathbf{P}_l and \mathbf{P}_r are generated and transferred by relay nodes. The individuals within Interpipe will not have direct operations to state synchronization, as it automatically continues in the background to keep the consistency between parachains. We evaluate the proof generation efficiency in this process, and compare it with the existing work zkBridge [14], which is illustrated in Section VIII-B. In the next process, two operators, respectively situated in \mathbf{P}_l and \mathbf{P}_r systems, first achieve the synchronization of a blank cross-chain transaction ct by using UITS and JITS. Then, ct is replaced by ctopen, ct^{update}, ct^{close}, and pct^{update} to achieve the opening, updating, closing, and disputing operations to cross-chain state channel. We evaluate the throughput occupancy and time cost with different round duration, and compare the performance between Interpipe and the previous intra-chain state channel, which is illustrated in Section VIII-C.

B. Proof Generation Efficiency

We compare the proof generation time cost of Interpipe with the most recent work zkBridge [14] by the blockchain length as a variable. Based on the strategy of zkBridge, we divide the arithmetic circuits in the parachain into M copies, and distribute the M copies to M relay nodes for calculation, thereby increasing the proof generation speed by M times. In our experiment (see Fig. 7), we set the value of M to be 8 and 4, although this value can be larger in practical situations. However, zkBridge is only designed for one-round proof and does not make use of the proof generated in the previous round. Consequently, the arithmetic circuits in old blocks have to be recalculated in every round. It results in an increase in proving time as the blockchain length grows. In contrast, we use recursive SNARK to generate the state proof in Interpipe. To facilitate proof generation, the cross-chain transactions are included in a subtree of the Merkle tree in each parachain block. It takes about 7 seconds to finish the calculation of the arithmetic circuits in one block. The processes of proof generation and proof transfer can be carried out in parallel, with minimal impact on the time costs of each other. The experiment result shows that Interpipe's proving time remains relatively constant, as it does not require the recalculation of old blocks, and the number of new blocks generated in each round is almost constant.

We also evaluate the proof generation time cost with different cross-chain transaction proportions q (see Fig. 8). For a parachain, each parachain block includes about 55 transactions, with a proportion of cross-chain transactions denoted as q where (0 < q < 1). In a practical situation, the value of qdepends on the preferences of all users in a parachain system. Considering most of the transactions in existing blockchains, such as Bitcoin and Ethereum, primarily focus on the internal



Fig. 7: Proof generation time cost with different blockchain length



Fig. 8: Proof generation time cost with different cross-chain transaction proportion

affairs within the system, we set a relatively small value for q, in which 0 < q < 0.1. The result shows that the time cost of Interpipe increases with q. Because batch transaction proof needs to prove every cross-chain transaction in the new block, leading to increased computation with a higher number of cross-chain transactions. In comparison, the time cost of zkBridge does not exhibit significant changes, as zkBridge is designed to prove individual cross-chain transactions. However, the time cost of Interpipe is still lower than the time cost of zkBridge, as the scale of cross-chain transactions in new blocks is much smaller than the scale of old blocks.

C. Comparison to Intra-chain State Channel

We begin by evaluating the performance of state synchronization nization. The duration of each round of state synchronization can be adjusted. Its value must be sufficiently large to prevent an excessively high frequency of state synchronization, which could lead to an accumulation of redundant state proofs in \mathbf{R} , thereby occupying its throughput (see Fig. 9). Conversely, a longer round duration results in increased wait times for users (see Fig. 10). The time costs associated with opening, closing, and disputing operations all rise with longer durations, while the time cost of updating operations remains constant, given that updates are executed off-chain. Consequently, there exists a trade-off between minimizing throughput occupancy and ensuring better service quality. The maintainers of a cross-chain platform need to find an appropriate balance in practical situations.

Adhering to our threat model, we maintain that a transaction within a blockchain achieves persistence when it reaches a depth of k blocks, where k = 9. Concerning the trade-off in round duration, we have selected 240 seconds as



Fig. 9: Throughput occupancy with different round duration



Fig. 10: Operation time cost with different round duration

the suitable duration for state synchronization. To compare the performance of the cross-chain state channel (CCSC) in Interpipe with the existing intra-chain state channel (ICSC) operating within a blockchain system, we deploy the ICSC protocol [19] to a parachain system. The comparison of their performance is outlined in Table II. The opening, closing, and disputing operations to CCSC indeed have a larger time cost than the same operations to ICSC. Because each operation to CCSC needs to have a transaction synchronization including 2 or more steps. A step refers to a cross-chain transaction or membership witness being recorded into a blockchain and becoming stable over time, with $Steps^{JITS} = 2$ and $Steps^{UITS} = 5$. Moreover, each transaction synchronization needs to wait for the state synchronization to enable crosschain verification to the cross-chain transaction or membership witness, thereby incurring additional time costs. However, in updating operation, CCSC and ICSC exhibit similar time costs with relatively small values. As the updating operations play the main roles in off-chain interactions, if there are no urgent needs or malicious behaviors to close the channel, CCSC can be nearly as efficient as ICSC in most cases.

IX. CONCLUSION

In this paper, we present a distributed cross-chain state channel scheme, called Interpipe. To meet the cross-chain verification needs of large-scale users, we propose a batch transaction proof scheme based on recursive SNARK. To achieve consistent operations between two blockchains, we propose a real-time cross-chain synchronization scheme. Based on the above designs, Interpipe offers protocols for opening, updating, closing, and disputing to cross-chain state channels. We have a security analysis of Interpipe, in which Interpipe can keep consistency, and withstand various existing attacks.

TABLE II: Comparison between ICSC and CCSC

	Operation	Steps	Time Cost
ICSC	Opening	1	3.6 min
	Updating	0	62 ms
	Closing (Joint)	1	3.7 min
	Closing (Unilateral)	1	3.7 min
	Disputing	1	5.5 min
CCSC	Opening	2	12.5 min
	Updating	0	105 ms
	Closing (JITS)	2	13.4 min
	Closing (UITS)	5	29.5 min
	Disputing	5	36.9 min

The experimental results show that cross-chain state channels can be nearly as efficient as existing intra-chain state channels.

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X. BIOGRAPHY SECTION



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