Towards Aggregated Payment Channel Networks

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***Abstract*—Payment channel networks (PCNs) have been designed and utilized to address the scalability challenge and throughput limitation of blockchains. It provides a high-throughput solution for blockchain-based payment systems. However, such "layer-2" blockchain solutions have their own problems: payment channels require a separate deposit for each channel of two users. Thus it significantly locks funds from users into particular channels without the flexibility of moving these funds across channels. In this paper, we proposed Aggregated Payment Channel Network (APCN), in which flexible funds are used as a per-user basis instead of a per-channel basis. To prevent users from misbehaving such as double-spending, APCN includes mechanisms that make use of hardware trusted execution environments (TEEs) to control funds, balances, and payments. The distributed routing protocol in APCN also addresses the congestion problem to further improve resource utilization. Our prototype implementation and simulation results show that APCN achieves significant improvements on transaction success ratio with low routing latency, compared to even the most advanced PCN routing.**

I. Introduction

Blockchain is a promising solution for decentralized digital ledgers, but *low throughput* remains a huge problem with growing numbers of users and transactions [1], [2]. For instance, Bitcoin can only support 10 transactions per second at peak in 2020 [3]. Payment channel networks (PCNs) [2] are a leading concept to provide a high-throughput solution for blockchains. In a PCN, two users can conduct transactions with each another through a bi-directional channel. The blockchain is only involved when the users open and close the channel. Each user commits a certain fund at the opening of this channel. Then they can make any number of transactions that update the tentative distribution of the channel's funds as long as the remaining funds allow. These transactions only need to be signed by the two users, and do *not* need to be broadcast to the entire blockchain. Each user can establish channels with multiple other users. If a channel does not exist between two users, they can make a transaction via a multi-hop path, where any two consecutive users on the path share a channel. The PCN is a promising solution to achieve the scalability of blockchains because most transactions can be achieved in an off-chain manner.

However, such "layer-2" blockchain solutions have their own problems: PCNs require a separate deposit for every channel and significant locked-in funds from users [4]. Besides, funds are not equally distributed among all the channels of one user. A situation might happen that a user cannot support a transaction due to insufficient funds in a required channel, but in fact, the node has sufficient unused funds in other channels. Redistributing funds among channels immediately is not realistic here, because users need to react with blockchain to set up new channels which is time-consuming. Such inflexibility of fund utilization results in significant resource under-utilization in PCNs. Many recent studies focus on using routing protocols to improve resource utilization in PCNs, such as Spider [5] and Flash [6]. However, our evaluations show that **routing cannot fully solve the problem of imbalanced fund utilization problem across different channels.** The key reason is that per-channel funds also limit routing path selections.

In this paper, we introduce Aggregated Payment Channel Network (APCN), a system that enables sharing and freely allocating funding among all payment channels of a single user. In APCN, funds are maintained in a *per-user* basis instead of *per-channel*, which provides higher *flexibility* of fund utilization and hence much higher payment success rate (from 70% to $> 95\%$ in our evaluation). When users perform multi-hop payments, those intermediate nodes only deliver the payments to the next-hop node, instead of adjusting funds in the channels as in the PCNs. So intermediate nodes actually act as relay hops which is more similar to packet-switching networks compared to existing PCNs. A multi-hop payment is successful as long as: 1) a path exists between the sender and receiver; 2) the sender has enough funds to pay the receiver. Unlike PCNs, there is no requirement that every channel on the path must have that amount of lock-in funds.

However, there are multiple challenges in designing APCN. **1)** How to prevent users from double-spending. Since funds are not maintained in separate channels, the user cannot determine whether the funds sent to her have been paid to others until she makes the settlement on the main chain. **2)** How to make settlements when shutting down channels or users going offline. In PCNs, payments only change the distribution of the channel's funds, and the total balance of the channel always keeps the same. When closing a channel, two users only need to broadcast a blockchain transaction with the final balance. However, in APCN, the funds are not kept in a single channel, and it is difficult to trace payments in the network. In order to address these two challenges, we design protocols based on the widely available trusted execution environment (TEE) for controlling funds, balances and payments. TEE is a hardware security feature in modern CPUs [7] that ensures the confidentiality and integrity of code and data. **3)** We further assume not every user of APCN has a TEE device. Hence how

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users can rely on other TEE devices and trust the execution remains another challenge. **4)** We consider the *congestion control* problem in APCN: if too many payments go through a certain node, the transaction processing rate on this node should be slower than the transaction arrival rate which causes congestion. Such a node will become the bottleneck of the whole network. To prevent this situation, we design a routing protocol with congestion control in APCN that each channel locally keeps a congestion factor, and nodes would consider the congestion factors of channels to select the next hop.

We conduct both *prototype implementation* and *large-scale simulations* for APCN, based on real-world PCN topologies and transactions. The results show that even the most advanced PCN routing protocols cannot achieve 75% transaction success rate – a transaction is successful if there is a routing path with sufficient funds – while APCN always achieves over 95% transaction success. We show APCN is also cost-efficient.

The rest of this paper is organized as follows. The system overview and model are presented in Section II. We describe an overview in Section III and the detail design of the APCN and routing protocol in Section IV. Section VI presents the evaluation results of APCN. Section VII describes the related work. Section VIII concludes this work.

II. Overview

A. Network Model

APCN is a payment channel network in which the funds are maintained in a per-user basis instead of per-channel. In APCN, each user is called a *node*. The bi-directional payment channel shared by two nodes is called a *physical channel* or *direct link*, and these two nodes are called *direct neighbors*. Each node maintains some funds to make transactions with others or help to relay transactions. We model an APCN as a graph $G = (V, E, \Psi)$, where E is the set of links, V is the set of nodes with a weight function w, and $\psi_u \in \Psi$ is the funds of user u in the network. Each node is assigned a congestion rate which can reflect the time it will take on average to process a transaction going through it. This value is periodically updated according to the number of transactions going through it in the last time slot. Furthermore, a path p is a sequence of links $e_1 ... e_k$ with $e_i = (v_i, v_{i+1})$ for $1 \leq i \leq k-1$. The path of a transaction is accepted only if the amount of this transaction is less than the fund of the sender, ψ_1.

Problem definition. The problem of making successful payments in APCN is described as follows. Consider a transaction t initiated by *sender* s that should be received by the *recipient* r. APCN needs to find a path from s to r, where two consecutive nodes on the path should share a physical link (payment channel) to transfer the payment to the next-hop. The success of the payment implies that s can make a transaction with r by a sequence of transactions involving other intermediate nodes, even if s and r have no trusted channel.

