Moving (and averaging) values over channels with message loss, replay, and re-ordering

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Introduction

Moving/Handoff Problem

Nodes in a network have splittable value quantities, and the task is to reliably move quantities from node to node.

Each transfer involves only two parties, no global agreement.
Possible uses include:

- Non-negative inc/dec shared counters (Positive PN-Counter)
- Stock escrow
- Token/lock transfers
- Distributed averaging and derived data aggregates

Sketch of Handoff

Source Node i

state: v

on $\mathrm{transfer}(j, q)$ *move q to node j; $q \leq v$*

$v := v - q$

$\mathrm{send}_j(q)$

Destination Node j

state: v

on $\mathrm{receive}_i(q)$

$v := v + q$

Sketch of Handoff, commutative monoid with split

Split definition:

$(v', q) = \mathrm{split}(v, h)$ such that $v' \oplus q = v$ and $q \leq h$

Source Node i

state: v any commutative monoid
on $\mathrm{transfer}(j, h)$ *move* h, or less, *to node* j
$(v, q) := \mathrm{split}(v, h)$
$\mathrm{send}_j(q)$

Destination Node j

state: v any commutative monoid
on $\mathrm{receive}_i(q)$
$v := v \oplus q$

Network

- Conservation of quantities requires an **exacly-once** delivery from each send to corresponding receive.
- TCP mostly ensures **exactly-once**, but degrades to **at-most-once** upon connection break.
- UDP can **duplicate**, **drop** and **re-order** messages.

Naive exactly-once over UDP

- Source assigns a unique id to each sent message
- Messages are re-transmitted until acknowledged
- Destination stores unique ids to avoid duplicated delivers
- (more compact sequence numbers ids can be used for FIFO)

+ Source can transmit immediately (**one-way handshake**)

– Node state at least **linear** on the number of (past) parties

TCP connection management

- No connection specific information between incarnations
- Three-way handshake to make connection
- Unbounded memory, to keep counters

A transfer over TCP pays a latency price and yet is still sensible to connection breaks

Handoff

System Model

- Network can **duplicate**, **drop** and **re-order**
- Nodes only have connection specific info during transfers
- Nodes can fail, but eventually recover

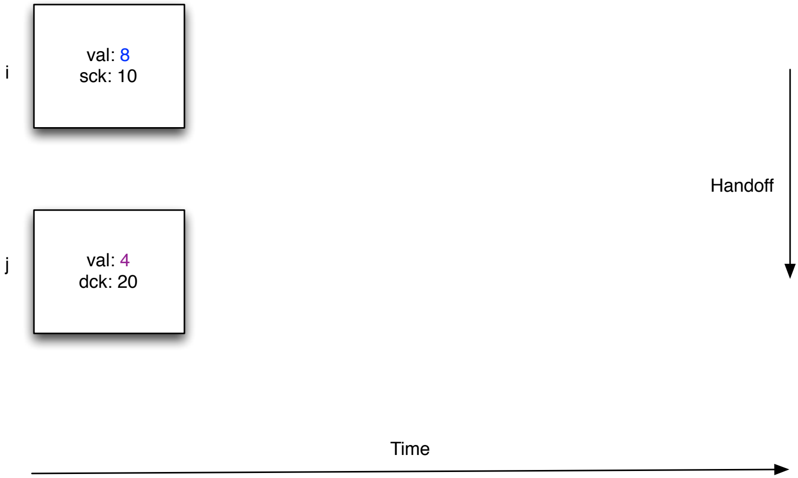
Three-way handshake is needed (Attiya, Rappoport. DC 1997)

