Parameterized and Runtime-tunable Snapshot Isolation in Distributed Transactional Key-value Stores

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RVSI: Relaxed Version Snapshot Isolation

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Distributed key-value stores:

cassandra

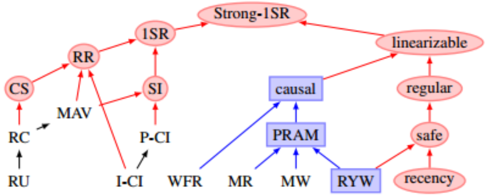
amazon DynamoDB

redis

阿里云 aliyun.com

`put(K key, V val)` `get(K key)`

Transactions are performed on a group of keys in an "all-or-none" way.



Transactional consistency models (from [Bailis@VLDB'14])

Snapshot isolation (SI [Berenson@SIGMOD'95], [Adya@Thesis'99]):

- Each transaction reads from the "latest" snapshot as of the time it started.
- If multiple concurrent transactions write to the same data item, at most one of them can commit. (WCF: *write-conflict freedom*)

Reading the "latest" in a distributed setting
often requires intensive coordinations.

Relaxed variants of (distributed) SI:

- GSI [1]: allows to read from "older" snapshots
- NMSI [2]: allows to observe non-monotonically ordered snapshots
- PL-FCV [3]: allows a transaction to observe the updates of transactions that commit after it started
- PSI [4]: causal ordering of transactions across sites

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[1] GSI: Generalized Snapshot Isolation [Elnikety@SRDS'05]
[2] NMSI: Non-Monotonic Snapshot Isolation [Ardekani@SRDS'13]
[3] PL-FCV: Forward Consistent View [Aday@Thesis'99]
[4] PSI: Parallel Snapshot Isolation [Sovran@SOSP'11]

Two possible drawbacks:

1. Unbounded inconsistency
   - no specification of the severity of the anomalies w.r.t SI
2. Untunable at runtime
   - determined at the system design phase
   - remain unchanged once the system is deployed

The idea of "parameterized and runtime-tunable snapshot isolation".

RVSI: Relaxed Version Snapshot Isolation

- k_1-BV: k_1-version bounded *backward* view
- k_2-FV: k_2-version bounded *forward* view
- k_3-SV: k_3-version bounded *snapshot* view

CHAMELEON [1]: a prototype distributed transactional key-value store

- Achieves RVSI
- Allows each transaction to tune its consistency level at runtime
- Deployed on Alibaba Cloud (Aliyun) [2]
- Evaluate the impacts of RVSI on the transaction abort rates

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[1] https://github.com/hengxin/chameleon-transactional-kvstore

[2] http://www.aliyun.com/

RVSI: Relaxed Version Snapshot Isolation

Transaction $T_i: \quad s_i \quad (r_i/w_i)^+ \quad c_i/a_i$

s_i: `start operation`

r_i/w_i: `read/write operation`

c_i/a_i: `commit/abort operation`

x_i: version i of data item x written by T_i

$r_i(x_j)$: transaction T_i reading x_j

$w_i(x_i)$: transaction T_i writing x_i

History: modeling an execution of a transactional key-value store

- *time-precedes partial order* $\prec_h$ over all operations

A history h is in *snapshot isolation* iff it satisfies [Adya@Thesis'99]

Snapshot Read: Each transaction reads data from the "lastest" snapshot as of the time it started.

$$\forall r_i(x_{j \neq i}), w_{k \neq j}(x_k), c_k \in h :$$
$$(c_j \in h \wedge c_j \prec_h s_i) \wedge (s_i \prec_h c_k \vee c_k \prec_h c_j).$$

Snapshot Write: No concurrent committed transactions may write the same data item. (WCF: write-conflict freedom)

$$\forall w_i(x_i), w_{j \neq i}(x_j) \in h \implies (c_i \prec_h s_j \vee c_j \prec_h s_i).$$

Principles of RVSI:

- Using parameters (k_1, k_2, k_3) to control the severity of the anomalies w.r.t SI
- RC [3] $\supset$ RVSI$(k_1, k_2, k_3) \supset$ SI
- RVSI$(\infty, \infty, \infty) =$ RC   RVSI$(1, 0, *) =$ SI

[3] RC: Read Committed isolation.

