Efficient Metadata Management in Large Distributed Storage Systems

Scott Brandt, Ethan Miller, Darrell Long, and Lan Xue
Storage Systems Research Center
University of California, Santa Cruz
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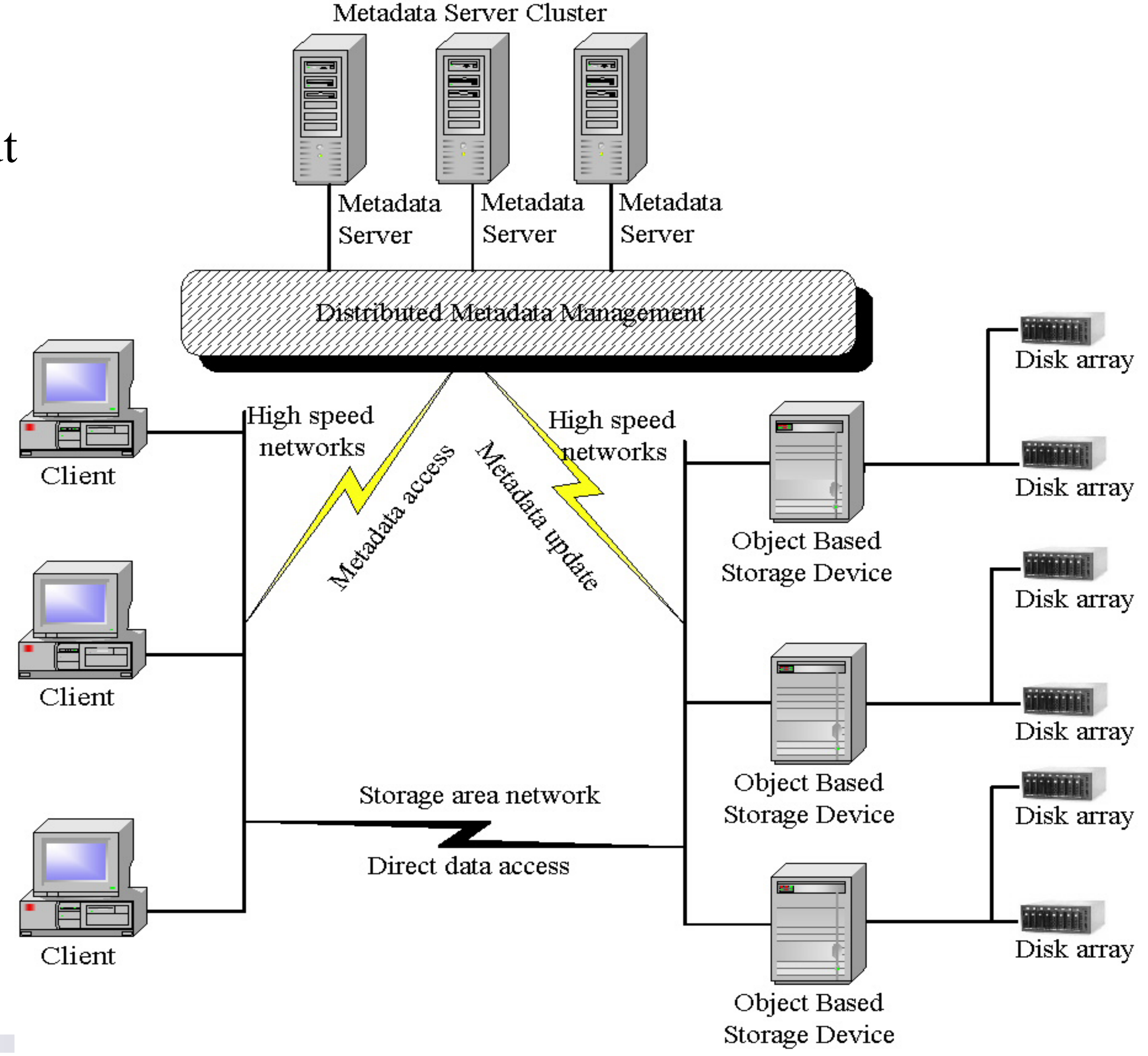
UC Santa Cruz

OSD Storage System Overview

- 2PB data (billions of files)
- 100 GB/sec throughput
- 10,000 client nodes active simultaneously
  - To different directories, same directory, or even same file
- Research issues:
  - OSD FS
  - Reliability
  - Data distribution
  - Metadata server internals
  - Metadata server cluster architecture



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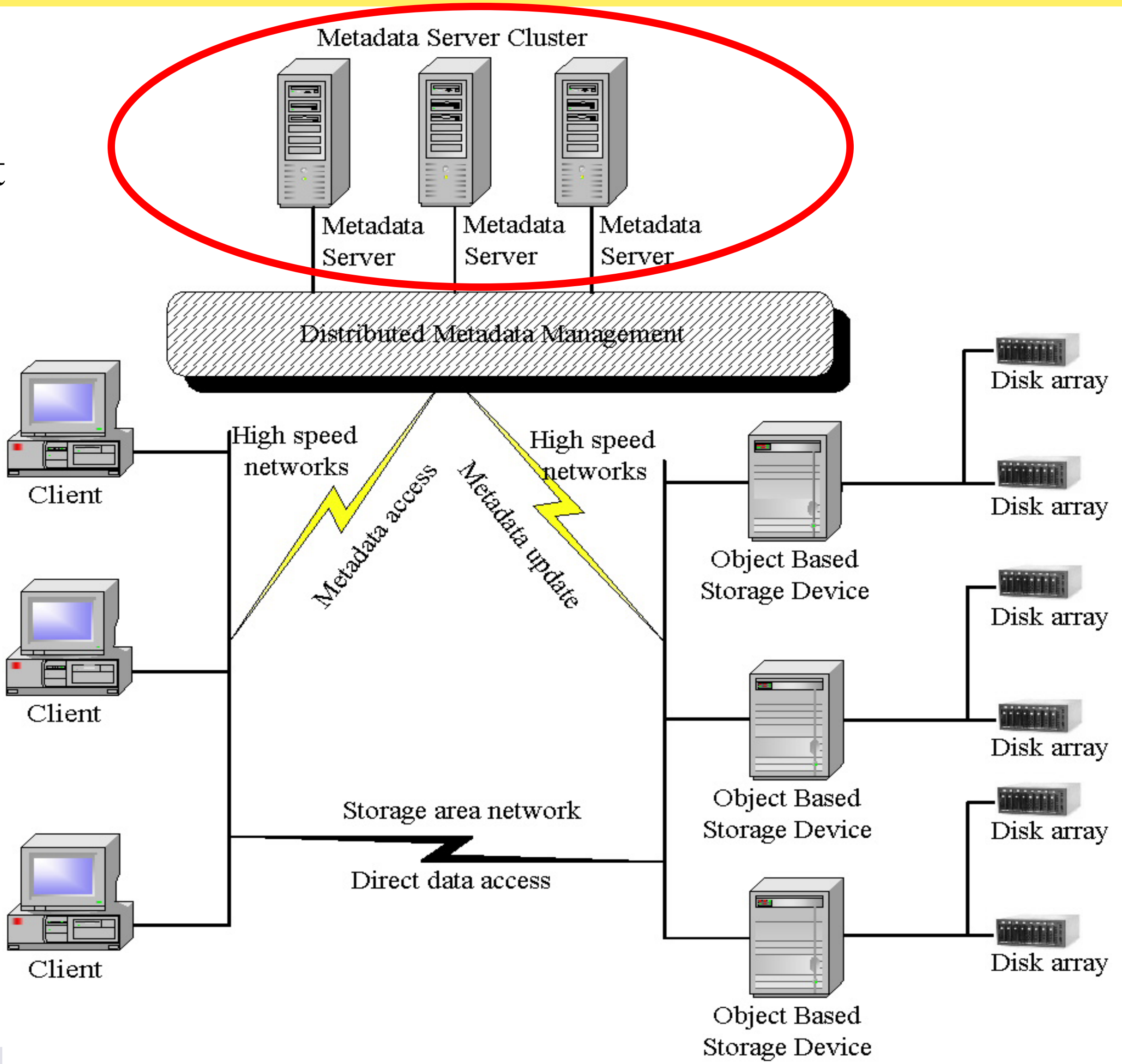