Strategy

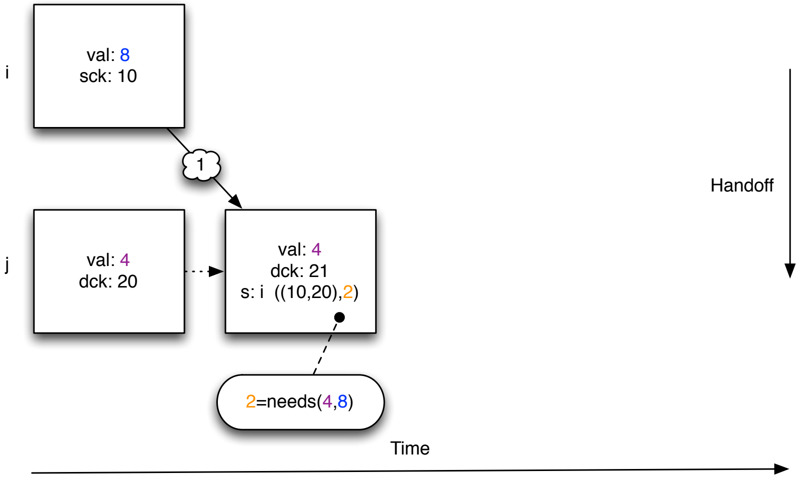
Adapt (piggybacking) three-way handshake steps:

1. Announce available value and sender counter/clock
2. Prepare receive slot and request quantity hint
3. Split value, up to hint, and send exactly-once quantity
4. (Garbage collect at sender, upon acknowledge)

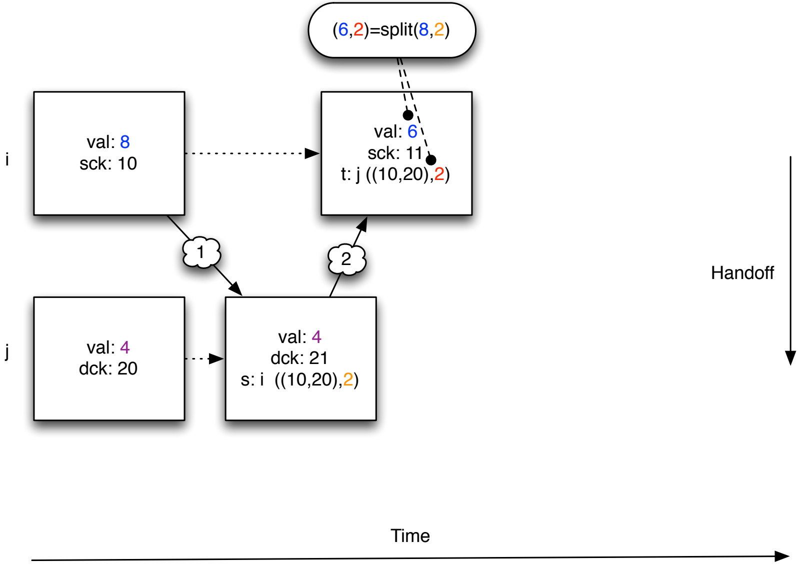
Handoff



Handoff

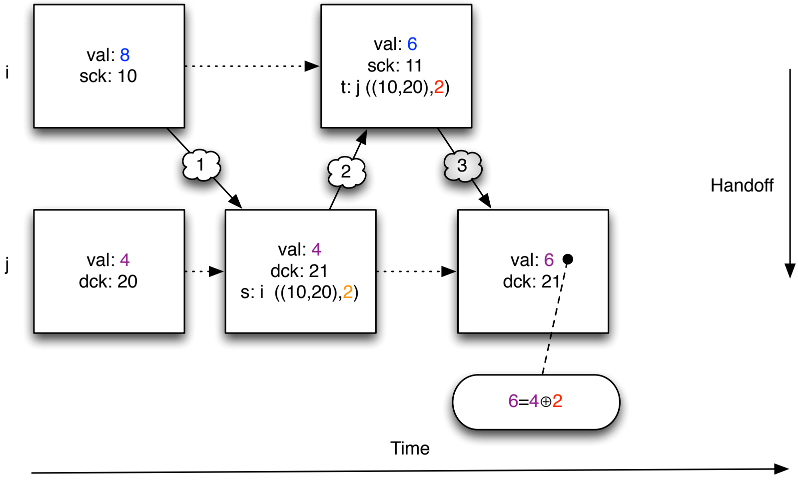

i
val: 8
sck: 10
1
j
val: 4
dck: 20
val: 4
dck: 21
s: i ((10,20),2)
2=needs(4,8)
Handoff
Time

