A Case for Epidemic Fault Detection and Group Membership in HPC Storage Systems

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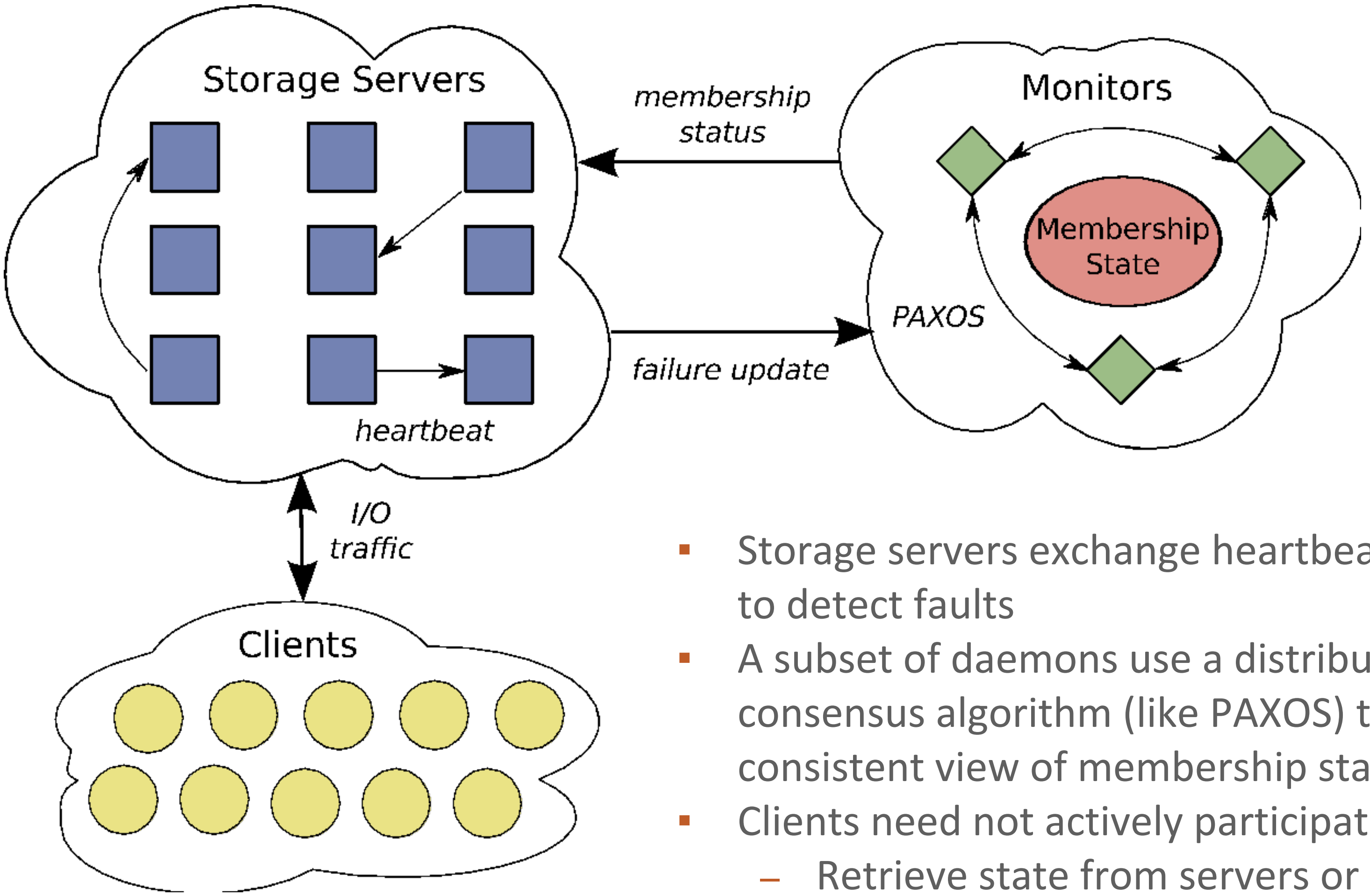
Background and motivation

- Fault detection and group membership are a critical to fault tolerance in **large-scale storage systems**:
  - Server joins group → migrate data to new server to improve load balance
  - Server leaves group → re-replicate data to maintain redundancy

- Why is it so important to get this right?
  - Inefficient (i.e., slow) fault detection may result in data loss
    - Slow recovery increases the window of vulnerability to coincident failures
  - Inaccurate fault detection interferes with performance and availability
    - False positives can trigger (unnecessary) costly rebuilds of the storage system and job failures