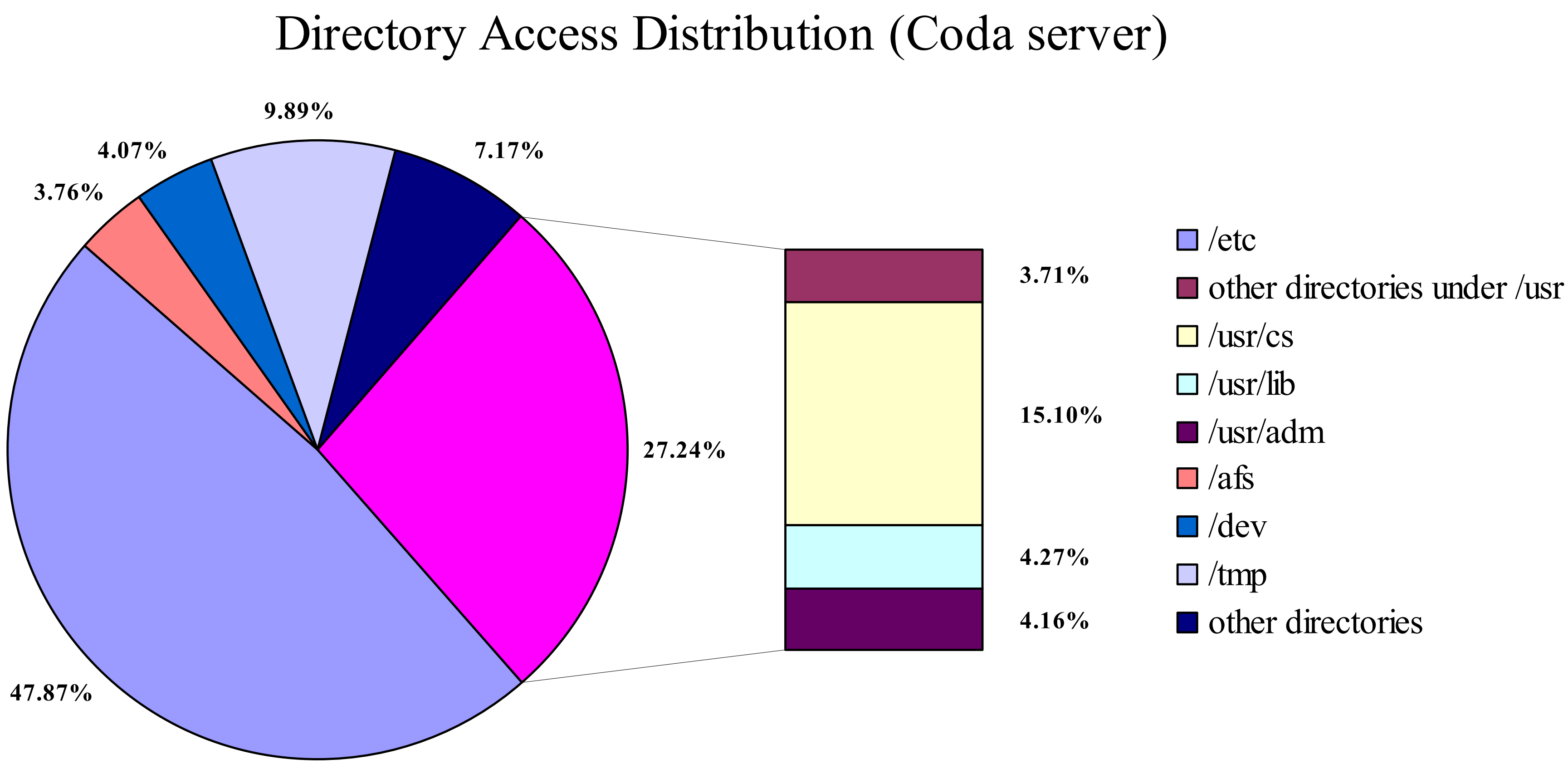
Metadata Server Cluster Goals

- POSIX-compliant API
  - Standard UNIX-style file and directory semantics
- High Performance
  - Efficient metadata access
  - Efficient directory operations
  - Efficient access control
  - High degree of parallelism
- Scalability
  - Performance scales with the number of metadata servers
  - Uniform namespace
  - Load balancing among metadata servers under various conditions
  - Easy addition and removal of metadata servers

Background: Directory Subtree Partitioning

- Hierarchical namespace partitioned by directory subtrees (e.g. NFS)
- Pros:
  - Supports standard directory semantics
  - Efficient access to multiple files in same directory
- Cons:
  - Bottlenecks with high concurrent accesses
  - Coarse granularity of load balancing
  - Adding or removing metadata servers is costly
    - Difficulty to manage
    - May have to move a significant amount of metadata

Sample Workload



- Conclusion: some directories are MUCH more popular than others.

Background: Pure Hashing

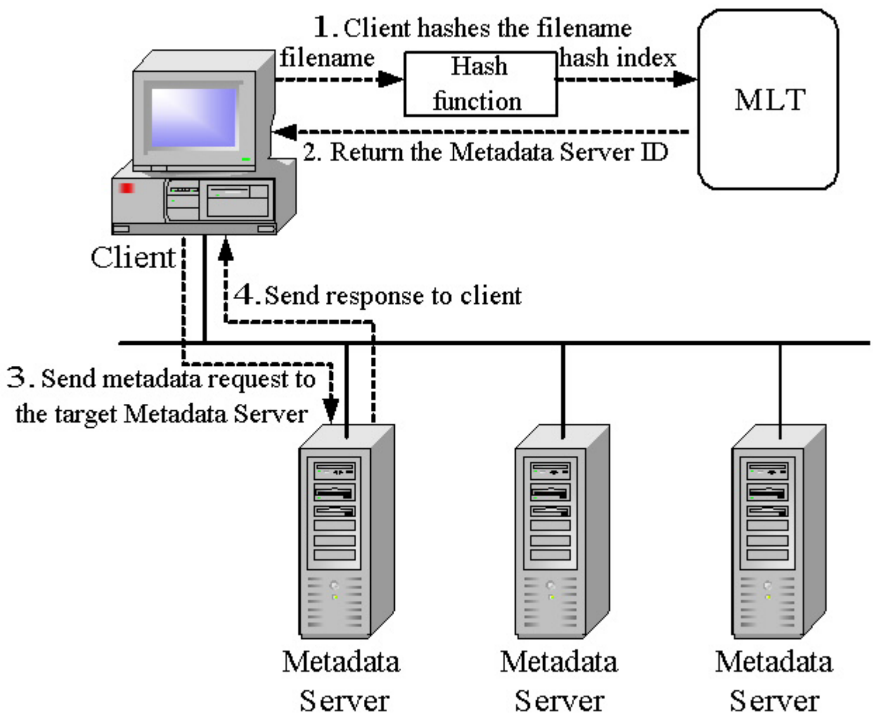
- Namespace widely distributed among the metadata servers based on hash of file or pathname (e.g. Vesta)
- Pros:
  - One-request metadata lookup
  - Bottleneck avoidance
- Cons:
  - Hard to support standard directory semantics
    - ls, directory permissions, etc.
  - Adding or removing metadata servers is costly
    - May have to move most of the metadata