Handoff



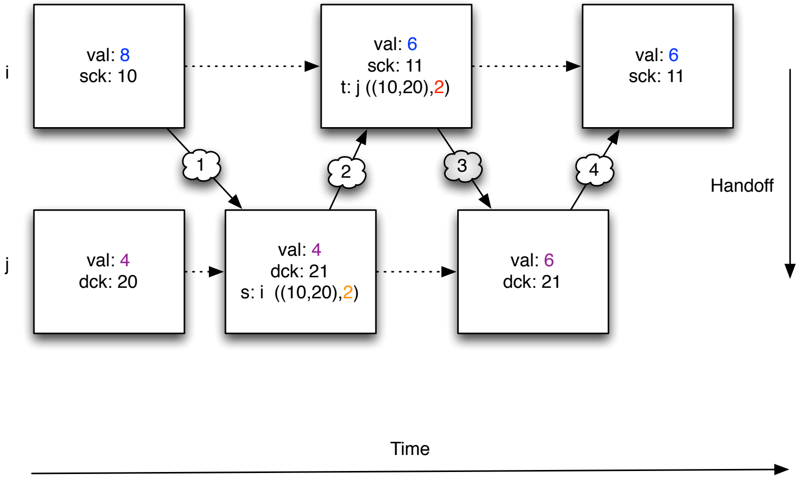
(6,2)=split(8,2)
i
val: 8
sck: 10
val: 6
sck: 11
t: j ((10,20),2)
1
2
j
val: 4
dck: 20
val: 4
dck: 21
s: i ((10,20),2)
Handoff
Time

Handoff

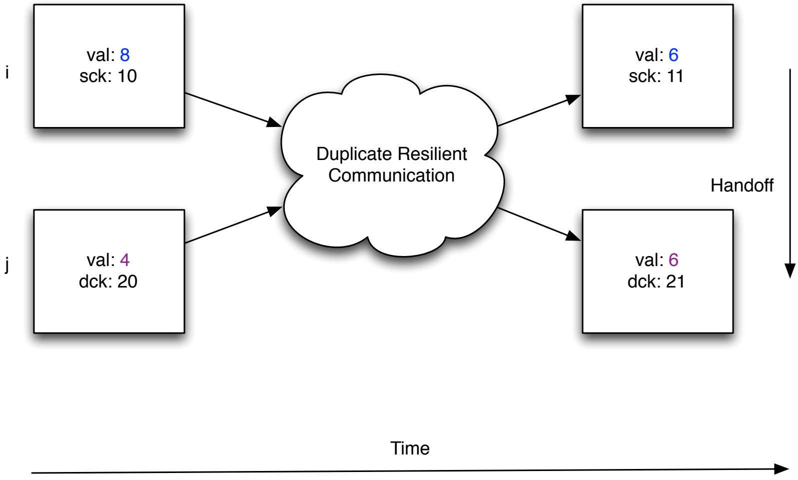


i
j
val: 8
sck: 10
val: 6
sck: 11
t: j ((10,20),2)
1
2
3
val: 4
dck: 20
val: 4
dck: 21
s: i ((10,20),2)
val: 6
dck: 21
6=4⊕2
Handoff
Time

Handoff


i
j
val: 8
sck: 10
val: 6
sck: 11
t: j ((10,20),2)
val: 6
sck: 11
1
2
3
4
Handoff
val: 4
dck: 20
val: 4
dck: 21
s: i ((10,20),2)
val: 6
dck: 21
Time

Handoff



i
val: 8
sck: 10
j
val: 4
dck: 20
Duplicate Resilient
Communication
val: 6
sck: 11
val: 6
dck: 21
Handoff
Time