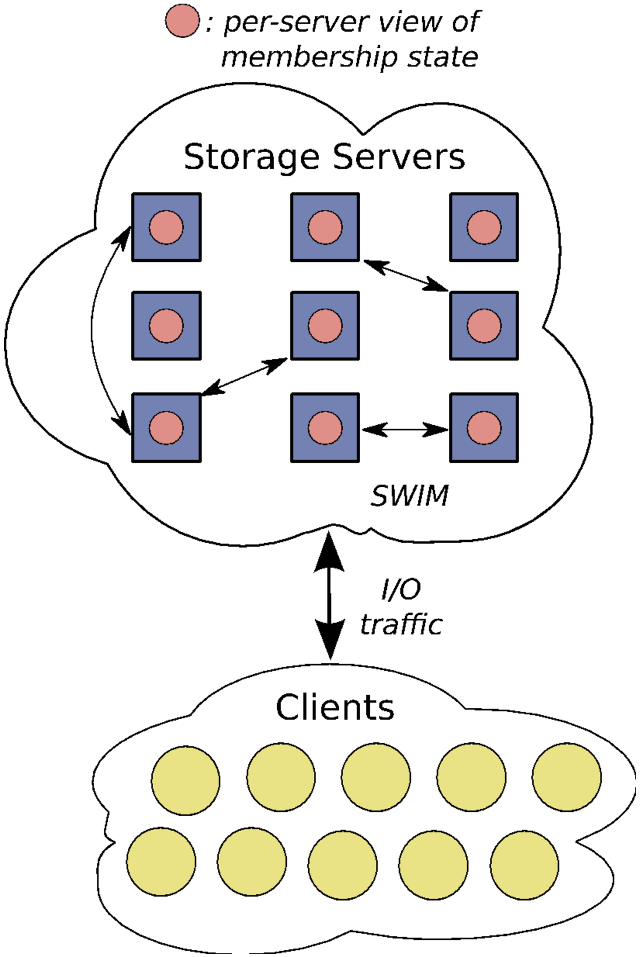
- Approach: use discrete event simulation to evaluate candidate algorithms at scale
  - What algorithms are viable?
  - Identify parameters needed for HPC storage systems
  - Explore long-running behavior not captured by analytical models

Background: conventional group membership



- Storage servers exchange heartbeat messages to detect faults
- A subset of daemons use a distributed consensus algorithm (like PAXOS) to maintain a consistent view of membership state
- Clients need not actively participate
  - Retrieve state from servers or monitors when needed
  - Limit the scaling requirements

Alternative: group membership with SWIM



- Similarities:
  - Clients need not actively participate
  - Servers exchange heartbeat messages to detect faults
- Differences:
  - No dedicated service for distributed consensus
  - Each storage server maintains its own view of the system
  - Disseminate updates using epidemic principles

SWIM does not provide strongly consistent ordering of group updates, but it does guarantee convergence and time-bounded completeness.

These semantic differences may require some accommodations from the storage service.

SWIM protocol background

Scalable **W**eakly-consistent **I**nfection-style Process Group **M**embership Protocol [1]

- Scalability
  - Probe-based (ping/ack) failure detection
    - The failure of a probe triggers ***indirect ping requests*** from other peers
    - A node is ***suspected*** to be failed if both direct and indirect pings fail
  - Infection-style (a.k.a. epidemic-style or gossip-style) dissemination
    - Membership updates are piggybacked on ping/ack messages
    - A ***suspected*** node is ***confirmed*** as failed after a suspicion timeout with no live messages

- Other properties:
  - Expected network load & time to detect a failed node is independent of group size
  - Epidemic dissemination and random pinging is robust against message loss
  - Parameters can be tuned to adjust sensitivity, network utilization, dissemination capacity, etc.

[1] Das, A., Gupta, I., Motivala, A.: Swim: Scalable weakly-consistent infection-style process group membership protocol. In: Proceedings of the 2002 International Conference on Dependable Systems and Networks. pp. 303–312. DSN '02, IEEE Computer Society Press, Washington, DC, USA (2002)

Simulation methodology

- We developed a high-resolution model of the SWIM protocol using the CODES framework [2]
  - Leverages ROSS, a high-throughput, optimistic PDES
  - Individual network message costs are calculated using the LogGP network model
  - Full-duplex network message queueing at each node
- Simulation strategy:
  - Use existing analytical models from the literature to choose initial parameters
  - Cross-validate analytical and simulation predictions
  - Use simulation to evaluate behavior that can’t be predicted using analytical models
  - Assess if the SWIM protocol is viable for further comparative studies

[2] Cope, J., Liu, N., Lang, S., Carns, P., Carothers, C., Ross, R.: Codes: Enabling co-design of multilayer exascale storage architectures. In: Proceedings of the Workshop on Emerging Supercomputing Technologies (2011)

Target: adapting SWIM for HPC

- O(thousands) of file servers
  - Protocol does not execute on compute nodes
- Low latency network and RTT
  - Enables short protocol periods (if desired)
- Tolerate transient errors < 15 seconds
  - Long enough to absorb NIC firmware restarts, busy servers, etc.
- Take action (confirm failure) within 30 seconds
  - Based on expectations from HA deployments in the field
- Keep network load “low”
  - What is an acceptable threshold here?

