P⁴PCN: Privacy-Preserving Path Probing for Payment Channel Networks

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Blockchain Basics

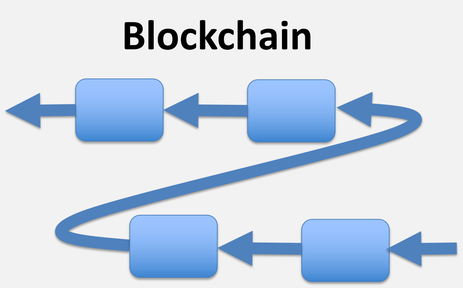
Blockchain is a distributed sequential / transactional data store (a ledger) whose security (non-manipulability) is guaranteed via distributed consensus.

The biggest challenge of blockchain right now is its **scalability** issue due to global consensus.

Payment channels were invented to enable **instant payment settlement**, **high transaction throughput.**

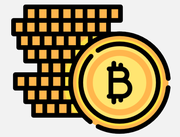
Bound by **crypto protocols**, a payment channel is able to ensure blockchain-level security with an assumption on blockchain availability (connectivity).

Channels are more importantly used to construct multi-hop networks (PCN).



Global Consensus
Every user validates all transactions to accept.

(Chained) Hash Pointers
Efficient data storage, dissemination and validation.



Incentive
Incentivized participation and honest validation.

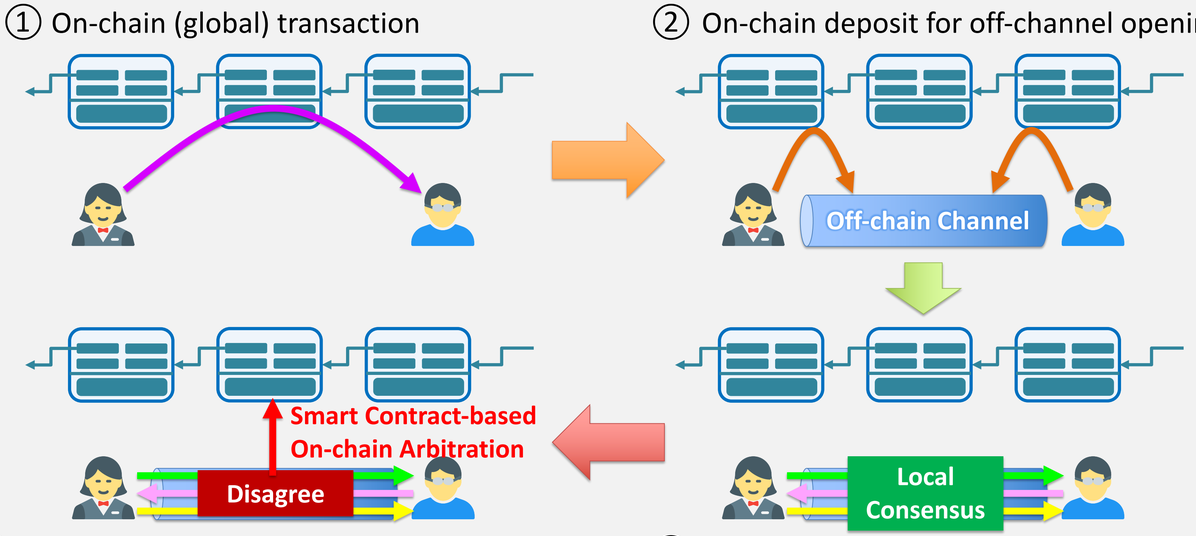
Blockchain Scalability

Example: Bitcoin

1. Tx Throughput
< 7 transactions per second (tps)

2. Tx Confirmation Time
~1 hour (6-block conf.)

Off-chain Payment Channel | Instant Transactions via Local Consensus



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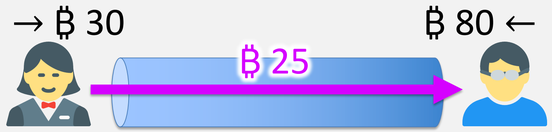
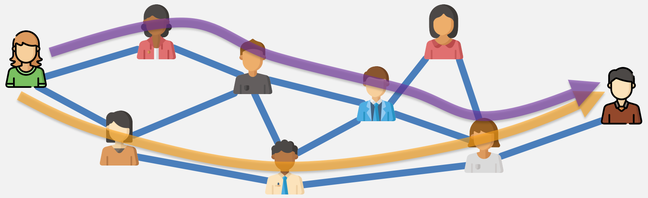
Payment through Channel

Balances BEFORE payment



Balances AFTER payment

Multi-hop Payment in PCN



Quest: Find a set of paths that satisfy a payment

Given: Only local balance information for each node

PCN Basics

A well-connected PCN enables instant payment to arbitrary parties in the network with blockchain-level security.

