GigaPaxos: System Support for Group Scalability in Nano-Grained, Reconfigurable Replicated State Machines

Paper #340

Abstract

We present GigaPaxos, a novel system for group-scalable state machine replication. *Group scalability* refers to the ability to easily manage a very large number of different reconfigurable consensus groups, one for each lightweight fault-tolerant principal as small as a single record in a key-value store or an ephemeral service replica created on the fly each end-user. GigaPaxos drives down the marginal memory overhead of a Paxos group to ≈350 bytes while keeping the messaging overhead, throughput, and latency of each group independent of the total number of groups and comparable to or vastly better than state-of-the-art consensus systems. Our comparative evaluation against state-of-the-art consensus systems shows that they can only sustain up to tens or hundreds of consensus groups on commodity machines while GigaPaxos can easily support millions of Paxos groups; furthermore, it can support billions or more groups, limited only by the persistent storage on each machine, with a small latency penalty that is negligible in geo-distributed settings. We study the benefits of scalable object-group configurability using a number of case studies including myCloud, a hypothetical suite of cloud applications that creates a custom, reconfigurable Paxos group for each user's personal cloud data , and show that agile group reconfigurability and object-group configurability can significantly enhance end-to-end user-perceived performance.

1 Introduction

Many cloud services today use geo-replication for maintaining high availability despite failures, proximity to end-users, and flexibility of resource provisioning and load balancing. A fundamental building block for replicating stateful services with consistency requirements is *consensus* that is also at the heart of the widely used replicated state machine (RSM) approach, an approach that relies on distributed consensus for replicas to agree on the order of operations before executing them in that order.

Traditionally, consensus-based replication has been viewed as expensive, so its use has been limited to heavy-weight applications–such as data stores [27], distributed file systems [18, 16], lock services [12], etc.–that are shared by a large number of users. However, the monolithic design of such services is a hurdle standing in the way of *customization*, or the flexibility to tailor server replica groups to individual users based on their access patterns, availability or performance requirements, etc.; and *agility*, or the ability to quickly reconfigure replica groups in response to changing access or load patterns.

Our position is that the ability to easily create and map lightweight fault-tolerant principals to a desired set of replica nodes can potentially transform how we build distributed systems. We envision applications "sprinkling" principals as small as a single record in a key-value store, a counter, a user's calendar, a shared document, etc. wherever and whenever needed. We refer to this ability as *object-group configurability* (§2). An example of an application that can leverage this ability is `myCloud`, which also forms one of our case studies. `myCloud` is a personalized cloud system wherein each user's cloud data always appears to be located nearby and moves with them, a vision also shared by research on cloudlets [35], micro-datacenters, multi-tenant gateways[36], etc.

Our contribution, GigaPaxos, is a small but concrete step towards realizing the above vision. A key challenge that GigaPaxos addresses is *group scalability*, i.e., the ability to scale to a very large number (millions or even billions) of independent consensus groups. Although a large body of prior work has focused on improving the performance, cost, or robustness of consensus-based systems, to our knowledge, group scalability is a dimension that has not been explored before. Indeed, we find that state-of-the-art Paxos implementations can barely sustain tens or hundreds of groups. In comparison, GigaPaxos can scale to millions of Paxos groups on commodity machines with little performance or cost penalty.

GigaPaxos achieves group scalability through a novel design and implementation that carefully separates *idle* and *active* Paxos groups so as to drive down the memory overhead of an idle Paxos instance to roughly 350 bytes; uses a novel hot-swap technique to pause idle Paxos instances; amortizes the overhead of failure detection and logging across groups; enables programmatic policy for automating group reconfiguration at scale; and uses a highly event-driven design that does not rely on any per-instance background tasks that are commonplace in consensus implementations.

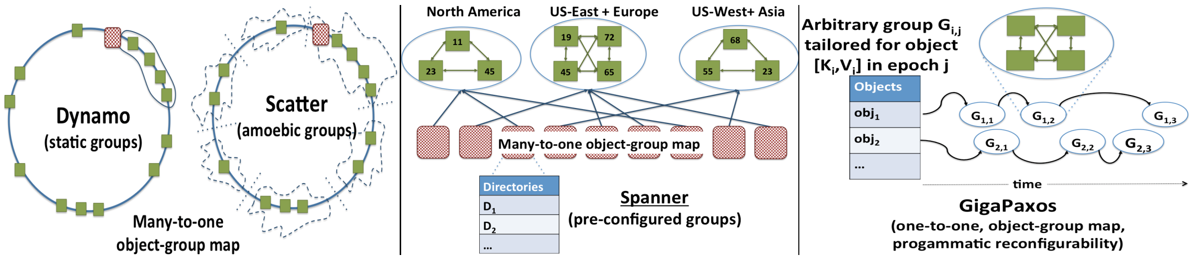


Figure 1: Extent of object-group configurability in recent geo-replicated systems.

We have implemented a prototype of GigaPaxos with a simple API that allows black-box applications to leverage object-group configurability. Our prototype-driven experiments show that:

(1) GigaPaxos achieves comparable or vastly superior performance compared to state-of-the-art consensus implementations even for a single group but comfortably scales to orders of magnitude more groups (§4.1).

(2) GigaPaxos' **`Replicable`** and client API and support for programmatic reconfiguration policies are easy to use with a number of third-party applications (§4.3).

(3) Per-object reconfigurability can significantly enhance end-to-end client-perceived performance in geo-distributed mobile cloud services (§4.3).

2 Background and related work

Object-group configurability, or the ability to assign different subsets of machines to manage different objects, as a key abstraction is motivated by a number of recent large-scale geo-distributed storage systems [17, 14, 15, 32]. This capability enhances (1) *availability*, as the failure of a machine or even an entire group impacts only a subset of objects; (2) *flexibility* of resource provisioning and load balancing; and (3) *isolation* across different objects, which can translate to performance gains when unrelated objects are not forcibly combined into a consensus group.

The extent of *object-group configurability* allowed by a system design has nontrivial operational implications, as illustrated in Figures 1(a)–1(c). A baseline example with little flexibility is consistent hashing with replication, e.g., Amazon Dynamo is a key-value system that uses consistent hashing to determine the set of machines that manage an object. While this approach is simple and scalable when machines and object workload patterns exhibit predictable characteristics, it is cumbersome in environments with more unpredictability and flux such as peer-to-peer (P2P) environments. Sharing this motivation, Scatter [17], a P2P storage system uses consistent, configurable groups as a defining abstraction. Scatter's support for "amoebic" reconfiguration of groups, i.e., the ability to split, merge, or migrate members of objects across adjacent consensus groups, enhances a group's ability to self-organize under dynamic conditions while maintaining linearizability consistency for operations to a single object.