> *Each transaction reads data from the "latest" snapshot as of the time the transaction started.*
>
> – *The "Snapshot Read" property of SI*

RVSI relaxes "Snapshot Read" in three ways:

k_1-BV (Backward View): "stale" data versions — staleness $\leq k_1$

k_2-FV (Forward View): "forward" data versions — forward level $\leq k_2$

k_3-SV (Snapshot View): "non-snapshot" data versions — distance $\leq k_3$

$(k_1\text{-BV})$

$$\forall r_i(x_j), w_k(x_k), c_k \in h : \left(c_j \in h \wedge \bigwedge_{k=1}^{m} (c_j \prec_h c_k \prec_h s_i) \right) \Rightarrow m < k_1,$$

$(k_2\text{-FV})$

$$\forall r_i(x_j), w_k(x_k), c_k \in h : \left(c_j \in h \wedge \bigwedge_{k=1}^{m} (s_i \prec_h c_k \prec_h c_j) \right) \Rightarrow m \leq k_2,$$

$(k_3\text{-SV})$

$$\forall r_i(x_j), r_i(y_l), w_k(x_k), c_k \in h : \left(\bigwedge_{k=1}^{m} (c_j \prec_h c_k \prec_h c_l) \right) \Rightarrow m \leq k_3.$$

$$\boxed{h \in \text{RVSI} \iff h \in k_1\text{-BV} \cap k_2\text{-FV} \cap k_3\text{-SV} \cap \text{WCF}}$$

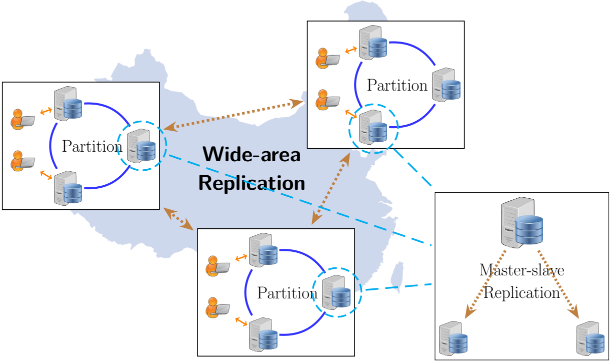
RVSI: Relaxed Version Snapshot Isolation

Chameleon:

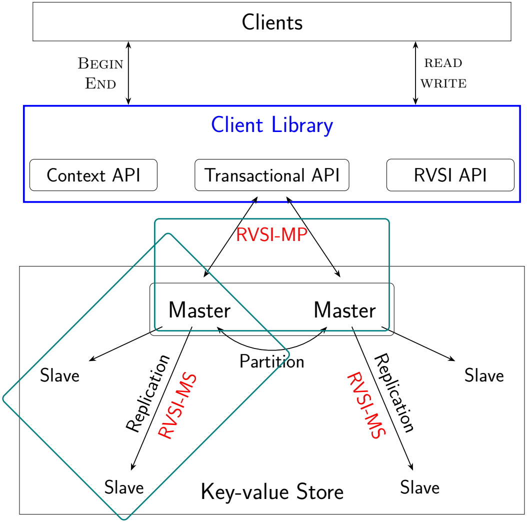
A prototype **partitioned replicated**

distributed transactional **key-value** store

Key: (row key, column key)



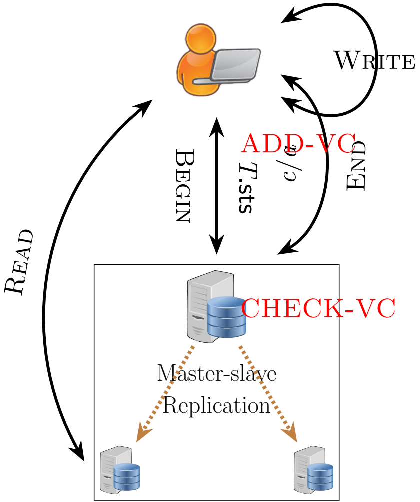
Keys are **partitioned** within a single datacenter. Each key is **replicated** across datacenters in a **master-slave** manner. Transactions are first executed and committed on the **masters**, and are then asynchronously propagated to **slaves**.