Nevertheless, **routing** is a big problem, because the network is:

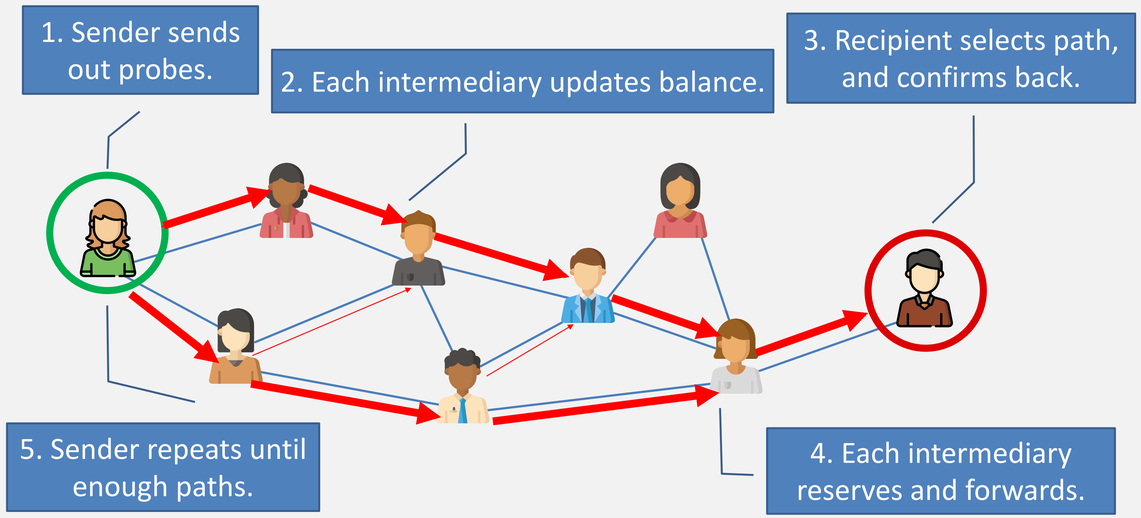
1. Fully distributed
2. Highly dynamic

Many algorithms employ **path probing** to find payment paths with enough capacity (balance).

Probing is used to gather current path information for dynamic routing.

However, probing commonly reveals sender &/ recipient information for a payment, leading to **privacy concerns**!

A Typical Dynamic PCN Routing Algorithm[1]



Privacy Concerns

#1 Sender / Recipient Privacy

Adversary may infer sender & recipient location &/ identity from probes.

#2 Cross-link Inference

Adversary may infer sender/recipient location by seeing a probe on two links.

#3 Path Confidentiality

Adversary may extract the probed paths either to locate sender/recipient or "steal" the paths (denial-of-service).

[1] R. Yu, G. Xue, V. T. Kilari, D. Yang, and J. Tang, "CoinExpress: A Fast Payment Routing Mechanism in Blockchain-based Payment Channel Networks," in *Proc. IEEE ICCCN*, 2018.

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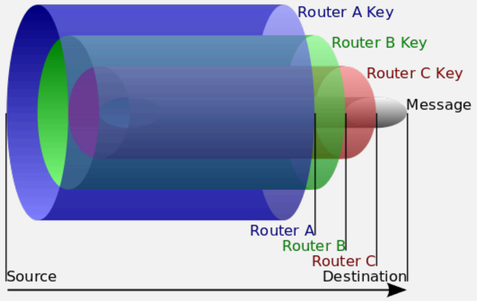
Existing Anonymous Communication Protocols



Example: Onion Routing

1. Obtain all intermediate pub keys.
2. Wrap message & forwarding info with each key.
3. Each intermediary peels off one layer and forwards.

Problems

1. Before a probe is sent, sender does not know which paths it will take, hence public keys are not available.
2. There is no way to modify payload to append/update probed information.

How to encrypt something if you don't know who will receive it?

Privacy-preserving path probing has a main challenge:

The paths to be probed are not known in advance!

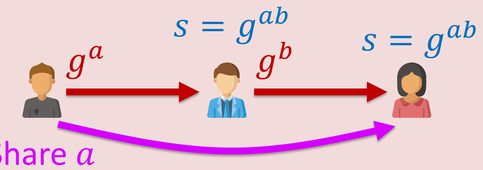
This prevents us from using existing anonymous communication protocols, all requiring knowing the intermediate public keys.

Thus, we define a new secure protocol for probing and information collection.

Our Idea (based on Sphinx[2] and Universal Re-Encryption (URE)[3])

In-Path ElGamal Key Exchange[2]

Each intermediary establishes a **symmetric key** using a sender-supplied ElGamal component.



Reversed Onion

Established symmetric key is used to attach probed path in a **reversed onion** manner:

Adds path info and onion-encrypts

The established key s is used.

Universal Re-Encryption[3]

Each intermediary further **re-encrypts** the entire probe (header + payload) to avoid inter-link inference.

