AuditPCH: Auditable Payment Channel Hub with Privacy Protection

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Outline

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3. Linkable Randomizable Puzzle Scheme
4. Auditable Anonymous PCH
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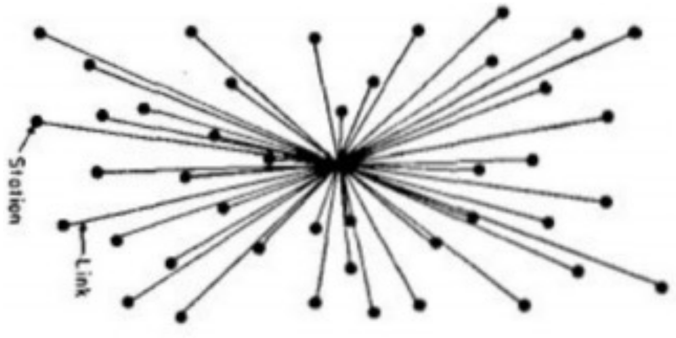
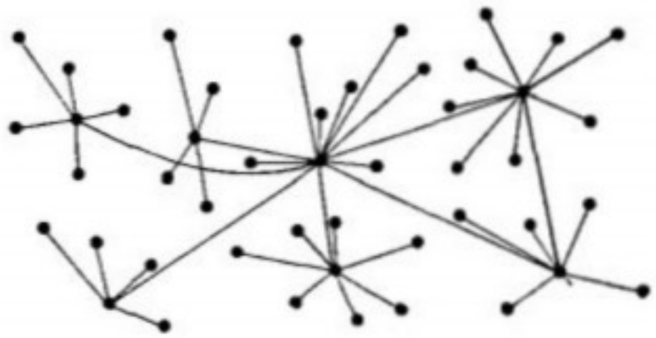
1 Background

1.1 Payment Channel

- Two users open a payment channel and perform off-chain payments by updating the channel state enjoying high payment throughput and low confirmation delay.
- If there are more than two users, each pair of users needs to establish their own payment channel to facilitate the payment, which is a non-scalable approach.
- Payment Channel Networks (PCN) enable two users with no direct payment channel to pay each other through the channels of some intermediaries.
- PCN payments may require multi-channel paths and intermediaries to actively participate in relaying the payments, which can lead to their failure.



Centralized



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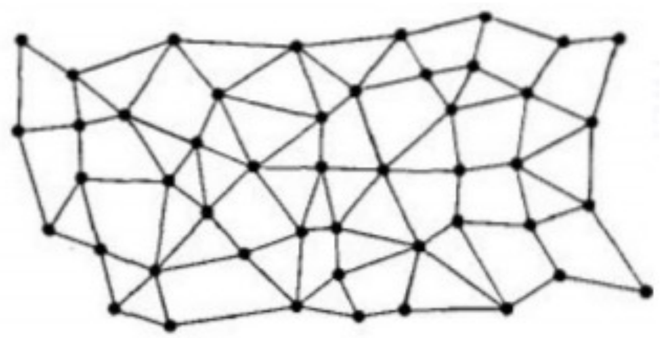

Distributed

1.2 Challenges in Auditable Anonymous PCH

- **Atomicity:** For any payment of m coins from S to R, the PCH should ensure that either R receives m coins from T and T receives m coins from S, or both parties receive none.
- **Value Privacy:** T should not know the payment amount between S and R.
- **Relationship Anonymity:** T should not be able to find out if there is any relation between S and R of a specific payment.
- **Griefing Resistance:** The PCH should only initiate a payment procedure if R can prove that the payment request are previously backed by some coins locked by a S during the payment procedure.
- **Illegal Financial Activity Auditability:** A should know the relationship of S and R and verify the integrity of payments.

1.3 Abstract

- **PCH Definition:**

Anonymous Payment Channel Hub (PCH), one of the most promising layer-two solutions, settles the scalability issue in blockchain while guaranteeing the unlinkability of transacting parties.

- **Problem:**

Developments bring conflicting requirements, i.e., hiding the sender-to-receiver relationships from any third party but opening the relationship to the auditor. Existing works do not support these requirements simultaneously since off-chain transactions are not recorded in the blockchain.

- **This work:**

The first anonymous PCH solution that provides privacy & auditability.

① Linkable randomizable puzzle for conditional transactions.

② A novel auditable solution for PCH.

③ Formal security proof & extensive experiments and evaluation.

2 Preliminaries

2.1 Public Key Encryption

Public Key Encryption. The encryption scheme includes the algorithms (Gen, Enc, Dec) [18]. $(pk, sk) \leftarrow \mathsf{Gen}(\lambda)$ is the key generation algorithm to produce a key pair (sk, pk), where sk is a selected value. $c \leftarrow \mathsf{Enc}(pk, m)$ is the encryption algorithm to encrypt a message m with the public key pk as a ciphertext c. $m' \leftarrow \mathsf{Dec}(c, sk)$ decrypts the ciphertext c as the plaintext m' via the private key sk. We utilize the ElGamal encryption scheme Π_{El} [18] and the Castagnos-Laguillaumie (CL) encryption scheme Π_{CL} which satisfy the Indistinguishability under Chosen Plaintext Attacks (IND-CPA).