Payload monoid data types
Value averaging

Positive reals that ask for half difference, give as much as possible

$$
\begin{aligned}
0 &\doteq 0 \\
\oplus &\doteq + \\
\mathrm{needs}(x, y) &\doteq \frac{y - x + |y - x|}{4} \\
\mathrm{split}(x, h) &\doteq \left(\frac{x - h + |x - h|}{2}, \frac{x + h - |x - h|}{2}\right)
\end{aligned}
$$

Derived aggregates include global sums and node counting

Payload monoid data types

Hotel booking (with averaging strategy)

Monodic values might not be in total order

$$X = \{\mathit{single} \mapsto 8, \mathit{double} \mapsto 12\}$$

$$Y = \{\mathit{single} \mapsto 1, \mathit{double} \mapsto 20\}$$

Leading to transfers in both directions

$$\{\mathit{double} \mapsto 4\} = \mathrm{needs}(X, Y)$$

$$\{\mathit{single} \mapsto 3\} = \mathrm{needs}(Y, X)$$

Eventually stabilizing with

$$X = \{\mathit{single} \mapsto 5, \mathit{double} \mapsto 16\}$$

$$Y = \{\mathit{single} \mapsto 4, \mathit{double} \mapsto 16\}$$

Experiment setup
Graph properties

- Graph with n nodes and each with $2 \log n$ links
- (Symmetric forward and backward Chord)
- Small world topology. Low path lengths, High clustering
- Synchronous message model
- Initial values from integer uniform distribution $0:255$
- All converge to average, about 128

Experiment setup
Faults

Simple experiment that aims to check resilience to message drop and message duplication faults (dropping and duplication can also lead to re-ordering events), and show final GC of all connection meta-data.

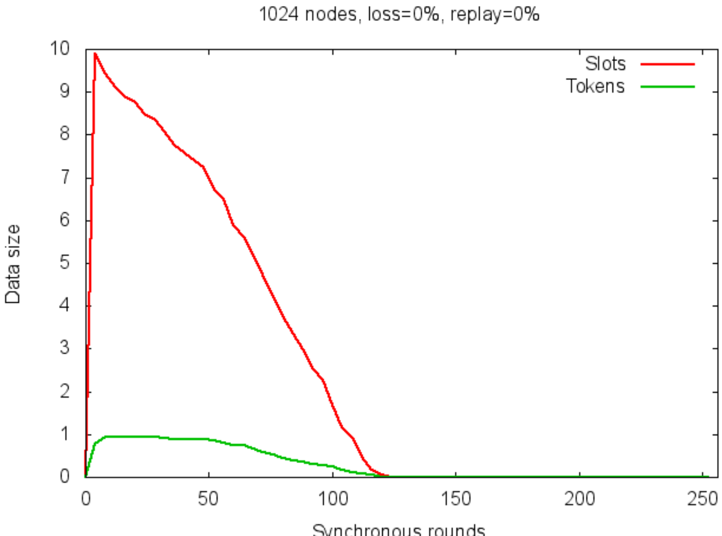
- Execution with no faults
- Executions with 25, 50 and 75% message loss faults
- Executions with 25, 50 and 75% message replay faults
- Execution with 75% mixed faults

Storage probability for replay is at 20% (lower means older replays)

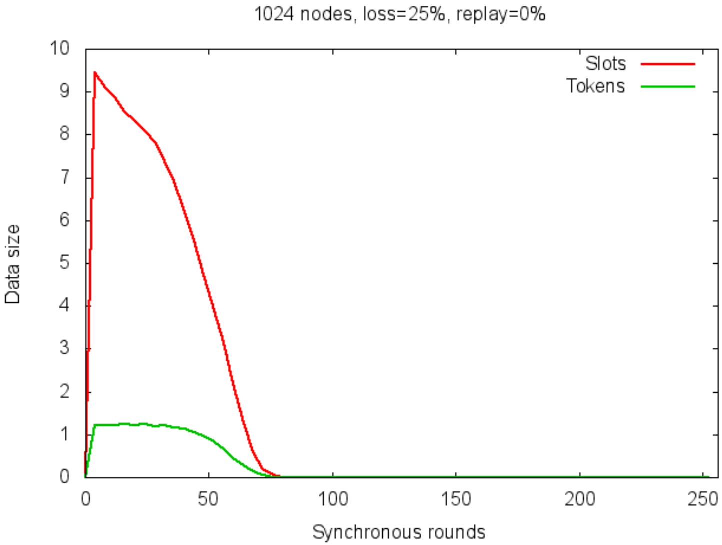
(Note: *need* and *split* functions not yet optimized for this topology)