Client library RVSI protocol: RVSI-MS + RVSI-MP RVSI-MS: RVSI for Master-Slave replication RVSI-MP: RVSI for Multiple Partitions

Code snippet for specifying RVSI specification for a transaction:

RVSI-MS: RVSI protocol for Master-Slave replication



$$\mathcal{O}_x(t) = \text{version NO. of } x \text{ before time } t$$

$$r_i(x_j) \in T_i$$

The version actually observed *vs.* The version just before T_i starts:

k_1-BV:

$$\mathcal{O}_x(T_i.\textit{sts}) - \mathcal{O}_x(T_j.\textit{cts}) < k_1$$

k_2-FV:

$$\mathcal{O}_x(T_j.\textit{cts}) - \mathcal{O}_x(T_i.\textit{sts}) \leq k_2$$

$$r_i(x_j), r_i(y_l) \in T_i \quad (\text{Assume } T_j.\textit{cts} < T_l.\textit{cts})$$

k_3-SV: The snapshot x_j is born in *vs.* The snapshot y_l is born in:

$$\mathcal{O}_x(T_l.\textit{cts}) - \mathcal{O}_x(T_j.\textit{cts}) \leq k_3$$

RVSI-MP: RVSI protocol for Multiple Partitions

Distributed transactions spanning multiple masters
need to be committed atomically.

Using the two-phase commit (2PC) protocol [Bernstein@Book'87].

We have two issues to address.

Assumes a global timestamp oracle [Peng@OSDI'10]:

Client: asks for the start-timestamp in Begin

Coordinator: asks for the commit-timestamp in Commit

Split the RVSI version constraints according to partitions:

$$r_i(x_j) \in T_i$$

k_1-BV:

$$\mathcal{O}_x(T_i.\mathit{sts}) - \mathcal{O}_x(T_j.\mathit{cts}) < k_1$$

k_2-FV:

$$\mathcal{O}_x(T_j.\mathit{cts}) - \mathcal{O}_x(T_i.\mathit{sts}) \leq k_2$$

$$r_i(x_j), r_i(y_l) \in T_i$$

k_3-SV:

$$\mathcal{O}_x(T_l.\mathit{cts}) - \mathcal{O}_x(T_j.\mathit{cts}) \leq k_3$$

Each version constraint involves only one data item.

RVSI: Relaxed Version Snapshot Isolation

Impacts of RVSI specification

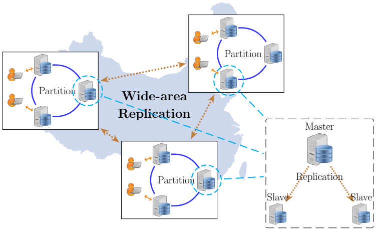
on the *transaction abort rates* in various scenarios

Performance is *not* reported in this work

because it is *not* sensitive to the parameters k_1, k_2 or k_3.

CHAMELEON on Alibaba Cloud:

- 3 datacenters [1]
- 3 nodes in each datacenter
- Partition & Replication
- Clients in our lab [2]



[1] Located in East China, North China, and South China, respectively.
[2] Located in East China.

Workload parameters for the experiments on Alibaba Cloud.

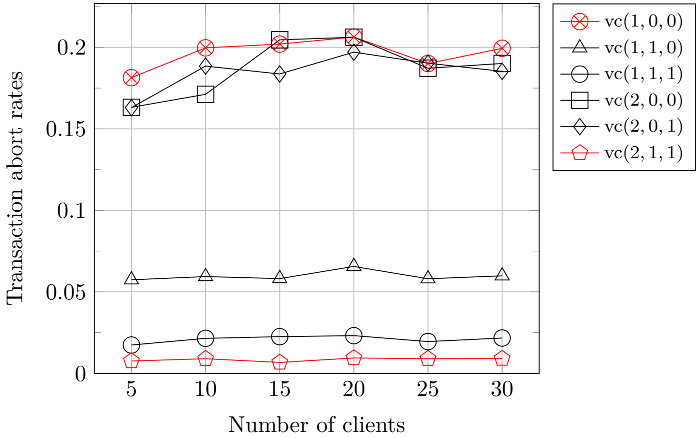
Parameter	Value	Explanation
#keys	$25 = 5$ (rows) $\times$ 5 (columns)	
#clients	5, 10, 15, 20, 25, 30	
#txs/client	1000	
#ops/tx	$\sim$ Binomial(20, 0.5)	
rwRatio	1:2, 1:1, 4:1	#reads/#writes
zipfExponent	1	parameter for Zipfian distribution
minInterval	0ms	min/max/mean inter-transaction time
maxInterval	10ms	
meanInterval	5ms	
(k_1, k_2, k_3)	(1,0,0) (1,1,0) (1,1,1) (2,0,0) (2,0,1) (2,1,1)	

Overview:

1. Transaction abort rates because of violating the RVSI version constraints ("vc-aborted") are quite *sensitive* to different values of k_1, k_2, or k_3.
2. In the Alibaba Cloud scenarios, most transactions have been aborted because of violating k_2-FV.
3. In controlled experiments, the impacts of k_1-BV emerge when the "issueDelay" gets shorter.

