Atomic and Fair Data Exchange via Blockchain

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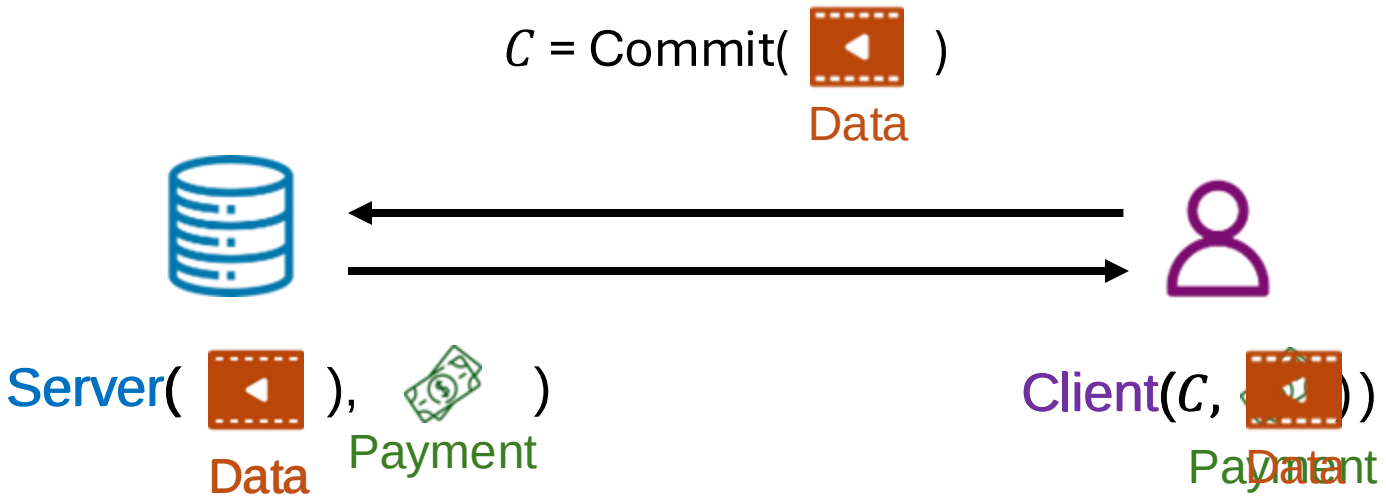
The Fair Data Exchange (FDE) Problem



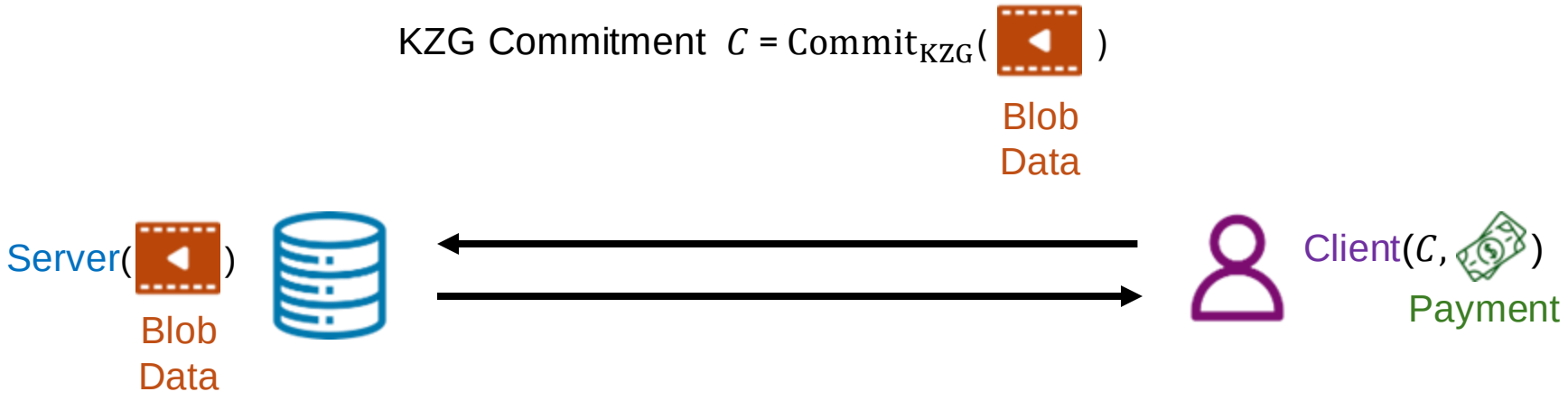
Server Fairness:
An adversarial client cannot learn anything about the data without paying the server.

Correctness:
If the client and the server are honest, the client obtains the data, and the server obtains the payment.

Client Fairness:
An adversarial server cannot receive any payment if the client does not obtain the data.