SysGen: The system parameter generation algorithm takes as input a security parameter λ. It chooses a cyclic group $(\mathbb{G}, p, g)$ and returns the system parameters $SP = (\mathbb{G}, p, g)$.

KeyGen: The key generation algorithm takes as input the system parameters SP. It randomly chooses $\alpha \in \mathbb{Z}_p$, computes $g_1 = g^\alpha$, and returns a public/secret key pair (pk, sk) as follows:

$$pk = g_1, \quad sk = \alpha.$$

Encrypt: The encryption algorithm takes as input a message $m \in \mathbb{G}$, the public key pk, and the system parameters SP. It chooses a random number $r \in \mathbb{Z}_p$ and returns the ciphertext CT as $CT = (C_1, C_2) = \left(g^r,\ g_1^r \cdot m\right)$.

Decrypt: The decryption algorithm takes as input a ciphertext CT, the secret key sk, and the system parameters SP. Let $CT = (C_1, C_2)$. It decrypts the message by computing

$$C_2 \cdot C_1^{-\alpha} = g_1^r m \cdot (g^r)^{-\alpha} = m.$$

Algorithm $\mathsf{KeyGen}(1^\lambda)$

1. $(B, n, p, s, g, f, G, F) \xleftarrow{\$} \mathsf{Gen}(1^\lambda, 1^\mu)$
2. Pick[a] $x \xleftarrow{\$} \{0, \ldots, Bp-1\}$ and set $h \leftarrow g^x$
3. Set $pk \leftarrow (B, p, g, h, f)$ and $sk \leftarrow x$.
4. Return (pk, sk)

Algorithm $\mathsf{Encrypt}(1^\lambda, pk, m)$

1. Pick $r \xleftarrow{\$} \{0, \ldots, Bp-1\}$
2. Compute $c_1 \leftarrow g^r$
3. Compute $c_2 \leftarrow f^m h^r$
4. Return (c_1, c_2)

Algorithm $\mathsf{Decrypt}(1^\lambda, pk, sk, (c_1, c_2))$

1. Compute $M \leftarrow c_2 / c_1^x$
2. $m \leftarrow \mathsf{Solve}(p, g, f, G, F, M)$
3. Return m

Algorithm $\mathsf{EvalSum}(1^\lambda, pk, (c_1, c_2), (c_1', c_2'))$

1. Compute $c_1'' \leftarrow c_1 c_1'$ and $c_2'' \leftarrow c_2 c_2'$
2. Pick $r \xleftarrow{\$} \{0, \ldots, Bp-1\}$
3. Return $(c_1'' g^r, c_2'' h^r)$

Algorithm $\mathsf{EvalScal}(1^\lambda, pk, (c_1, c_2), \alpha)$

1. Compute $c_1' \leftarrow c_1^\alpha$ and $c_2' \leftarrow c_2^\alpha$
2. Pick $r \xleftarrow{\$} \{0, \ldots, Bp-1\}$
3. Return $(c_1' g^r, c_2' h^r)$

2.2 Commitment Scheme

Commitment scheme. Our construction requires a commitment scheme that allows users to commit a message (e.g., token identification) and verify its correctness. A commitment scheme Π_{com} is composed by three algorithms ($\mathsf{CMSetup}$, Com, $\mathsf{CMVerify}$). $pp \leftarrow \mathsf{CMSetup}(\lambda)$ inputs λ and generates the public parameter pp. $(com, r) \leftarrow \mathsf{Com}(pp, m, r)$ commits the message m in the commitment com with the randomness coin r. $\{0, 1\} \leftarrow \mathsf{CMVerify}(com, r, m)$ verifies if the message m is committed in com. Our solution introduces the Pedersen commitment scheme [14], satisfying the information-theoretically hiding and computationally binding properties.

Let us consider $\mathbb{G} = \langle g \rangle$, a cyclic group of prime order q, and two random generators $g, h \in \mathbb{G}$. The Pedersen commitment scheme allows to commit to scalar elements from $\mathbb{Z}_q$:

Commitment: to commit to a scalar $m \in \mathbb{Z}_q$, one chooses a random $r \xleftarrow{\$} \mathbb{Z}_q$, and sets $c \leftarrow g^m h^r$, while the opening value is set to r;

Opening: to open a commitment $c \in \mathbb{G}$, one reveals the pair (m, r). If $c = g^m h^r$, the receiver accepts the opening to m, otherwise it refuses.