Experiments
No loss

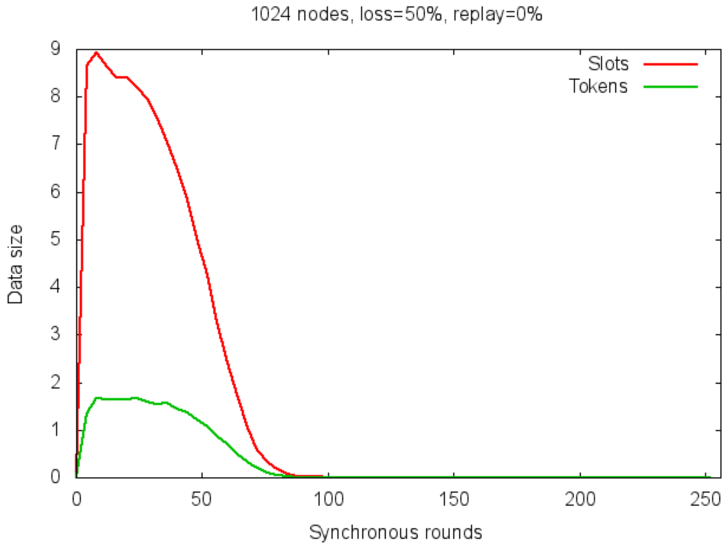
Showing linear meta-data size, excluding log growing clocks