APCN should make use of a *routing protocol* that finds an end-to-end path from the sender to the recipient in the network graph. In fact, APCN is able to apply any existing routing protocol of PCNs and make corresponding adjustments

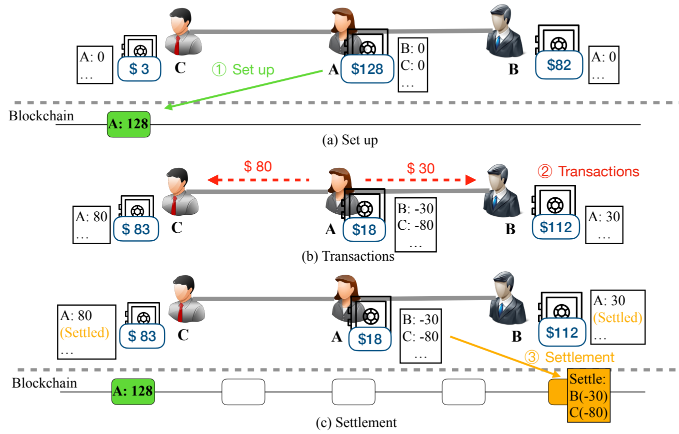


Fig. 1. APCN overview: APCN nodes operate TEEs to store and manage funds. Users construct payment channels between nodes to exchange funds directly, and execute multi-hop payments along concatenated payment channels.

to allow them to work in APCN. In our implementation, we use the virtual coordinates based greedy routing introduced in a recent work WebFlow [8] and extend it for APCN.

B. Trusted execution environment (TEE)

The requirement for synchronous blockchain access in existing payment networks comes from the fact that their protocols use the blockchain as a root-of-trust: parties executing the payment protocol monitor the blockchain to discover when other parties deviate from the protocol, and react appropriately. In traditional PCNs, users can easily verify transactions by checking their channel states and balances. This mechanism also prevents the *double spending* problem since a single fund cannot be used in two different channels. A single fund cannot be paid to the same receiver twice either, since both the receiver and sender keep a view of channel state. They could detect misbehaving parties when a dispute happens. However, in APCN, the channel is stateless. We should prevent the situation where a malicious node tries to spend a fund twice to two different receivers.

In order to ensure the faithful execution of the payment protocol in APCN, we make use of trusted execution environments (TEEs) [9]. TEEs are encrypted and integrity-protected memory regions, which are isolated by the CPU hardware from the rest of the software stack. Multiple TEE implementations are commercially available, including Intel SGX [10], ARM TrustZone [11] and AMD SEV [9], with several others currently underway, such as KeyStone Enclave [12], Multizone [13] and OP-TEE [14]. Intel CPUs from the Skylake generation onwards support SGX [15], a set of new instructions that permit applications to create TEEs called SGX enclaves. TEEs ensure faithful execution of software and the owners cannot make changes on either the data or software in TEEs.

APCN constructs a peer-to-peer payment network in which each node comprises: (i) an API for users to interact with the payment network; (ii) an interface through which to read and write blockchain transactions; and (iii) a TEE-protected program called *Ledger* that securely holds and manages users' funds. Ledgers ensure the faithful execution of the payment protocol. They are responsible for managing payment channels, executing payment transactions, and controlling access to funds. They communicate via secure channels established by two neighboring nodes to update user funds.

Fig. 1 shows an example of APCN. For a user A, to join in the APCN at initialization, it needs to construct a set-up message and send it to the blockchain. This message should include a transaction that A makes a deposit of \$128 to the blockchain. After this message being confirmed in the blockchain, A can open channels with other users and make or relay transactions in the APCN. Assume A opens channels with user B and C respectively. When A wants to make a payment of \$30 to B, the TEE of A, denoted as TEE_A, will record this transaction in the local ledger as $B : -\$30$, and update A's remaining funds to \$98. The TEE of B, denoted as TEE_B, will also record this transaction in its local ledger as A : \$30, and update B's remaining funds to \$112. The next time when A wants to make another payment of \$80 to user C, TEE_A and TEE_C will update their local ledgers to $C : -\$80$ and A : \$80 respectively, and update A and C's remaining funds to \$18 and \$83 as well. When A wants to go offline and make a settlement, it first needs to retrieve the encrypted ledger of the latest version from TEE_A, and then send it to the blockchain. It keeps monitoring the blockchain until its ledger is confirmed. In this process, TEE_A denies all the transactions to or through it. After the ledger showing up in the block, A sends messages to all its neighbors. The neighbors' TEEs who receive the messages will update their local ledgers to mark the transaction records with A as confirmed.

C. Attacker Model

We assume users and webservers can exchange messages through a traditional secure communication channel such as TLS. Information leakages among them are beyond the scope of our discussion. We assume the attackers can gain complete physical access to a node in which the funds are stored and complete control of its network connections. They may drop, modify and replay messages. An attacker may also delay or prevent the node it controls from accessing the blockchain for an unbounded amount of time. However, they cannot make changes to the TEEs on the controlled nodes. The widely applied TEE implementation SGX is known to be vulnerable to attacks such as controlled-channel attacks, and there have been some countermeasures to them [16]. To prevent information leakage from access patterns, existing oblivious RAM library can be adopted [17]. There are also existing timing and memory-access side-channel resistant libraries for sensitive data [7]. Shih et al. [18] presented a modified LLVM compiler dubbed T-SGX, which is effective against all known controlled-channel attacks. Lee et al. [19] proposed ZigZagger as a defence against their own branch shadowing attack. To defeat enclave specific attacks such as ROP attacks, Seo et al. [20] activated ASLR inside SGX enclaves to make exploitation more difficult. BYOTee [21] put forward a method to build multiple equally secure enclaves by utilizing commodity FPGA devices. Microcode patch could also help, but it can only be changed by the manufacturer of the CPU, which is out of scope of this paper. We apply side-channel resistant libraries and T-SGX in our implementation. We consider the user security of their funds in a fully distributed PCN. Users may be malicious and attempt to steal funds and deviate from the payment protocol, if it benefits them.

D. Requirements

Security: The main security requirement of APCN is that it should enable transactions to be executed between users safely and correctly. For safety, we consider two situations. The first is online users making transactions. Since funds are not kept in a single channel, we should ensure that APCN could prevent double spending. If a malicious node tries to spend a fund twice to two different receivers, the receivers should be able to detect it and reject the transaction. The second situation we consider is the settlement. When a user goes offline, all the transactions related to this user should be settled and written to the blockchain. If other users want to go offline later, we need to guarantee that the same transaction will not be written to the blockchain twice.

