Saguaro: An Edge Computing-Enabled Hierarchical Permissioned Blockchain

Mohammad Javad Amiri\textsuperscript{1}  Ziliang Lai\textsuperscript{2}  Liana Patel\textsuperscript{3}  Boon Thau Loo\textsuperscript{1}  Eric Lo\textsuperscript{2}  Wenchao Zhou\textsuperscript{4}

\textsuperscript{1}University of Pennsylvania, \textsuperscript{2}Chinese University of Hong Kong, \textsuperscript{3}Stanford University, \textsuperscript{4}Georgetown University
Scalable deployment of blockchain applications over wide-area networks
Edge network structure

Cloud Servers (Height 3)

Fog Servers (Height 2)

Edge Servers (Height 1)

Edge Devices (Height 0)
Saguaro

Processing cross-domain transactions using a coordinator-based approach by relying on the lowest common ancestor of all involved domains.

Aggregating data by propagating (a summarized version of) the ledgers up the hierarchy.

Optimistically processing cross-domain transactions and rely on higher-level nodes to detect inconsistencies.

Supports the mobility of nodes by relying on edge servers in the local and remote height-1 domains.
Scalability over wide-area networks

• **Coordinator-based sharding** (e.g., AHL [SIGMOD’19])
  • Runs two-phase commit on top of BFT
    • The coordinator node (cluster) is either close to clients or the data shards
    • Cannot avoid slow network links when cross-shard transactions take place.

• **Flattened sharding** (e.g., SharPer [SIGMOD’21])
  • Run consensus among all nodes of all involved shards
    • Requires several rounds of communication over high-latency low bandwidth Internet links.

• **Full replication of the entire ledger on every cluster** (e.g., GeoBFT [VLDB’20])
  • Clusters process disjoint sets of transactions and sync after each round
    • Shifts the wide-area communication from running the consensus protocol across data centers to ledger synchronization messages over a wide-area network.
Coordinator-based consensus protocol

• **Transactions:**
  - Initiated by edge devices (height-0)
  - Executed by edge servers in height-1 domains

• **Transaction types:**
  - Internal: access records within a single domain
  - Cross-domain: access records across different height-1 domains

• **Consensus protocol:**
  - Internal: depending on the failure model of nodes (CFT vs BFT)
  - Cross-domain: coordinator-based protocol
Internal transactions

**Crash failure**: fail by stopping, no malicious behavior

**Byzantine failure**: exhibit arbitrary, potentially malicious, behavior

(Multi-)Paxos

PBFT
Coordinator-based cross-domain consensus

- Inspired by the traditional coordinator-based commitment protocols
- **Coordinator**: the Lowest Common Ancestor (LCA) of all involved height-1 domains
  - LCA domain has the optimal location to minimize the total distance
An example of Saguaro blockchain ledger
Lazy propagation of blockchain ledgers

- Perform data aggregation over transactions executed by edge servers in height-1
- Each domain maintains (a summarized version of) their child domains data.
- Block message: Transactions + an abstract version of the state updates
Optimistic consensus protocol

- Each involved height-1 domain **optimistically** commits a cross-domain transaction **independent** of other involved domains
- Keep a list of data-dependent transactions for each cross-domain transaction
Mobile consensus

• What if a node moves from a local to a remote domain?
  • The remote domain does not have access to the state of the mobile node
Experimental settings

• Platform: Amazon EC2

• Measuring performance
  • Throughput & Latency

• Application:
  • Micropayment

• Network:
  • A typical four-level edge network (f=1 in each cluster)

• Systems:
  • AHL [SIGMOD’19]
  • SharPer [SIGMOD’21]
  • Saguaro: Coordinator-based
  • Saguaro: Optimistic (contention: 10%, 50%, 90%)
Cross-domain transactions (crash-only)

Domains: Frankfurt, Milan, London, and Paris (RTT: 9-25 ms)

20% cross-domain transactions:
- Optimistic approach with 10% contention shows the best performance
  - only 0.16% of transactions appended to the ledgers in an inconsistent order
- Coordinator-based approach: 17% higher throughput compared to AHL

80% & 100% cross-domain transactions:
- Larger performance gap between the coordinator-based approach and existing systems
Cross-domain transactions (Byzantine)

Domains: Frankfurt, Milan, London, and Paris (RTT: 9-25 ms)

- Similar behavior, with lower throughput and higher latency
A mobile node initiates 10 transactions within the remote domain before moving back to its local domain.

- 20% mobile transactions: 4% reduction in throughput
- Increasing mobile devices from 0% to 100% (crash-only): 25% reduction in throughput
- Increasing mobile devices from 0% to 100% (Byzantine): 36% reduction in throughput
Wide-area networks

Domains: California, Oregon, Virginia, Ohio, Tokyo, Seoul, and Hong Kong

- Conflicting transactions significantly reduce the performance of the optimistic protocol in high contention workloads
- Larger gap between the performance of the coordinator-based approach and AHL
- AHL demonstrates better performance compared to SharPer
- Increasing mobile devices from 0% to 100% (crash-only): 38% reduction in throughput
# Evaluation Summary

- The coordinator-based protocol outperforms SharPer and AHL
  - Scalable solution that can be practically deployed over wide-area networks

- The optimistic protocol processes transactions efficiently in low-contention workloads

- The protocol performance is significantly reduced in high-contention workloads
  - due to inconsistency between the ledgers of different domains

- While SharPer outperforms AHL in nearby domains, AHL demonstrates better performance in far apart domains.

- Saguaro supports mobility over wide-area networks efficiently
Thank You!

Questions?

mjamiri@seas.upenn.edu