2.3 Malleable Proof Scheme

Malleable proof scheme. The malleable proof schemes [16, 19] support users to transform their receiving proofs into new proofs against the converted witness (e.g., a randomized solution of a randomized puzzle) and statement. Let $R(x, w)$ be a relation related to the language $L := \{x \mid \exists w$ such that $(x, w) \in R\}$, where x is a statement and w is a witness of the statement. Two transformation functions ($w' = \mathcal{T}_{wit}(w)$, $x' = \mathcal{T}_{stmt}(x)$) are defined to restrict the allowed transformation of users. The malleable proof scheme is formulated as: $\Pi_{\mathsf{MP}} = (\mathsf{CRSSetup}, \mathsf{Vry}, \mathsf{Prove}, \mathsf{ZKEval})$. $crs \leftarrow \mathsf{CRSSetup}(\lambda)$ generates the Common Reference Strings (CRS) crs. $\pi \leftarrow \mathsf{Prove}(w, crs, x)$ is the prover algorithm with the witness w, the CRS crs, and the statement x as inputs to produce a proof π stating $(x, w) \in R$. $\{0, 1\} \leftarrow \mathsf{Vry}(\pi, crs, x)$ is the verifier algorithm to check whether the existence of w and x satisfies the relation R. $\pi' \leftarrow \mathsf{ZKEval}(crs, x, \{\mathcal{T}_{wit}, \mathcal{T}_{stmt}\}, \pi)$ produces a transformed proof π' for stating $(x', w') \in R$, where x' and w' come from the transformation functions $\{\mathcal{T}_{wit}, \mathcal{T}_{stmt}\}$. Note that the transformed proof π' still can be verified by the algorithm Vry. Here, a malleable proof scheme [16] is initialized by the Groth-Sahai proof scheme [19] and satisfies the Witness Indistinguishability (WI) property.

Malleable Proof Systems and Applications

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Efficient Non-interactive Proof Systems for Bilinear Groups *

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2.4 Adaptor Signature

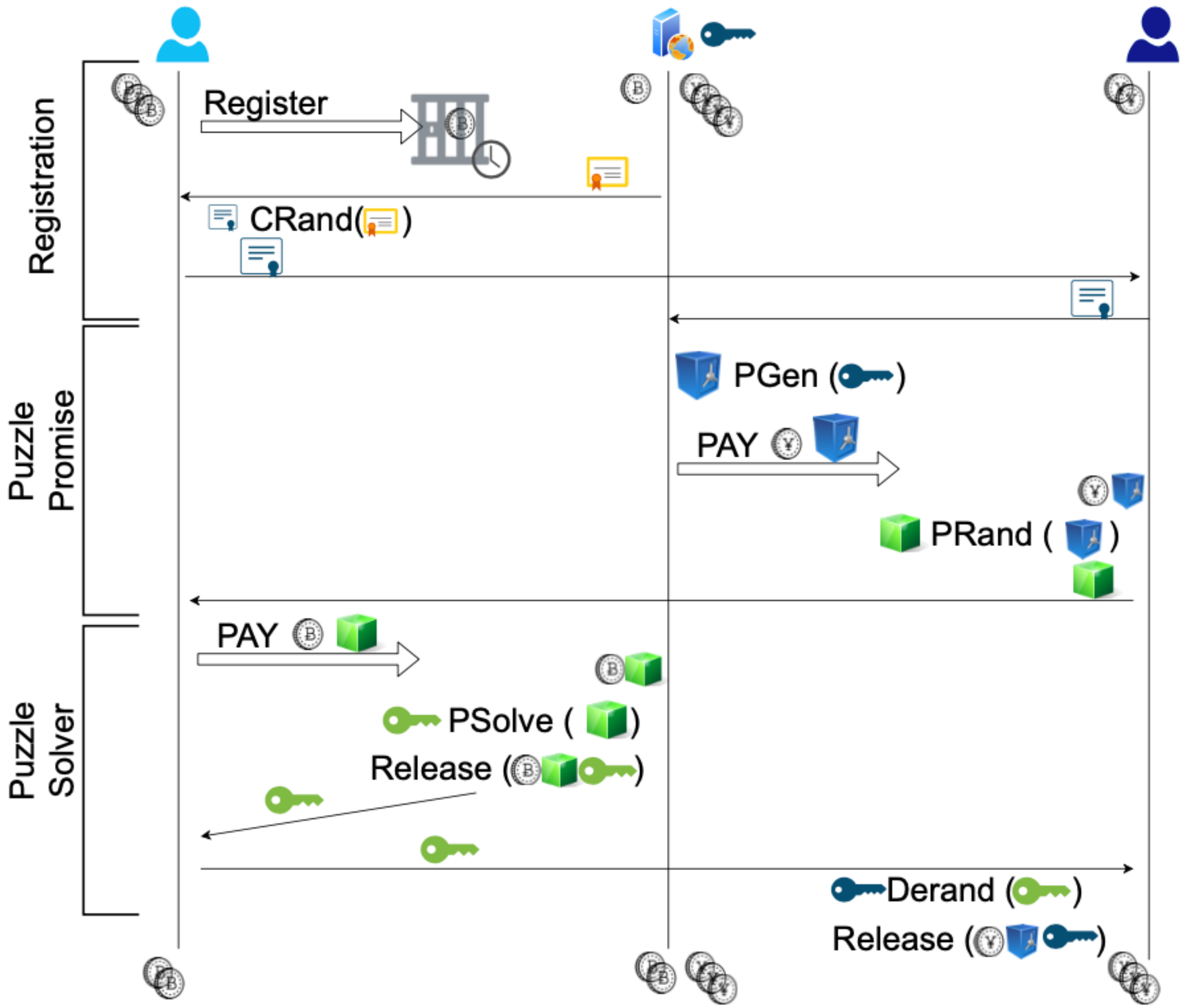
Adaptor signature scheme. Different from traditional signature schemes, the adaptor signature scheme Π_{ad}, which consists of five algorithms (SKeyGen, PSign, Adapt, PVrfy, Ext), enables signers to give a *pre-signature* concerning the revelation of a secret value. We define a statement $Y = g^y$, where g is the generator of the group. $(pk, sk) \leftarrow \mathsf{SKeyGen}(\lambda)$ initializes a key pair (pk, sk) for signing. $\widetilde{\sigma} \leftarrow \mathsf{PSign}(m, Y, sk)$ inputs the secret key sk, a message m, and a statement Y to generate a pre-signature $\widetilde{\sigma}$. $\{0,1\} \leftarrow \mathsf{PVrfy}(pk, m, \widetilde{\sigma}, Y)$ checks the validity of the pre-signature $\widetilde{\sigma}$. $\sigma \leftarrow \mathsf{Adapt}(y, \widetilde{\sigma})$ takes the witness y and the pre-signature $\widetilde{\sigma}$ as inputs to produce a valid signature σ. $y \leftarrow \mathsf{Ext}(\widetilde{\sigma}, \sigma, Y)$ computes the witness y via the inputs $\widetilde{\sigma}$ and σ. The adaptor signature scheme satisfies pre-signature adaptability, which guarantees parties collect a valid signature from a valid pre-signature, and witness extractability, which ensures parties extract a valid witness via a valid signature and its pre-signature. Here, the scheme is formalized in [20, 21] and matches the security property against Existential Unforgeability under Chosen Message Attack (EUF-CMA) [18].