Performance: The main performance goal of ACPN is a high transaction success rate, which is determined by many factors including available funds, routing protocols, and congestion control to handle concurrent requests.

III. Design Overview of APCN

We provide an overview of transaction executions in APCN. Table I shows the API that APCN provides to users. It supports 1) creating deposits, 2) operating payment channels, and 3) settlement. APCN generates unique identifiers for each deposit and channel, e.g., when a deposit is created (new_deposit), a unique identifier is returned as a handle to be used in subsequent API calls. TEEs of each user are identified through unique public keys.

TEE service providers. Users generate public/private key pairs for their wallet addresses, which are cryptocurrency addresses owned exclusively by a user's TEE. They are generated securely inside each TEE, and their private keys are stored in TEE memory. The owner of the TEE cannot see the private key. Users can send funds to these addresses in the form of fund deposits. Then deposits can be used in any payment channels of the users. Note that **not all users are equipped with TEEs on their devices**, while some machines with TEEs are willing to provide their TEEs to others. These machines can serve as TEE service providers. Those users without a TEE-enabled node of their own can use a remote TEE service provider to manage their funds.

Users must verify the integrity of TEE before trusting them. APCN uses the remote attestation support of TEEs for verification [22]. A TEE (i) measures the enclave code, (ii) cryptographically signs the measurement and the user's public key, and (iii) provides the signed measurement and public key to the remote user. The remote user then verifies the attestation, i.e., the remote user ensures that the attestation is correctly signed by the TEE hardware and that the measurement corresponds to a known TEE implementation. Users

TABLE I
APCN API

APCN APIs	Inputs	Outputs	API Description
Deposits:			
`new_deposit`	t, k	d_i	Create a new fund deposit with ID d_i using a transaction t and the TEE's public key k
`new_pay_channel`	k	c_i	Create a new payment channel with ID c_i with a given TEE identified by k
Payments:			
`Update_ledger`	v, c_i, L	L	Pay an amount v to the other user in a payment channel c_i and update the Ledger
Routing:			
`routing`	v, n_d	n_j	Determine the next hop node n_j of a transaction to destination n_d
Settlement:			
`close_channel`	c_i, L	-	Shut down a payment channel c_i by updating the ledger. Mark the status of c_i as Inactive
`settle_deposit`	v, d_i	t	Refund a deposit d_i by generating and returning a transaction t

can thus verify that a specific service provider, identified by its public key, is operating genuine TEE hardware. And remote TEE providers have the same abilities as a local TEE. To deal with the situation that the machine with remote TEE going offline and avoid having to trust a single remote TEE service provider, APCN constructs committees with multiple remote service providers.

Service provider Committee. Committees are groups of TEE service providers that jointly manage fund deposits, ledgers and transactions. They are used to prevent single point failure when a user does not have a local TEE and has to rely on a TEE service provider to manage their funds. For each deposit owned by a committee, a minimum number of committee members are required to sign transactions before that deposit can be spent, thus tolerating a fixed number of TEE failures. For this, APCN used multi-signature support of the blockchain: each fund deposit is paid to a m-out-of-n wallet address, where m TEE signatures are required to spend the deposit. The n committee members are responsible to manage the user deposit.

IV. Payment Protocol

This section describes the design of APCN protocols.

A. Deposits allocation

In order to create a deposit for a user, a transaction indicating making deposits related to the user needs to be recorded on the blockchain. To construct a new deposit d, users invoke `new_deposit`, and present a deposit transaction t and the public key of the user's TEE. The TEE then verifies that t sends funds to the correct address using its public key k. The TEE then constructs a new deposit d, forwards t to the blockchain, and returns d's unique identifier signed by the TEE to the user.

Although the deposit is maintained by each user, we still need payment channels for transactions among users. Since the channels in APCN are stateless without funds in them, it is not necessary to associate a determined number of deposit with a certain channel. To create payment channels between users without a blockchain interaction, participants call `new_pay_channel` and provide the public key of the TEE with which to create the channel. The two TEEs then establish a secure communication channel using authenticated Diffie-Hellman for key provisioning and remote attestation. Using the secure channel, the TEEs assign a unique channel identifier to the channel c and return the channel identifier.

B. Using payment channels

To execute a payment t along a channel, the sender u calls `update_channel`, which specifies the amount ω to send and the channel identifier c_i. The sender's TEE first ensures that the sender has sufficient funds, $d_u > \omega$, before decrementing the sender's balance and incrementing the recipient v's balance locally. It then forwards the payment to the recipient's TEE to update balances. If the payment is not received by the recipient in a pre-determined time slot, e.g., due to a network failure, the sender's TEE rolls back the payment to prevent balance inconsistencies. If the payment is received by the recipient successfully, the sender's TEE needs to update the remaining deposit to be $d_u - \omega$, and the recipient's TEE needs to update the deposit to $d_v + \omega$. They also need to update the ledgers of the users respectively, which is $v : -\omega$ in the sender's ledger, and $u : +\omega$ in the recipient's ledger.

C. Congestion control

In PCNs like the Lightning and Raiden networks, most users by default pick the shortest path from the sender to the destination. However, it leads to the congestion problem [5]. Consider an example PCN shown in Fig 2. Suppose many users on the left side of a (in Cluster A) try to make transactions with users on the right side of b (in Cluster B) at the same time. Based on many routing protocols, when transaction requests from cluster A reach node a, a always forward those transactions to node b which has shorter paths to the receivers in cluster B. This leads to congestion on channel $a - b$, while channels $a - u$ and $b - u$ are under-utilized. And thus, all the transactions between clusters A and B would suffer from extra processing latency of channel $a - b$.

To address this problem, we introduce a congestion factor l_c for each channel, which shows the current processing latency for an incoming transaction in the channel. However, it is impossible to minimize the processing latency as well as maximize the success volume of the whole system as a linear programming problem, because we cannot probe and compare all the possible paths for every transaction in advance. Instead, we apply a heuristic mechanism to optimize the end-to-end latency - Latency Awareness (LA) forwarding, which avoids congested links.