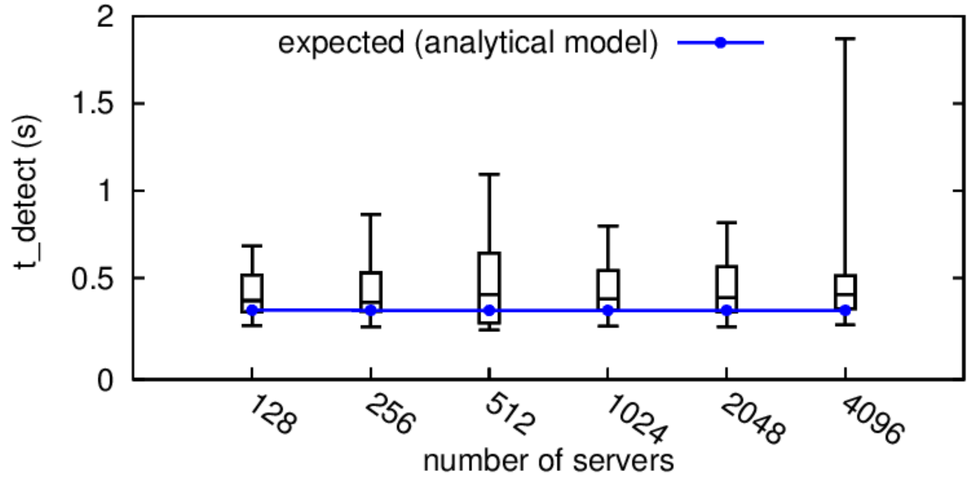
Different targets could be chosen for different use cases.

Initial parameters

Starting points chosen based on existing analytical models.

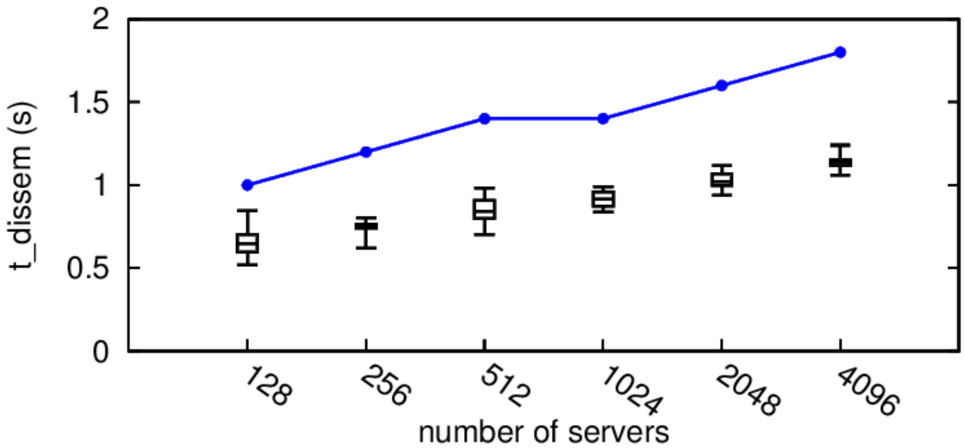
- Protocol period length: 200 ms
  - Time between randomized probes
- Suspicion timeout: 15 seconds (75 protocol periods)
  - Time before a suspected node is confirmed
- Packet size: 256 bytes
  - Allows up to 12 updates to be piggybacked per probe message
- Subgroup size (k) is critical as well; more on that later
- Expect 10s of messages per server per second

Validation with analytical model: detection



- **t_detect**: elapsed time between a failure and the first suspicion by a single peer
  - Expected to be constant with scale
- Simulation results:
  - 15 samples per box plot
  - randomized failure time and failed node
- Variability
  - Initial detection time as slow as ~2 seconds in the worst case
  - Due to random ordering of probes, not congestion