$\mathsf{pSign}_{sk}(m, I_Y)$	$\mathsf{pVrfy}_{pk}(m, I_Y; \tilde{\sigma})$	$\mathsf{Adapt}(\tilde{\sigma}, y)$	$\mathsf{Ext}(\sigma, \tilde{\sigma}, I_Y)$
$x := sk, (Y, \pi_Y) := I_Y$	$X := pk, (Y, \pi_Y) := I_Y$	$(r, \tilde{s}, K, \pi) := \tilde{\sigma}$	$(r, s) := \sigma$
$k \leftarrow_\$ \mathbb{Z}_q, \tilde{K} := g^k$	$(r, \tilde{s}, K, \pi) := \tilde{\sigma}$	$s := \tilde{s} \cdot y^{-1}$	$(\tilde{r}, \tilde{s}, K, \pi) := \tilde{\sigma}$
$K := Y^k, r := f(K)$	$u := \mathcal{H}(m) \cdot \tilde{s}^{-1}$	$\mathbf{return}\ (r, s)$	$y' := s^{-1} \cdot \tilde{s}$
$\tilde{s} := k^{-1}(\mathcal{H}(m) + rx)$	$v := r \cdot \tilde{s}^{-1}$		$\mathbf{if}\ (I_Y, y') \in R'_g$
$\pi \leftarrow \mathsf{P}_Y((\tilde{K}, K), k)$	$K' := g^u X^v$		$\mathbf{then\ return}\ y'$
$\mathbf{return}\ (r, \tilde{s}, K, \pi)$	$\mathbf{return}\ ((I_Y \in L_R) \wedge (r = f(K)) \wedge \mathsf{V}_Y((K', K), \pi))$		$\mathbf{else\ return}\ \perp$

2.5 High-level Design of A^{2}L$^+$

Puzzle-promise phase. During this phase, the receiver P_r starts by sending a valid signature σ_r' on a transaction message m' to the hub P_h. The hub generates a statement/witness pair (A, α) and creates a randomizable puzzle Z along with a zero-knowledge proof π_α [15, 22] that proves α is a valid solution to Z. The hub then produces an adaptor signature $\hat{\sigma}_h'$ over the transaction m' using α and shares both the puzzle and the adaptor signature with P_r. The receiver pre-verifies the signature and randomizes the puzzle Z to Z', which is then shared with the sender P_s, completing the puzzle promise protocol.

Puzzle-solver phase. Here, the sender further randomizes the puzzle Z' to Z'' and generates a pre-signature $\hat{\sigma}_s$ on the transaction m' using Z''. This randomized puzzle and the pre-signature are sent to the hub, which then solves the puzzle Z'' using the trapdoor information to obtain α''. The hub uses α'' to adapt $\hat{\sigma}_s$ into a valid signature σ_s and signs the transaction m' with its secret key, producing σ_h. After verifying the signature σ_s, the hub publishes both σ_s and σ_h. Finally, the secret α'' is extracted and shared with the receiver, allowing them to finalize the transaction by revealing the secret α.