In LA forwarding, a node u chooses a neighbor x as the next hop to receiver r such that it minimizes the heuristic function $h(u) = l(u, x) + \widetilde{l}(x, r)$. $l(u, x)$ is computed as how many transactions are currently using the channel $u - x$, and $\widetilde{l}(x, r)$ denotes the estimated routing latency from x to r from

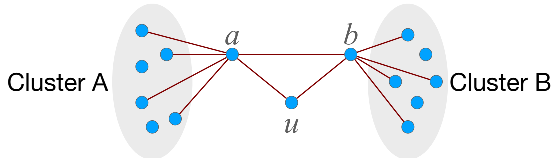


Fig. 2. Example illustrating the importance of congestion control in APCN.

locally computing the distance between the virtual positions of x and r. The first question is how to assign the congestion factor l_c for each channel. Assume the processing latency of a transaction at an idle channel c is Δ, and the channel can process one transaction at a time. If multiple transactions want to use the same channel, they will be put in a queue and l_c is adjusted according to the number of transactions in the queue. For example, the congestion factor of an idle channel c is $l_c = \Delta$. If there are 2 unfinished transactions in the channel c, the congestion factor becomes $l_c = 3\Delta$. The second question is how to estimate the remaining routing latency $\widetilde{l}$ from a neighbor node x to the receiver r. Note that we assign each node a virtual coordinate that reflects the network topology features. The node pair with small hopcounts in the network also shows a short distance in the Euclidean space. So we use the distance d_{xr} between the virtual positions of x and r as the estimated hopcounts between them. We estimate $\widetilde{l}(x, r)$ such that it is proportional to the estimated hopcounts between x and r. For simplicity, we assume all the channels between x and r are idle. So the heuristic function at node u is computed as: $h(u) = (n(u, x) + 1)\Delta + d(x, r)\Delta$, where $n(u, x)$ is the ongoing transactions in the channel ux.

However, simply assuming that all the channels between x and r are idle is not accurate since node u does not have any information on these channels. And selecting the next hop x according to the heuristic function $h(u)$ instead of choosing the next hop that is closest to the receiver r may lead to a larger routing stretch, and thus may introduce extra routing latency. There exists a trade-off between WebFlow which has lower routing stretch, and LA forwarding which has lower estimated routing latency. So we combine WebFlow and LA forwarding together. For each transaction arrived at node u, it has the probability p to apply WebFlow to be forwarded to the neighbor closest to the receiver. Otherwise, it runs the LA forwarding protocol. We will further evaluate and find the optimal p value in evaluation.

D. Deposits settlement

In PCNs, if a user wants to shut down a channel, he needs to have a transaction claiming the final state of the channel recorded on the blockchain. However, in APCN, shutting down a channel would not require any operation on the blockchain as we mentioned in Sec IV-B. Only if a user wants to go offline, does he need to settle his deposits and have his final deposits on the blockchain. The channel record in a ledger has four statuses: **Pending, Complete, Inactive, and Settled**. `Pending` is the status that there exist one or more ongoing transactions related to this channel. `Complete` is that all the transactions going through the channel is complete and confirmed by the sender and recipient. `Inactive` is the status that the user has shut down the channel and this channel does not exist anymore. `Settled` is the status that the neighbor that the user shares the channel with is offline and has settled all his channels and deposits.

To shut down a channel of the user u, it invokes `close_channel` and includes the channel id and the user id of its neighbor v whom it shares this channel c with as inputs. The TEE of u first checks the status of channel c in its ledger. If the status is `Inactive`, it means that the channel c has been closed before and does not exist currently. So `close_channel` will return 'FALSE'. If the status is `Settled`, it indicates that v is offline and has settled all the related channels. So the function will fail to shut down the channel and return 'FALSE'. If the status is `Pending`, it means that there exist one or more ongoing transactions related to this channel, including u sending payments via the channel c, other users sending payments to u via the channel c, and c served as intermediate hop of passing by transactions. In this case, the TEE of u will hold the `close_channel` request until the status of c becomes `Complete`. It is to prevent the situation that a transaction has probed and determined the path, but some channels of this path break down before the transaction completes. In the whole process, the TEE of u will reject any other transactions via the channel c. If the status of channel c becomes `Complete`, u's TEE can directly shut down the channel by changing the status to `Inactive` and inform v's TEE to change the status of channel c to `Inactive` in v's ledger as well. To prevent the case that a malicious u tries to close the channel using a stale state to benefit itself, when it invokes `close_channel`, v will have a bounded reaction time to invalidate the action by providing the latest state with the timestamp. If v approves or fails to respond within the time slot, u will continue closing the channel.

Consider user u wants to go offline and settle its deposit on the Blockchain. The first thing it needs to do is to settle all its channels by invoking `close_channel`.After the status of all the channel records in its ledger becomes `Complete`, the next step of u is to call `settle_deposit` and settle its deposits on chain. To do this, u need to obtain the latest ledger signed by its TEE from the TEE, and directly send its signed ledger to the Blockchain. u needs to keep monitoring the Blockchain until its ledger is verified, packed into a block, and added to the Blockchain. Then, u constructs a proof that its ledger has been added to Blockchain and sends the proof to all its neighbors. If some neighbors do not agree on the channel states, they could provide the correct signed ledger to Blockchain to dispute. If the proof is correct, the neighbor nodes will mark the channel $u - v$ as `Settled` in their own ledgers.

E. Transaction data format

Transactions. All transactions among users are conducted via channels by TEE service providers. Each transaction τ includes the address of the transaction recipient τ_{to}, the transaction amount τ_a, the address of the last hop user τ_f, and a monotonically increasing transaction index τ_i. We note that τ_f here is not necessarily the sender. For multi-hop transactions, τ_f records the last hop where the transaction comes from.

TABLE II
LEDGER STATE

Field	Symbol	Description
`Channel`	c	The channel id of this entry
`Neighbor`	c_N	Neighbor's address the user build channel c with
`Amount`	c_a	The overall transaction amount of the user
`State`	s	the state of transactions going on in the channel
	$\hookrightarrow s_p$	Pending, ongoing transaction in the channel
	$\hookrightarrow s_c$	Complete, all transactions in the channel complete
	$\hookrightarrow s_i$	Inactive, user has closed the channel
	$\hookrightarrow s_s$	Settled, user's neighbor has settled the channel
`Version`	ω	The version number of the latest transaction

For each intermediate user received a transaction, it needs to replace the τ_f field to be the address of it, and relay the transaction to the next hop.

Ledger state. The ledger in the TEE maintains state that contains the remaining deposit amount of the user, and several entries as shown in Table II. Each entry denotes a channel of the user u, and consist of the following items: the channel c built by u and its neighbor, the neighbor c_N the user u shares the channel c with, the overall amount u sent to the neighbor c_N via channel c, and the state s of this channel c as introduced in Sec IV. The amount of the channel can be negative, which is the amount user u owes c_N.