Lazy Hybrid Metadata Management

1. Indirect hash-based metadata location
2. Hierarchical directories
3. Lazy metadata relocation
4. Dual-ACL access control
5. Metadata update logging

Indirect Hash-based Metadata Location

- Hash of pathname is used as an index into the Metadata Lookup Table (MLT)
  - The MLT is a global data structure – cached everywhere, updated infrequently
- MLT location specifies which metadata server contains the metadata
  - Provides for efficient addition and removal of metadata servers from the cluster
  - Updated only when metadata servers are added or removed
  - Only affected metadata is moved
- Result
  - One-request lookup
  - Fine-grained load balancing



Hierarchical Directory Structure

- Directories contain locations of file metadata
- Each metadata object is accessible both by hashing the pathname and by traversing the directory tree
- Directories are updated synchronously
  - Directory lookup always locates metadata
- Result
  - Standard directory semantics are supported

Lazy Metadata Relocation

- Several operations change location of metadata
  - Renaming a file or directory, adding or removing a metadata server
- Moving everything immediately can take a long time (but if it's not moved a metadata lookup may fail)
- Solution: Move directory and file metadata lazily, as it is accessed
  - The metadata server looks in the parent directory to determine the location, the metadata is moved to the new location, and the request is processed
  - Can proceed recursively if the parent directory also needs to move
- Result:
  - Metadata can always be located
  - Metadata is always correctly moved to new location
  - Movement overhead is distributed
  - Can also be accomplished in the background

Dual-ACL Access Control

- Hierarchical directory semantics expect path traversal to determine permissions
  - Disallows direct hash-based metadata lookup
- Solution: Dual ACLs allow for direct lookup
- File permissions
  - Ordinary file permissions
- Path Permissions
  - "Intersection" of file permissions and parent directory permissions
  - Computed at file creation and updated as appropriate

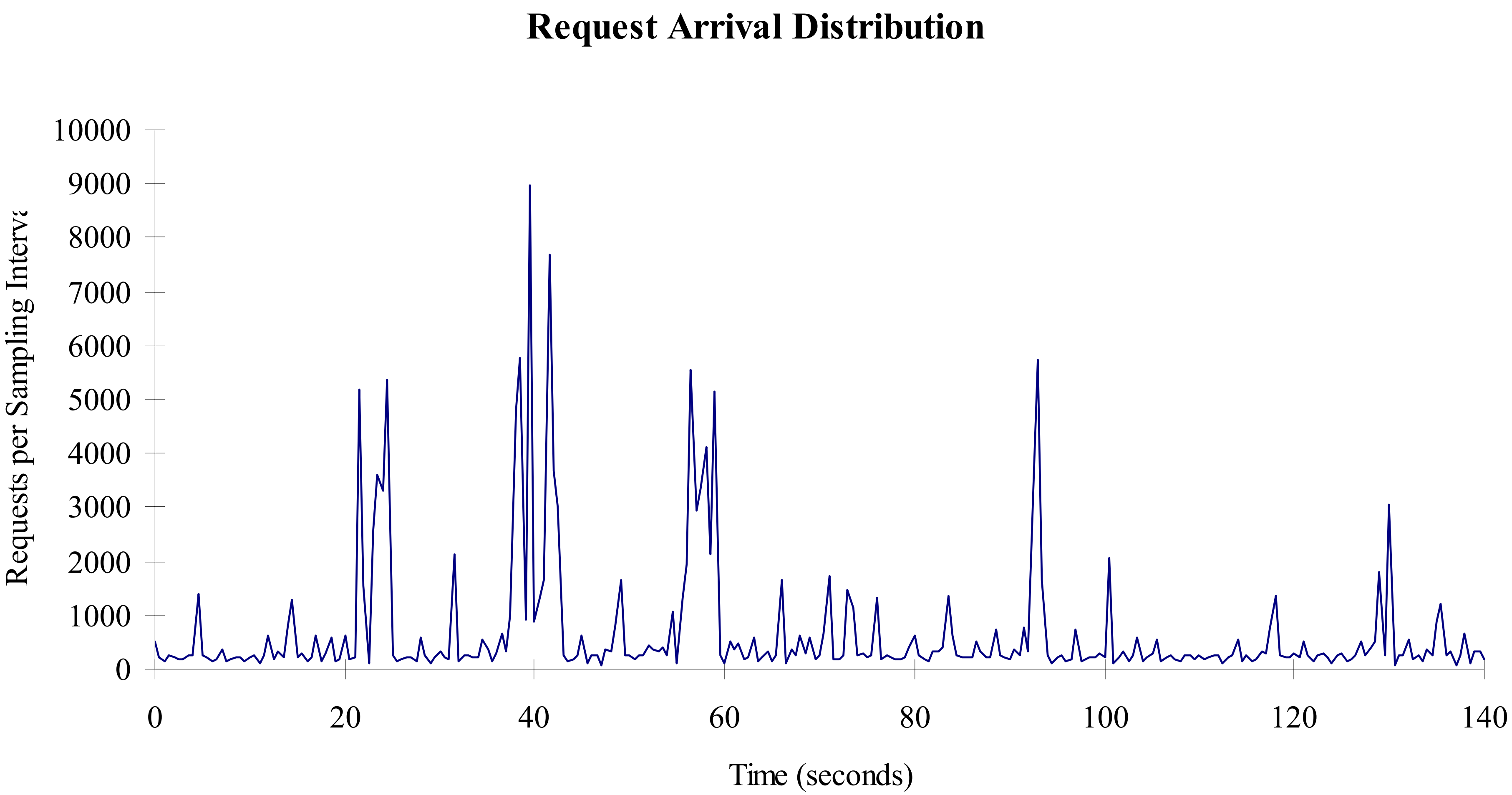
Metadata Update Logging

- Directory rename and permission change require updates to a lot of metadata
- Solution: large metadata updates are synchronously broadcast and recorded in a log on each server
- Metadata is compared to the log and appropriate updates are applied before each request is processed
- Update timestamp allows for efficient log search
  - Metadata stores timestamp of last update compared
- Result:
  - Large metadata updates can be accomplished quickly
  - Updates can be accomplished lazily or in the background