3 Linkable Randomizable Puzzle Scheme

3.1 Randomizable Puzzle Scheme

- Assuming that $(KGen, Enc, Dec)$ is a linearly homomorphic encryption with statistical circuit privacy, the there exists a randomizable puzzle with statistical privacy.

Definition A.1 (Randomizable Puzzle). A randomizable puzzle scheme RP = (PSetup, PGen, PSolve, PRand) with a solution space $\mathcal{S}$ (and a function ϕ acting on $\mathcal{S}$) consists of four algorithms defined as:

$(\mathsf{pp}, \mathsf{td}) \leftarrow \mathsf{PSetup}(1^n)$: is a PPT algorithm that on input security parameter 1^n, outputs public parameters pp and a trapdoor td.

$Z \leftarrow \mathsf{PGen}(\mathsf{pp}, \zeta)$: is a PPT algorithm that on input public parameters pp and a puzzle solution ζ, outputs a puzzle Z.

$\zeta := \mathsf{PSolve}(\mathsf{td}, Z)$: is a *DPT* algorithm that on input a trapdoor td and puzzle Z, outputs a puzzle solution ζ.

$(Z', r) \leftarrow \mathsf{PRand}(\mathsf{pp}, Z)$: is a PPT algorithm that on input public parameters pp and a puzzle Z (which has a solution ζ), outputs a randomization factor r and a randomized puzzle Z' (which has a solution $\phi(\zeta, r)$).

It is not hard to see that a linearly homomorphic encryption scheme (KGen, Enc, Dec) matches the syntax of a randomizable puzzle, setting pp to the encryption key and td to be the decryption key. For the PRand algorithm, we can sample a random $r \leftarrow_\$ \mathbb{Z}_p$ and compute

$$\mathsf{Enc}(\mathsf{ek}, \zeta) \circ \mathsf{Enc}(\mathsf{ek}, r) = c$$

which is an encryption of $\phi(\zeta, r) = \zeta + r$. Next we recall the definition of security for randomizable puzzles.

3.2 Linkable Randomizable Puzzle Scheme

The Linkable Randomizable Puzzle (LRP) Scheme

$(pp, sk_0) \leftarrow$ **Setup**(λ): is a PPT algorithm (used by the auditor) that on input security parameter λ, outputs public parameters $pp = (G, g, q, r_0, \Pi_{\mathsf{MP}}, crs, \Pi_{\mathsf{El}}, pk_0)$ and private key sk_0. The details of the outputs are as follows:

- G is an elliptic curve group of order q with generator g.
- r_0 is a random number in Z_q.
- Π_{MP} is a secure malleable non-interactive zero-knowledge proof scheme [16] under a common reference string crs.
- Π_{El} is the ElGamal encryption scheme [18] of which $\mathrm{Enc}(pk_0, \cdot)$ is for encryption and $\mathrm{Dec}(pk_0, sk_0, \cdot)$ is for decryption, and (pk_0, sk_0) is a key pair of Π_{El}.

$(pk_1, sk_1) \leftarrow$ **KGen**(λ) : is a PPT algorithm (used by the hub) that on input security parameter λ, outputs a key pair (pk_1, sk_1) from the Castagnos-Laguillaumie (CL) encryption scheme Π_{CL} [29], of which $\mathrm{Enc}(pk_1, \cdot)$ is for encryption and $\mathrm{Dec}(pk_1, sk_1, \cdot)$ is for decryption.

$(pz, \pi) \leftarrow$ **PGen**$(pp, pk_1, \aleph)$: is a PPT algorithm (used by the hub) that on input public parameters pp, public key pk_1, and a puzzle solution $\aleph \in Z_q$, outputs a puzzle $pz = (\alpha, \beta, \gamma)$ and associated proof π. The details of the outputs are as follows:

- $\alpha = \Pi_{\mathsf{El}} \cdot \mathrm{Enc}(pk_0, r_0)$.
- $\beta = \Pi_{\mathsf{CL}} \cdot \mathrm{Enc}(pk_1, \aleph)$.
- $\gamma = g^{\aleph}$.
- π is a malleable proof of existence of witness $(\aleph, r_0)$ for a statement $\alpha \wedge \beta \wedge \gamma * g^{r_0}$ using Π_{MP}[a].

$0/1 \leftarrow$ **PVerify**(pp, pz, π): is a Deterministic Polynomial Time (DPT) algorithm that on input public parameters pp, a puzzle pz, and a proof π, outputs either 0 (failure) or 1 (success) for verifying pz. The process of generating the outputs is as follows:

- Parse $pz = (\alpha, \beta, \gamma)$.
- Check if proof π is correct for statement $\alpha \wedge \beta \wedge \gamma \wedge \gamma * g^{r_0}$ using scheme Π_{MP}.
- Return 1 if the proof is correct and 0 otherwise.