F. Users with and without TEE

Here we describe two categories of users separately, the user with local TEE, and the user without local TEE. Algorithm 1 shows the protocol executed by each node and TEE service provider. To construct a new deposit d, users with local TEE invoke `new_deposit_withTEE` (Alg. 1, line 1) and present a deposit transaction t and the TEE public key that t sends funds to. TEE verifies that t sends funds to the correct address using its public key k, and then constructs a new deposit d, forwards t to the blockchain, and returns d's unique identifier to the requester (line 7), signed by the corresponding TEE. For users without local TEE, they have to use more than one remote TEE service provider to prevent malicious attackers. To construct a new deposit d, users without local TEE invoke `new_deposit_withoutTEE` (line 8), and present a deposit transaction t and the list of TEE service providers' public keys forming the committee that t sends funds to. The service providers then verify that t sends funds to a k-out-of-m multi-signature address using the committee members' public keys, $k_1 ... k_m$, and notify the committee of the new t. The user then constructs a new deposit d, forwards t to the blockchain, and returns d's unique identifier to the requester (line 14), signed by all committee members.

Payment channels do not hold any funds, and can be set up or close at any time. Creating a payment channel c is to add an entry in the ledger of user u and v. Before the channel c can be set up, it must be approved by the the remote party (e.g., v if u requests channel creation approval) using `approve_channel` (line 15). Approval contacts the remote user via its TEE and queries if the user is online to build a channel c.

After approval, to create payment channels between users without blockchain interaction, participants call `new_pay_channel` and provide the public key of the TEE with which to create the channel (line 18). The TEEs of two users then establish a secure communication channel using authenticated Diffie-Hellman for key provisioning and remote attestation. Using the secure channel, the TEEs assign a unique channel identifier c_i to the channel c, initialize both participant's balances to 0, and return the channel identifier (line 24). Then the two users u and v need to create the corresponding entry of the channel in their ledgers using `add_ledger` (line 33). When u creates the channel c, its TEE initializes the amount of entry c in the ledger to be 0, and the channel state to be s_c. Only after the ledger created successfully, can the channel c be used by user u and v for future transactions. If one of them wants to close this channel, she needs to call `close_channel` (line 44) to close the corresponding entry of the channel in both u and v's ledgers. At any time, users may settle the deposit using `settle_deposit` (line 60) by calling `close_channel` for all channels.

G. TEE operations

In this section, we describe three functions associated with ledger: Ledger creation, Ledger update and Ledger close. The construction consists of the instructions for two users, Alice and Bob, and their ledgers on their TEEs.

Ledger creation: We start with describing a procedure in which Alice and Bob register in the APCN system with the initial balance, a_A and a_B. As mentioned in Sec IV-F, after their TEEs verifying the correctness of their deposit transactions t_A and t_B, respectively, their TEEs need to construct new deposits d_A and d_B, forward their deposit transactions to the blockchain, and initialize a ledger with the deposit d_A and d_B, with the amount being a_A and a_B. The current version of the ledgers is empty ones with no entry.

When Alice and Bob agree to open a channel c in APCN, their TEEs negotiate and assign a unique channel identifier c_i to the channel c. Then TEEs need to create the corresponding entry of the channel in their ledgers, whose format should follow Table II. For the new ledger entry in Alice's TEE, the Deposit field continues to be a_A, since no transaction happens at this time. The Channel field is c_i as the return value of the function `new_pay_channel` in Alg. 1. The Neighbor field c_N is set to be Bob's address. The Amount field is initialized as 0, since no transaction happens and the overall transaction amount Alice sends to Bob is 0. The State field is s_c, which means the channel is active and there is no pending transaction in the channel, so the channel is ready to serve future transactions.

Ledger update: When Alice and Bob want to make a new transaction when there is an ongoing transaction in channel c, we use a standard technique (see, e.g, Sec. 3.3 in [2]) for updating the entry for a payment channel in the ledger that is based on counters called "version numbers" $\omega \in N$. Note that the transaction here includes the direct transaction between Alice and Bob, and the multi-path transaction going through Alice and Bob. We do not distinguish between these two situations. Initially, ω is set to 0, and it is incremented after each transaction via channel c. Suppose Alice initiates

Algorithm 1 APCN payment protocol executed by each node and TEE service provider.

```
def new_deposit_withTEE(t, k):
  verify_tx(t, k)
  d ← create_new_deposit(t)
  deposits[d_i] ← d
  write_to_blockchain(t)
  create_Ledger(d_i)
  return d_i

def new_deposit_withoutTEE(t, k_1 ...k_m):
  verify_tx(t, k_1...k_m)
  d ← create_new_deposit(t)
  deposits[d_i] ← d
  write_to_blockchain(t)
  create_Ledger(d_i)
  return d_i

def approve_channel(k):
  apprv ← ask_approve_remote(k)
  return apprv

def new_pay_channel(k):
  c ← create_channel_with(k)
  channels[c_i] ← c
  add_Ledger(c_i)
  add_Ledger(c_N)
  return c_i

def pay_channel(v, c_i):
  c ← channels[c_i]
  assert(c.my_bal ≥ v)
  Update_Ledger(-v, c_i)
  Update_Ledger(v, c_N)

def create_Ledger(d_i):
  d ← deposits[d_i]
  a ← d
  return L

def add_Ledger(c_i, L):
  c ← channels[c_i]
  c.a ← 0
  s ← s_c
  return L

def Update_Ledger(v, c_i, L):
  c ← channels[c_i]
  c.my_bal ← c.my_bal + v
  c_a ← c_a + v
  s ← s_p
  return L

def close_channel(c_i, L):
  c ← channels[c_i]
  Close_Ledger(c_i,L)
  Close_Ledger(c_N,L)

def Close_Ledger(c_i, L):
  // Collect all entries of channel c
  c ← channels[c_i]
  if s == s.c then
    s ← s.i
    return TRUE
  else
    wait for time Δ
    if s == s.c then
      s ← s.i
      return TRUE
  return FALSE

def settle_deposit(d_i):
  for all channels c in U's ledger do
    close_channel(c_i)
  t ← construct_tx(d_i, k)
  return t
```

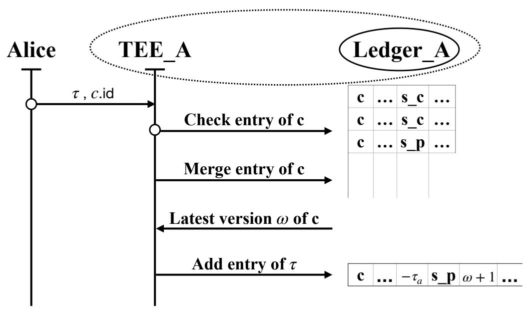


Fig. 3. Illustration of ledger update protocol.

the first transaction τ of amount τ_a in channel c. If Bob agrees on this transaction, TEE_A and TEE_B both need to update the corresponding entry in their ledgers. On Alice's side, there is only one entry of channel c in its ledger, and the current status of the entry is s_c with version number 0. So Alice will update its ledger by updating this entry. The Amount field is set to be $c_a - \tau_a$. The State field is changed to s_p until the transaction is complete. Also, the version number ω is incremented by 1. In Bob's ledger, its TEE updates the Amount field to be $c_a + \tau_a$, the State field to be s_p, and the version number to be 1 in the entry for channel c.