A system like Google's Spanner [14] significantly increases object-group configurability over static or amoebic replica groups. Spanner has a fixed number of predefined (or slow-changing) Paxos groups to which it maps a large number of directory objects (i.e., a bag of key-value mappings) in a many-to-one manner. Spanner allows administrators to control the "number and types of replicas, and the geographic placement of those replicas", for example, by specifying policies such as *[Object A: North America, replicated 5 ways with 1 witness]; [Object B: Europe, replicated 3 ways]*, etc. However, Spanner is designed to remap objects across existing Paxos groups, not reconfigure the Paxos groups themselves. The distinction is important as the total number of conceivable Paxos groups is exponential in the total number of machines, so a practical system is forced to create a manageable[1] number of packaged groups (like North America, Europe, etc.) and adopt a many-to-one object-group mapping, an approach that works well in the common case.

Our goal is to take object-group reconfigurability to the extreme, namely, allow for each arbitrarily small object to be mapped to an arbitrary consensus group specifically for that object. We refer to this flexibility as *maximal object-group configurability*, wherein object-group configurability is defined as the ratio of the total number of objects to the total number of separate consensus groups in the system. Thus, the maximal value is 1; for Spanner, it is typically much lower than 1; for Scatter or Dynamo, it is roughly equal to the ratio of the number of machines and the product of the number of keys and the average replication factor.

Our vision is similar to that of fluid replication [30] proposed by Noble et al. in the late 90s. Our goal of agile reconfigurability also overlaps with more recent systems like Tuba [9] but differs significantly in its focus on group scalability and consensus. We focus on consensus primarily because of the simplicity and power of the replicated state machine abstraction that can ensure linearizability consistency when needed but also serves as a useful building block for applications with weaker consistency requirements (§3.1).

This paper requires the reader to be intimately familiar

[1] "Typical deployments might have up to hundreds or thousands of paxos groups per machine, but not much more." [6]

with Paxos[21]. Below is a brief primer, and [22] and [33] are excellent resources respectively for a simplified conceptual and implementation-oriented exposition.

2.1 Paxos and RSM primer

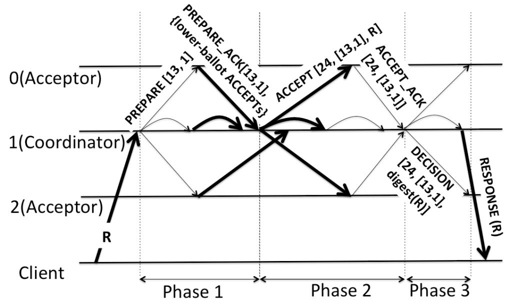


Figure 2: Coordinator 1 acquires ballot [13, 1] in phase 1 and commits client request R in slot 24 and its ballot [13, 1] in phases 2,3. Thick lines carry application data.

Paxos (or Multi-Paxos) is a consensus algorithm that enables a set of nodes to agree on a growing sequence of values over time despite node failures and unbounded network delays. As shown in Fig. 2, Paxos consists of two phases: the first allows one (or more) node(s) to assume the role of a *coordinator*, and the second determines a *decision* value for each position in the sequence. With long-lived coordinators, only the second phase is needed for each new value in the common case. Paxos guarantees the agreement safety property that two different decision values for the same slot are never delivered to any (including singleton) subset of nodes. Progress, i.e., any values being agreed upon at all, is ensured only when a majority of nodes are up and can communicate with each other in a timely manner.

In the replicated state machine (RSM) approach, the values are client requests and nodes in a consensus group supply the sequence of requests to their locally running replicas of an arbitrary (but identical) deterministic application. A common optimization is to batch multiple client requests within each value, which helps when agreement throughput as opposed to application execution [38] is the bottleneck.

3 GigaPaxos design

GigaPaxos is designed to meet the following goals.
(1) **Maximal object-group configurability**: An application should be able to easily request a consensus group for an fine-grained fault-tolerant object.
(2) **Group scalability**: The aggregate performance across consensus groups should be independent of the total number of consensus groups.
(3) **Application agnosticism**: The design must provide a simple API for black-box applications, remaining agnostic to application-specific details.
(4) **Automated reconfiguration**: Applications should be able to specify policies to programmatically reconfigure the membership of the consensus instances.

3.1 Design overview

To address the above goals, GigaPaxos is designed as a two-tier reconfigurable consensus engine consisting of two logically distinct types of nodes: *app-containers* and *reconfigurators*. A group of app-containers form a consensus group for a named object that they manage. A group of reconfigurators form a consensus group that is responsible for making decisions about when and how to reconfigure the app-container group for a subset of objects, and to help correctly redirect client requests to the current group. An app-container encapsulates a third-party application that contains the logic needed to process a client request, modify the corresponding object, and send a reply back to the client.

Applications can specify if only a subset of request types need replica coordination, allowing them to use consensus as a building block for different consistency semantics. For example, enforcing consensus for every client request to a named object ensures linearizability (as in [17]) across all operations to that object while enforcing consensus for writes alone (or reads alone) ensures sequential consistency for all operations to that object [10]. Relaxing it further to eventual consistency does not need consensus among replicas, but reconfigurators must still rely on group-scalable consensus to make reconfiguration decisions in a fault-tolerant and consistent manner (detailed in §3.7.1).

GigaPaxos achieves its goals using the following key mechanisms described in the following subsections: (1) a compact representation of Paxos instances; (2) separating and amortizing machine-specific overhead from group-specific overhead; (3) a hot-swap mechanism to relieve memory pressure while maintaining correctness; (4) a group-scalable persistent logger; and (5) simple client API and programmatic reconfigurability support.

The following terms are used throughout the paper: a *Paxos instance* is the Paxos-related, application-agnostic state stored at a machine for a single, named object; a *Paxos group* is the set of distributed Paxos instances managing a single object, which in conjunction with the application logic forms the corresponding RSM.

3.2 Managing compact Paxos instances

GigaPaxos' core consists of a `PaxosManager` per machine that is responsible for *machine-specific* functions of which there are four key ones: (1) Paxos instance management, (2) persistent logging, (2) failure detection, and (3) messaging and demultiplexing.

`PaxosManager` maintains a map from the name of a Paxos group, `objectID`, to a data structure maintaining the minimum Paxos instance state necessary for safety, i.e., the state blocks marked "Fixed Instance", "Acceptor Idle", and "Coordinator Idle" respectively in Fig. 3. The first remains unchanged throughout the lifetime of this Paxos instance, i.e., until the `epoch` and `group` are reconfigured or the object is deleted. The latter two are referred to as *idle state* because this state must be remembered by each Paxos group member even during periods when the group is not actively processing client requests.

3.2.1 Idle Paxos instance state

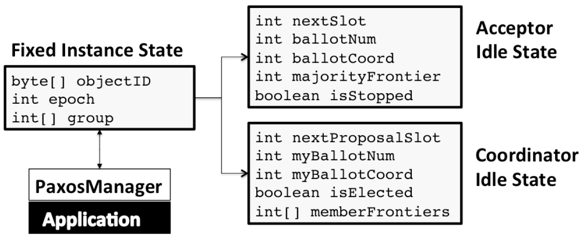


Figure 3: Idle Paxos instance state.