$\aleph \leftarrow$ **PSol**(pk_1, sk_1, pz): is a DPT algorithm (used by hub) that on input public key pk_1, private key sk_1, and a puzzle pz, outputs $\aleph = \Pi_{\mathsf{CL}}.\mathrm{Dec}(pk_1, sk_1, \beta)$, where pz is parsed as $pz = (\alpha, \beta, \gamma)$.

$(pz', \pi', r) \leftarrow$ **PRand**(pp, pk_1, pz, π): is a PPT algorithm (used by users) that on input public parameters pp, pubic key pk_1, a puzzle pz, and a malleable proof π, outputs a randomized puzzle pz', randomized proof π', and associated random number r. The process of generating the outputs is as follows:

- Parse $pz = (\alpha, \beta, \gamma)$.
- Sample a random number $r \in Z_q$.
- Randomize puzzle pz to $pz' = (\alpha', \beta', \gamma')$ using r such that $\alpha' = \Pi_{\mathsf{El}} \cdot \mathrm{Enc}(pk_0, r_0 + r), \beta' = \Pi_{\mathsf{CL}} \cdot \mathrm{Enc}(pk_1, \aleph + r)$, and $\gamma' = g^{\aleph + r}$ (note that both Π_{CL} and Π_{El} are homomorphic).
- Randomize π to π' using r to prove the existence of witness $(\aleph + r, r_0 + r)$ for statement $\alpha' \wedge \beta' \wedge \gamma' \wedge \gamma' * g^{r_0}$. Note that $T_{wit}((\aleph, r_0)) = (\aleph + r, r_0 + r)$ and $T_{stmt}(\alpha \wedge \beta \wedge \gamma \wedge \gamma * g^{r_0}) = \alpha' \wedge \beta' \wedge \gamma' \wedge \gamma' * g^{r_0}$
- Return $pz' = (\alpha', \beta', \gamma')$, π', and r.

$0/1 \leftarrow$ **PLink**(pp, sk_0, pz, pz'): is a DPT algorithm (used by the auditor) that on input public parameters pp, (auditor's) private key sk_0, and two puzzles pz and pz', outputs 1 (success) or 0 (failure). Respectively, pz and pz' are parsed as $pz = (\alpha, \beta, \gamma)$ and $pz' = (\alpha', \beta', \gamma')$. The process of generating the output is as follows:

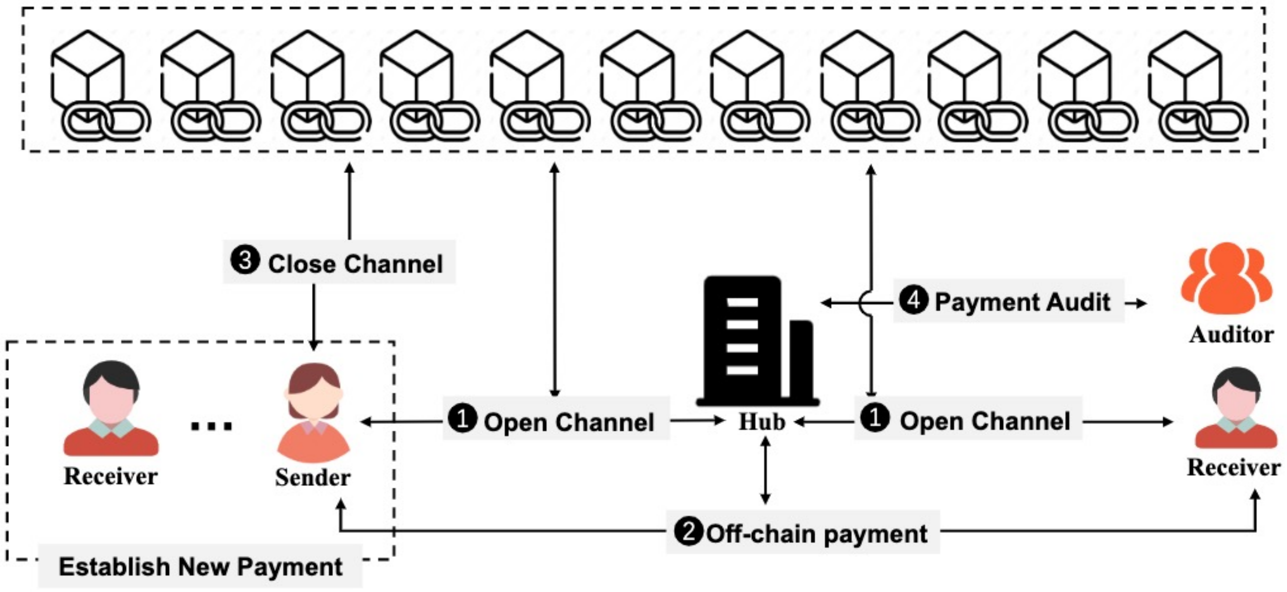
- If $g^{\Pi_{\mathsf{El}}.\mathrm{Dec}(pk_0, sk_0, \alpha')} / g^{\Pi_{\mathsf{El}}.\mathrm{Dec}(pk_0, sk_0, \alpha)} = \gamma' / \gamma$, return 1.
- Otherwise, output 0.