Ledger close: If one of the parties, say Alice, wants to close the channel c, she first needs to negotiate with Bob. After approval by Bob, both of them needs to close the entry of channel c in their ledgers. Again, their TEEs need to check their ledgers, collect all entries of channel c, and merge all those with status s_c. After this, if there is only one entry of channel c and its state is s_c, TEEs can directly close the channel by setting the State field of the entry to be Inactive s_i. If there exists some entries of channel c with status s_p, TEEs wait time Δ for those transactions to complete. After the waiting time Δ, TEEs merge those entries with status s_c and update the State field to be Inactive s_i. Those entries whose status are still s_p will be abandoned.

H. TEE committees

We provide TEE committees to prevent malicious TEE service providers for users without TEEs. For a new TEE service provider who wants to join the system, it has to perform remote attestation with a group of TEE committee to verify that it has the correct code and works correctly. It also has to pay certain amount of participation fee to be included in this committee. Every time when the committee performs a transaction correctly, all the members will receive incentive from the user.

When creating channels or sending a payment, a user should get approval from the committee and update its ledger. In order to achieve agreement and consistency of ledger state among all committee members, APCN uses Committee chains introduced in TeeChain [7]. The chain replication offers strong consistency without requiring all committee members to communicate directly. The committee members form a chain, with the primary at the head, and the last backup at the tail. The user first sends the update request to the primary in the committee. The primary will check if the user has sufficient funds and propagates the update down the chain. Each committee member does the same check, forwards the update to its backup, and waits for an acknowledgment before updating the ledger. When the primary receives an acknowledgment, the entire chain has updated. If any committee member fails or refuses to update to the latest agreed upon ledgers, the replication chain is broken, freezing all nodes at the current ledger state. And this member will lose all its participation fees and incentive in the committee.

V. Protocol Security Analysis

APCN protects the funds of all users in the PCN: despite what others may do, funds cannot be stolen or double spent. At any time during the payment protocol execution, each user should be able to perform a finite set of actions that eventually results in them receiving their perceived balance on the underlying blockchain.

We now prove that APCN achieves funds security using the Universal Composability (UC) framework [23] similar to prior work [7], [24]. The UC framework includes parties executing the protocol in the real world, ideal functionalities performed by idealized third parties, and a set of adversaries $\mathcal{A}$. A protocol is said to be UC secure if the real-world execution of the protocol cannot be distinguished from the idealized protocol execution by the environment.

We model committees as a single TEE executing the protocol. Under UC, we consider a real world, in which users run the APCN protocol, π_{APCN}, as described in Sec III, and an ideal world, in which users interact with an ideal functionality, F_{APCN}, implemented by a trusted third party. Attackers behavior is introduced in the ideal world by a simulator $\mathcal{S}$ with appropriate attacker abilities as described in Sec II-C. To prove that APCN achieves fund security, we show that (i) the real and ideal worlds are indistinguishable to an external observer ε. This implies that any attack violating fund security in the real world is also possible in the ideal one; and (ii) F_{APCN} achieves fund security in the ideal world. This proves that π_{APCN} also achieves fund security. We'll show that the simulator $\mathcal{S}$ in the ideal-world translates every adversary $\mathcal{A}$ in the real-world into a simulated attacker, which is indistinguishable to the environment.

We prove indistinguishability between the real and ideal worlds through a series of five *hybrid steps*, starting at the real world H_0, and ending in the ideal world H_5. In each step, a key element is changed and indistinguishability is proven. As commonly done [25], in H_0, the desired behavior of TEEs and the blockchain are replaced by two ideal functionalities, F_{TEE} and F_B respectively. F_{TEE} is an ideal functionality that models a TEE. It abstracts an enclave as a third party trusted for execution, confidentiality and authenticity, with respect to any user that is part of the system. F_B is an ideal functionality that represents the blockchain. H_1 behaves the same as H_0 except that $\mathcal{S}$ simulates F_{TEE}. When the adversary $\mathcal{A}$ wants to communicate with its F_{TEE}, $\mathcal{S}$ faithfully emulates F_{TEE}'s behavior and records $\mathcal{A}$'s messages. As $\mathcal{S}$ simulates the real-world protocol perfectly, the environment ε cannot distinguish between H_0 and H_1. In H_2, $\mathcal{S}$ simulates F_B. When the adversary $\mathcal{A}$ wants to interact with the blockchain, $\mathcal{S}$ emulates F_B's behavior for $\mathcal{A}$, and no environment can distinguish between H_1 and H_2. H_3 behaves the same as H_2 except that if $\mathcal{A}$ invoked its F_{TEE} with an incorrect call, $\mathcal{S}$ aborts and drops incorrectly signed messages to F_{TEE}. Otherwise, $\mathcal{S}$ delivers the message to the honest party in the protocol. H_2 and H_3 are indistinguishable, or else ε and $\mathcal{A}$ can be leveraged to construct an adversary that succeeds in a signature forgery. In H_4, the only difference is that incorrectly signed messages to F_B are dropped by $\mathcal{S}$. H_4 is indistinguishable from H_3 for the same reasons as the last step. H_5 is the ideal world execution, that calls of $\mathcal{S}$ to F_{APCN} are mapped from the calls in the simulated real-world. In H_4, $\mathcal{S}$ can faithfully interact with F_{APCN}, while faithfully emulating $\mathcal{A}$'s view of the real-world. $\mathcal{S}$ can then output to ε exactly $\mathcal{A}$'s output in the real-world. So it is equivalence between π_{APCN} and F_{TEE} to ε.

Since for any environment the ideal-world and the real-world executions are indistinguishable, funds security that holds in the ideal-world will also hold in the real-world. We now discuss why the ideal functionality F_{APCN} satisfies the security requirements from Sec. II-D.

Correctness on channel update. For users sharing a channel with their own TEEs, the correct channel activities are achieved by the ideal functionality notifying the users of whether the channel has successfully been created or updated. For users without TEEs, chain replication in the TEE committee offers strong consistency among all TEEs, which will finally achieve consensus on channel state and notify users.