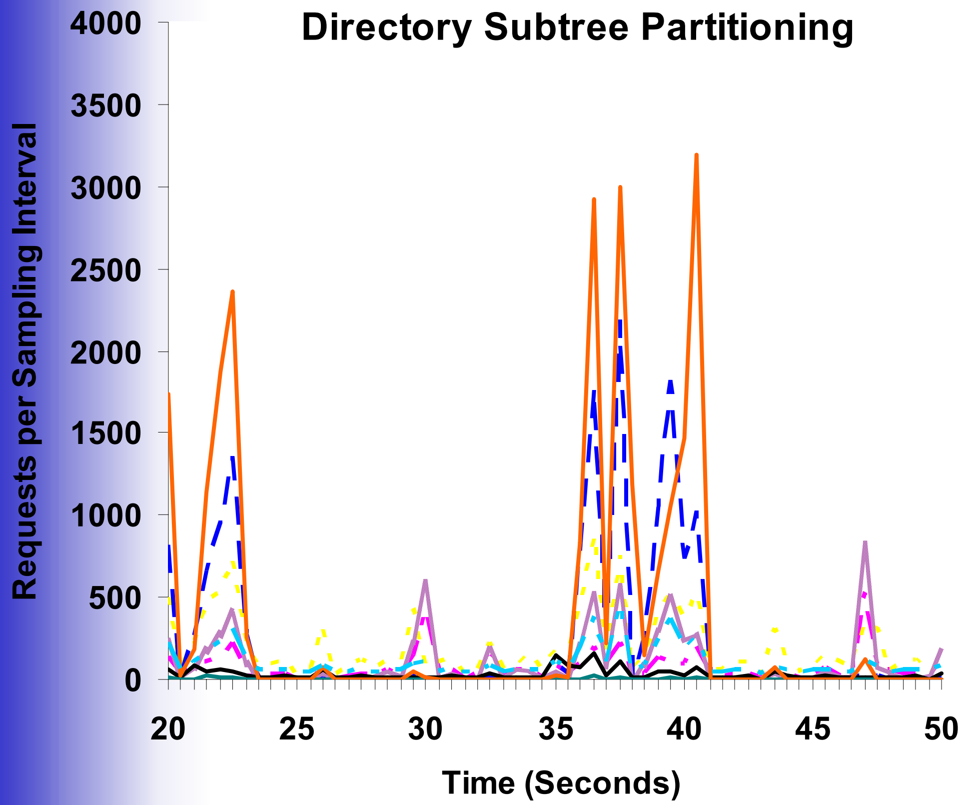
Simulation Environment

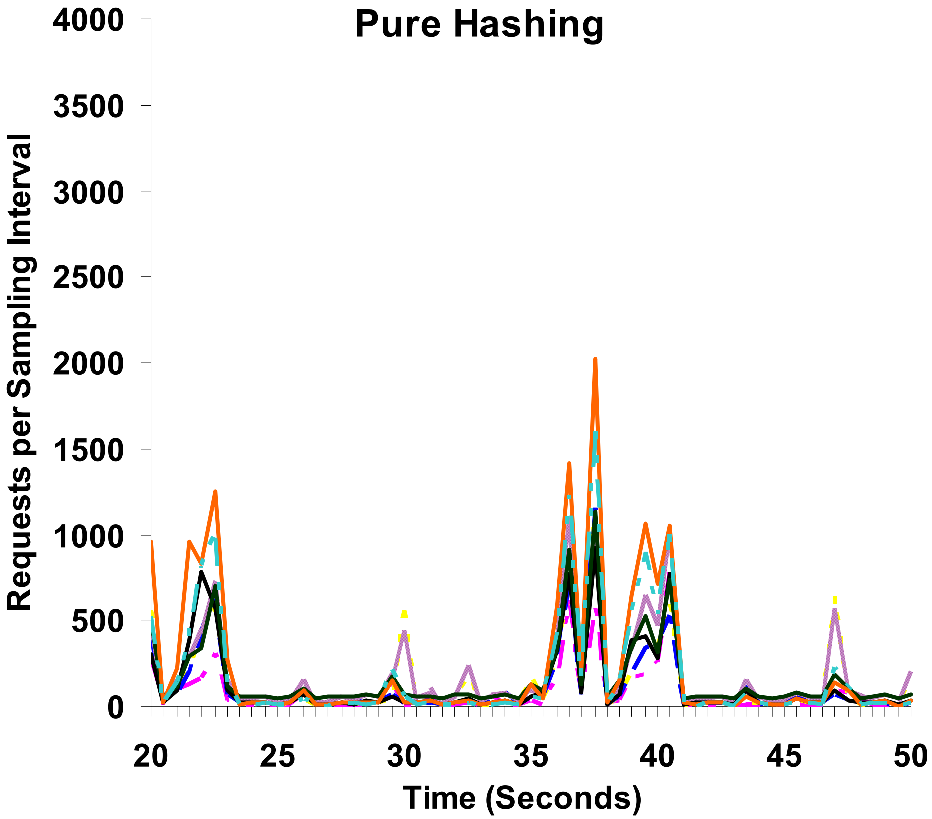
- Simulated Directory Subtree Partitioning, Pure Hashing, and Lazy Hybrid
- Server cache hit rate: 99%
- Client cache hit rate: 100%
- Disk I/O cost (1KB): 15msec
- Memory access cost (1KB): 15µsec
- Network transfer cost (1KB): 100µsec
- Asynchronous write every 30 sec
- Simulation traces: an 8-day file server trace scaled by a factor of 5,000
- Sampling Interval: 0.5 sec
- Number of metadata servers: 8

