Replication-based Highly Available Metadata Management for Cluster File Systems

Zhuan Chen, **Jin Xiong**, Dan Meng

Institute of Computing Technology
Chinese Academy of Sciences

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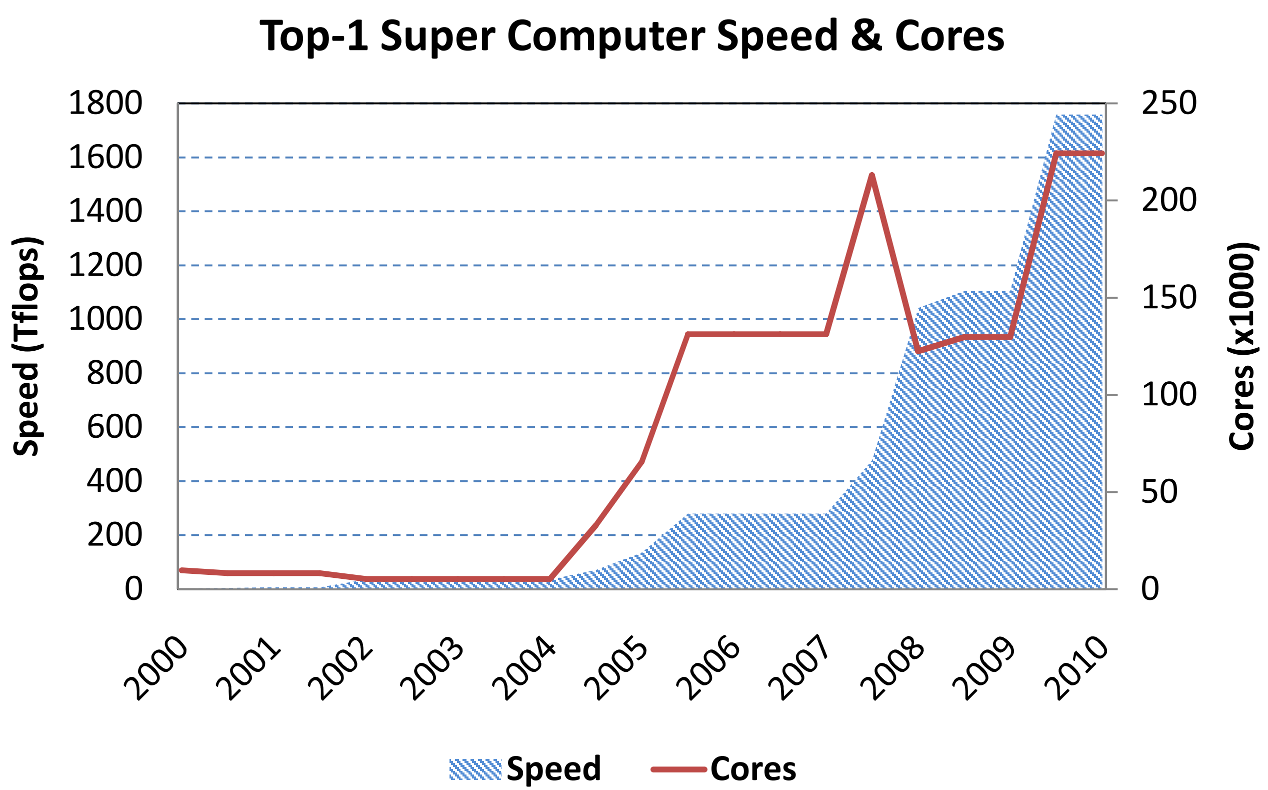
Outline

- Motivation
- Related work
- Our approach
- Experiment Results
- Conclusion

Motivation

Speed of supercomputers

- Speed of supercomputers keeps increasing
  - 62x from June 2007 to June 2010, according to top500 lists



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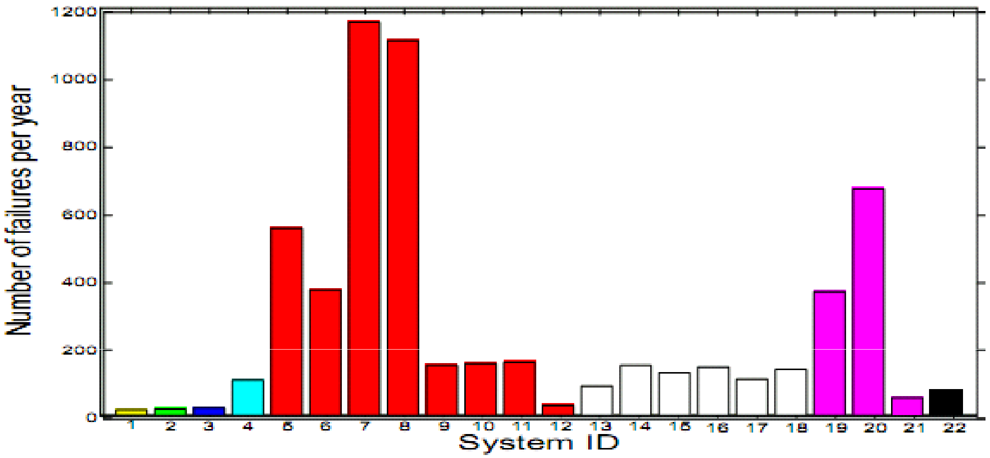
Scale of supercomputers