Re-encrypts with obfuscation key

Anonymous Probing

[2] G. Danezis and I. Goldberg, "Sphinx: A Compact and Provably Secure Mix Format," in *Proc. IEEE S&P*, 2009, pp. 269–282.
[3] P. Golle, M. Jakobsson, A. Juels, and P. Syverson, "Universal Re-encryption for Mixnets," in *Proc. CT-RSA*, 2004, pp. 163–178.

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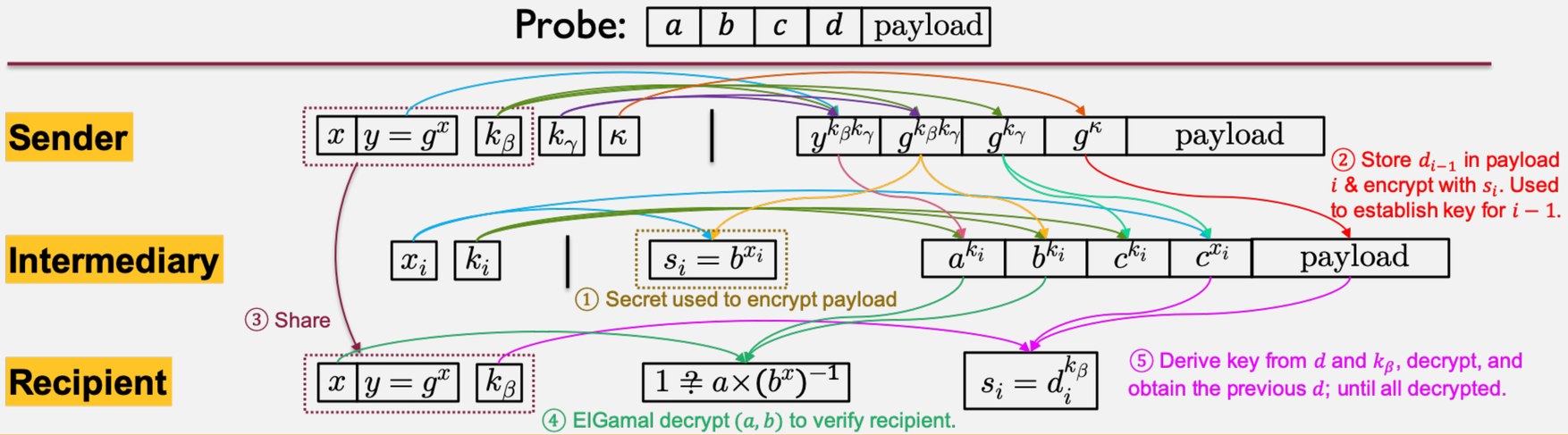
Our construction novelly combines Sphinx [2] and URE [3], enabling in-path information appending with full anonymity guarantee.

We address additional challenges:
- Reversed onion for appending
- URE-aware ElGamal key exchange
- ElGamal component hiding

Our protocol enables efficient creation and processing of probes, as well as having a smaller probe size, compared to another construction (also our new contribution based on URE).

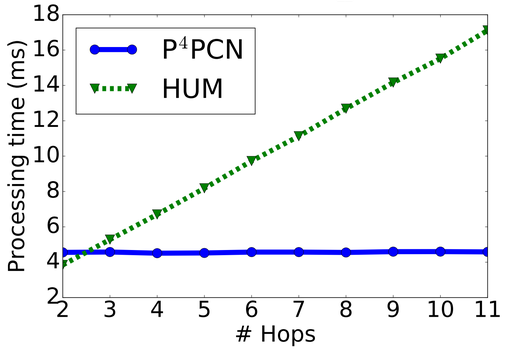
We believe the protocol can also find applications in many other scenarios, such as sensor or trust networks.

Our Construction (based on Sphinx[2] and Universal Re-Encryption (URE)[3])

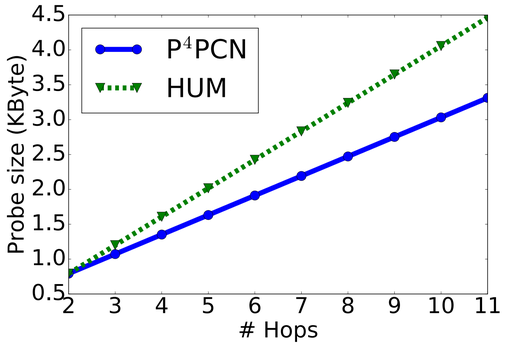


Our Results

Probe Processing Time



Probe Size



Evaluation Results (with HUM[3])

Discussions

- **Flooding**: opportunistic probing and other methods will be explored.
- **Other applications**:
  - Wireless sensor networks
  - Vehicular networks
  - Anonymous trust network

[2] G. Danezis and I. Goldberg, "Sphinx: A Compact and Provably Secure Mix Format," in *Proc. IEEE S&P*, 2009, pp. 269–282.
[3] P. Golle, M. Jakobsson, A. Juels, and P. Syverson, "Universal Re-encryption for Mixnets," in *Proc. CT-RSA*, 2004, pp. 163–178.

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