Applications of FDE over Blockchains

ProtoDanksharding (EIP-4844)

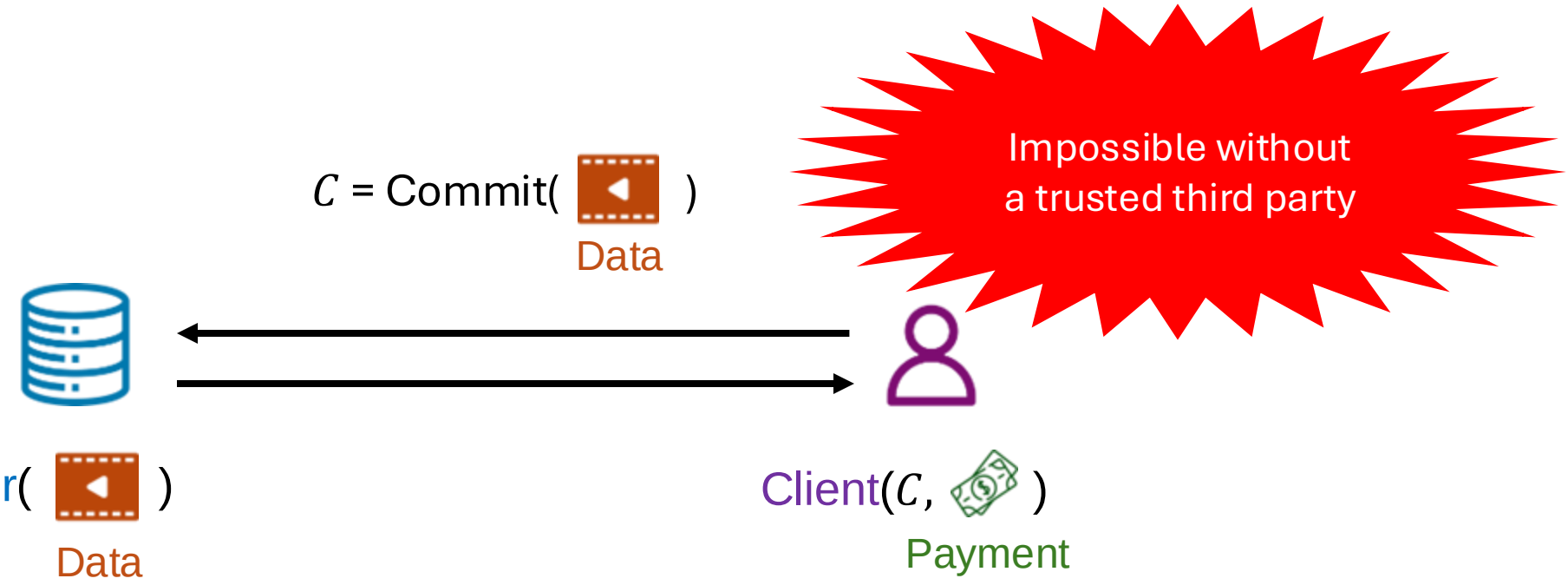


Other Applications:

- Other archival blockchain data
- Data marketplaces (e.g., streaming movies, …)

The Fair Data Exchange (FDE) Problem

TTP?
Blockchains!