- Scale of supercomputers is also increasing
  - 1,000s to 10,000s nodes
  - 100,000s processing cores

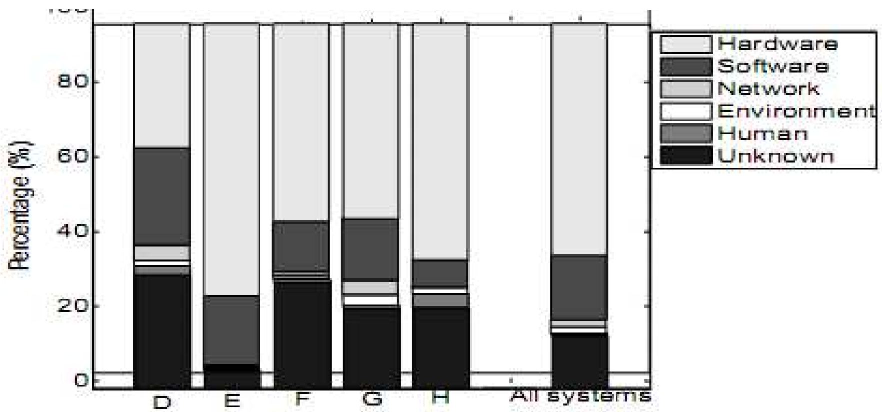
	Nodes	CPUs	Processing Cores
Google, Yahoo	Thousands		100s thousands
Roadrunner	3240	6,480AMD Opteron 12,960Cell	129,600
Jaguar	26520	45208	255,584
Tera-100	4300		140,000

Number of failures

- Component failures are so frequent for supercomputers

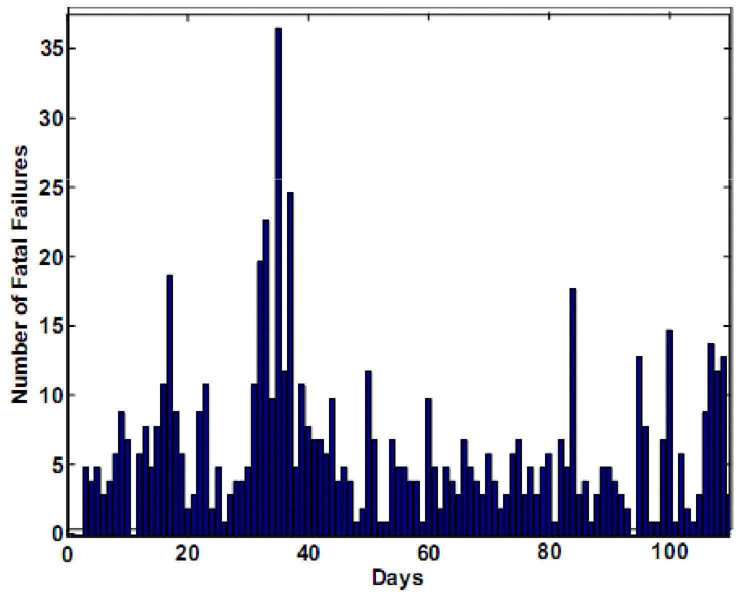


Schroeder & Gibson (DSN'06)



(a)

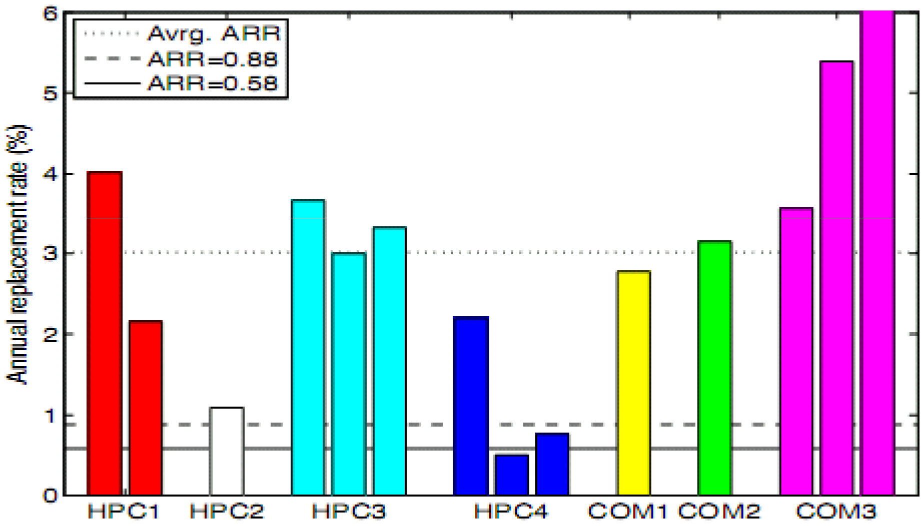
Schroeder & Gibson (DSN'06)