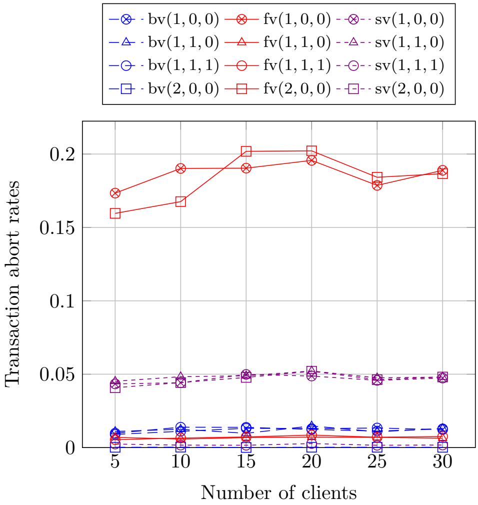
We report the results under the read-frequent (#rwRatio = 4:1) workloads [4].

[4] `https://github.com/hengxin/chameleon-transactional-kvstore`



The transaction abort rates due to "vc-aborted" can be greatly reduced by slightly increasing the values of k_1, k_2, or k_3:

$$vc(1,0,0) = 0.1994 \implies vc(2,1,1) = 0.0091 \quad (\text{\#clients} = 30)$$



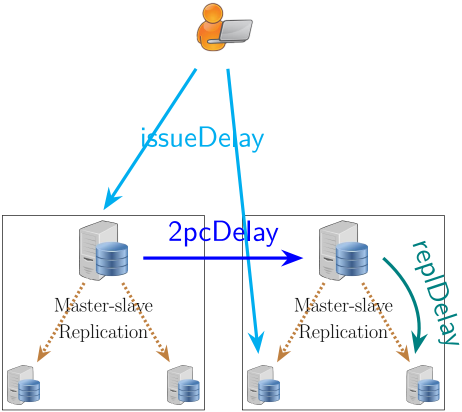
Most “vc-aborted” transactions abort because of violating k_2-FV.

$$fv(1,0,0) = 0.1889 \implies fv(2,0,0) = 0.1866 \implies fv(1,1,0) = 0.0064$$

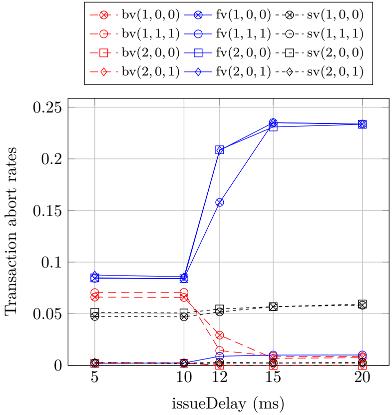
In the Alibaba Cloud scenarios, we saw *little* impacts of k_1-BV.

We therefore explore the impacts of k_1-BV in controlled experiments.

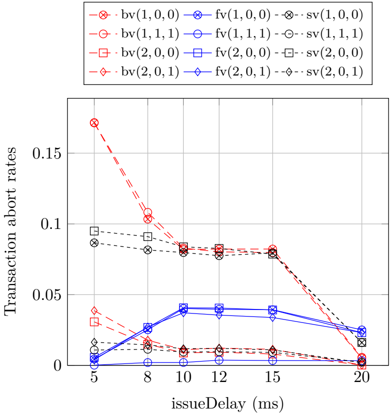
Three types of delays for controlled experiments on local hosts.



Types	Values (ms)	
issueDelay	5, 8, 10, 12, 15, 20	d



(Under read-frequent workloads.)



(Under write-frequent workloads.)

When the "issueDelay" gets shorter,
the impacts of k_1-BV have begun to emerge.

What about the impacts of k_3-SV?