An acceptor's idle state must maintain (1) **nextSlot**, the highest slot number below which all proposals have been executed by the local application replica in agreement order; (2) its current ballot, ⟨**ballotNum**, **ballotCoord**⟩, which is the highest ballot it has received across all PREPARE messages from any group member seeking to become coordinator; (3) **majorityFrontier**, the slot number up to which a majority of group members have cumulatively executed application requests, which is needed in order to safely garbage-collect logged messages corresponding to lower slots [33]; (4) **isStopped**, whether or not the paxos group has been stopped, which is needed to perform reconfiguration safely (§3.7.1).

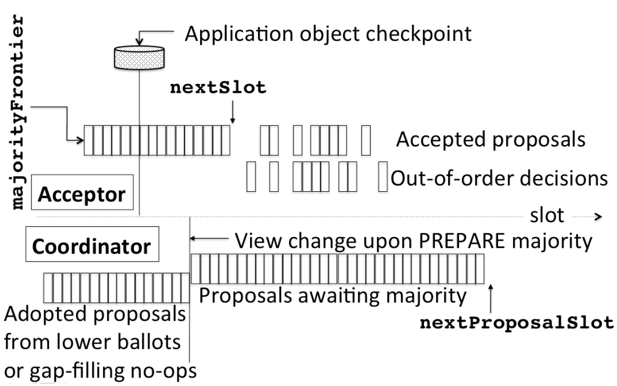


Figure 4: Active Paxos instance state.

A coordinator, strictly speaking, does not have to persistently maintain any idle state at all as coordinators are already presumed to be perishable. However, garbage collecting coordinator state during idle periods means that a new coordinator must be elected (with the first PREPARE phase) upon the arrival of a client request. In order to maintain Paxos' low, essentially optimal, message overhead per client request during graceful execution, i.e., just the second ACCEPT/DECISION phase, it is important to support long-lived coordinators. So, each GigaPaxos coordinator instance must either maintain all of the coordinator idle state in Fig. 4 or immediately relinquish its role as coordinator by ceasing to commandeer further proposals in its ballot.

The coordinator's idle state must thus maintain: (1) **nextProposalSlot**, the lowest slot such that the coordinator has not yet used that or any higher slots to commandeer any proposals; (2) its ballot that in general may be out of sync with the local acceptor's perceived ballot; (3) **isElected**, indicating whether its ballot has been accepted by a majority of acceptors, at which point it can garbage-collect its pre-election state (§3.2.2); and (4) **memberFrontiers**, the slot numbers up to which, in its view, acceptors have cumulatively executed application requests; the coordinator piggybacks the median slot number in its ACCEPT and DECISION messages to all acceptors who use it to refresh their **majorityFrontier**.

Compactness. The point of listing the seemingly mundane details above is to emphasize that this state–the variables in the three shaded boxes in Fig. 3 plus the connecting pointers–is literally all of the state GigaPaxos adds per idle Paxos instance to whatever state the application itself maintains. The size of this idle state is ≈350 bytes for Paxos instances with three members in our implementation; larger groups cost 8 more bytes (or one integer each in the two `int` arrays).

3.2.2 Active Paxos instance state

An *active* Paxos instance, i.e., one that is currently agreeing on the order of client requests for the underlying application, typically needs to maintain much more state than the idle state above. Fig. 4 illustrates the active state that must be maintained for safety.

An acceptor's active state consists of (1) a sequence of *accepted proposals* in slot number order, possibly with gaps, that it has previously accepted, and (2) a set of *committed decisions* received out-of-order. The former sequence starts at **majorityFrontier**+1 or higher, and the latter sequence starts strictly higher than **nextSlot**, the first slot for which no decision has been received.

A coordinator's active state additionally consists of (1) *adopted proposals*, i.e., lower-ballot proposals received from acceptors in their replies to this coordinator's PREPARE message, wherein the coordinator picks for each slot the proposal with the highest ballot; (2) one **waitFor** data structure (not shown) to track whether a majority of acceptors have replied successfully to the PREPARE message; and (3) **myProposals**, a sequence of proposals being commandeered by the coordinator, i.e., proposals for which it has or will send out ACCEPT messages, and for each of which it maintains a **waitFor** structure to track a majority of acceptances. The first two are needed only until the coordinator gets elected by receiving a majority of suppo `PREPARE` replies. If a coordinator receives any client requests during this election, it enqueues them with the first available (tentative) slot number in `myProposals`. When a coordinator receives a `PREPARE` majority ("view change" in Fig. 4), it merges all of the adopted proposals into and with strict priority over `myProposals`, marks itself as active, and begins commandeering `myProposals`. An active coordinator thus only maintains a single queue, `myProposals`, of proposals awaiting majority acceptance; when that happens, they are announced as committed decisions to all acceptors and are dequeued.

Bulk. The size of an active Paxos instance can be orders of magnitude larger than an idle Paxos instance, e.g., a burst of rapid requests to a group can result in thousands [18] of requests being concurrently processed, each causing hundreds or thousands of bytes of queued entries at acceptors as well as coordinators, thereby easily inducing megabytes of state. This active state needs to be maintained at an acceptor until a majority of acceptors have caught up, i.e., `majorityFrontier`$+1$ equals `nextSlot`, and at a coordinator until it is no longer commandeering any proposals, i.e., `myProposals` is empty.

3.3 Bounded number of active instances

We claim that under realistic conditions, with a very large number of consensus instances, the number of idle instances will overwhelmingly dominate active ones. This insight motivates GigaPaxos' hot-swap mechanism.

Consider a GigaPaxos application distributed across M machines managing a total of N objects with each object managed by a separate consensus group. Let T denote the average response time of a request with state machine replication, inclusive of both the unreplicated application execution time and the latency to establish its consensus order. Suppose the maximum request throughput that can be steadily sustained by the underlying (unreplicated) application on a single machine is C per second. By Little's law [25], the average number of outstanding requests being processed at any single machine is $A = C \cdot T$. Note that, if C and T are fixed, A is independent of the size of a consensus group, the total number of machines M, or the total number N of objects in the system.

For example, if C is 25,000 requests/sec and the average response time of a request is as high as $T = 500$ ms, then the average number of outstanding requests at a machine is 12,500. In practice, the throughput of most applications employing an RSM approach is likely to be much lower, e.g., for a database application, synchronous random write throughput is typically on the order of a hundred/sec with hard drives, and up to several thousands/sec with typical solid state drives.

The number of active consensus instances at a machine is at most the total number of outstanding requests being processed at that machine. Indeed, the worst case workload is one that, in a round-robin manner, issues requests to all other objects (or consensus groups) before returning to the first. Thus, in a GigaPaxos system with millions of consensus groups, the vast majority of consensus instances must be idle.

There are two caveats however. First, this analysis implicitly assumes graceful or failure-free execution. Second, even if the average size of an idle consensus instance is small, as is the case in GigaPaxos, the total number of Paxos groups that can fit in memory on commodity hardware is limited, e.g., with 16GB memory and 400 bytes per Paxos instance, the number of sustainable idle instances is 40 million. To address these issues, GigaPaxos uses *hot swapping*, a mechanism that helps GigaPaxos scale to billions of groups per machine with commodity disk capacities.