Liang etc. (DSN'06)

Disk failures

- Disk failures are also frequent



Schroeder & Gibson (FAST’07)

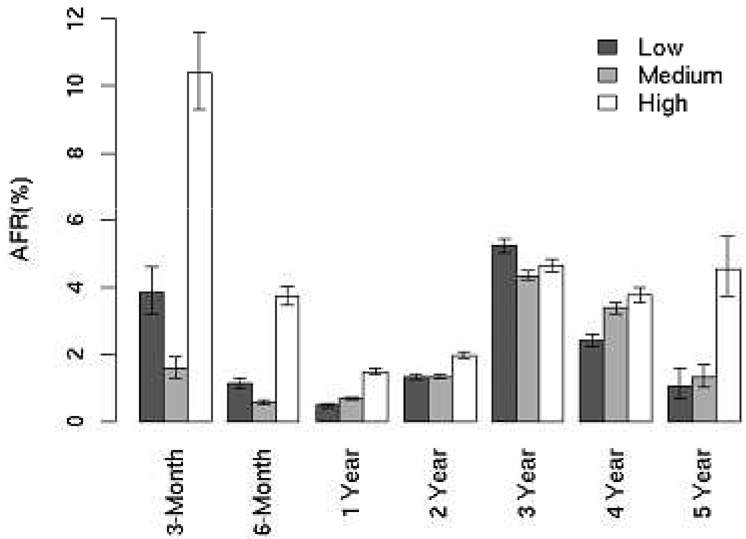


Figure 3: Utilization AFR

Schroeder & Gibson (FAST’07)

File system unavailable

- Node crashes, disk failures, comm. errors may cause the file system unavailable

Lustre-FS outage time			
Cause of Failure	Start time	End time	Hours
I/O hardware	07/21/07 23:03	07/22/07 12:00	12.95
I/O hardware	07/31/07 01:49	07/31/07 20:01	18.18
I/O hardware	08/22/07 18:08	08/23/07 02:15	08.12
I/O hardware	08/28/07 16:20	08/29/07 18:01	01.67
I/O hardware	09/25/07 18:00	09/26/07 09:30	15.50
I/O hardware	10/04/07 09:30	10/04/07 21:55	12.42
Batch system	10/16/07 17:56	10/16/07 21:24	03.47
Network	10/29/07 11:53	10/29/07 15:15	03.36
File system	11/16/07 09:30	11/16/07 10:00	00.40
File system	11/19/07 09:04	11/19/07 11:00	01.93

Table 1. User notification of outage of the Lustre-FS

Date	#	Date	#	Date	#
07/03/07	102	07/19/07	258	08/16/07	375
08/20/07	591	09/05/07	005	09/17/07	002
09/18/07	004	09/19/07	003	09/28/07	463
09/29/07	477	10/01/07	051	10/02/07	035

Table 2. Lustre mount failure notification by compute nodes from 07/01/07 to 10/02/07; column with "#" represents the number of compute nodes that experienced mount failure

Goankar etc (DSN'08)

Challenge for cluster file system design

- Handle frequent component failures
  - Hide the failures from applications
  - High-performance I/O
- Data replication is not enough
  - Only consider failures in data paths
  - Cluster file systems have separate metadata paths
- Metadata management
  - Maintain the namespace, file attributes, data location, access permission, etc
  - The disruption of metadata service could lead to the outage of the entire file system

Issue to address

- How to ensure highly available metadata management
  - Previous work: tolerate failures in the data path through replication

    Building Highly Available Cluster File System Based on Replication, L. Cao, Y. Wang, J. Xiong, PDCAT'09, Dec. 2009

  - This work: tolerate failures in the metadata path through replication

Related work

Metadata journaling

- Adopted by many cluster file systems
- Ensure atomicity of metadata operations
- Keep metadata consistency after metadata server failures
- 2 methods for writing log back to disk
  - Synchronous write: poor metadata performance by a large number of small and synchronous disk writes
  - Asynchronous write: better throughput, but operation latency is hardly improved, and loss of memory metadata and state information

Limitation: cannot provide seamless recovery and fail-over

Replication

- The symmetric active/active metadata service
  - Ou et al. , PDCS 2007
  - Total order for all metadata write requests by broadcasting
  - Large amount of network transmissions
- Google FS replicates its master on multiple machines
  - Operation log and checkpoints
  - Shadow masters (not mirrors) provide read-only access to some files in some situation

