Enhancing Throughput of

Zhongmiao Li, Peter Van Roy and Paolo Romano

NCA 2017
Enhancing Throughput of Partially Replicated State Machines via

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Enhancing Throughput of Partially Replicated State Machines via Multi-Partition Operation Scheduling

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Background

- Online services strive to have 7*24 availability.

- Replication is crucial to ensure availability.

- State-machine replication (SMR) is a key technique to implement fault-tolerant services.
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State-machine replication

• Applications are abstracted as ‘deterministic state machines’
  • All replicas store application state
  • Replicas agree on operation order (e.g. using Paxos), then execute
  • Deterministic operation => equivalent final state of replicas
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Consensus

A, B, C
A, B, C
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Partially-replicated state machines (i)

- The classical SMR does not scale
  - Replicas store full state & execute all update ops
    =>$\text{throughput limited by single replica's capacity & speed!}$

- Recent work propose to \textit{partially-replicate} state machines to enhance scalability
  - “High performance state-machine replication”, DSN’11
  - “Calvin: fast distributed transactions for partitioned database systems”, SIGMOD’12
  - “Scalable state-machine replication”, DSN’14
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Partially-replicated state machines(ii)
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Partially-replicated state machines

- Each replica splits their state to multiple partitions
- Ops involving single partition (SPOs) only executed by that partition
- Ops involving multiple partitions (MPOs) coordinated and then executed by involved partitions
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Partially-replicated state machines (ii)

- Each replica splits their state to multiple partitions
- Ops involving single partition (SPOs) only executed by that partition
- Ops involving multiple partitions (MPOs) coordinated and then executed by involved partitions
- But.. can we scale linearly by adding more partitions?
Problems

Coordinating MPOs (i)

• Partitions have to agree on the order of MPOs.
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\[\text{OP1: } A=10\quad B=10\]

\[\text{OP2: } A=5\quad B=5\]
Problems

Coordinating MPOs (i)

• Partitions have to agree on the order of MPOs.

OP1: A=10

OP2: A=5 B=5

OP1: B=10
Problems

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• Partitions have to agree on the order of MPOs.

OP1: $A=10$
OP2: $A=5$

OP1: $B=10$
OP2: $B=5$
Problems

Coordinating MPOs (i)

• Partitions have to agree on the order of MPOs.

OP1: A=10
OP2: A=5
A=5

A

OP1: B=10
OP2: B=5
B=10

B
Problems

Coordinating MPOs (i)

• Partitions have to agree on the order of MPOs.

  OP1: A=10
  OP2: A=5

A=5

  B=10
  OP1: B=10
  OP2: B=5

• Coordinating MPOs is slow
  • Replication + multiple inter-group communication

• In existing systems, the coordination of MPOs lies on the critical path of execution!
  • Partitions sit idle while coordinating MPOs=> throughput reduced
Problems

Coordinating MPOs (ii)

- Calvin requires all-to-all synchronization to order ops
  - Progresses in round, in each round:

  \[
  \begin{align*}
  \text{OP1: } A &= 10, \quad B = 10 \\
  \text{OP2: } A &= 5, \quad B = 5 \\
  \text{OP3: } C &= 100
  \end{align*}
  \]
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    • Ordering lies on the critical path of execution
    • Non-scalable
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  - Progresses in round, in each round:
    - OP1: A=10, B=10
    - OP2: A=5, B=5
    - OP3: C=100
    - Ordering lies on the critical path of execution
    - Non-scalable

- Scalable SMR leverages atomic multicast to order ops
  - More scalable than Calvin, but ordering still lies on the critical path of execution
  - Additional messages exchanged between partitions to ensure linearizability*

*Omitted due to time constraints; refer to paper if interested
Solution

Genepli

• Remove the coordination of MPOs from the critical path of operation execution by:
  • Schedule MPOs to future round
    => overlap the ordering of MPOs & processing of ordered ops

• Genepli:
  • Efficient execution protocol ensuring linearizability*
  • Scraper: an ordering building block for Genepli
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Genepi

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Scraper abstraction

• Formal specifications can be found in the paper

• S-Propose(SPOs, Rs, MPOs, Rm)
  • Propose accumulated ops for each round
  • Rs current round & Rm a future round => only low bound on final round

• S-Decide(OPs, R)
  • Triggered when the operations for R has been decided
  • R can only be decided if 1, 2, …, R-1 have all been decided
Solution
Genepe Execution

Scraper

Partition A

Partition B
Solution
Genepli Execution

Round 1

Scraper

Partition A
Partition B
Solution
Genepli Execution

Round 1

- Propose(SPO1, 1, MPO1, 2)
- Propose(SPO2, 1, MPO2, 2)