Guaranteed channel closing with latest state. A channel $u - v$ can be closed by either u or v with latest state. If u sends a channel closing request to the ideal functionality F_{APCN}, it will inform v with a message. If it does not receive any dispute or response from v within time Δ, it will close the channel after the channel finishing all the ongoing transactions or reaching time bound. If v provides a dispute with the correct signed ledger and latest timestamp, F_{APCN} will accept this channel state to close the channel, and also for future settlement.

Guaranteed no double spending. Consider a user u, it calls the ideal functionality F_{APCN} to make a transaction to v. F_{APCN} always guarantees that u has enough funds to pay v, and updates funds after each transaction. It makes sure that u cannot use the same amount of money to pay others twice.

VI. Performance Evaluation

We present the evaluation results based on prototype implementation and simulations.

A. Methodology

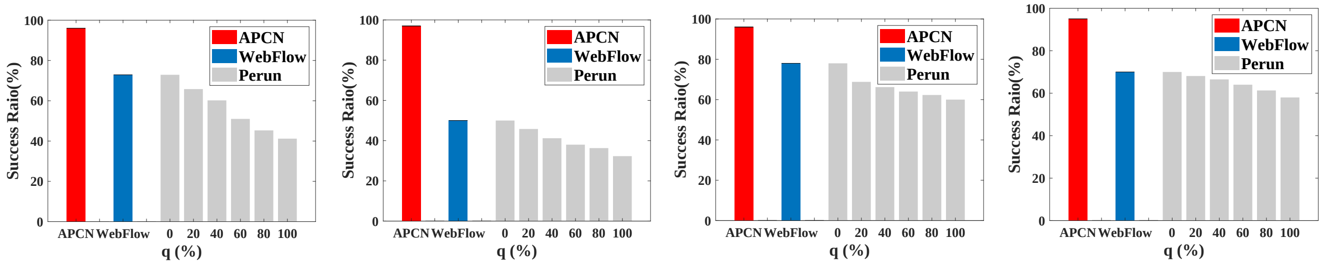
We implement the APCN prototype using Intel SGX SDK in C++. The prototype is mainly used for evaluating the real latency to generate ledgers, links, and transactions. Note that multiple TEE implementations are commercially available, including ARM TrustZone and AMD SEV. They can also be applied.

The simulations use two real PCN topologies: Ripple [26] and Lightning [2], as well as synthesis topologies. For Ripple, we use the data from January 2021 to December 2021, and get the network topology with 1,783 nodes and 18,395 edges in our simulation. For Lightning, we get the network topology with 3,519 nodes and 47,311 edges on one day in January 2022. The node balance in APCN is assigned as the sum of the channel balances of a node. We build two sets of synthetic PCN topologies based on the Waxman model [27] and the scale-free network model [28]. The node balances are assigned similar to those of Ripple. The payments are also generated by mapping the Ripple transactions to the synthetic topologies.

In order to defend side-channel attacks, we use timing and memory-access side-channel resistant libraries, AES-NI based AES-GCM [29], [30]. To further enhance the security of APCN, we apply T-SGX [18], a countermeasure for controlled-channel attacks.

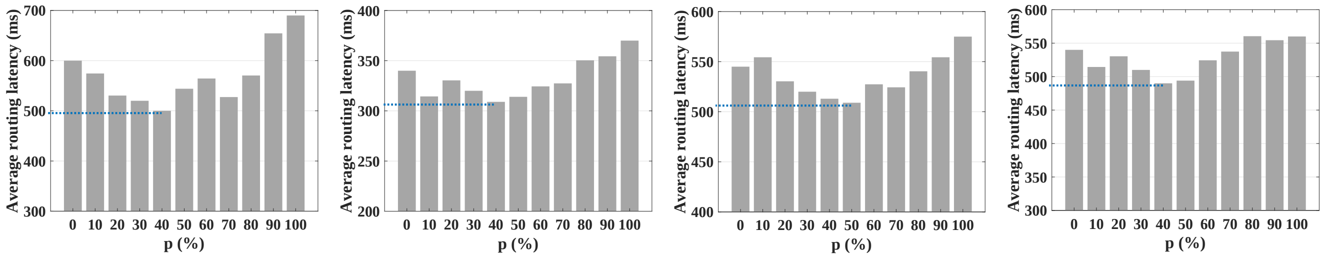
Comparisons. To evaluate the performance of APCN, we compare APCN with WebFlow [8], SpeedyMurmurs (SM) [31], Spider [5], Perun [32], and shortest paths (SP).

Metrics. We use average processing latency and the number of hopcounts to evaluate the congestion control mechanism in APCN. The processing latency of payment is calculated as the sum of per-hop delay along the path which is related to the channel condition. Similar to prior work [6], [31], we also use success rate as evaluation metric for resource utilization, defined as the percentage of successful payments whose demands are met overall generated payments. We report



(a) Ripple (b) Lightning (c) Waxman (d) Scale-free

Fig. 4. The success ratio comparison of APCN, PCN and virtual payment channel network with varying proportion of virtual channels.



(a) Ripple (b) Lightning (c) Waxman (d) Scale-free

Fig. 5. The average routing latency with varying p values.

TABLE III
CHANNEL PERFORMANCE

Operation and Latency(ms)	APCN	APCN w/ T-SGX
Single Local TEE:		
`new_payment_channel`	2,310	6,183
`close_channel`	2,205	5,830
`makepayments`	105	291
Remote TEE:		
`new_payment_channel`	4,317	25,294
`close_channel`	2,984	12,523
`makepayments`	427	1,015

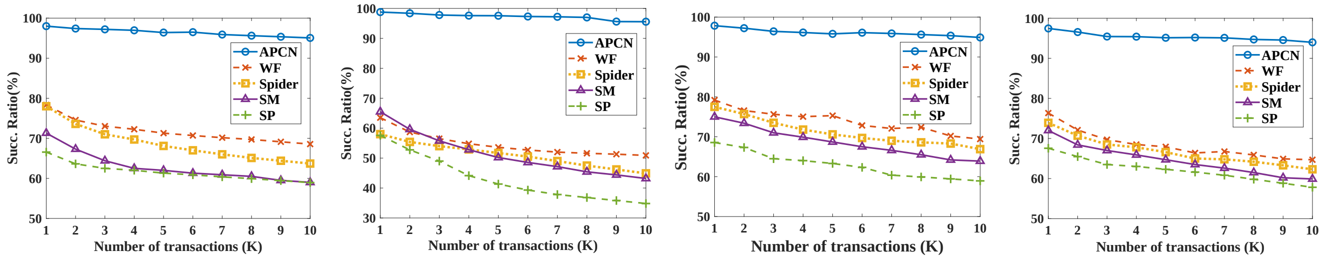
the average results over 10 runs, each of which includes hundreds of communication pairs.