Challenges

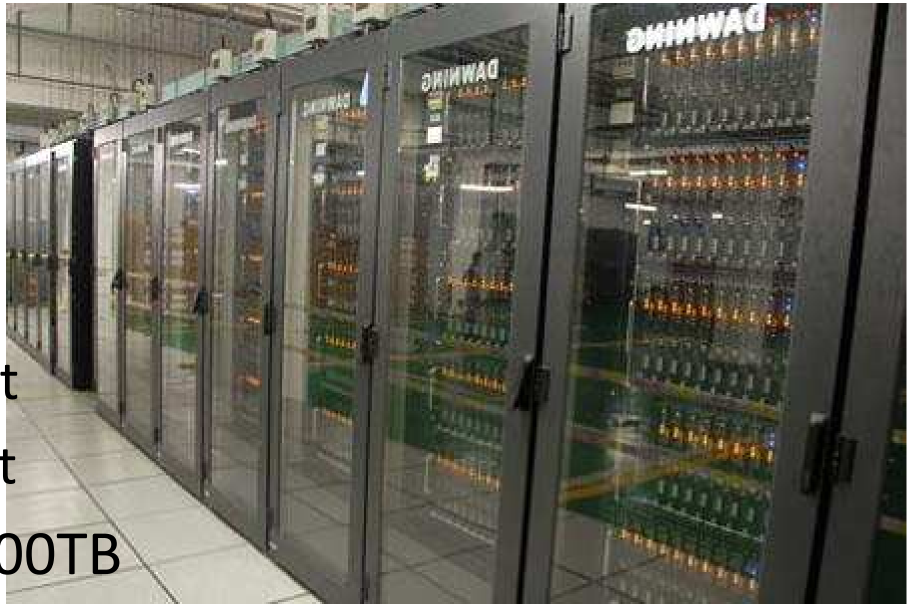
- Reduce costs brought by replication & consensus protocol
- Well utilize the redundant MDS

of applications on supercomputers

Our approach

Background

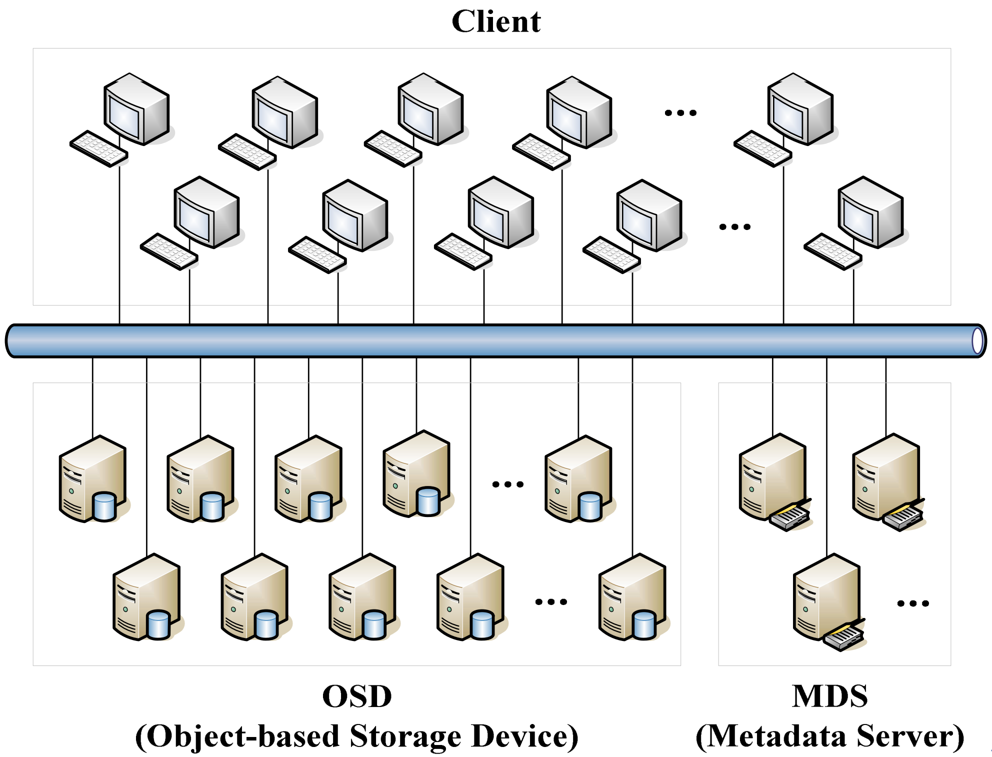
- Dawning5000A
  - 1,650 nodes
  - 30,720 cores
  - 100TB memory
  - Linpack: 180.6 Tflops
    - No.10 at Nov 2008 Top500 list
    - No. 24 at Jun 2010 Top500 list
  - Total storage of local disks: >500TB
    - 320GB SATA disk per node



A high-performance cluster file system over all local disks

Our prototype: DCFS3

- Global namespace shared by thousands of nodes
- Logically, 3 types of components
  - Client, OSD, MDS
- may co-locate at the same physical node