3.3.1 Hot swapping Paxos instances

A simple hack to juggle too many Paxos instances on a machine is for the manager to simply "soft-crash" that Paxos instance, i.e., to dequeue it from its instances map allowing for the state get garbage collected. This action will preserve safety as it will just appear to the rest of its group like a member failure. However, this simplistic approach has several shortcomings. First, it forces a roll forward of the Paxos instance from the most recent checkpoint when a request for a Paxos group arrives at a manager, stalling the request handling until the recovery is complete. The alternative of simply not handling the request is not viable, as that will over time prevent most Paxos groups from making any progress at all, a much worse state of affairs than the theoretical lack of guarantee of liveness under asynchrony. Second, the overhead of doing a checkpoint recovery upon a request arrival as a common case operation can itself overwhelm memory, computation, and I/O cycles on a machine severely hurting overall performance.

GigaPaxos instead employs a far nimbler *hot swapping* technique that capitalizes on the two observations above: (1) most Paxos instances will be idle when the total number of instances on a machine is very large; and (2) idle state is extremely compact (Fig. 3 as opposed to 4). To this end, the manager on each machine maintains a background process that periodically but infrequently (e.g., every few minutes), makes a sweep over all active instances and *pauses* instances that have been idle for the threshold interval, i.e., it synchronously dequeues the instance from its map and writes the compact idle state to a database. Subsequently, upon the arrival of a client request or a Paxos protocol message for that instance, the manager's demultiplexer as usual first consults its instance map to route the message. If the instance is not found, the manager must check the database for paused state that, if found, must be used to reconstruct the Paxos instance. Hot swapping shares some similarities with Cheap Paxos [24] or ZZ [37] for bringing up virtual machines, but those approaches are comparable to the "crash" option above.

A downside of hot swapping is that it imposes a small latency penalty (<10ms typically) for the unpause operation. However, this penalty only impacts the first client request (or Paxos protocol message) in a burst of activity for that group. Subsequent requests do not incur any penalty as the instance will not be re-paused until it has been idle for the threshold duration. On the flip side, hot swapping will disproportionately affect unpopular Paxos instances with longer-than-threshold idle periods between successive client requests. Still, we believe that the penalty—an additional database lookup for a small record—is unlikely to significantly impact most applications as (1) most applications using consensus are likely to touch the disk for common operations anyway; and (2) with persistent logging, enabled by default in GigaPaxos, each client request must encounter at least one synchronous disk write in order for acceptors to log an ACCEPT message before responding. Finally, in geo-distributed scenarios, the unpause penalty is unlikely to affect end-to-end latency as that is dominated by network delays fundamental to Paxos.

3.3.2 Graceful vs. failure-prone operation

With machine failures, the fraction of active instances at GigaPaxos machines can be higher. The reason is that a Paxos instance can not fully gabage-collect the log of accepted proposals at an acceptor as that requires a majority of replicas in the group to have executed (or at least persistently logged the decision for the corresponding slot number) the application up to that slot. Nevertheless, during periods of synchrony when at least a majority of replicas in all groups are available—exactly when Paxos guarantees liveness—healthy GigaPaxos machines will be unaffected and will only see a small number (as quantified above) of active instances. Fate sharing makes the number of active Paxos instances at failed machines a non-issue.

However, under more severe machine failure patterns that result in a significant fraction of Paxos instances on a machine being unable to make progress because of a lack of a quorum in their respective groups, the number of active instances on otherwise healthy machines can grow to unsustainable levels. There are several reasonable ways to handle this case: (1) the strawman outlined above that crashes an instance to pause it; (2) checkpointing immediately at `nextSlot` and then crashing the instance so as to reduce the length of the roll forward; (3) pausing and unpausing active state (that could be potentially much larger than the compact idle state). All options incur higher overhead compared to hot swapping idle instances, but will *not* impact client-perceived latency as they are required only when the corresponding Paxos group is not live anyway. Our current implementation supports the second option.

3.4 Amortized failure detection and logging

Failure detection is a key component of any consensus implementation. Although failure detection need not be reliable (a problem as hard as consensus itself [13]), it is needs to be responsive in order to ensure prompt replacement of a failed coordinator. Failure detectors are typically implemented using keep-alives between all or a nontrivial subset of machine pairs in a consensus group. However, unlike typical Paxos implementations, group scalability in GigaPaxos makes it impractical to maintain a separate failure detector per group; for example, 1000 groups each of size 5 and a keep-alive frequency of 4 secs imply 1000 packets/sec for failure detection; with 100K groups, failure detection alone becomes a full-time job! Thus, GigaPaxos pushes failure detection to `PaxosManager` maintaining just one failure detector per machine as opposed to one per group.

Likewise, the persistent logger resides in the manager and is common across all Paxos instances on the machine. This design not only amortizes the overhead of logging PREPARE/ACCEPT/DECISION messages across all instances, but also allows log messages from *different* Paxos instances to be batched, driving down the overhead of persistent logging to negligible levels. Without such batching, GigaPaxos' request throughput will be limited by the synchronous disk write throughput.

3.5 Log indexing, pruning, and compaction

In a traditional RSM, garbage collecting safety-critical acceptor logs is easy; they can simply be tail-pruned below the highest slot, `majorityFrontier`, up to which a majority (or even just $f+1$ if at most f can fail) have received all decisions. This just requires tracking file offsets on disk or maintaining slot-indexed records in a database such that it is easy to check whether all logs before some offset are below `majorityFrontier`. Looking up logged messages when needed is efficient as the number of log messages is at most the checkpoint interval.

Indexing. In GigaPaxos, this *indexing* problem is harder. As shown in Figure 5, a single write-ahead log for all groups is extremely efficient (e.g., disabling logging improves capacity by barely 15%), but makes it difficult to track where what is logged; for example, upon a coordinator change or a catch-up request from a lagging acceptor for a group X, an acceptor needs to retrieve logged ACCEPTs or DECISIONs for X in a specific slot range. To this end, GigaPaxos needs to additionally maintain a *log index* map keyed by group names that tracks the `[file,offset, length]` and `[slot,ballot]` information for every logged message. This is tricky because, by design, the number of groups can be much larger than that can be stored in memory, and simply using a traditional database

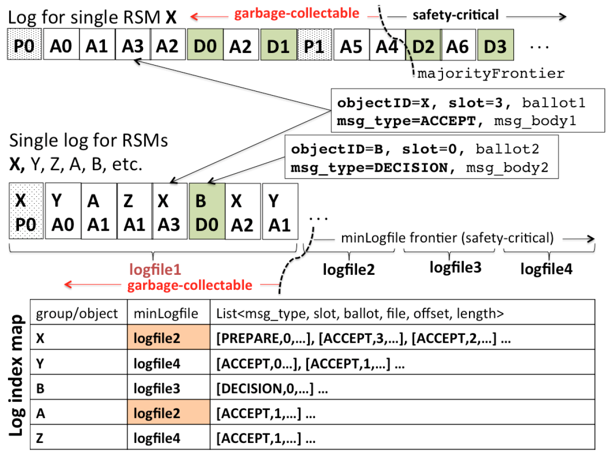


Figure 5: GigaPaxos' group-scalable logger (bottom) compared to traditional RSM logger (top).