B. Evaluation Results

Performance of payment channels. We conduct a testbed evaluation with the prototype. In the experiments, we construct a payment channel between two users with local TEEs. So the users only use a single local TEE to manage their ledgers and transactions instead of the TEE service providers committee. We execute several transactions between them. Table III shows the performance of different actions of APCN, and the latency when applying T-SGX to improve system security. Each channel creation takes 2.3 secs on average. It is much faster than channel creation in Lightning Network, which is approximately 60 mins, as a transaction must be placed onto the blockchain and confirmation takes 6 Bitcoin blocks. Channel creation in APCN only requires the corresponding TEE to perform remote attestation and add an entry in its ledger, without the participants of the blockchain. Even though remote attestation requires participation of the Intel attestation service, it will not become the bottleneck when the system scales up. The reason is that each user only has limited number of channels with its neighbors, and channel creation is not a frequent action. As long as the channel is there, users can perform unlimited number of transactions via the channel. To close a channel, TEE has to wait until the channel status in the ledger becomes ‘Complete’. The waiting time can vary a lot, so we only evaluate the time to close a channel whose status is Complete. In APCN, closing a channel only requires status change in the ledger and takes 2.2 secs on average, which is much less than the time to close a channel in Lightning Network which requires a transaction in blockchain. For the payments processing latency, we only consider the time of an idle channel processing one payment. It is 105 ms on average. We use this time as Δ in our congestion control mechanism in evaluation.

We then consider the case of non-SGX users. we construct a payment channel between two users, one is equipped with SGX, one is not and uses a TEE service provider committee at size of 3. Creation of such a payment channel takes 4.3 secs, as the non-SGX user must verify the integrity of TEEs of the committee. Closing channel and processing payment also take more times, 2.9 secs and 427 ms respectively, since each TEE service provider in the committee needs to verify and sign each update of the user's ledger. When applying T-SGX to APCN, the processing latency increased within 5 times in all the cases, which is tolerable for better security.

Comparison with other PCNs. We use simulations to compare the performance of APCN, WebFlow, and Perun – a virtual payment channel system. For virtual payment channels, we analyze the historical transaction dataset in different network topologies. The virtual channels are built according to the transaction frequency of user pairs. We tends to build virtual channel for user pairs making transactions with higher frequency. We set the proportion of virtual channels to be q, and vary the q value from 0% to 100% to test the performance. Here, we use 5,000 transactions in each run. Figure 4 shows the success rates of transactions in APCN, WebFlow, and Perun with varying q value. When q is 0, Perun has no virtual channel, and it becomes the same scheme as WebFlow. All users need to execute the routing protocol to probe the



(a) Ripple (b) Lightning (c) Waxman (d) Scale-free

Fig. 6. The success ratio with varying transaction numbers under different network topologies.

payment channels to send or relay transactions. So it has the same performance as WebFlow. With more payment pairs setting up virtual channel, the overall success rate decreases a lot. The reason is that, with more virtual channels in the networks, more funds are locked in the virtual channels, and those funds cannot be used in other channels. Although virtual payment channels provide a very fast way to stream payments, it actually affect the overall success rate.

Efficiency of congestion control mechanism. We first consider the influence of parameters in our congestion control mechanism. With congestion control, the intermediate node would send the payment to the direct neighbor closest to the receiver with a probability p in APCN. To find the optimal p for our system, we vary the p value from 0% to 100%, and see how the choice impacts the performance, i.e. average processing latency. Here, we use 5,000 transactions in each run. Figure 5 shows the average processing latency with varying p values. It is understandable that both settings: $p = 0\%$ and 100% result in relatively high average processing delay. Because when p equals to 0%, it becomes the same routing protocol as WebFlow without congestion control. Even if the algorithm always chooses the next hop that is closest to the receiver and more likely to have lower routing stretch, the next hop itself may introduce large processing delay, and thus lead to higher overall processing latency along the path. On the contrary, when p equals to 100%, our heuristic routing algorithm at intermediate nodes estimates the remaining processing latency proportional to the distance from the node to the recipient. However, this estimation is not accurate reflecting the processing latency, since hop-delay is not a stable metric and changing over time. Observed from the evaluation result, when p equals to 40%, the congestion control mechanism could achieve a better performance. So we set p value to 40% in the following experiments.

Performance with different networks. We evaluate APCN with four PCN topologies and a varied number of transactions. As shown in Fig. 6, by increasing of the number of transactions, the success rate of all schemes except APCN decreases significantly in all topologies. The reason is that, for other schemes under traditional payment channel networks, as more transactions flowing into the network, more channels are saturated in one direction, making them cannot be used for future transactions. However, in APCN, the success ratio almost keeps over 95% and does not have obvious changes, while success ratio of other schemes are always below 80%.

VII. Related Work

PCNs provide a high-throughput solution for blockchains [33]. Lightning Network [2] uses max-flow routing algorithms to find paths. Flash [6] also uses modified max-flow routing algorithms but treats elephant and mice payments differently. SilentWhispers [34], SpeedyMurmurs [31], and have been proposed to improve routing scalability.

In order to improve the fund utilization and avoid channel imbalance, Spider [5] develops a multi-path congestion control algorithm. It is a centralized offline routing algorithm and still has a high probing overhead. REVIVE [35] enables users to securely rebalance their channels, according to the preferences of the channel owners. Sprites [36] supports partial withdrawals and deposits, during which the channel can continue to operate without interruption, but requires smart contracts. Teechain [7] supports dynamic deposits with treasuries by TEEs, in order to prevent parties from stealing the fund. Different from them, APCN enables shared deposits among all payment channels of each user and allows funds to be used with high flexibility.

VIII. Conclusion

We present APCN, a novel design for PCNs that enables shared funds among all the payment channels of a node. This design provides high fund-allocation flexibility and hence significantly increases transaction success rates. To prevent users from misbehavior, we use TEEs to control funds, balances, and payments. We also design a routing protocol in APCN that takes congestion control into account. We build a prototype of APCN with Intel SGX and evaluate the performance with both prototype experiments and simulations with real PCN data. Results show that APCN achieves evidently higher success rates of multi-hop payments with lower average hops and latency, compared to existing PCNs.

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