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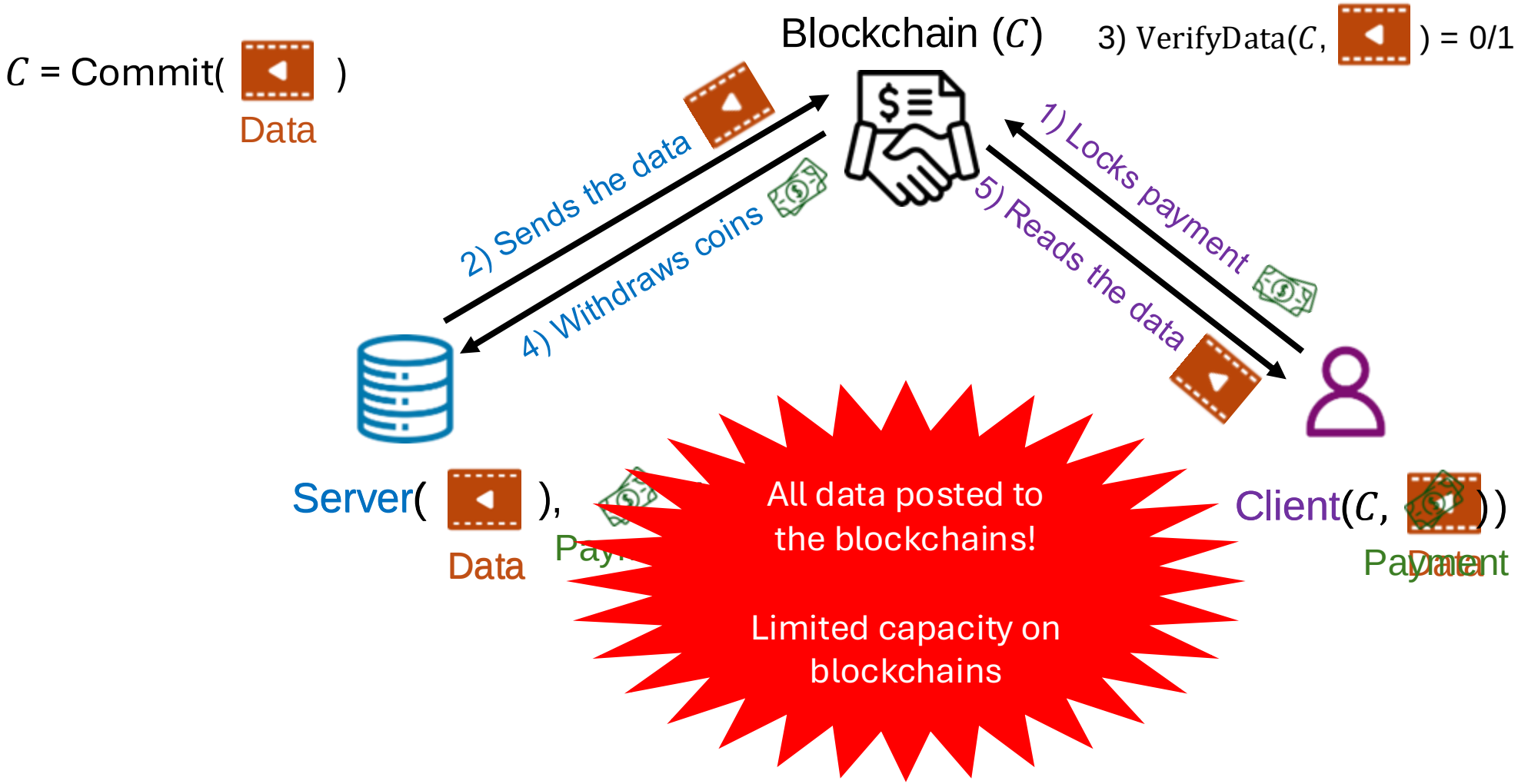
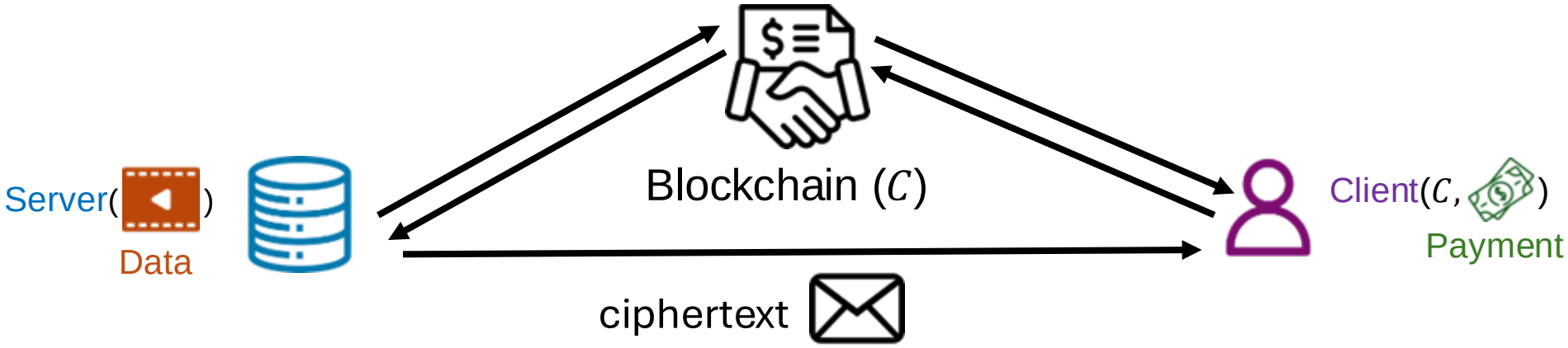
Strawman Solution



The FDE Protocol

- Server encrypts the data.
- Transfers the encrypted data off-chain **(large off-chain bandwidth)**
- Sells the key on-chain **(small on-chain bandwidth)**



Server must prove that the key sold on-chain decrypts the ciphertext to the data committed by C!

Verifiable Encryption under Committed Key (VECK)

- $\mathrm{Gen}(\mathrm{crs}) \to \mathrm{pp}$

- $\mathrm{Enc}(C, w) \to (vk, sk, ct, \pi)$

- $\mathrm{Verify}_{\mathrm{key}}(vk, sk) \to 1/0$

- $\mathrm{Verify}_{\mathrm{ct}}(C, vk, ct, \pi) \to 1/0$

- $\mathrm{Decrypt}(sk, ct) \to w/\perp$

Proof π: ct is the encryption of the data committed by C under the secret key sk committed by the verification key vk.