(even with batching) makes the critical path about two orders of magnitude slower.

Pruning. GigaPaxos's log index is a swappable in-memory map that is as fast as a hash table lookup for working sets that fit in memory, but swaps infrequently used records to a database table indexed by the group name. The log itself is split across logically timestamped files each of a fixed maximum size, and each log index record in addition to the information above tracks `minLogfile`, the log file storing that group's log message with the lowest slot number, i.e., the lower of `majorityFrontier` (for `ACCEPTs`) and the most recent checkpointed slot (for `DECISIONs`). The garbage collector periodically queries the database for the `minLogfile` frontier, i.e., the set of `minLogfiles` across all groups, and then removes log files older than the oldest log file in that frontier set from the file system.

Compaction. Alas, the logger's garbage collection woes do not end here. With highly skewed workloads, for example, one where most requests go to just one (or a small number) of group(s) but a request occasionally goes to a "rare" group, it is possible that every log file contains at least one (or a few) log message that prevents the log file from being safely removed. In pathological cases, with pruning alone as above, the number of log files can be as high as $N \cdot I$ with N groups and a checkpoint interval of I requests (proof deferred to [3]). So, GigaPaxos needs to infrequently (1) *compact* sparse log files, i.e., files with very few safety-critical entries; (2) *merge* them with other sparse log files; and (3) *update* the log index map entries in a consistent manner.

With all of the above mechanisms, GigaPaxos' logger scales to a very large number of consensus groups while imposing negligible overhead when the working set fits in memory. The worst-case disk storage overhead for N groups is $O(INR)$, where I is the checkpoint interval and R the average request size. For example, with I=100 and R=100B, a machine needs over 1TB of storage to safely participate in N=100M groups. Thus, secondary storage, not memory, is what limits GigaPaxos' group scalability.

3.6 Safety and liveness properties

GigaPaxos preserves safety despite arbitrary failure patterns for each Paxos group by maintaining the critical Paxos invariant as-is, namely, if a coordinator c issues a proposal for request r for slot n in its ballot (b, c), then there exists a majority of acceptors such that either none of them have accepted any proposal for slot n in ballots lower than (b, c), or r is the request accepted for slot n in the highest ballot less than (b, c) by any acceptor in that majority[2]. GigaPaxos does not provide any ordering, consistency, or isolation properties for operations across different RSMs currently (supporting multi-object transactions is part of ongoing work.). Hot swapping preserves safety as the set of actions performed by a a GigaPaxos instance is a subset of actions that an acceptor or coordinator *could* have performed even without hot swapping.

GigaPaxos ensures liveness for each RSM during periods of synchrony when a majority of acceptors are available. Hot swapping only has a performance impact when the number of consensus groups is very large, and a significant fraction of GigaPaxos machines across all groups have failed. Persistent logging at acceptors ensures that, even if all acceptors crash at some point, the group eventually makes progress during subsequent periods of synchrony and majority availability. Without this, manual intervention would be required to safely recover from the crash of a majority of group members, which is impractical for a large number of groups.

3.7 Automated reconfiguration

A large number of consensus groups means it is impractical for an operator to manually reconfigure group membership, so GigaPaxos provides support for programmable policies that automate reconfiguration.

3.7.1 Reconfiguration protocol

GigaPaxos' reconfiguration protocol is similar to Liskov and Cowling's Viewstamped Replication Revisited (VRR) [26], but differs in important ways. First, GigaPaxos uses an external reconfigurator (similar in spirit to Vertical Paxos[23]) that also integrates the function of *group location*, i.e., determining the current group for an object, a concern outside the scope of VRR (that suggests that clients could obtain this information from a "web site run by the administrator"). With a very large number of application RSMs and frequent reconfigurations, group location requires a systematic, scalable solution. Second, the reconfigurator for each application RSM itself must

[2]This invariant is usually stated without referring to the slot number n [22] as a coordinator can use its ballot to issue any number of different proposals each with a different slot.

be replicated in order to prevent the application RSM from stalling permanently because of a reconfigurator failure.

Replicated GigaPaxos reconfigurators must agree on when to initiate a reconfiguration for an application RSM and on the composition of the new group as divergence can result in reconfigurators permanently losing track of the group. So each reconfigurator replica group is itself organized as an RSM whose state is the set of all application RSMs mapped to it via consistent hashing (Fig. ommitted). Any reconfigurator can propose an `RC_INTENT(X)` command to reconfigure an application RSM X it manages and, when committed, the proposing reconfigurator in the common case single-handedly conducts the STOP/START/DROP reconfiguration sequence [26] for X. When done, it proposes and commits `RC_COMPLETE(X)` in its group. Persistently logging every state change in its RSM ensures that, upon the proposing reconfigurator's failure or upon recovery, a reconfigurator can detect and complete unfinished reconfigurations of its managed application RSMs. A formal protocol description and a detailed proof of correctness of the reconfiguration protocol is nontrivial and is deferred to the techreport [3].

3.7.2 Extensible reconfiguration policy support

GigaPaxos enables applications to specify flexible policies that automate reconfiguration. Each reconfigurator RSM accepts periodic statistics about load or other metrics from any application RSM it manages and uses a customizable reconfiguration policy to decide whether and how to reconfigure the reconfiguree RSM. It is trivial also to let the application RSM simply send a request to its reconfigurator RSM when it deems a reconfiguration as necessary (or self-reconfigure as in VRR [26] and update the group location service), but allowing reconfigurators to make this decision allows implementing *global* reconfiguration policies, i.e., policies that take into account statistics across many RSMs to make reconfiguration decisions for each RSM. Applications using GigaPaxos extend an abstract class, `DemandProfile`, to specify sophisticated reconfiguration policies based on failure, demand, or access patterns, performance, etc.

3.8 Group creation: phantoms and corpses

With a large number of Paxos groups, some groups may get created when a member machine has failed. Upon recovery, `PaxosManager` on the machine will have no checkpointed or paused state for this instance. It is impractical for a recovering machine to contact all other machines for a list of all recently created Paxos groups, and for alive group members or reconfigurators to keep polling the failed member machine after group creation without introducing more instance-specific state and messaging overhead. For example, with 100 million Paxos groups, 100 machines, and an average group size of 5, each machine will have on average 5 million Paxos instances, so any additional instance-specific state and messaging unless ephemeral can significantly increase memory and bandwidth consumption.