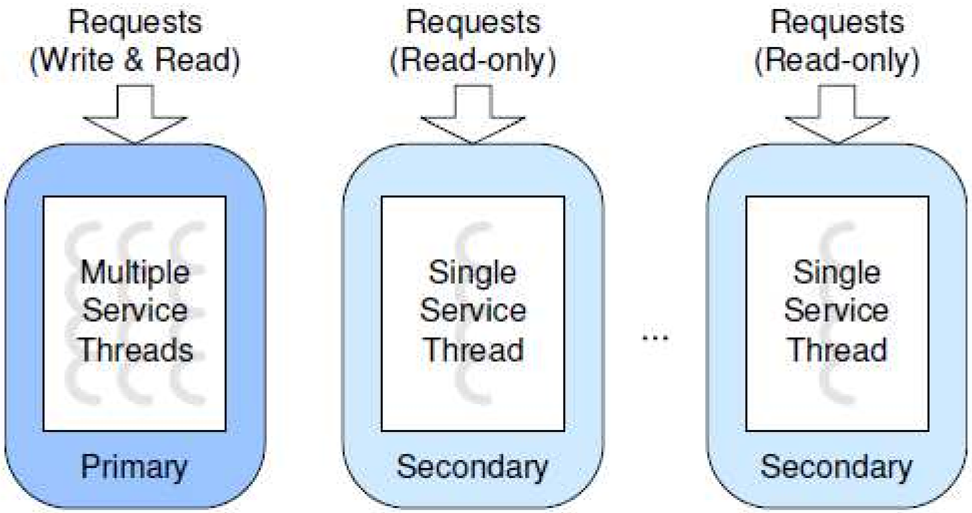


Metadata management in DCFS3

- Metadata is partitioned according to users
  - Each partition is also the loading unit
- Access and updates are performed on memory data
- Periodically write back dirty data to disk
- Metadata modification log: metadata consistency
  - Asynchronously write log back to disk
  - A pair of log buffers: to avoid blocking of processing

Asymmetric architecture of replicated MDS

- Each metadata server replicates its data to other MDS
- Role of MDS in each group: *Primary* & *secondaries*
- Clients view
  - send metadata write operations to the *primary*
  - send metadata read operations to any MDS
- *Primary* determines the execution order of write ops
- *Secondaries* apply updates according to this order



Metadata replication

- Replicate each write operation's results
- A log record for each write operation at the *primary*
  - Operation type, arguments, results , time stamp
  - Sequence number
- *Secondaries* directly apply the results from log records
  - Expedite the replication by saving the time for repeated processing
- No interactions among the *secondaries* to complete the replication
- Replication on a *secondary* is completed if the results have been applied to the memory metadata
- *Primary* replies the client once the replication is completed by all the *secondaries*

Consensus of replicas

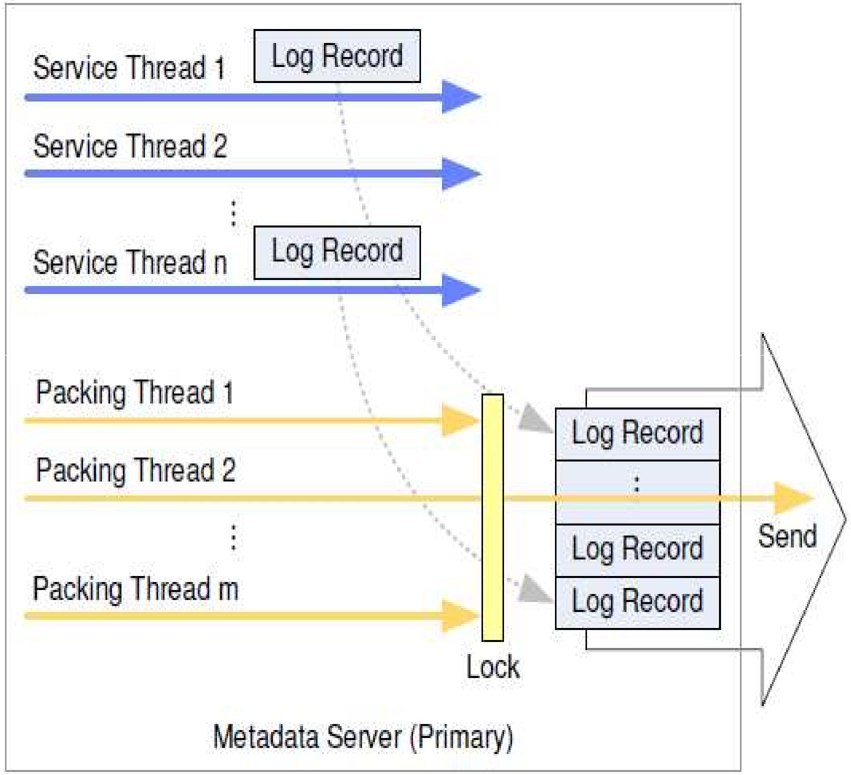
- Consensus protocol is needed in case of failure occurrence
  - Paxos algorithm
    - Primary also plays the role of issuing proposals
    - 3 rounds of messages: prepare, accept, success
  - Multi-Paxos
    - 2 rounds of messages in most cases: accept & success
- Problem of applying Paxos in metadata management
  - Cannot make full use of the network bandwidth
    - A large number of messages under heavy load: every replication requires 2 rounds of network messages
    - Each message is small: the metadata of each file is small
  - Poor metadata throughput under heavy load