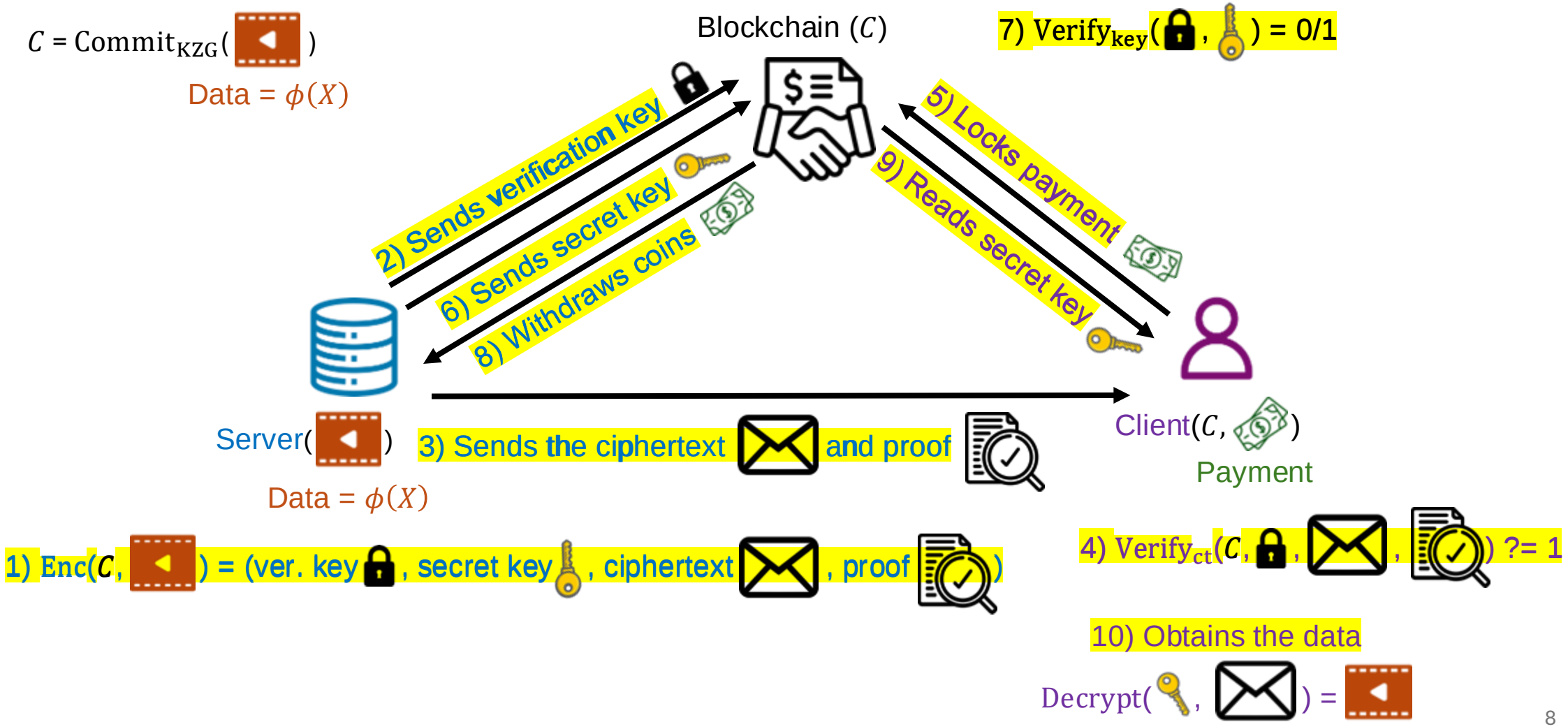
Correctness:
Verifications for honestly generated encryption succeed.
⇒ **correctness of FDE**

Soundness:
No PPT adversary can generate sk, vk, ct, π such that verification succeeds, yet decryption does not output w.
⇒ **client-fairness of FDE**

Computational Zero-Knowledge:
The ciphertext and the proof leak no additional information about the witness.
No client can help the others recover w.
⇒ **server-fairness of FDE**

VECK for KZG Commitments: $w = \phi, \mathrm{data} = \big(\phi(0), \ldots, \phi(l)\big), \quad C = \mathrm{Commit}_{\mathrm{KZG}}(\phi)$

The FDE Protocol for KZG Commitments



ElGamal-based VECK for KZG Commitments

$$\text{pp} = (h, h_0, \ldots, h_l)$$

Prover (Server):

$\mathbf{Enc}(\boldsymbol{C}, \boldsymbol{\phi}(\boldsymbol{X})) \rightarrow (\boldsymbol{sk}, \boldsymbol{vk}, \boldsymbol{ct}, \boldsymbol{\pi})$

Sample $s \leftarrow_R \mathbb{F}_p$

Set $sk := s$ (ElGamal secret key)

$vk := h^s$ (ElGamal verification key)

Data points: assume small

$\boldsymbol{ct} := \left\{h_i^s g_1^{\phi(i)}\right\}_{i=0}^{l}$ (ElGamal ciphertexts)

Generate $\pi :=$ SNARK. Prove$(crs,\ \text{instance} = (C, vk, ct),$ witness $= (s, \phi(X)))$

$vk, \boldsymbol{ct}, \pi$

Verifier (Client):

$\mathbf{Verify}_{\mathbf{ct}}(\boldsymbol{C}, \boldsymbol{vk}, \boldsymbol{ct}, \boldsymbol{\pi}) \rightarrow \mathbf{0/1}$

Output 1 if π verifies against C, vk, ct

$\mathbf{Decrypt}(\boldsymbol{pp}, \boldsymbol{sk}, \boldsymbol{ct}) \rightarrow \boldsymbol{w}/\perp$

Decryption algorithm for ElGamal

Blockchain Contract:

$\mathbf{Verify}_{\mathbf{key}}(\boldsymbol{pp}, \boldsymbol{vk}, \boldsymbol{sk}) \rightarrow \mathbf{1/0}$

Check if $h^{sk} == vk$

More on VECK for KZG Commitments

Requires inclusion of the 'encryption' as part of the SNARK relation → Potential effects on efficiency!