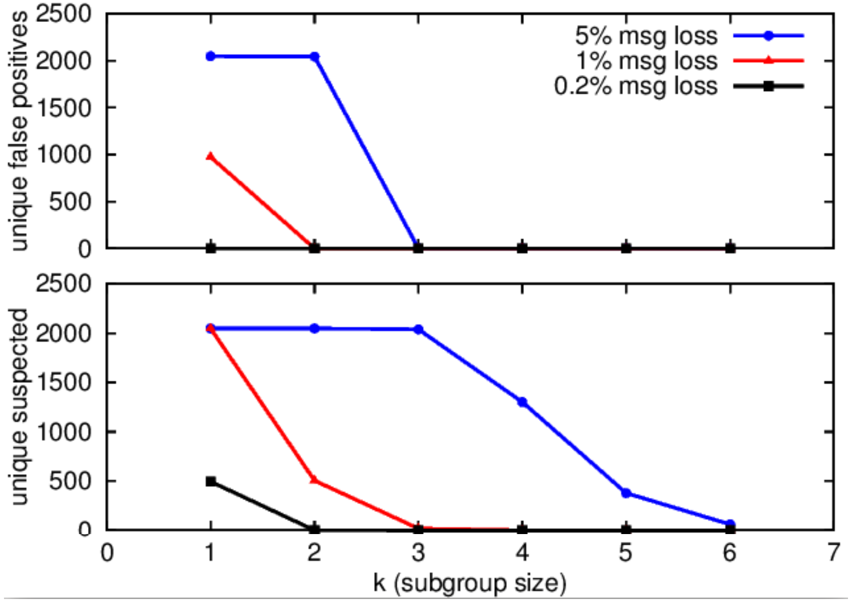
Validation with analytical model: dissemination



- **t_dissem**: time needed to propagate a state update to all servers
  - Expected to be logarithmic
- Simulation results
  - 15 samples per box plot
  - randomized failure time and failed node
- Simulation consistently faster than analytical prediction
  - round robin probing insures maximum dispersal
  - de-synchronized probe intervals reduces per-round latency
- (detection + dissemination) < 4s, but additional 15s suspicion timeout is used to avoid false positives

Tolerating packet loss

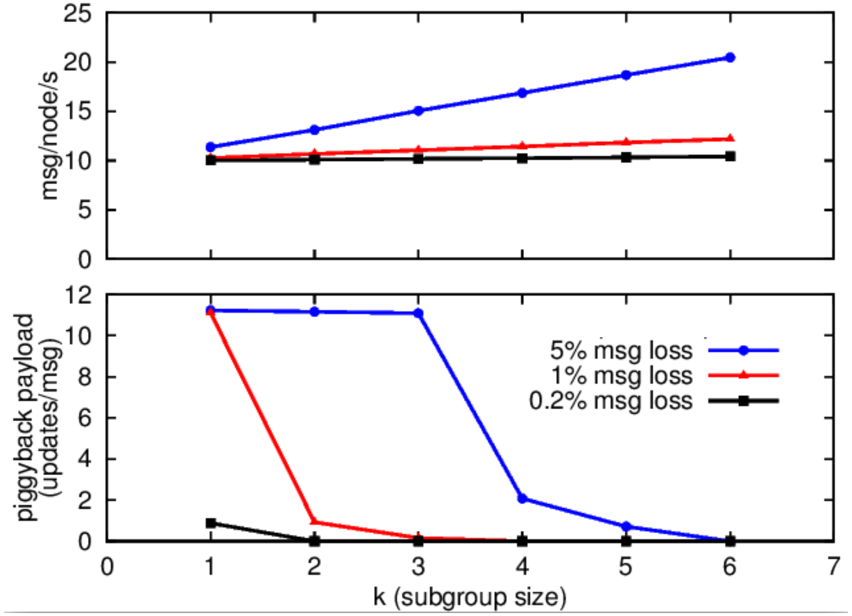
- Subgroup size (k): the number of peers to use for indirect pings
- Figure shows 30 minutes of simulated time for 2048 servers with ***no*** true failures, just lost packets
- Vary k from 1 to 6



- Increasing k:
  - reduces number of false suspicions by requiring more confirmation from indirect pings
  - reduces number of false positives (i.e. false confirmations) by increasing epidemic capacity and opportunities to revoke suspicion
- What is the downside?

Tolerating packet loss

- Figure shows utilization metrics from the same 30-minute simulations
- **msg/node/s**: average number of messages transmitted by each server per second
- **updates/msg**: average number of piggyback slots used per message



- Per server load increases linearly with k in lossy network environment
  - Total load is still modest
- Piggyback slot usage indicates if the epidemic dissemination protocol is saturated or not
- *K=6 imposes minimal overhead to insure robust message loss tolerance*

Conclusions

- The SWIM protocol is a promising approach to group membership in large-scale HPC storage systems
  - Robust against transient failures
  - Rapid detection and dissemination
  - Low network overhead
- We successfully modeled the SWIM protocol using parallel discrete event simulation in the CODES framework
  - Especially useful in exploring long-running behavior
  - Offers the potential to scale to much larger sizes (not ready in time for this presentation)
  - Can be integrated with other CODES models
- Future work
  - Comparison with other group membership protocols
  - More complex failure scenarios
  - Impact of semantic differences in group membership protocols
  - Consider the use of SWIM for detection of client failures

Acknowledgements

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- www.mcs.anl.gov/research/projects/codes

- Thank you for your time!

- **Questions?**