Packed Multi-Paxos

- Goal: reduce number of messages in the system
- Idea: to pack several metadata log records together and transmit them by one message
- Problem: how many log records to be packed each time?
  - Trade off between the number of log records per message and the operation latency
    - Wait for more log records may increase operation latency
  - ☹ Fixed method: unnecessary increase of latency under light load
    - ☹ Fix the number of log records per packing
    - ☹ Fix the time for each packing

Packed Multi-Paxos

- A self-adaptive method making use of OS thread scheduling
- Multiple packing threads
  - Only one active packing thread at any time
  - The active one packs all current log records into one message
- Multiple service threads
  - Do not directly replicate log records to the secondaries
  - Notify the active packing thread when a log record is generated

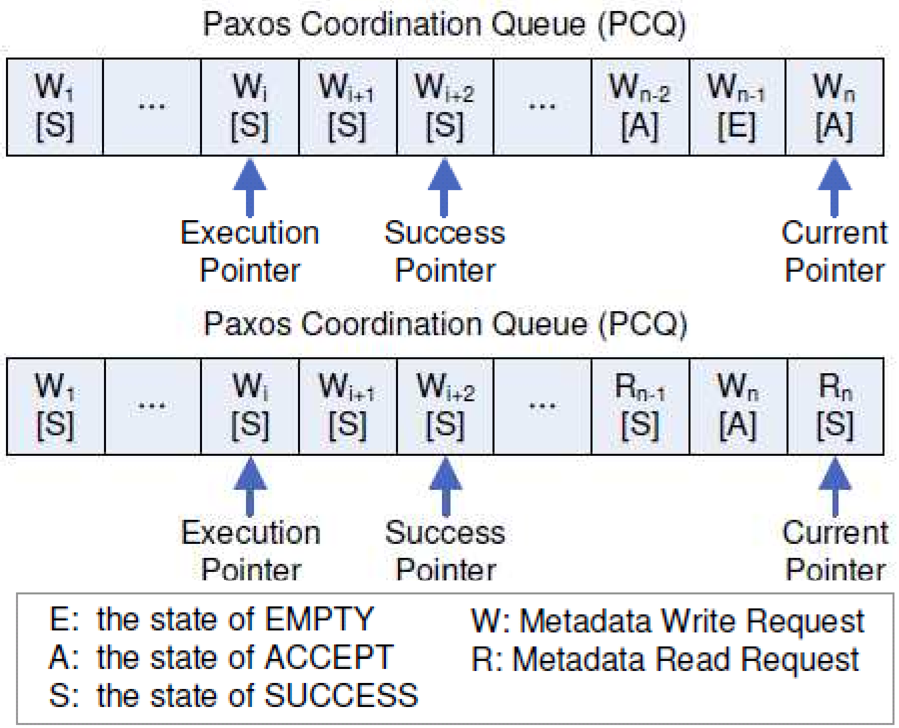


Packed Multi-Paxos

- Service threads & packing threads are equally scheduled
  - Same priority
  - Heavy load: several log records are packed into one message
    - Several service threads are scheduled before the active packing thread
    - Improve metadata throughput: less messages and better utilization of network bandwidth
  - Light load: immediately send log records
    - Some sleeping service threads (have no task) are just bypassed by the OS scheduler
    - Immediately execute the active packing thread
    - Prompt response

Paxos Coordination Queue (PCQ)

- Control execution order on the secondaries
  - execution order of log records of write requests
  - the relevance between metadata write and read requests
  - 3 states
    - Accept: log record enqueue
    - Success: ready to be executed
      - Receive Success message
      - Read requests
    - Empty: discontinuous seqno
  - Execute requests of Success state sequentially
    - Wait at the request in Accept/Empty state



Recovery

- Failure of any secondary
  - Remove it from this group's view
- Failure of the primary
  - New primary: largest Accept seqno (or Current Pointer)
  - Recovery range: smallest Success Pointer to largest Current Pointer
    - Success State: send this log record to all the Secondaries
    - Accept State: redo Paxos phase 2, ask if others can accept it
    - Empty State: ask if others have it, if yes, do as Accept state or Success state; Otherwise, discard it (no-op)