An efficient VECK protocol that exploits the (shared) structure of the ElGamal ciphertexts and KZG commitments! Can support large messages by splitting the messages into $k \in [8,16]$ chunks with range proofs.

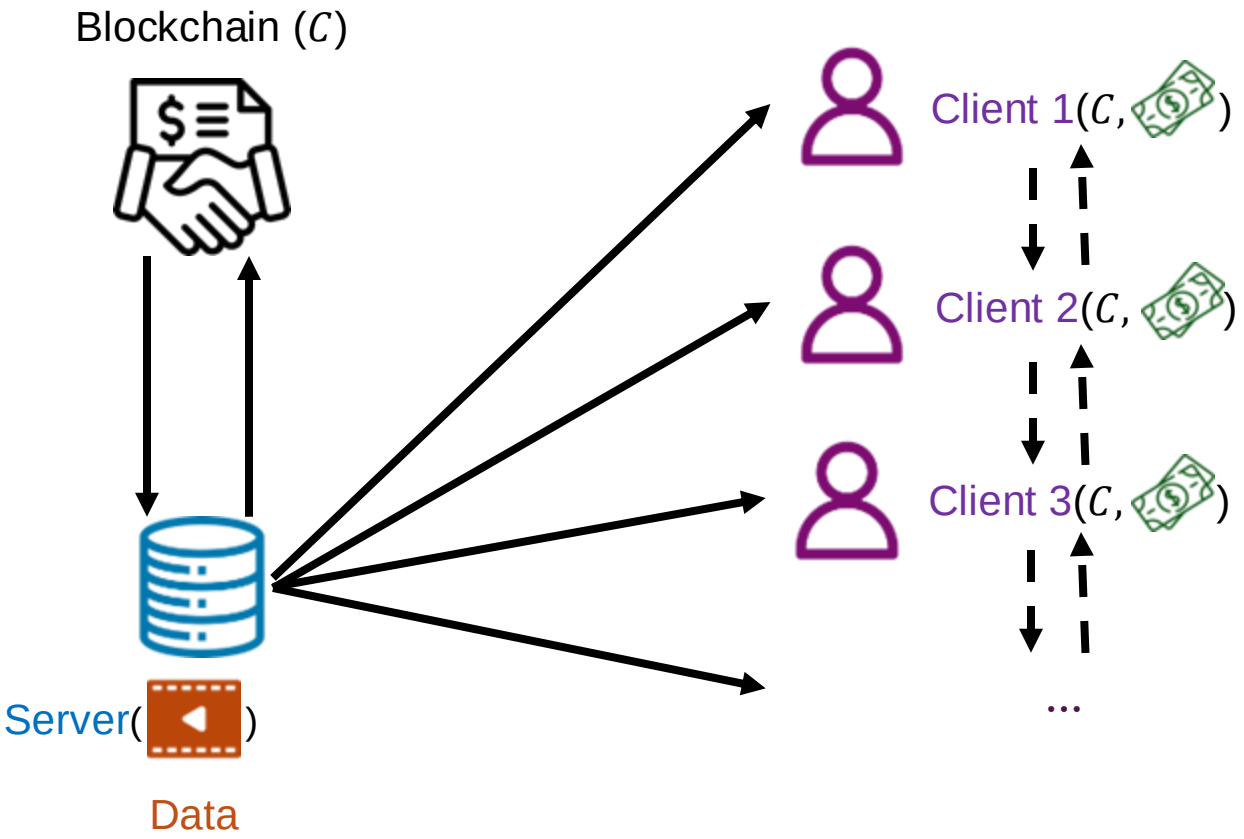
But, blows up ciphertext size by k!

Paillier-based VECK for KZG commitments to avoid the ciphertext blow-up!

Thm: Assuming Decisional Diffie-Hellman (DDH) assumption, ElGamal-based VECK protocol satisfies security (correctness, soundness and computational zero-knowledge) in the random oracle and algebraic group models.

Thm: Assuming Decisional Composite Residuosity (DCR) assumption, Paillier-based VECK protocol satisfies security in the random oracle and algebraic group models.

Multi-client Model



Can the server save work by amortizing proof generation across many clients?

Strawman

Reuse the same sk, vk, ct across all clients.

Can share $o(|\text{Data}|)$ bits with each other $\Rightarrow$ Must rerandomize sk across clients!

Multi-client VECK (MC-VECK) protocol:
Prover saves work by moving parts of the proof generation to a preprocessing step.

No need to generate **new ciphertexts** and **range proofs** per client!