Instead, GigaPaxos machines adopt a lazy approach to create Paxos groups whose birthing they missed. When a machine receives a protocol message for a *phantom* Paxos instance, i.e., for which it has no state, it assumes that the group may have gotten created in its absence, and contacts the sender of the message to enquire about the group's membership so as to create the corresponding Paxos instance locally. Care needs to be taken to only create Paxos instances, identified by the $\langle name, epoch \rangle$ two-tuple, for the same name with strictly increasing epoch numbers for safety. The reconfiguration protocol ensures this invariant by preserving the most recent epoch's final checkpoint, taken synchronously and immediately after executing corresponding STOP request, for a long threshold expiry time. Even though it would be futile to try to recreate a Paxos instance right after it was explicitly deleted, say, because of the receipt of a protocol message from a laggard member, it is unnecessary overhead to check the disk upon receiving phantom protocol messages; instead, the manager keeps deleted Paxos instance "corpses" in an in-memory "morgue" map for a fixed timeout, and tries to create a new Paxos instance if and only if a matching corpse is not found in the morgue.

3.9 Replicable application and client API

In order to remain agnostic to application-specific details, GigaPaxos requires an application to implement the following simple `Replicable` interface in order to be both *replicable* and *reconfigurable*. An application may choose to use just one of the two features, for example, to create an unreconfigurable RSM or reconfigure an unreplicated state machine.

```
boolean execute(Request request, boolean dontReply);
String checkpoint(String name);
boolean restore(String name, String state);
```

The flag `dontReply` is useful during (1) recovery to inform the application to withhold interaction with the end-client while rolling forward, and (2) regular execution to hint that only the "entry" replica need reply back to the end-client. The interface assumes that an application `Request` is serializable to a string and returns the RSM name via a `getServiceName()` method. The GigaPaxos logger maintains checkpoints up to a configurable maximum size in its own database (distinct from the application's if any); for large checkpoints, the application can also use the string `state` as simply an application-specific handle, e.g., a file name or URL, a mechanism also internally used by GigaPaxos' reconfigurators whose state can be very large.

The client API is simple consisting of `createService(X, S)` (`deleteService(X)`) to create (delete) a service X with initial state S, and **sendRequest(R)** to send a **Request** R to the RSM; querying reconfigurators to locate and select the closest app-container replica is internally handled. Upon creation, reconfigurators randomly choose the initial set of app-containers that later get reconfigured automatically.

3.10 Implementation miscellany

We implemented GigaPaxos with all of the features described above largely in Java with 21.3K semi-colons (72.3K newlines including documentation) of which 9.3K is for a stoppable Paxos implementation; 7K is for the reconfiguration protocol, and the rest is for `nio`, a non-blocking IO library with support for server-only or mutual-authentication-based SSL; and `protocoltask`, a package to simplify writing event/action protocols in asynchronous steps without worrying about messaging, scheduling, etc. The persistent logger uses an embedded database, Apache `derby`, by default, and also supports `mysql`. All transport is based on TCP; our `nio` library maintains and reuses a persistent connection to each machine, automatically attempts to create a new one if machine failures or other events cause I/O exceptions, and buffers a bounded number of messages to each destination to mask intermittent network failures. The size of an idle Paxos instance is ≈350B in our implementation because it is in Java; with a leaner language like C, it can be reduced further to ≈100B.

4 Evaluation

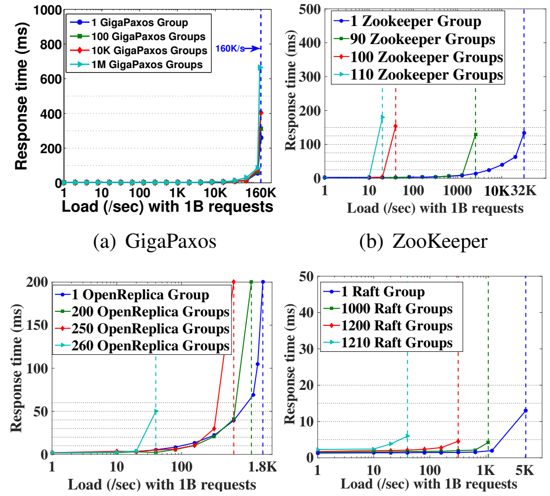
Our high-level goal is to quantify the costs and benefits of group scalability in GigaPaxos. To this end, we conduct the following experiments: (1) Comparison of GigaPaxos against state-of-the-art Paxos-based systems w.r.t. the number of supported groups and the impact on client-perceived performance; (2) Microbenchmarks evaluating the benefit and overhead of mechanisms in GigaPaxos; and (3) Case studies involving a number of third-party applications evaluating GigaPaxos' usability and the benefits of object-group configurability.

4.1 Group scalability comparison

In this section, we study the load vs. response time profile and the memory overhead for varying numbers of groups for three state-of-the-art systems that either *are* or comprise a consensus system, namely, ZooKeeper [18], OpenReplica [8], and Raft [31], compared to GigaPaxos. Unless otherwise specified, all experiments were performed on Amazon EC2 t2.medium (2 vCPUs, 4GB memory, and 8GB SSD disk) servers and sufficiently many c4.4xlarge clients to saturate the servers in the same region.

4.1.1 Load vs. response time with varying no. groups

In this experiment, clients send requests at increasing rates to a *single* active RSM at servers that maintain varying numbers of mostly idle RSMs. There are 3 servers in all and each RSM's consensus group is the set of all 3 servers. We measure the average response time over at least five runs each lasting 60s after discarding at least one or more warmup runs as needed to stabilize the servers. The request rate is increased until the system can not sustain that load, i.e., one or more servers either crashes, or the response time exceeds 1s, or the response rate drops below 99.9%.

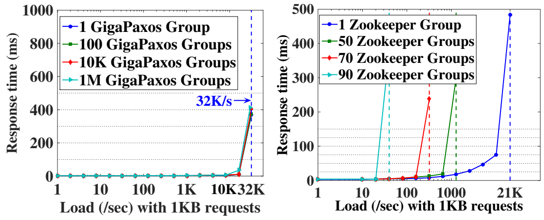


(a) GigaPaxos (b) ZooKeeper (c) OpenReplica (d) Raft

Figure 6: Group scalability: Load vs. latency for 1B requests with varying numbers of idle groups.

Fig. 6 shows the load vs. response time profile of GigaPaxos, ZooKeeper, OpenReplica, and the Raft authors' LogCabin [31] implementation for 1B no-op requests. Among the latter three systems, ZooKeeper scales to the highest capacity (32K/s) with a single group, but breaks down at barely hundred groups, while OpenReplica and Raft have significantly lower capacities with one group but don't hit breakdown point until hundreds of groups. ZooKeeper scales to fewer groups in part because of the overhead of running separate JVMs with servers listening on different sets of three ports for each RSM, which, though cumbersome, we confirmed with its developer forums [7] as well as via code inspection was the most reasonable option to maintain separate consensus groups. Raft's C++ implementation is leaner, so it scales to more groups. All three systems show a stark, qualitatively similar degradation with increasing groups.

In contrast, GigaPaxos is fast, scaling up to 160K/s capacity with a negligible performance drop as the number of groups increases all the way to a million. Given that only a single group is active in this experiment, GigaPaxos mainly benefits from amortizing failure detection across groups, its holistic, single-process design, and its compact representation of idle Paxos instances that we further study next.