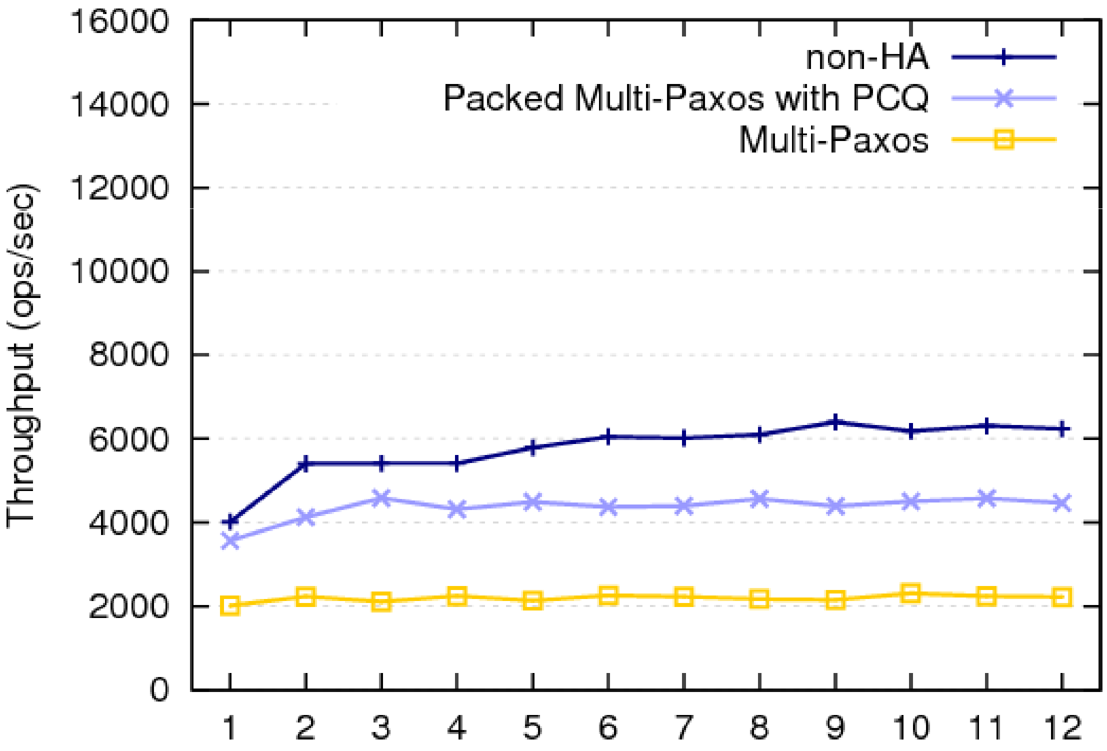
Experiment results

Test platform

- 16 virtue machines created by VMware
- Each virtue machine
  - 1 Intel Xeon Processor (2.00GHz)
  - 1 GB Memory
  - 36 GB disk
- GE interconnection
  - Actual network transmission speed is 764.91 MB/s (*netperf*)

Performance of metadata write operations

- Benchmark: *mdtest*
- Reported performance: file creation



- Configuration:
  - 12 clients, 1 OSD
  - Non-HA: 1 MDS
  - Others: 3 MDS
- *mdtest* parameters
  - 100 threads
  - 100,000 files

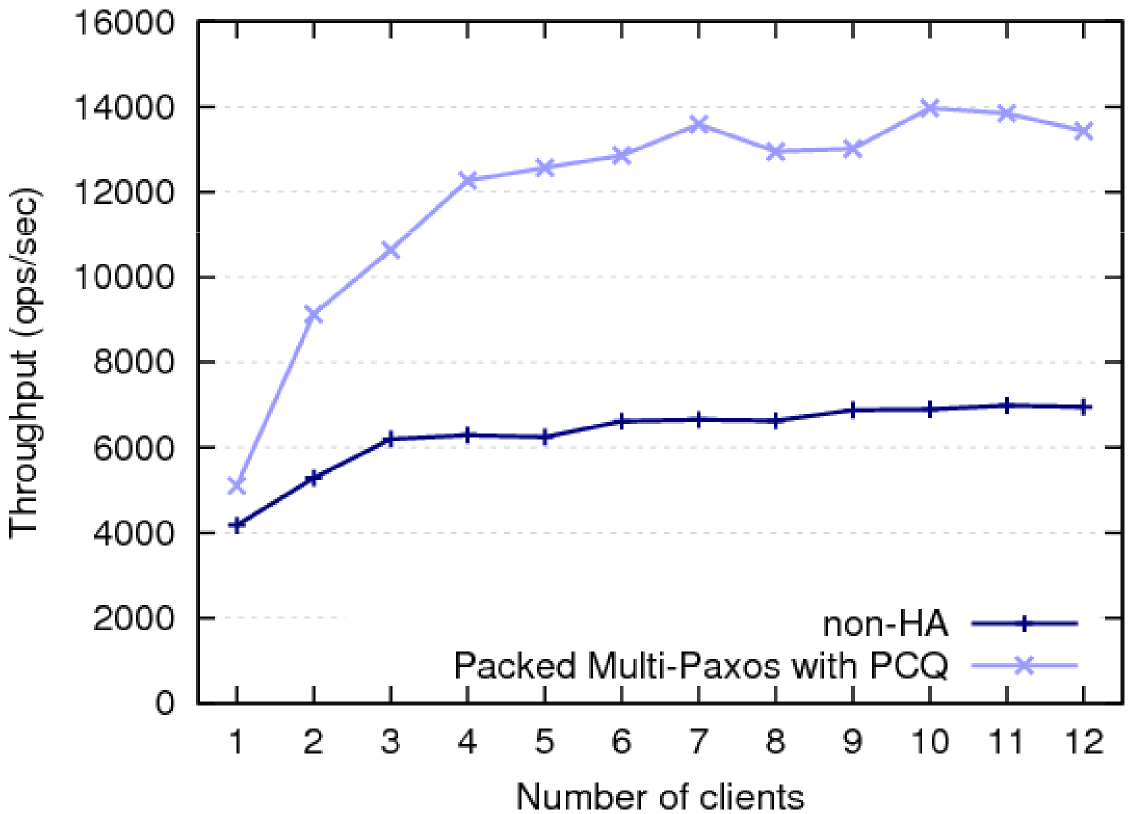
Performance of metadata write operations