Request Arrival Distribution



Throughput: Directory Subtree Partitioning and Pure Hashing

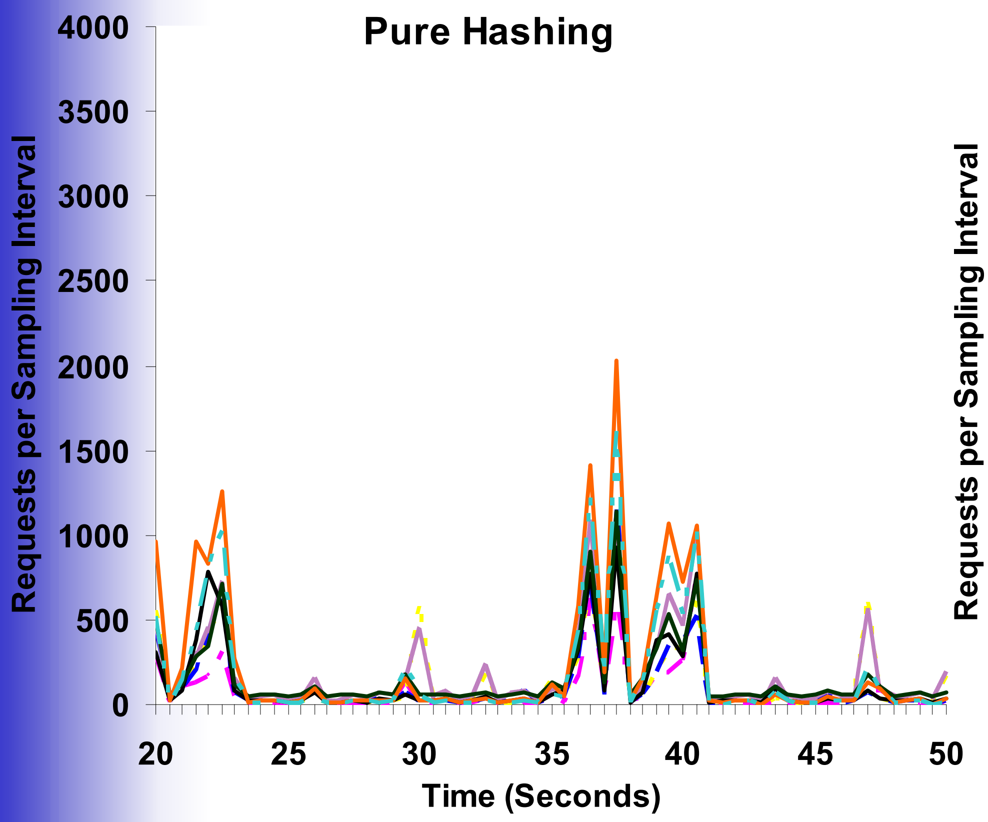


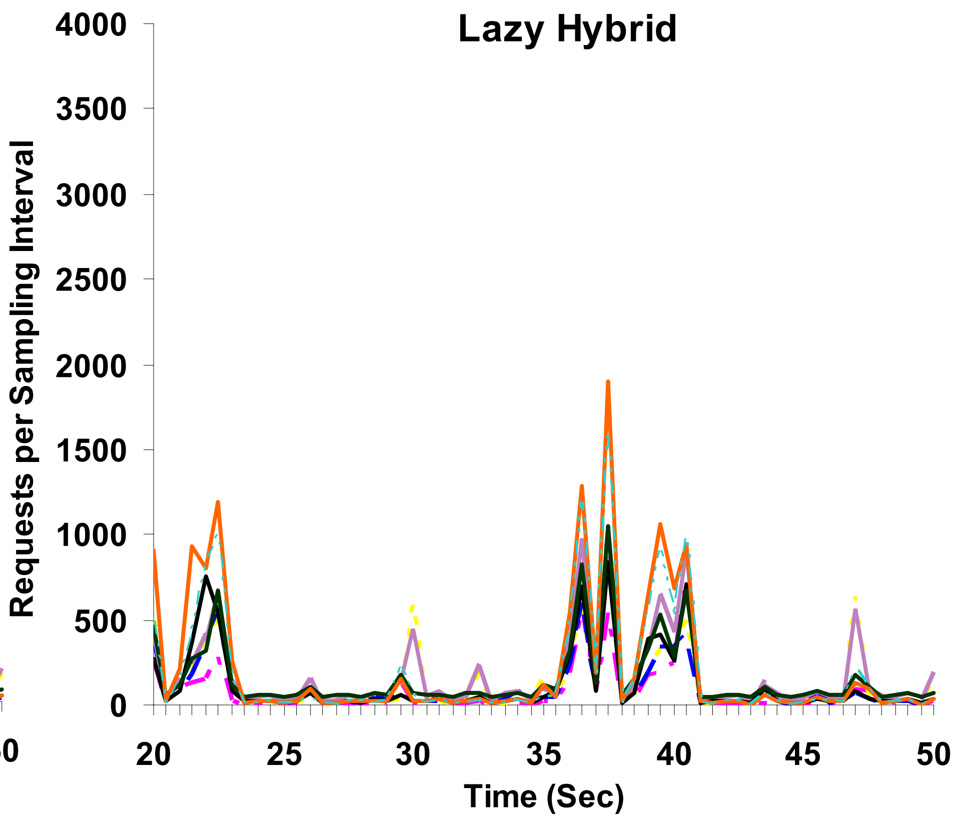


Maximum throughput difference between metadata servers at a given time point:

max/min = 42.05 max/min = 3.44

Throughput: Pure Hashing and Lazy Hybrid

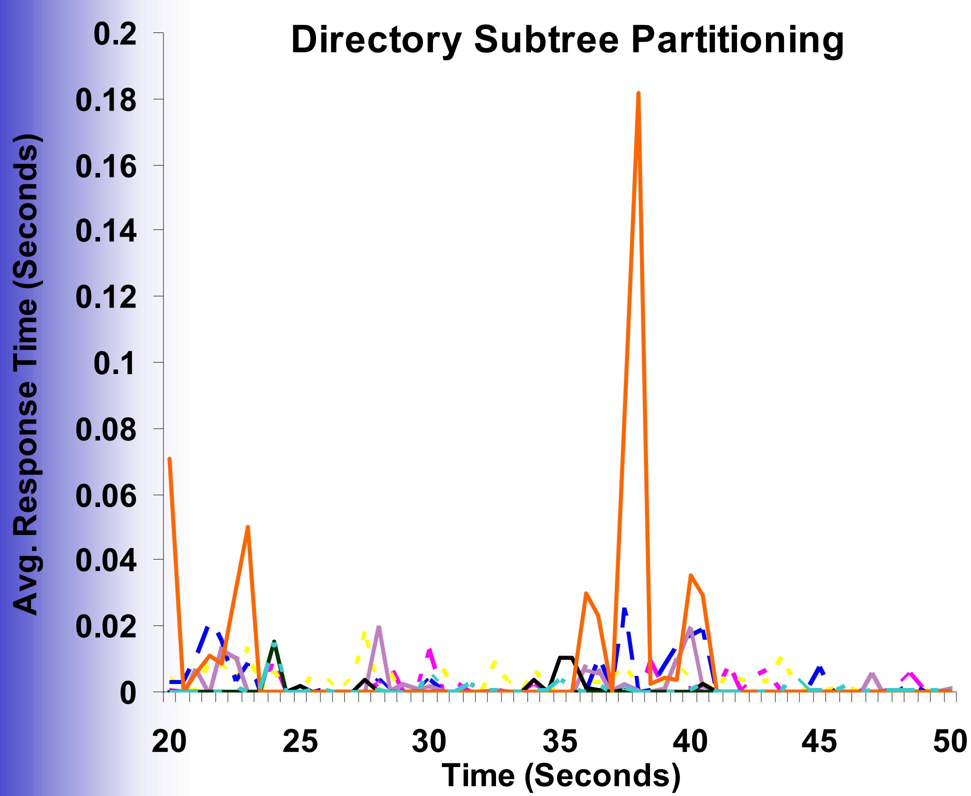


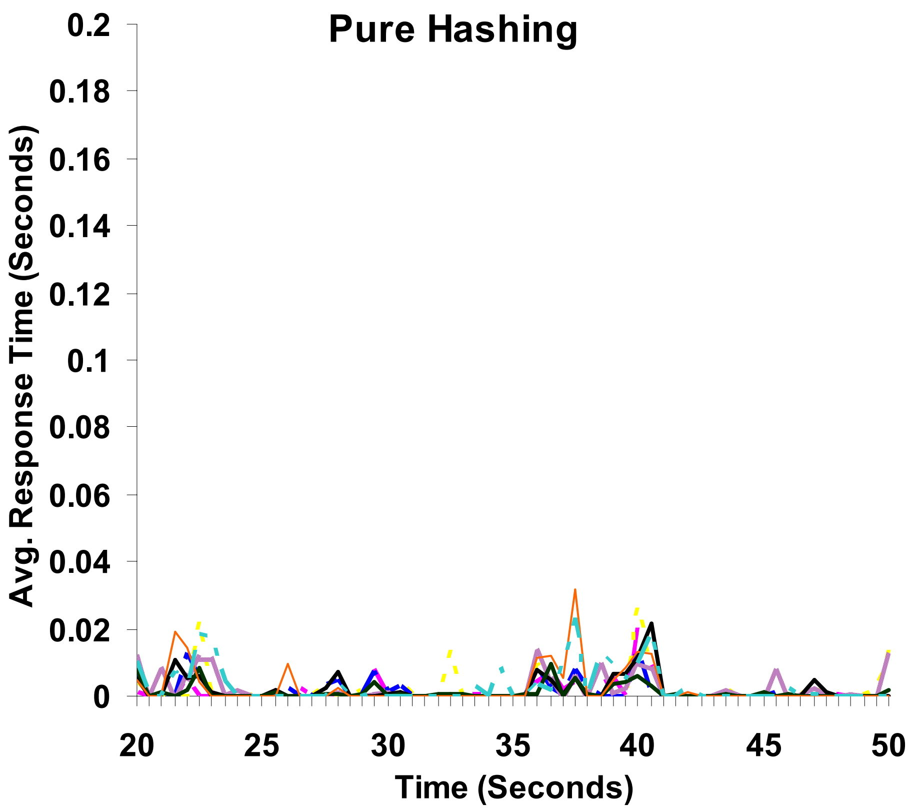


Maximum throughput difference between metadata servers at a given time point:

max/min = 3.44 max/min = 3.49

Response Time: Directory Subtree Partitioning and Pure Hashing

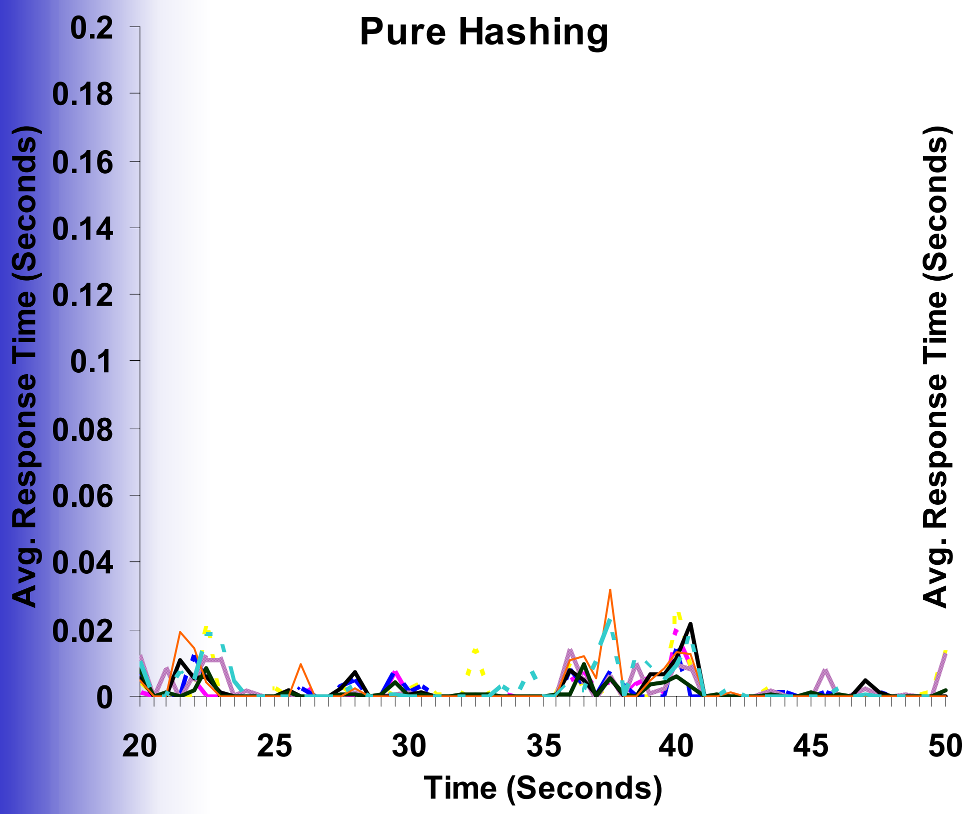


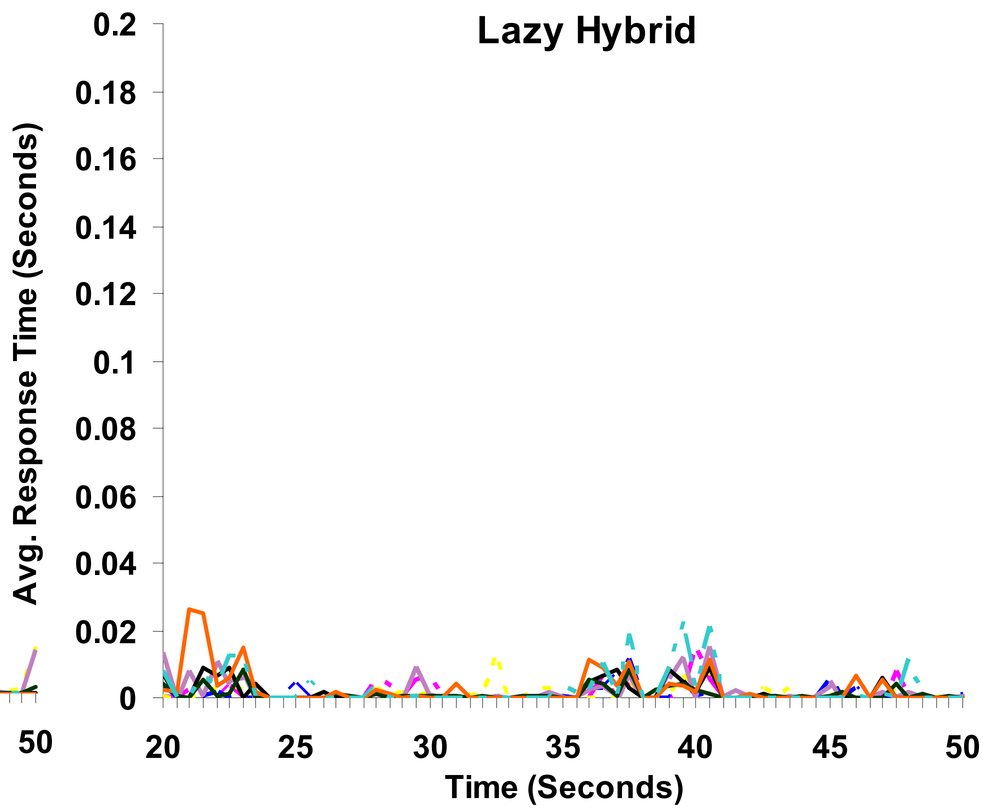


Maximum response time difference between metadata servers at a given time point:

max/min = 5680.25 max/min = 762.72

Response Time: Pure Hashing and Lazy Hybrid

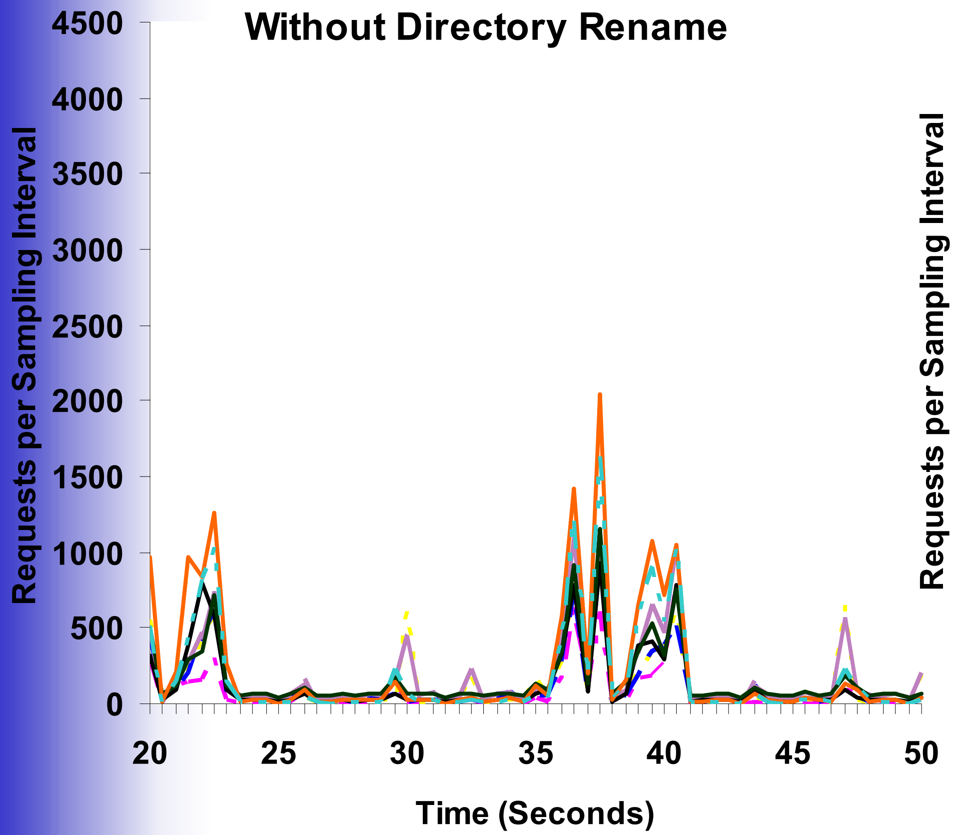


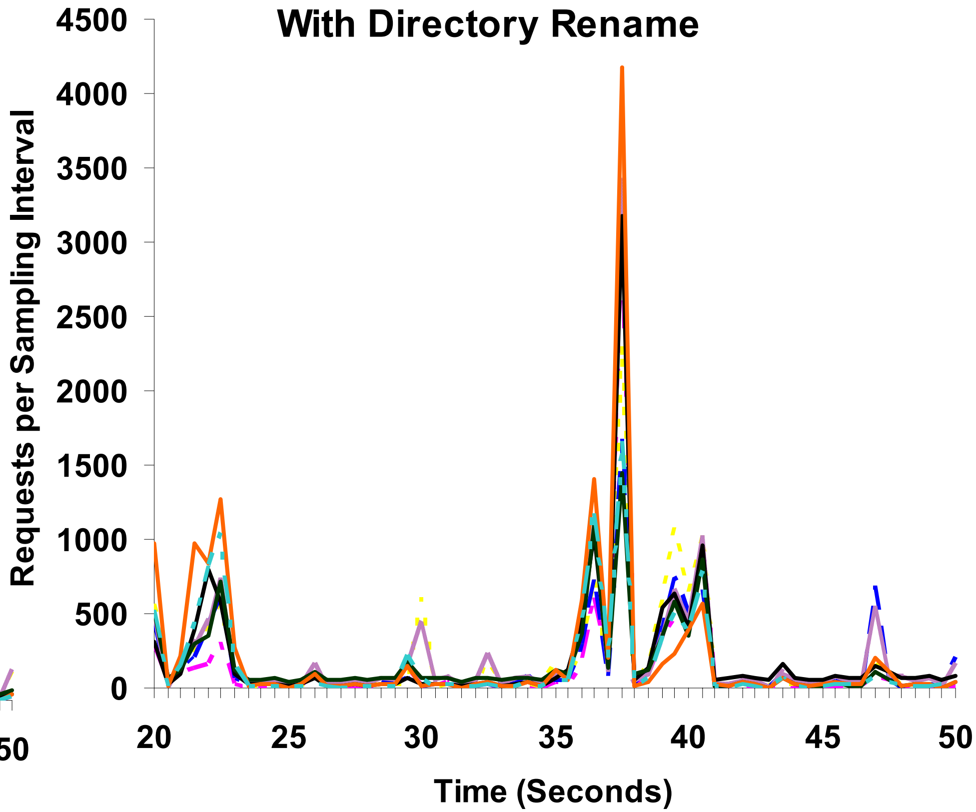


Maximum response time difference between metadata servers at a given time point:

max/min = 762.72 max/min = 802.63

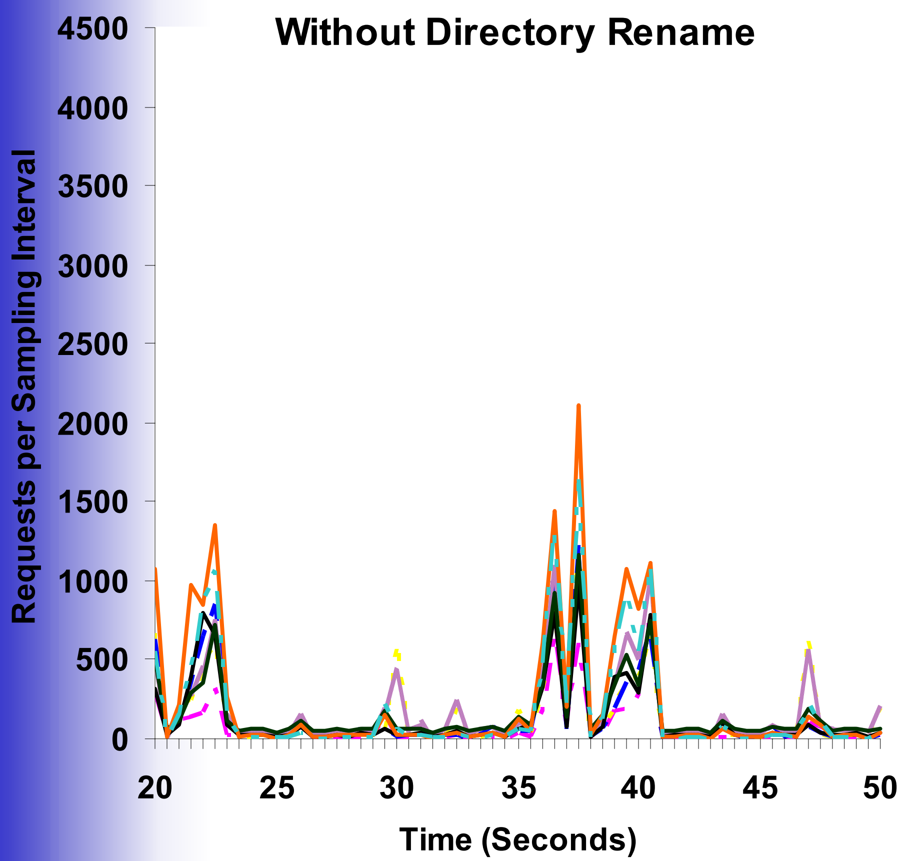
Workload Variation with Directory Rename: Pure Hashing