- k_3-SV involves multiple data items
- Complex and challenging
- Have not found any simple and significant patterns

RVSI: Relaxed Version Snapshot Isolation

The idea of "bounded transactional inconsistency" is partly inspired by the work on

- Relaxed Currency and Consistency (C&C) semantics [Guo@SIGMOD'04]
- Relaxed Currency Serializability (RC-SR) [Bernstein@SIGMOD'06]

Two main differences:

- Serializability (SR) *vs.* SI
- Currency in real-time *vs.* Versions in order

Bounded transactional inconsistency (others):

Epsilon-SR inconsistency introduced by concurrent update transactions [Pu@SIGMOD'91] [Ramamritham@TKDE'95]

- uncommitted *vs.* RC (for RVSI)

N-ignorant System ignorant of $\leq K$ "prior" transactions [Krishnakumar@PODS'91]

- SR *vs.* SI (for RVSI)

Dynamic consistency choices:

- **Parameterized** ESR, N-ignorant, RC-SR, C&C semantics, RVSI
- **Pileus** strong, intermediate, and eventual consistency [Kotla@MSR-TR'2013]
- **SIEVE** a tool automating the choice of consistency levels [Li@ATC'14] (based on the theory of RedBlue consistency [Li@OSDI'12])
- **Salt** combining ACID and BASE transactions [Xie@OSDI'14]
- **Multi-level** a transaction model supporting four consistency levels [Tripathi@BigData'15]

RVSI: Relaxed Version Snapshot Isolation

The idea of "parameterized and runtime-tunable snapshot isolation".

RVSI: Relaxed Version Snapshot Isolation

$$h \in \text{RVSI} \iff h \in k_1\text{-BV} \cap k_2\text{-FV} \cap k_3\text{-SV} \cap \text{WCF}$$

CHAMELEON: a prototype distributed transactional key-value store

- Allows each transaction to tune its consistency level at runtime
- Evaluates the impacts of RVSI on the transaction abort rates

Two possible future work:

- To evaluate the impacts of k_3-SV on transaction abort rates, probably with data mining technologies
- To study the impacts/anomalies of RVSI from the perspectives of developers

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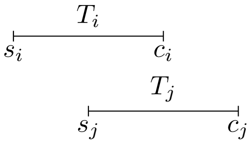
Two transactions are *concurrent* if

$$s_i \prec_h c_j \wedge s_j \prec_h c_i$$



An online bookstore application [1] for motivating "bounded inconsistency" and "runtime-tuable":

Title	Authors	Sales	Inventory	Ratings	Reviews	···

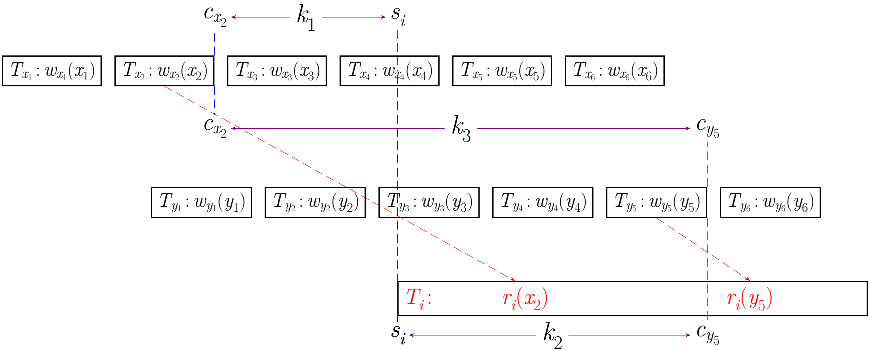
Customer (T_1): Obtaining the basic info. about a book
- *out-of-date* reviews

Bookstore Clerk (T_2): Checking the inventory of a book
- updated by concurrent transactions that commit *after* T_2 starts

Sales Analyst (T_3): Studying sales vs. ratings of a book
- sales and ratings from *separate snapshots*

[1] Adapted from [Guo@SIGMOD'04] and [Bernstein@SIGMOD'06].