Implementation: Prover Time

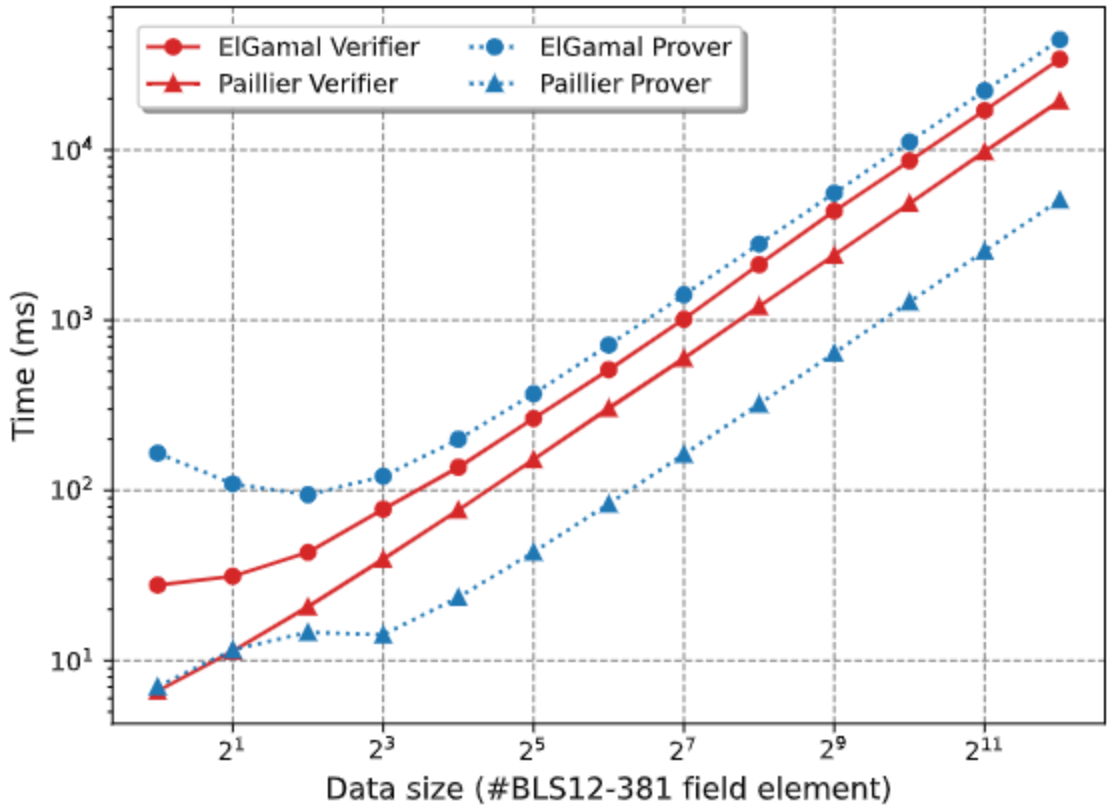
- PoC implementation in **Rust v1.74.0** on **consumer PC** with **AMD Ryzen 5 3600 (6-core) CPU** and **8GB RAM**.
- Criterion benchmarking **crate8**.

Prover time for 4096 BLS12-381 field elements (≈ 128 kB):

Exponential ElGamal encryption ($k = 8$):

- Range proofs + ciphertexts: $\approx$ **89 s**
- Overhead for proving the consistency of ciphertexts w.r.t. C and vk: $<$ **40 ms**

Paillier encryption: $\approx$ **5.09 s**.



Implementation: Proof Size, Verification & Decryption

Proof size for 4096 BLS12-381 field elements (≈ 128 kB):

Exponential ElGamal encryption ($k = 8$):

- Ciphertexts & proofs total size: $\mathbf{1,56}$ **MB**
- $\approx \mathbf{12}\times$ bandwidth overhead
- Proof has constant size ($6|\mathbb{G}|$).

Paillier encryption:

- Ciphertexts & proofs total size: $\mathbf{6,55}$ **MB** ($\lambda = 128, \log_2 N = 3072$)
- $\approx \mathbf{50}\times$ bandwidth overhead
- Proof has linear size in the data.

Verification & decryption time for 4096 BLS12-381 field elements (≈ 128 kB):

Exponential ElGamal encryption ($k = 8$):

- Verification time: $\mathbf{34.15}$ **s**
- Decryption time: Quick with lookup tables.

Paillier encryption:

- Verification time: $\mathbf{19.45}$ **s**
- Decryption time: $\mathbf{9.54}$ **s**

Implementation: On-chain Costs

- Constant in the size of the exchanged data: 3 signatures, 1 vk, 1 sk!

Ethereum (L1) costs:

Transaction	Gas cost		USD cost	
	ElGamal	Paillier	ElG.	Pail.
serverSendsPubKey	158, 449	176, 296	5.11 $	5.68 $
clientLocksPayment	30, 521	30, 521	0.98 $	0.98 $
serverSendsSecKey	73, 692	82, 475	2.37 $	2.65 $
withdrawPayment	43, 836	43, 836	1.41 $	1.41 $

Registers server's verification key with the on-chain contract, sets the data price. It

Locks client's payment according to the server's verification key

Enables the server to withdraw the payment

On L2, can be made 200 × less!