(a) GigaPaxos (b) Zookeeper

Figure 7: Group scalability: Load vs. latency for 1KB requests with varying number of idle groups.

Memory overhead. In order to measure the memory overhead of simply maintaining consensus instances (with zero request load), we pick two sets of server configurations, t1.micro EC2 servers with 1GB memory, and t1.small with 2GB memory. We then create as many consensus groups as the machine could sustain before hitting physical memory limits for each of the four systems. We compute the *marginal memory* overhead of consensus instances as 1GB divided by the difference between the number of groups respectively sustainable with 2GB and 1GB of physical memory.

Marginal memory per instance	
GigaPaxos	346.4 Bytes
ZooKeeper	42.7 MB
OpenReplica	10.8 MB
Raft	5.4 MB

Table 1: Memory cost.

Table 1 shows the marginal memory overhead of the four systems for idle consensus instances. GigaPaxos can create over 3 million Paxos instances per machine resulting for a cost of ≈350B per instance (consistent with Fig. 3), which is orders of magnitude smaller than the other systems. We defer a more detailed breakdown of the constituent costs and the load vs. memory consumption behavior of the systems to the techreport [3].

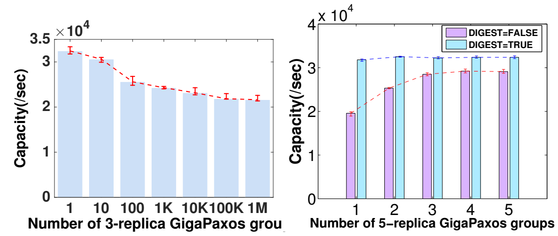
Impact of request size. 1B requests measure the raw agreement throughput, but are hardly useful for any real application. We repeat the above experiment with 1KB requests and (because of space limits) show the results only for GigaPaxos and ZooKeeper in Fig. 7. Both systems are network bottlenecked[3][19], and see a significant drop in capacity. Both have ≈100-120B of protocol overhead for each ACCEPT/ACCEPT_REPLY/DECISION message (or their one-one equivalents in ZooKeeper's Zab protocol [19]) on the critical path. So, 1KB vs. 1B requests increase the ACCEPT message size by ≈8-10×.

4.2 GigaPaxos microbenchmarks

4.2.1 Impact of batching on group scalability

The results above (§4.1) with a single active group may suggest that GigaPaxos is phenomenally group-scalable with no apparent costs, but that is hardly the case. Next,

[3]more precisely, by networking-related actions such as serialization and the TCP/IP stack, not the bare-metal bits/sec.



(a) Reduced batching (b) Coordinator balancing

Figure 8: (a) Reduced opportunistic batching hurts; (b) Coordinator load balancing helps.

we stress-test GigaPaxos when a large number of groups are simultaneously active. We use 1KB requests and repeat the experiment above with the only difference that requests are sent in a round-robin manner across groups.

Fig. 8(a) shows that the throughput capacity of the system drops as the number of groups increases. The reason is reduced opportunities for batching requests. Opportunistic batching, i.e., without explicitly waiting for more requests to arrive, is well known to significantly improve the performance of Paxos-like protocols. However, it is in general not possible to batch requests across different RSMs as their group membership may be different. With increasing groups, GigaPaxos' capacity drops until it hits ≈22K/s, which we have verified is its capacity with 1KB requests with batching disabled.

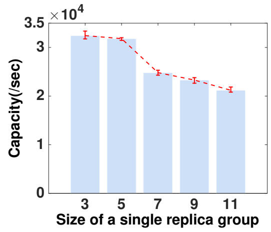
Fig. 8(b) shows an experiment similar to that in 8(a) but with 5-replica groups (instead of 3). Seemingly contradictorily, the first set of bars show the capacity increasing with the number of groups. However, there is a simple explanation–coordinator load balancing–for this observation. As the number of groups increases from 1 to the total number of physical servers 5, the capacity increases because the coordinators for different 5-replica groups get randomly assigned to the servers. As the coordinator's role—receiving every request and sending them as ACCEPTs to the group—is a key bottleneck, multiple groups naturally increase capacity. In contrast, the latter set of bars enable the `digest_requests` option wherein the entry replica broadcasts the request to all acceptors and the coordinator issues ACCEPTs only with request digests. Safety is preserved because an acceptor acknowledges an ACCEPT only if it has already received the corresponding body.

The benefit of coordinator balancing has been noted before, e.g., S-Paxos [11] proposes an optimization similar to GigaPaxos' request digests (albeit with a more complex protocol), and others such as Mencius[28], E-Paxos[29] etc. [20] take different approaches to coordinator load balancing. In GigaPaxos, such optimizations are needed only when the number of groups is very small and the request size is not small (≫tens of bytes).

3-replica groups with 4GB RAM/replica

Latency under light load (up to a few million groups)	**2.8ms ± 0.3**
Latency of requests to paused instances (>10M groups)	**12.4ms ± 0.6**
Capacity w/ 1KB round-robin workload (>10M groups)	**2.6K/s ± 30**
Capacity w/ 10B round-robin workload (>10M groups)	**4.6K/s ± 67**

(a) Hot-swapping overhead



(b) #replicas vs. capacity

Figure 9: (a) Group scalability "fine print" with very large number of groups; (b) Fault scaling.

4.2.2 Hot swapping overhead

Table 9(a) summarizes the "fine print" limiting GigaPaxos' group scalability. The experiments thus far considered up to a million groups that barely consume half a gigabyte of memory. However, 10 million instances is higher than what can be supported on the 4GB RAM servers. With such a large number of instances and a round-robin workload, every request encounters a paused instance, so the average latency is over 12ms compared to under 3ms for up to a few million instances (both measured under a round-robin light load of 100/s). Unpausing an instance currently requires two database lookups, one each for the paused instance state and the corresponding log index record (§3.5) that are currently paused and looked up independently; combining them (not yet implemented) will further reduce this penalty. The throughput takes a much more severe hit at 2.6K/s for 1KB requests vs. 22K/s for 1M groups (Fig. 8(a)).

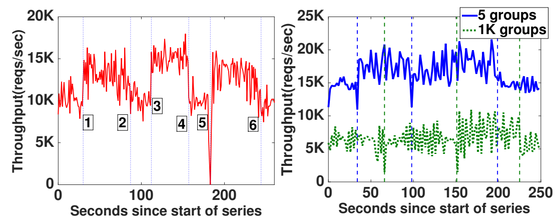
4.2.3 Fault scaling

Fig. 9(b) shows the impact of the size of the group on the capacity with 1KB requests and a single group. As expected, the capacity decreases as the replication factor increases because of the increase in message overhead. With multiple groups (not shown), this trend w.r.t. the replication factor remains unchanged; for any given replication factor, the aggregate throughput initially remains steady as the number of groups increases up to the replication factor because of coordinator load balancing (Fig. 8(a)), but then decreases with more groups because of reduced batching up until it matches the unbatched capacity.