- The effect of packing
- Reduced 88% network transmissions
- 90% messages contain 3-6 log records

Number of log records within a network transmission	Number of network transmission		
	1 MDS, non-HA	3 MDS, HA (Multi-Paxos)	3 MDS, HA (Packed Multi-Paxos + PCQ)
0	0	300300	304
1	0	300300	764
2	0	0	3134
3	0	0	11136
4	0	0	20403
5	0	0	19476
6	0	0	10148
7	0	0	2411
8	0	0	336
9	0	0	45
10	0	0	1
Total	0	600600	68158

Performance of metadata read operations

- Benchmark: *mdtest*
- Reported performance: file stat



- Configuration:
  - 12 clients, 1 OSD
  - Non-HA: 1 MDS
  - Others: 3 MDS

- *mdtest* parameters
  - 100 threads
  - 100,000 files

mpiBLAST

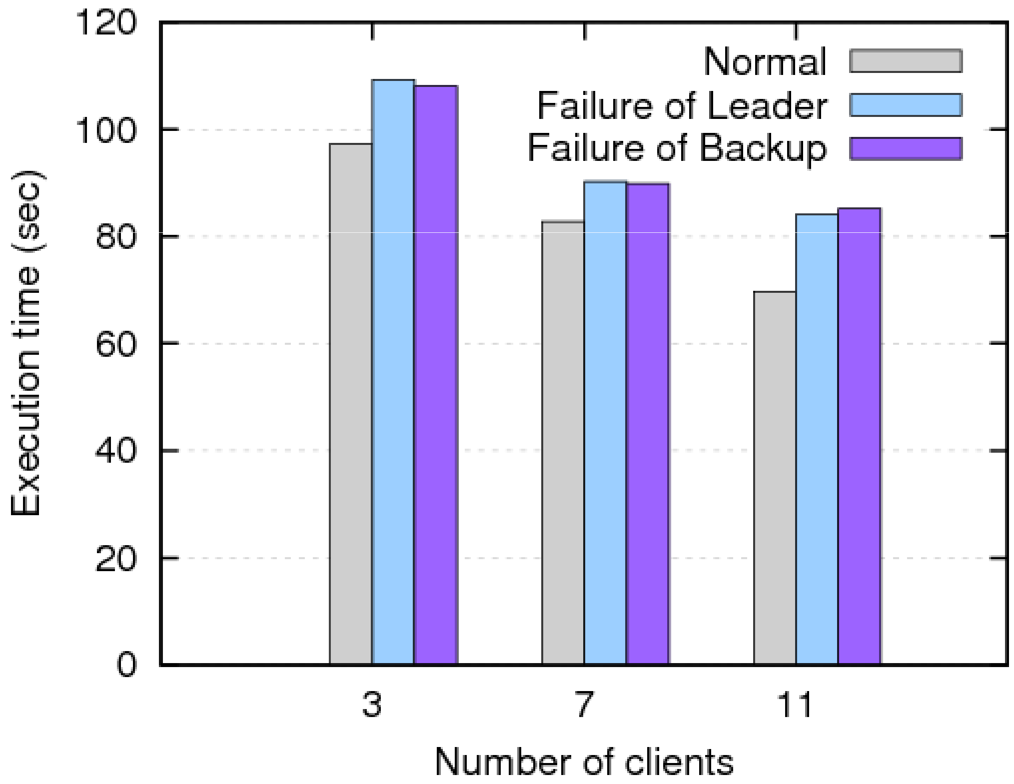
- Time spent in gene query and matching

- Configuration:
  - 11 clients, 2 OSD
  - Non-HA: 1 MDS
  - Others: 3 MDS

- *mpiBlast* parameters
  - Database size: 977MB

mpiBLAST

- Fault-tolerance
  - Inject failures during its execution



- Configuration:
  - 11 clients, 2 OSD
  - Non-HA: 1 MDS
  - Others: 3 MDS

- *mpiBlast* parameters
  - Database size: 977MB

Summary

- Our contributions
  - Adopt replication and the Paxos protocol to construct a highly available metadata management
  - To improve metadata throughput, propose a method that packs multiple log records into one message and controls execution order by a Coordination Queue

Thank you!
&
Questions?

Jin Xiong: xj@ncic.ac.cn