Conclusion and Future Directions

FDE and VECK protocols for KZG commitments with application to Danksharding.

More in the Paper:

- Using Bitcoin as the TTP via adaptor sigs.
- Supporting VECK for subset openings.
- Framework to design alternative FDE & VECK protocols for different commitment schemes.

Future Directions:

- Paillier-encryption with constant-size proofs.
- Other commitment and encryption schemes?
- Server griefing?
- Pricing the data?

Blog post

Paper

Open-source implementation

‘FairSwap: How To Fairly Exchange Digital Goods’ CCS 2018
‘Fair Peer-to-Peer Content Delivery via Blockchain’ ESORICS 2021
‘FileBounty: Fair Data Exchange’ IEEE EuroS&P 2020
‘ZKCPlus: Optimized Fair-exchange Protocol Supporting Practical and Flexible Data Exchange’, CCS 2021

Appendix: Related Work

	#rounds	Data struct.	$\lvert\pi_{\mathbf{disp}}\rvert$	S to C	C to B	S to B	Online?
FairSwap	5	Merkle tree	$3\log(k)\,\lvert\mathbb{H}\rvert$	$(k+1)\lvert\mathbb{H}\rvert$	$2\lvert\mathbb{H}\rvert+\lvert\sigma\rvert$	$2\lvert\sigma\rvert+\lvert\mathbb{G}\rvert$	✓
FileBounty	k	Merk.-Dam.	$3\lvert\mathbb{G}\rvert$	$k(\lambda+\lvert\mathbb{H}\rvert)$	$k\lvert\sigma\rvert$	$2\lvert\sigma\rvert$	✗
FairDownload	k	Merkle tree	$\log(k)\,\lvert\mathbb{H}\rvert$	$k\lvert\mathrm{ct}\rvert$	$k\lvert\sigma\rvert$	$2\lvert\sigma\rvert+O(\log k)\lvert\mathbb{H}\rvert$	✗
FDE-ElGamal	3	KZG	N/A	$k\lvert\mathbb{G}\rvert+6\lvert\mathbb{G}\rvert$	$\lvert\sigma\rvert$	$2\lvert\sigma\rvert+\lvert\mathbb{G}\rvert+\lvert\mathbb{F}_p\rvert$	✓
FDE-Paillier	3	KZG	N/A	$k(2\lvert\mathrm{ct}\rvert+\lvert\mathbb{F}_p\rvert)$	$\lvert\sigma\rvert$	$2\lvert\sigma\rvert+\lvert\mathbb{G}\rvert+\lvert\mathbb{F}_p\rvert$	✓

$\lvert\mathbb{H}\rvert$, $\lvert\mathbb{G}\rvert$ and $\lvert\mathbb{F}_p\rvert$ refer to the size of a single hash function output, (an elliptic curve or) group element, and field element, respectively, whereas $\lvert\sigma\rvert$ refers to the signature size. If there is a dispute protocol involved, $\lvert\boldsymbol{\pi}_{\mathbf{disp}}\rvert$ is the size of the submitted proof.

ZKCPlus: MiMC-p/p block cipher in CTR mode + commit-and-prove NIZKs (CP-NIZKs)

Appendix: ElGamal-based VECK for KZG Commitments

Prover (Server):
$\mathbf{Enc}(\boldsymbol{C}, \boldsymbol{\phi}(\boldsymbol{X})) \rightarrow (\boldsymbol{sk}, \boldsymbol{vk}, \boldsymbol{ct}, \boldsymbol{\pi})$

Verifier (Client):
$\mathbf{Verify_{ct}}(\boldsymbol{C}, \boldsymbol{vk}, \boldsymbol{ct}, \boldsymbol{\pi}) \rightarrow \mathbf{0/1}$

1. Sample $s \leftarrow_R \mathbb{F}_p$, set $sk := s, vk := h^s, \boldsymbol{ct} := \left\{h_i^s g_1^{\phi(i)}\right\}_{i=0}^{l}$

$\boldsymbol{vk}, \boldsymbol{ct}$

Can be made non-interactive with Fiat-Shamir

$\alpha \leftarrow_R \mathbb{F}_p$

To ensure zero-knowledge

2. Compute $C_\alpha := g_1^{\phi(\alpha)+s(\tau-\alpha)}$
3. Compute KZG proof π_α for $\phi(X) - s(X-\alpha)$ at α.
4. Compute a proof π_{LIN} that $C_\alpha = g_1^u (g_1^{\tau-\alpha})^v$ and $vk = 1^u h^v$ for the same v and known u.
5. Compute $Q := g_1^{-(\tau-\alpha)} \prod_{i=0}^{l} h_i^{L_{i,l}(\alpha)}$
6. Compute DLOG eq. proof π_{DLeq} for (Q, Q^s, h, vk).