4.2.4 Failure recovery

Can GigaPaxos groups recover quickly from failures? To study this, we use 5 servers either with one group, as in Fig. 10(a), or with 5 and 1000 groups respectively as in Fig. 10(b). In the 1-group case, the 6 numbered marks respectively correspond to the (1) failure of an acceptor; (2) recovery of the acceptor; (3) failure of two acceptors; (4) recovery of the two acceptors; (5) failure of the coordinator; (6) recovery of the coordinator.

We find that the throughput initially decreases but eventually *increases* upon the failure of acceptors and is chugging along most happily after the failure of two acceptors (mark 3) as the coordinator has to do less messaging. This increase in throughput with acceptor failures is different from the finding in the ZooKeeper paper [18] (that inspired this experiment) where the throughput roughly *decreases* by the share of requests going to the failed nodes. Unlike Zab [19] that pins each client to a single server (to preserve primary order causal consistency), GigaPaxos clients can send requests to any server. But coordinator failures do force a downtime commensurate to the failure detection timeout, which defaults to 6s in our implementation and is automatically increased with more machines if the aggregate probe rate at a machine exceeds 10/s.



(a) One group (b) Multiple groups

Figure 10: Responsiveness of failure recovery.

The experiment in Fig. 10(b) is similar to 10(a) with the only difference that the labels "acceptor" and "coordinator" are not meaningful here because different groups' coordinators get randomly mapped on to different servers. As a result, the aggregate throughput never goes down to zero as there are always some groups whose coordinators are alive. The 1000-group case does plunge significantly upon a machine failure because, in addition to the 0–6s of downtime for roughly a fifth of the groups, there is also the added message overhead of electing new coordinators for those groups. More generally, in a GigaPaxos system with M machines, a total number N of consensus groups, and a total number n of *active* groups, the failure of a single machine will in expectation temporarily stall N/M groups and induce n/M elections (as paused groups do not elect a coordinator until stirred by a client request).

4.3 Application usability case studies

In this section, we present several application case studies to show (1) that GigaPaxos' `Replicable` API (§3.9) can be implemented easily for third-party applications, with or without intrinsic support for replication, so as to make them replicable and reconfigurable; (2) the latency benefit of object-group configurability.

4.3.1 `myCloud`: Share document editing and storage

We implemented a `Replicable` wrapper for `etherpad` [1], an open-source, document editor that allows users to collaboratively edit documents or "pads" in real-time via a web browser (similar to the popular, proprietary Google Docs). `etherpad` does not intrinsically support replication or fault-tolerance. Client libraries for its API are available in a

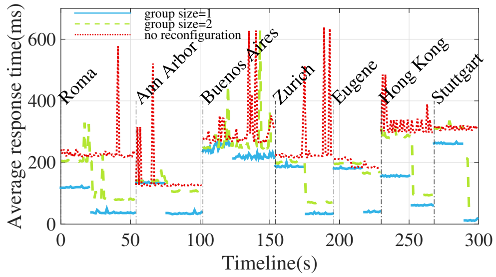


Figure 11: The placement of **etherpad** servers significantly affects user-perceived response times.

variety of languages; we used the Java API [2] to make it fault-tolerant and reconfigurable via the **Replicable** wrapper. GigaPaxos also has general-purpose support for applications to easily delegate messaging of replies back to the client originating the request, which we used here.

In this *wide-area* experiment, we deploy 7 **etherpad** servers respectively at California, Frankfurt, Ireland, Sydney, Seoul, Tokyo, and Virginia. A GigaPaxos client creates a single pad using the **createService(.)** client API, which by default is set to create an RSM group of all 7 replicas. A controller script in our lab then emulates a "mobile" **etherpad** client that trots across different cities as shown in Fig. 11 sending tens of requests from each city. The **DemandProfile** policy is designed to reconfigure the RSM once every 20 requests to either 1 (blue/solid) or 3 (green/dashed) closest app-container locations.

Fig. 11 shows that the carefully-chosen 3-replica RSMs can significantly reduce end-to-end client-perceived latency, sometimes by over 200ms. The 1-replica RSM as expected yields the lowest latency but only ensures durability, not availability amidst failures, and is included just to show the best-case. Reconfiguration itself roughly takes as much time as 2-3 Paxos operations, so requests are occasionally lost when sent to an app-container where the Paxos instance no longer exists.

4.3.2 Usability and performance overhead

Application	#semi-colons
Etherpad	60
OpenKM [5]	89
MySQL	79
Cassandra	78
Mongo	53
Redis	40

Table 2: LOC for **Replicable** wrappers.

Implementing **Replicable** for **etherpad** was rather easy and involved just 60 lines of code to GigaPaxos' abstract, general-purpose "hello world" client and application classes in order to support **etherpad**'s three basic request types used in this experiment; supporting its full API will increase the integration overhead.

We have also implemented **Replicable** wrappers for a number of third-party applications as listed in Table 2 including OpenKM [5] (comparable to Google Drive) and popular key-value stores. Despite the simplicity, some of the wrappers are powerful, e.g., the mysql wrapper is schema-agnostic and anyone can reuse it to designate either each row or each table as an independently reconfigurable RSM. We could do this because **Replicable**'s **checkpoint** and **restore** methods could naturally avail of `sqldump` to checkpoint a single record, table, or database in a schema-agnostic manner. A more detailed study showing that GigaPaxos adds only a small penalty if at all to the *single-server* capacity of these applications is deferred to a techreport [3].

With the help of tutorials and starter code, GigaPaxos has been in used by a small distributed systems class of 10 students (6 undergraduate, 4 masters) to implement a simple, in-memory map that is gratuitiously durable, fault-tolerant, per-key reconfigurable, and ultra-fast (Fig. 6(a)) for small keys and values.

4.3.3 Global name service case study

GigaPaxos was inspired by the Auspice system [32], a global name service (GNS) that forms the "control plane" of a next-generation Internetwork [34], and also advocates per-object reconfigurability for *name records*. In comparison, GigaPaxos (1) is a separate system developed completely from scratch; (2) designed for general-purpose distributed objects or services; (3) outperforms Auspice's group scalability of 10K-100K groups [32] by orders of magnitude with over an order of magnitude better throughput. We have since worked with the MobilityFirst team to transition to GigaPaxos as the core of its GNS, a service that has been running using GigaPaxos for over a year on EC2 [4] for community use.

5 Conclusions

In this paper, we presented GigaPaxos, a novel system that enables group-scalable replicated state machines. Perhaps because of pedagogical challenges or because of the "costly" mental image replication already invokes, consensus implementations today inherently embed assumptions appropriate for heavyweight applications. In contrast, GigaPaxos easily allows any application to create an object managed by a consensus group on the fly and reconfigure the group as needed. We have conducted a number of application case studies to show that agile reconfiguration and object-group configurability in GigaPaxos can significantly improve client-perceived performance. The GigaPaxos code with tutorials, case study example code, and documentation is available at: `http://anonymizedforpeerreview.com/`.

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