Applicability



c_{x_2} k_1 s_i
$T_{x_1} : w_{x_1}(x_1)$ $T_{x_2} : w_{x_2}(x_2)$ $T_{x_3} : w_{x_3}(x_3)$ $T_{x_4} : w_{x_4}(x_4)$ $T_{x_5} : w_{x_5}(x_5)$ $T_{x_6} : w_{x_6}(x_6)$
c_{x_2} k_3 c_{y_5}
$T_{y_1} : w_{y_1}(y_1)$ $T_{y_2} : w_{y_2}(y_2)$ $T_{y_3} : w_{y_3}(y_3)$ $T_{y_4} : w_{y_4}(y_4)$ $T_{y_5} : w_{y_5}(y_5)$ $T_{y_6} : w_{y_6}(y_6)$
$T_i :$ $r_i(x_2)$ $r_i(y_5)$
s_i k_2 c_{y_5}

For convenience, the definition of RVSI specifies the bounds k_1, k_2, and k_3 globally w.r.t a history.

They can be easily generalized to support dynamic bounds

- per transaction
- even w.r.t each individual read operation or every pair of them.

In terms of *event* generation and handling:

Clients: BEGIN, READ, WRITE, END

Master: START, COMMIT, SEND

Slaves: RECEIVE

Algorithm 1 RVSI-MS Protocol for Executing Transaction T (Client).

procedure $\textsc{Begin}()$
  $T.\textit{sts} \leftarrow$ **rpc-call** $\textsc{Start}()$ at master $\mathcal{M}$
procedure $\textsc{Read}(x)$
  $x.\textit{ver} \leftarrow$ **rpc-call** $\textsc{Read}(x)$ at any site
procedure $\textsc{Write}(x, v)$
  add (x, v) to $T.\textit{writes}$
procedure $\textsc{End}(T)$
  $T.\textit{vc} \leftarrow \textsc{Add-VC}()$
  $c/a \leftarrow$ **rpc-call** $\textsc{Commit}(T.\textit{writes}, T.\textit{vc})$ at $\mathcal{M}$

Algorithm 1 RVSI-MS Protocol for Executing Transaction T (Master).

$\mathcal{M}.ts$: for start-timestamps and commit-timestamps
$\{x.ver = (x.ts, x.ord, x.val)\}$: set of versions of x

procedure START()
  return $++\mathcal{M}.ts$
procedure READ(x)
  return the latest $x.ver$ installed
procedure COMMIT($T.writes$, $T.vc$)
  if CHECK-VC($T.vc$) && write-conflict freedom **then**
    $T.cts \leftarrow ++\mathcal{M}.ts$
    ▷ *apply $T.writes$ locally and propagate it*
    $T.upvers = \emptyset$ ▷ *collect updated versions*
    for $(x, v) \in T.writes$ **do**
      $x.new\text{-}ver \leftarrow (T.cts, ++x.ord, v)$
      add $x.new\text{-}ver$ to $\{x.ver\}$ and $T.upvers$
    broadcast $\langle$PROP, $T.upvers\rangle$ to slaves
    return c denoting "committed"
  return a denoting "aborted"

Algorithm 1 RVSI-MS Protocol for Executing Transaction T (Slave).

$x.\textit{ver} = (x.\textit{ts}, x.\textit{ord}, x.\textit{val})$: the latest version of x

```
procedure READ(x)
    return x.ver
upon RECEIVED(⟨PROP, T.upvers⟩)
    for (x.ver' = (x.ts', x.ord', x.val')) ∈ T.upvers do
        if x.ord' > x.ord then
            x.ver ← x.ver'
```

Algorithm 2 RVSI-MP for Executing Transaction T (Client).

```
procedure BEGIN()
    return rpc-call GETTS() at 𝒯
procedure END()
    T.vc ← ADD-VC()
    c/a ← rpc-call C-COMMIT(T.writes, T.vc) at 𝒞
```

Algorithm 2 RVSI-MP for Executing Transaction T (Timestamp Oracle).

$\mathcal{T}$.*ts*: for start-timestamps and commit-timestamps

procedure $\textsc{getTS}()$

return $++\mathcal{T}.ts$

Algorithm 2 RVSI-MP for Executing Transaction T (Coordinator).

procedure C-COMMIT(T.*writes*, T.*vc*)

    split T.*writes* and T.*vc* with the data partitioning strategy

    ▷ *the prepare phase:*

    rpc-call PREPARE(T.*writes*, T.*vc*) at each $\mathcal{M}$

    ▷ *the commit phase:*

    if all PREPARE(T.*writes*, T.*vc*) return *true* **then**

        T.*cts* $\leftarrow$ **rpc-call** GETTS() at $\mathcal{T}$

        rpc-call COMMIT(T.*cts*, T.*writes*) at each $\mathcal{M}$

    else

        rpc-call ABORT() at each $\mathcal{M}$

        return a denoting "aborted"

    if all COMMIT(T.*cts*, T.*writes*) return *true* **then**

        return c denoting "committed"