$\boldsymbol{\pi} = (C_\alpha, \pi_\alpha \pi_{LIN}, \pi_{DLeq})$

Consistency of C and C_α

Consistency of vk and C_α

Consistency of $\boldsymbol{ct}$ and C_α

1. Verify π_{LIN} against $g_1, g_1^{\tau-\alpha}, h, C_\alpha, vk$.
2. Verify π_α : $e(C/\, C_\alpha, g_2) = e(\pi_\alpha, g_2^{\tau-\alpha})$
3. Compute Q, $Q^* := C_\alpha^{-1} \prod_{i=0}^{l} \boldsymbol{ct}_i^{L_{i,l}(\alpha)}$
4. Verify π_{DLeq} against (Q, Q^*, h, vk).
5. Output 1 iff all checks succeed.

Appendix: ElGamal-based VECK for KZG Commitments

Why is it secure?

- $\boldsymbol{sk} \coloneqq s, \boldsymbol{vk} \coloneqq h^s, \boldsymbol{ct} \coloneqq \left\{h_i^s g_1^{\phi(i)}\right\}_{i=0}^{l}$
- $\boldsymbol{C_\alpha} \coloneqq g_1^{\phi(\alpha)+s(\tau-\alpha)}$
- $\boldsymbol{\pi_\alpha}$: KZG proof for $\phi(X) - s(X-\alpha)$ at α.
- $\boldsymbol{\pi_{LIN}}$: proof that $C_\alpha = g_1^u (g_1^{\tau-\alpha})^v$ and $vk = 1^u h^v$ for the same v and known u.
- $\boldsymbol{Q} \coloneqq g_1^{-(\tau-\alpha)} \prod_{i=0}^{l} h_i^{L_{i,l}(\alpha)}$
- $\boldsymbol{\pi_{DLeq}}$: DLOG eq. proof for (Q, Q^s, h, vk).

1. π_{LIN} proves that $C_\alpha = g_1^{u+s(\tau-\alpha)}$ given $vk = h^s$.
2. Given (1), π_α proves that $C_\alpha = g_1^{\phi(\alpha)+s(\tau-\alpha)}$.
3. Given (1) and 2, π_{DLeq} proves that $\boldsymbol{ct}$ are ElGamal encryptions of $\phi(i), i = 0, \dots, l$; since then

$$Q^* = C_\alpha^{-1} \prod_{i=0}^{l} ct_i^{L_{i,l}(\alpha)}$$

$$= g_1^{-\phi(\alpha)-s(\tau-\alpha)} \prod_{i=0}^{l} h_i^{sL_{i,l}(\alpha)} g_1^{\phi(i)L_{i,l}(\alpha)}$$

$$= g_1^{-\phi(\alpha)-s(\tau-\alpha)} g_1^{\phi(\alpha)} \prod_{i=0}^{l} h_i^{sL_{i,l}(\alpha)} \left(g_1^{-(\tau-\alpha)} \prod_{i=0}^{l} h_i^{L_{i,l}(\alpha)}\right)^s = Q^s$$

Appendix: Multi-client VECK Protocol

Prover saves work by moving parts of the proof generation to a preprocessing step.

Prover (Server) Preprocessing:
$\mathbf{Prep}(\boldsymbol{C}, \boldsymbol{\phi}(\boldsymbol{X})) \rightarrow (\mathbf{aux}, \mathbf{msk})$

1. Run $\mathrm{Enc}(C, \phi(X)) \rightarrow (sk, vk, ct, \pi)$
2. Output $\mathrm{aux} = (vk, ct, \pi)$ and $\mathrm{msk} = sk$

Prover (Server) per client c:
$\mathbf{Enc}(\mathbf{aux}, \mathbf{msk}) \rightarrow (\boldsymbol{sk_c}, \boldsymbol{vk_c}, \boldsymbol{ct}, \boldsymbol{\pi_c})$

1. Sample $\delta_c \leftarrow_R \mathbb{F}_p$ To rerandomize sk
2. Calculate $Q = \prod_{\{i \in [n]\}} h_i^{e_i}$, where $e_i := H(h^{\delta_c}, i)$.
3. Compute DLOG eq. proof π_{DLeq} for $(Q, Q^{\delta_c}, h, h^{\delta_c})$.
4. $sk_c := sk + \delta_c$, $vk_c := vk \cdot h^{\delta_c}$,

$$\pi_c = \left(\pi, D_c := h^{\delta_c}, \pi_{DLeq}, \left(h_{c,i} := h_i^{\delta_c}\right)_{i=0}^{l}\right)$$

Consistency of $h_{c,i}$ and D_c

Verifier (Client):
$\mathbf{Verify}_{\mathbf{ct}}(\boldsymbol{C}, \boldsymbol{vk_c}, \boldsymbol{ct}, \boldsymbol{\pi_c}) \rightarrow \mathbf{0/1}$

1. Parse $\left(\pi, D_c, \pi_{DLeq}\right) \leftarrow \pi_c$
2. Compute Q, $\mathrm{Q}^* := \prod_{i=0}^{l} h_{c,i}^{e_i}$
3. Verify π_{DLeq} against (Q, Q^*, h, D_c).
4. Output 1 if all checks succeed & $\mathrm{Verify}_{\mathrm{ct}}(C, vk_c / D_c, ct, \pi) = 1$