Partition A
Partition B
Solution
Genepei Execution

Round 1

Scraper

Partition A  Partition B
Solution

Genepi Execution

Round 1

Decide(SPO1,1)

Decide(SPO2,1)

Partition A

Partition B
Solution
Genepi Execution

Round 1

Scraper

Partition A  Partition B
Solution
Genepi Execution

Round 2

MPO1: 2
Scraper

Partition A
Partition B
Solution
Genepli Execution

Round 2

MPO1: 2

Propose(SPO3, 2, MPO3, 3)
Propose(SPO4, 2, MPO4, 3)

Partition A
Partition B
Solution

Genepli Execution

Round 2

MPO1: 2

Scraper

Partition A

Partition B
Solution
Genepi Execution

Round 2

Scraper

Decide([SPO3, MPO1],2)

Partition A

Decide([SPO4, MPO1],2)

Partition B
Solution
Genepi Execution

Round 2

Scraper

Partition A

Partition B
Solution
Genebi Execution

Scraper

Partition A

Partition B
Solution
Genepi Execution

Round 3

MPO2: 3  MPO3: 3  MPO4: 3

Scraper

Partition A
Partition B
Solution
Genepi Execution

Round 3

MPO2: 3  MPO3: 3  MPO4: 3

Partition A

Partition B

Propose(…)

Scraper
Solution
Genepi Execution

Round 3

MPO2: 3  MPO3: 3  MPO4: 3

Scraper

Partition A  Partition B
Solution

Genepi Execution

Round 3

Decide([.., MPO2, MPO3, MPO4],3)

Partition A

Scraper

Partition B

Decide([.., MPO2, MPO3, MPO4],3)
Solution
GenePi Execution

Round 3

Scraper

Partition A
Partition B
Solution
Scraper design (i)

Avoiding synchronizing all partitions for scalability
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Partitions unilaterally advance rounds
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How to ensure they agree on rounds of ops?
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Scraper design (i)

Avoiding synchronizing all partitions for scalability

Partitions unilaterally advance rounds

How to ensure they agree on rounds of ops?

- Key idea: a two-phase-commit-like protocol for partitions to agree on the round of an operation
Solution
Scraper design (ii)

R: 10  Partition A
R: 13  Partition B
Solution

Scraper design (ii)

• 1. Coordinator sends request with min_round

![Diagram showing coordinator and partitions with round counts and partition labels.]
Solution

Scraper design (ii)

• 1. Coordinator sends request with min_round
• 2. Partitions propose max(min_round, decided round+1)
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Scraper design (ii)

- 1. Coordinator sends request with min_round
- 2. Partitions propose max(\(\text{min}_\text{round}, \text{decided round}+1\))
- 3. Coordinator decides max(\(\text{received rounds}\))
Solution

Scraper design (ii)

- 1. Coordinator sends request with min_round
- 2. Partitions propose max(min_round, decided round+1)
- 3. Coordinator decides max(received rounds)
- 4. Partitions finalize proposal
Solution

Other aspects in the paper

• Replication to ensure fault-tolerance

• Lightweight mechanism to ensure linearizability
  • Delay replying to clients

• Choosing round numbers for MPOS
  • Big enough to allow ordering MPOs
  • Not too large to avoid unnecessary latency overhead
Evaluation
Experimental setup

• Implementation:
  • Calvin, S-SMR and Genepli all implemented based on Calvin’s codebase (in C++)

• Deployment:
  • Deployed in Grid’5000.
  • Used up to 40 nodes in the same region; RTT is around 0.4ms
  • Replication cost emulated by injecting 3ms delay
  • 5ms round duration for batching
  • MPOs scheduled two rounds later (2*5ms)
Evaluation

Micro benchmark

- Each op reads & updates 10 keys
- Increase number of nodes & percentage of MPOs
Evaluation
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Micro benchmark

- Each op reads & updates 10 keys
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  😊: Genepi scales better than Calvin: 83% higher throughput with 40 nodes & 1% MPOs
  🤔: Latency of MPOs is 7~14 ms higher than SPOs
Evaluation

TPC-C

- About 10% distributed transactions
- Includes heavy-weight and/or read-only txns
- At 40 nodes, Genepi has 45% throughput gain
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Summary

• Genepi’s idea of postponing the execution of MPOs allow remove MPO coordination from the critical path of operation execution

• Questions?
Evaluation
Micro benchmark

- 10 nodes, Varying the % of MPOs and partitions accessed by MPOs
  - Genepi is only worse for workloads with lots of MPOs that access lots of MPOs!