[a] Including $\gamma * g^{r_0}$ in the statement is to bind $\aleph$ to r_0.

4 Auditable Anonymous PCH

4.1 Security Model

- Both hub and users can be malicious while auditor is entrusted with auditing and verifying.
- PPT adversary $\mathcal{A}$ adopts static corruption.
- Synchronous communication network $\mathcal{F}_{syn}$ and secure transmission $\mathcal{F}_{smt}$.
- Blockchain is a global ledger $\mathcal{F}_L$.
- $\mathcal{F}_{AuditPCH}$ defines five operations: setup, open, pay, close, and audit.



4.2 Auditable Anonymous PCH

Sender | **Hub** | **Receiver**

(a) Puzzle generation

Input: $pz', \pi', [\tau_{S\to H}], sk_S, pp, pk_1, pk_0$
Output: $pz'', \pi'', \tilde{\sigma}_{S\to H}, [\tau_{S\to H}]$

1. If **PVerify**(pz', π')=1, continue
2. $(pz'', \pi'', r_2) =$ **PRand**(pp, pk_1, pz, π)
3. $\tilde{\sigma}_{S\to H} =$ **PSign**$([\tau_{S\to H}], \gamma'', sk_S)$

π'': $\{(r_0 + r_1 + r_2, \aleph + r_1 + r_2);$
$\alpha'' = \Pi_{El}.\mathrm{Enc}(pk_0, r_0 + r_1 + r_2) \wedge$
$\beta'' = \Pi_{CL}.\mathrm{Enc}(pk_1, \aleph + r_1 + r_2) \wedge \gamma'' = \gamma' * g^{r_2} \wedge$
$\gamma'' * g^{r_0}\}$

3

Input: $pp, \aleph, [\tau_{H\to R}], sk_H$
Output: $pz, \pi, \tilde{\sigma}_{H\to R}, [\tau_{H\to R}]$

1. $(sk_1, pk_1) =$ **KGen**(λ)
2. $(pz, \pi) =$ **PGen**$(pp, pk_1, \aleph)$, where $(pz = \alpha, \beta, \gamma)$
3. $\tilde{\sigma}_{H\to R} =$ **PSign**$([\tau_{H\to R}], \gamma, sk_H)$

π: $\{(r_0, \aleph);$
$\alpha = \Pi_{El}.\mathrm{Enc}(pk_0, r_0) \wedge$
$\beta = \Pi_{CL}.\mathrm{Enc}(pk_1, \aleph) \wedge$
$\gamma = g^{\aleph} \wedge \gamma * g^{r_0}\}$

Record: $(\sigma_{H\to R}, \tilde{\sigma}_{H\to R}, pz, \pi, [\tau_{H\to R}])$

1

Input: $pz, \pi, \tilde{\sigma}_{H\to R}, [\tau_{H\to R}], pk_1, pp$
Output: π', pz'

1. If **PVrfy**$(\tilde{\sigma}_{H\to R}, [\tau_{H\to R}], pk_H) = 1$, continue
2. If **PVerify**(pz, π)=1, continue
3. $(pz', \pi', r_1) =$ **PRand**(pp, pk_1, pz, π)

π: $\{(r_0 + r_1, \aleph + r_1);$
$\alpha' = \Pi_{El}.\mathrm{Enc}(pk_0, r_0 + r_1) \wedge$
$\beta' = \Pi_{CL}.\mathrm{Enc}(pk_1, \aleph + r_1) \wedge$
$\gamma' = \gamma * g^{r_1} \wedge \gamma' * g^{r_0}\}$

2

(sk_h, pk_h), (sk_S, pk_S) are the key pairs for signing trnasaction

(b) Puzzle solution

Input: $(\sigma_{S\to H}, \tilde{\sigma}_{S\to H}, pz'')$
Output: $\aleph + r_1$

1. $(\aleph + r_1 + r_2) \leftarrow$ **Ext**$(\sigma_{S\to H}, \tilde{\sigma}_{S\to H}, \gamma'')$
2. $\aleph + r_1 = \aleph + r_1 + r_2 - r_2$

5

Input: $pz'', \pi'', \tilde{\sigma}_{S\to H}, [\tau_{S\to H}], sk_1, pk_1$
Output: $\sigma_{S\to H}$

1. $(\aleph + r_1 + r_2) \leftarrow$ **PSol**(pk_1, sk_1, pz'')
2. $\sigma_{S\to H} \leftarrow$ **Adapt**$(\aleph + r_1 + r_2, \tilde{\sigma}_{S\to H})$

Record: $(\sigma_{S\to H}, \tilde{\sigma}_{S\to H}, pz'', \pi'', [\tau_{S\to H}])$

4

Input: $(\aleph + r_1, \tilde{\sigma}_{H\to R})$
Output: $\sigma_{R\to H}$

1. $\aleph = \aleph + r_1 - r_1$
2. $\sigma_{H\to R} \leftarrow$ **Adapt**$(\aleph, \tilde{\sigma}_{H\to R})$

6

(c) Audit

Hub → **Auditor**

Record: $(\sigma_{S\to H}, \tilde{\sigma}_{S\to H}, pz'', \pi'', [\tau_{S\to H}])$

...