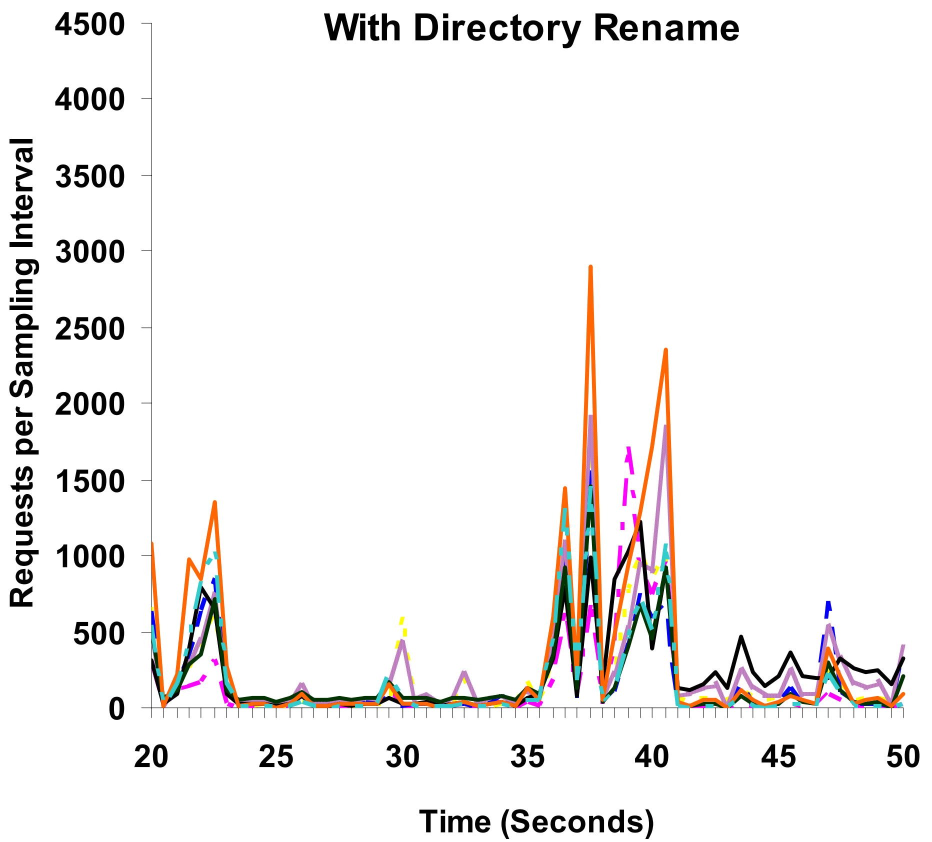




Directory rename at time 37.5 at depth 6 with 768 children

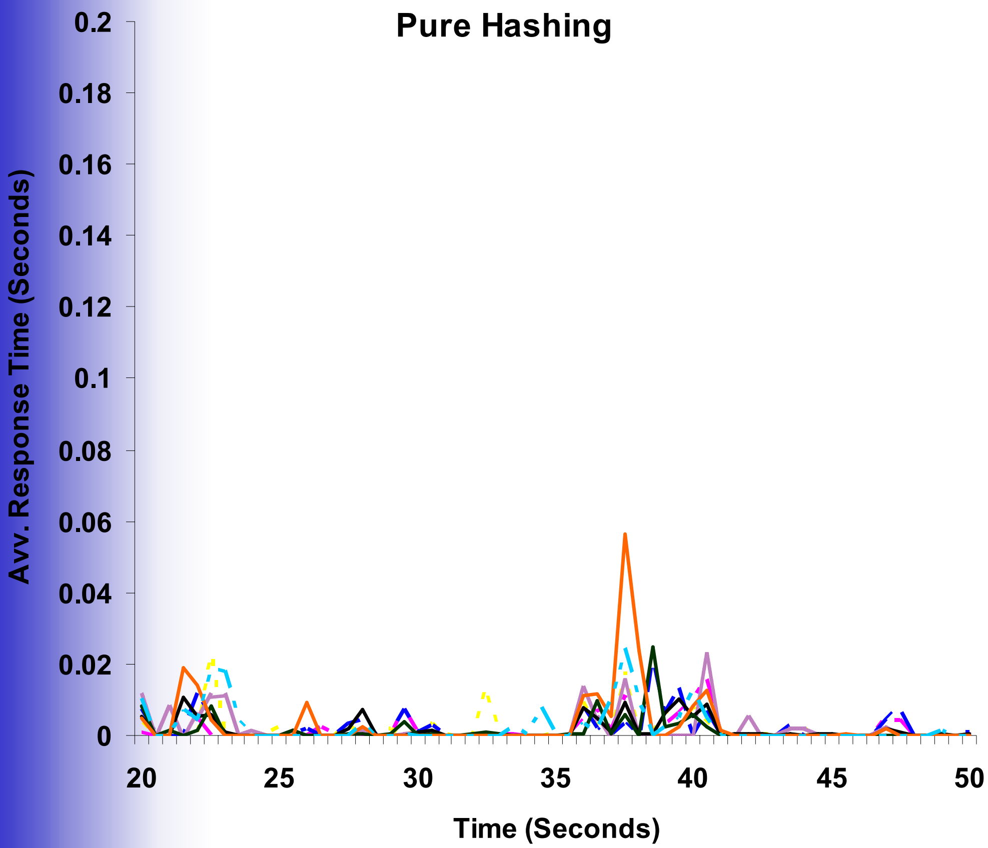
Workload Variation with Directory Rename: Lazy Hybrid

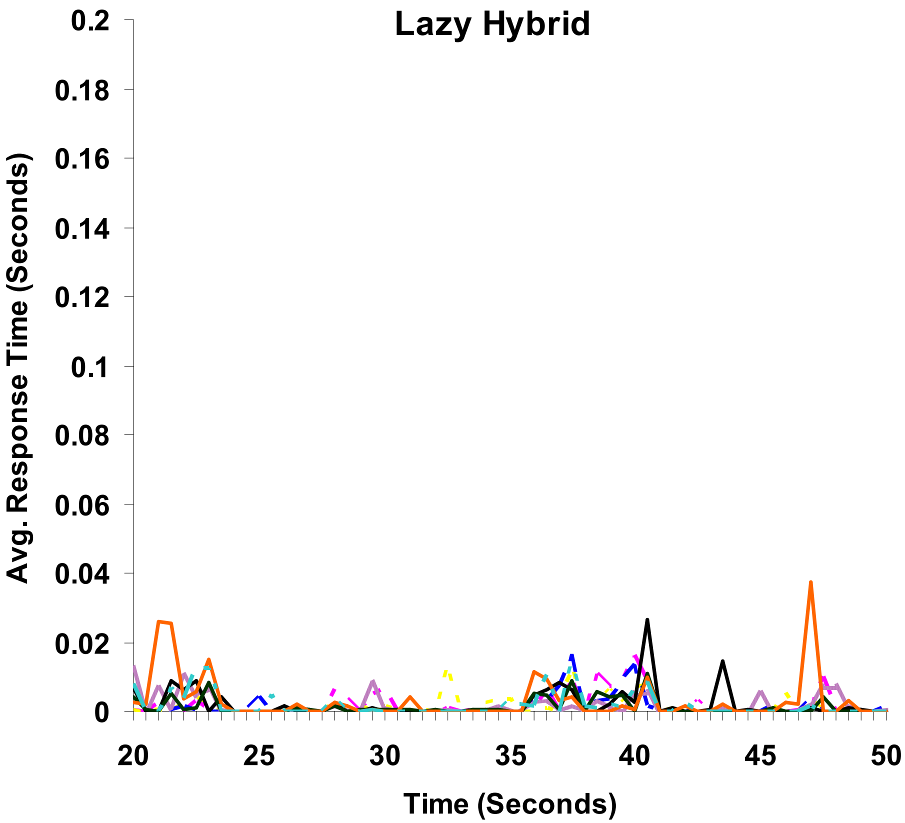




Directory rename at time 37.5 at depth 6 with 768 children

Response Time with Directory Rename: Pure Hashing and Lazy Hybrid





Response time increases sharply immediately

Delayed and distributed increase in response time

Conclusion

- Directory Subtree Partitioning supports standard file/directory semantics
  - But has scalability and bottleneck problems
- Pure Hashing efficiently balances the workload among servers
  - But has difficulty supporting standard directory semantics and incurs high overhead during some operations
- Lazy Hybrid metadata management combines the best of these two approaches, and sometimes does better than both
  - Provides both standard directory semantics and efficient metadata access