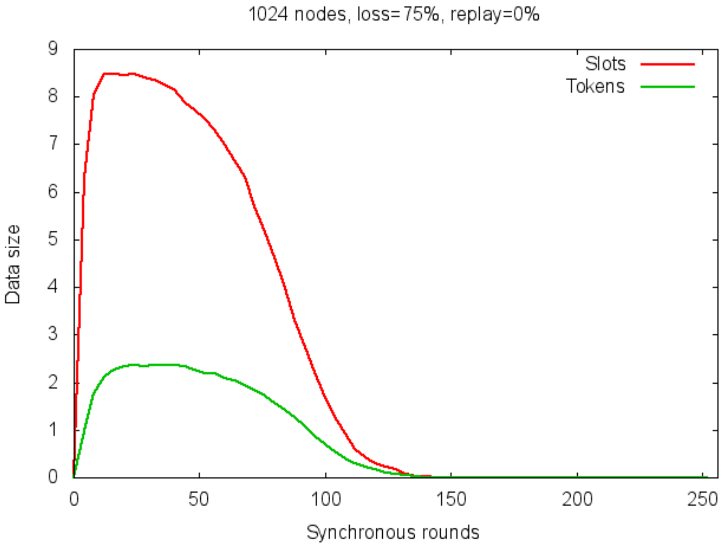
Experiments
25% loss



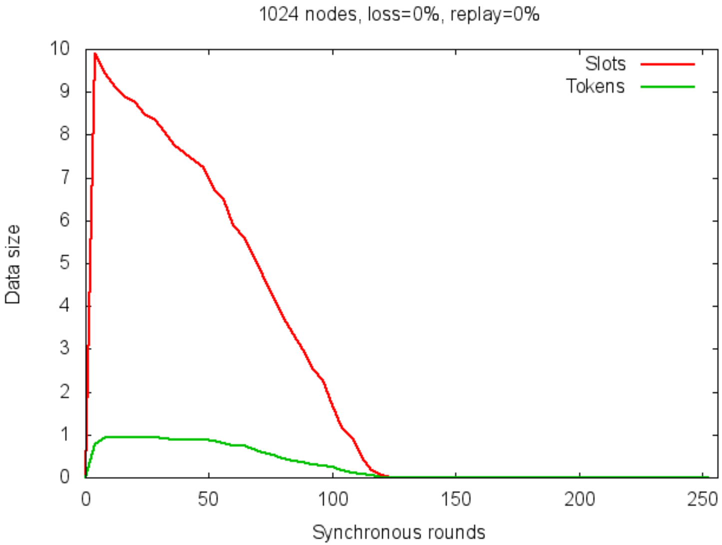
Experiments
50% loss



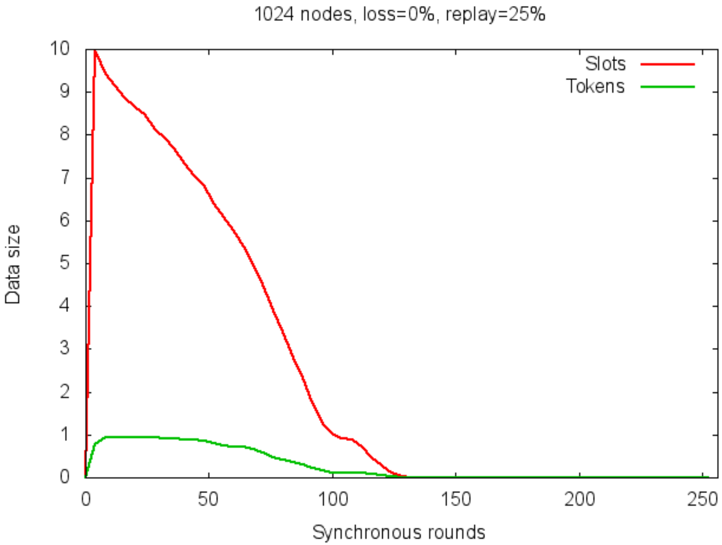
Experiments
75% loss



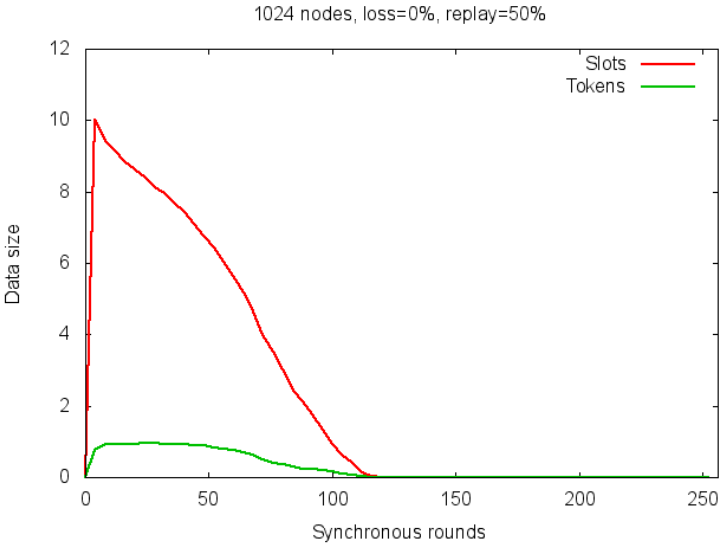
Experiments
No loss



Experiments
25% replay

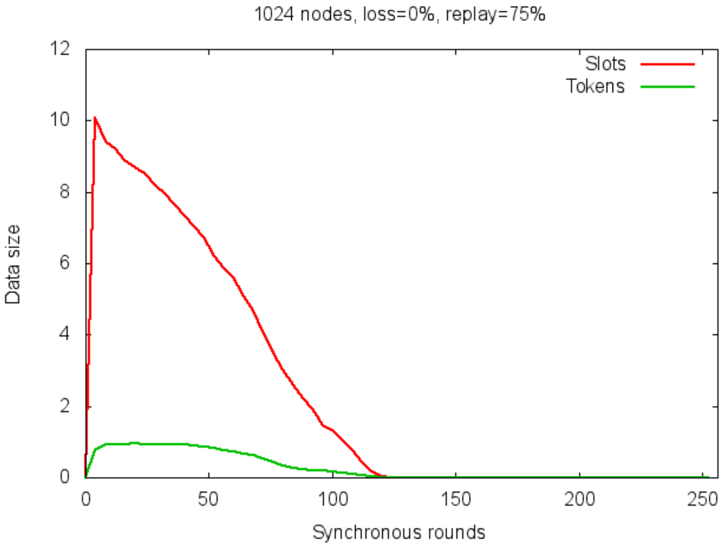


Experiments
50% replay

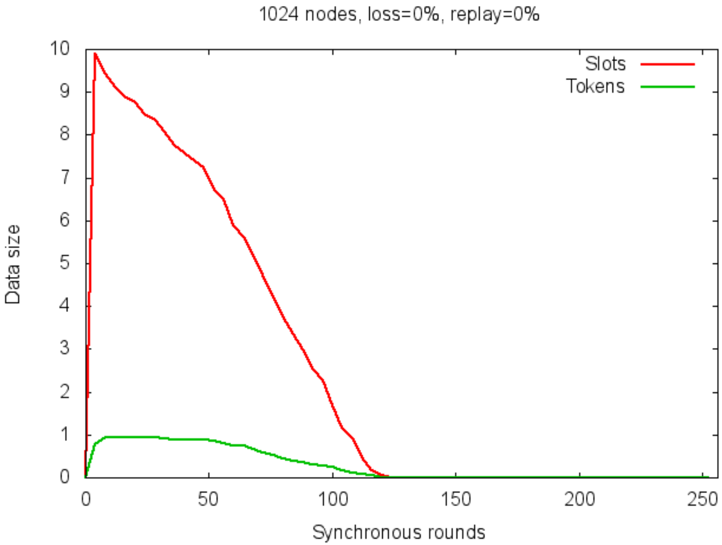


Experiments

75% replay

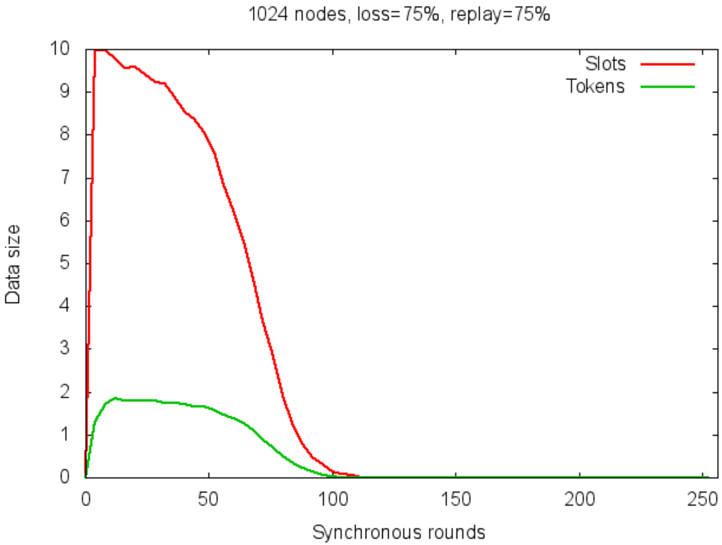


Experiments
No loss



Experiments

75% loss, 75% replay



Comments

- $+/-$ Base algorithm is not optimized for this experiment
- $+$ Still, there is clear high resilience to faults
- $+$ State after t transfers is eventually $O(\log t)$
- $-$ Topology must ensure symmetric exchanges
- $-$ Uncontrolled churn impacts GC:
  - $-$ Meta-data kept, linear with failed node peers k
  - $+$ If degree is $\log n$ then $k \leq \log n$
- $+$ Implemented in C++, for int, float and map payload

Related Work

- The level of handshake required for managing a connection. Hagit Attiya, Rinat Rappoport. Distributed Computing. 1997.
- Scalable Eventually Consistent Counters over Unreliable Networks. Paulo Sérgio Almeida, Carlos Baquero. ArXiv. 2013.

Questions?

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