Record: $(\sigma_{H\to R}, \tilde{\sigma}_{H\to R}, pz, \pi, [\tau_{H\to R}])$

Input: $(\sigma_{S\to H}, \tilde{\sigma}_{S\to H}, pz'', \pi'', [\tau_{S\to H}]), (\sigma_{H\to R}, \tilde{\sigma}_{H\to R}, pz, \pi, [\tau_{H\to R}]), pp, sk_0$
Output: 1 or 0

1. Check if $\sigma_{S\to H}, \tilde{\sigma}_{S\to H}, \sigma_{H\to R}, \tilde{\sigma}_{H\to R}$ is correct; else output $\perp$
2. $(\aleph + r_1 + r_2) \leftarrow$ **Ext**$(\sigma_{S\to H}, \tilde{\sigma}_{S\to H}, \gamma'')$
3. Check if $\gamma'' = g^{\aleph + r_1 + r_2}$, else output $\perp$
4. $\aleph \leftarrow$ **Ext**$(\sigma_{H\to R}, \tilde{\sigma}_{H\to R}, \gamma)$
5. Check if $1 = \mathrm{PVerify}(pp, pz, \pi)$ and $1 = \mathrm{PVerify}(pp, pz'', \pi'')$, otherwise output $\perp$
6. If **PLink**(pp, sk_0, pz, pz'') =1, output 1; Else output 0.

5 Performance Analysis

5.1 Performance Analysis

- 1.6GHz Intel Core i5-8265U with 8-Core and 8GB RAM.
- Java & C with JPBC and Relic.
- Secp256kl elliptic curve.

TABLE II: The computation cost of the LRP scheme.

	Setup	KGen	PVerify	PGen	PSol	PRand	PLink
Cost(s)	0.419	0.074	6.504	0.615	0.070	0.622	0.013

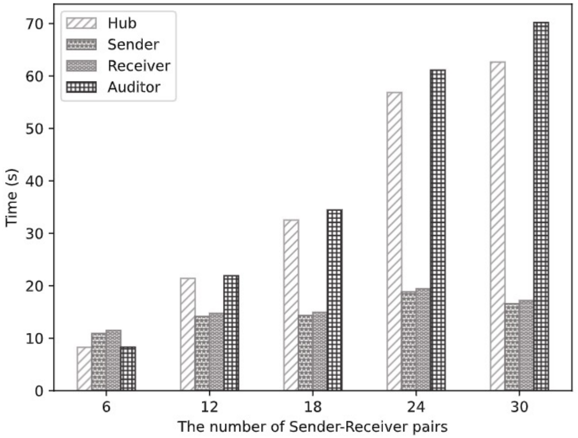


Fig. 4: The computation cost of each role while executing the AuditPCH protocol. The number of Sender-Receiver pairs ranges from 6 to 30.

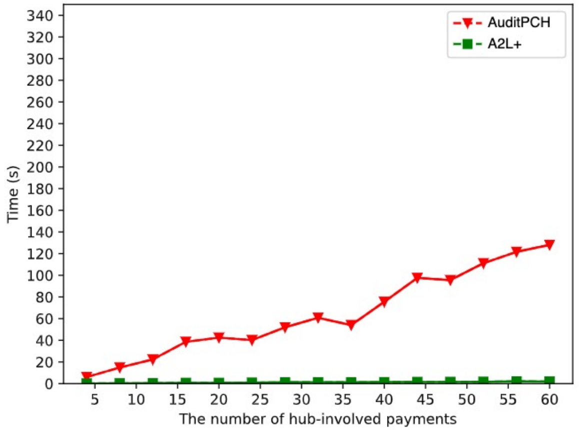


Fig. 5: The time cost comparison between AuditPCH and A^2L^+. The number of hub-involved payments ranges from 4 to 60.

TABLE III: The computation cost of AuditPCH. Time is shown in seconds.

	Pay			Open	Close	Audit	Total
	Channel Authentication	Puzzle Generation	Puzzle Solution				
Sender	0.002	7.279	0.008	–	–	–	7.289
Hub	0.004	0.768	6.582	0.004	–	–	7.358
Receiver	–	7.583	0.008	–	–	–	7.591
Auditor	–	–	–	0.485	–	13.258	13.716

TABLE IV: The communication cost of AuditPCH. n is the number of payments. Size is shown in KB.

	Pay			Open	Close	Audit
	Channel Authentication	Puzzle Generation	Puzzle Solution			
Sender	0.969	5.764	0.281	–	–	–
Hub	0.203	5.764	0.562	–	–	$11.52n + 2n[TX]$
Receiver	–	5.404	–	–	–	–
Auditor	–	–	–	7.230	–	–

Thanks! Questions?