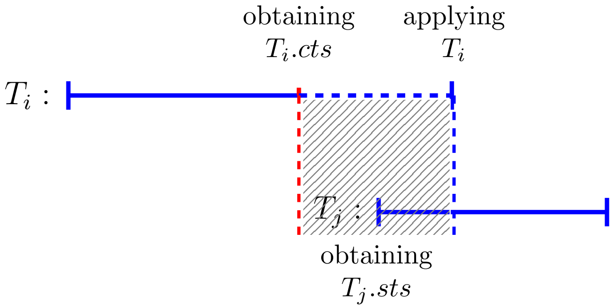
    else

        return a denoting "aborted"

Algorithm 2 RVSI-MP for Executing Transaction T (Master).

procedure PREPARE(T.*writes*, T.*vc*)
    return CHECK-VC(T.*vc*) && write-conflict freedom
procedure COMMIT(T.*cts*, T.*writes*)
    ▷ *apply T.writes locally and propagate it*
procedure ABORT()
    ▷ *abort*

Atomicity of the commit-timestamps:



All nodes are with the same configuration:

- a single CPU
- 2048MB main memory
- 2Mbps network

Sufficient for evaluating the transaction abort rates (not for performance)

Delays

(One-way) delays among nodes [2]:

Within datacenter: $1 \sim 2$ms

Across datacenters: $15 \sim 25$ms

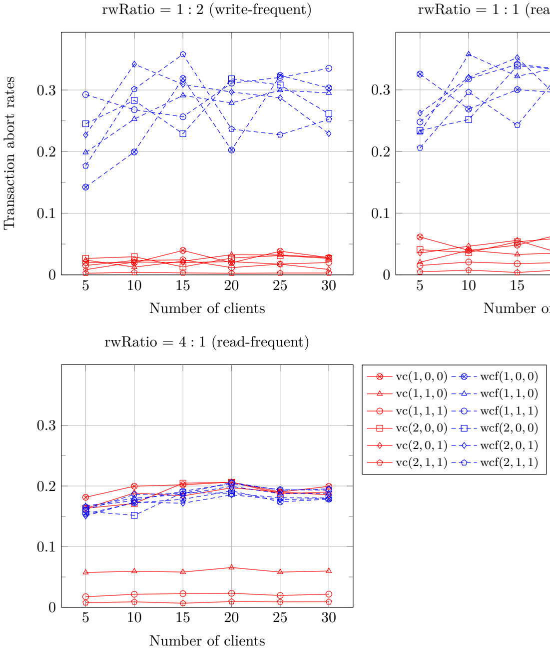
Clients to nodes: $15 \sim 20$ms

[2] https://github.com/hengxin/aliyun-ping-traces

Benchmarks

- The TPC-C benchmark is commonly used to benchmark relational databases.
- The YCSB benchmark [Cooper@SoCC'10] for distributed key-value stores does not support transactions.

We design our own workloads.


rwRatio = 1 : 2 (write-frequent)
rwRatio = 1 : 1 (read-write-balanced)
rwRatio = 4 : 1 (read-frequent)
Transaction abort rates
0 0.1 0.2 0.3
5 10 15 20 25 30
Number of clients
vc(1, 0, 0) wcf(1, 0, 0)
vc(1, 1, 0) wcf(1, 1, 0)
vc(1, 1, 1) wcf(1, 1, 1)
vc(2, 0, 0) wcf(2, 0, 0)
vc(2, 0, 1) wcf(2, 0, 1)
vc(2, 1, 1) wcf(2, 1, 1)

issueDelay = 20ms: $bv(1,0,0) = 0.0057 \quad fv(1,0,0) = 0.0251$

issueDelay = 15ms: $bv(1,0,0) = 0.08225 \quad fv(1,0,0) = 0.0393$

issueDelay = 5ms: $bv(1,0,0) = 0.1716 \quad fv(1,0,0) = 0.0045$

larger issueDelay $\Longrightarrow$ longer transaction

more concurrent transactions

more likely to obtain data versions updated by concurrent transactions

more sensitive to k_2-FV