Hierarchical Cache Consistency in a WAN[*]

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Abstract

This paper explores ways to provide improved consistency for Internet applications that scale to millions of clients. We make four contributions. First, we identify how workloads affect the scalability of cache consistency algorithms. Second, we define two primitive mechanisms, *split* and *join*, for growing and shrinking consistency hierarchies, and we present a simple mechanism for implementing them. Third, we describe and evaluate policies for using split and join to address the fault tolerance and performance challenges of consistency hierarchies. Fourth, using synthetic workload and trace-based simulation, we compare various algorithms for maintaining strong consistency in a range of hierarchy configurations. Our results indicate that a promising configuration for providing strong consistency in a WAN is a two-level consistency hierarchy where servers and proxies work to maintain consistency for data cached at clients. Specifically, by adapting to clients' access patterns, two-level hierarchies reduce the read latency for demanding workloads without introducing excessive overhead for nondemanding workloads. Also, they can improve scalability by orders of magnitude. Furthermore, this configuration is easy to deploy by augmenting proxies, and it allows invalidation messages to traverse firewalls.

1 Introduction

To improve performance and reduce bandwidth, caching has become a ubiquitous Internet technology. However, web caching introduces the problem of maintaining consistency. With weak notions of consistency users can observe confusing data, and innovative web services—such as agents, robots, and distributed databases—will likely produce incorrect results. Furthermore, consistency polling can increase server load, increase latency, and reduce the effectiveness of large-scale caches [9, 5]. Thus, improved consistency will become increasingly desirable.

Callback-based consistency can be used either to provide strong consistency—which guarantees that a client's read of an object returns the latest completed write of that object—or best effort consistency—which attempts to invalidate stale data when it changes and which can limit the amount of time during which a client unknowingly accesses stale data [20]. However, simple callbacks are unacceptable for a WAN because servers may be forced to delay their writes indefinitely when there are client failures or network partitions.

In previous work, we show how to combine callbacks with timely server writes by using *Volume Leases* [20], a generalization of the original notion of *leases* [7]. By coordinating per-volume and per-object leases, the Volume Leases algorithm presents a fundamental abstraction that provides a mechanism for enforcing strong consistency semantics that is separate from the policy question of when to renew volume leases. We focus on a policy where clients fetch volume lease renewals on demand when they access a volume; in the future we plan to explore other policies such as prefetching or multicasting lease renewals. Our earlier study uses trace-driven simulations and shows that Volume Leases performs well compared to object leases and polling.

The key questions that this paper answers are (1) how large a system can Volume Leases accommodate, and (2) what techniques can be used to scale to even larger systems? To answer these questions, this paper explores ways to accommodate popular web servers with millions of clients by combining Volume Leases with hierarchies.

Adding hierarchy to callback-driven consistency can yield three benefits. First, latency can be reduced if clients can register callbacks or renew leases by going to a nearby node in the consistency hierarchy rather than to the server. Second, hierarchy can improve network efficiency by forming a multicast tree for sending invalidation messages to caches and a reduction tree for gathering their replies. Third, hierarchy improves server scalability by distributing load and callback state across a collection of nodes.

However, using hierarchy for scalable consistency introduces its own challenges. Availability may suffer be-

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cause hierarchical structures consist of multiple nodes that can fail independently. Also, latency can increase if the hierarchy must be traversed to satisfy requests. Finally, it is unclear how best to configure the hierarchy.

This paper develops solutions for hierarchical consistency and addresses these issues. We make four contributions. First, we identify and quantify the ways in which specific characteristics of data-access workloads affect the scalability of cache consistency algorithms. Second, we define two primitive mechanisms, *split* and *join*, for growing and shrinking hierarchies, and we show how these primitives can be implemented with a simple mechanism already present in the Volume Leases algorithms. Third, we describe and evaluate policies for using split and join to address the fault tolerance and performance challenges of hierarchies. Fourth, we examine and compare algorithms for maintaining consistency in a range of hierarchy configurations.

We explore three configurations. First, in *generic hierarchy*, consistency proxies can be placed anywhere in the Internet. The second configuration, *server-proxy-client*, is designed to exploit widely deployed web proxies, which serve as gateways between enterprise LAN and web servers to improve security and network efficiency. In this configuration, web proxies are augmented to serve as consistency proxies that forward invalidation messages from web servers. This addresses the engineering challenge introduced by firewalls that generally prevent external machines from sending invalidation messages directly to clients within the firewall. The third configuration is the *server cluster* configuration in which hierarchy is introduced only within a LAN cluster of servers to improve scalability.

We evaluate our algorithms using simulation. To study scalability and to evaluate how the system is affected by different workload characteristics, we first use a series of synthetic workloads. To calibrate these results with realistic workloads, we also examine some smaller trace-based workloads. Overall, we find that even without hierarchies, Volume Leases can scale to services with tens of thousands of clients; with hierarchies, scalability beyond millions of clients appears feasible.

The thesis of this paper is not that all servers should provide strong consistency, but rather that for Internet-scale systems, strong consistency is feasible for a wide range of applications. We envision flexible systems where either servers or clients can specify the consistency semantics for their data [10]. The algorithms described here can also be used to provide *best effort consistency* where servers make a best effort to notify clients of changes to cached data, but servers do not delay writes. We discuss best effort versions of Volume Lease consistency algorithms in detail elsewhere [20].

The rest of this paper proceeds as follows. Section 2 discusses a few ideas that are needed to understand this work. Section 3 describes our new algorithm whose performance we evaluate in Section 4. We close by discussing related work and drawing conclusions.

2 Background

This section describes four concepts necessary to understand hierarchical consistency: callbacks, leases, the Volume Leases algorithm, and reconnection under Volume Leases.

In server-driven consistency, a client registers *callbacks* with a server for objects that it caches [9, 15]. Before modifying an object, a server sends invalidation messages to all clients that have registered interest in that object. The advantage of this approach is that servers have enough information to know exactly when cache objects must be invalidated. By contrast, in client-driven consistency schemes, such as those currently used in NFS and HTTP, clients periodically ask the server if objects have been modified. This creates a dilemma for the client. A short polling period increases both server load and client latency, while a long polling period increases the risk of reading stale cache data.

However, there are two challenges for server-driven consistency in large distributed systems. First, scalability is an issue, because large numbers of clients lead to large server state and large bursts of load when popular objects are modified. Second, performance in the face of failures is an issue because servers cannot modify an object until all clients have been notified that their cached copies are no longer valid. Because of this requirement, server writes can be delayed indefinitely while the server waits for acknowledgments from unreachable clients.

These challenges can be addressed by introducing *leases* [7]. When a client registers a lease with a server, the lease specifies some time T during which the server will notify clients of updates. Leases improve scalability because servers need to track only active clients, and they improve fault tolerance because even if a client is unreachable, writes are delayed only until the client's lease expires. The lease length T presents a trade-off. Long leases minimize the overhead of renewing leases, while short leases reduce server state and improve failure-mode write performance.

Leases do not perform well for web workloads because the interval between a client's reads is typically long, so object leases must be long to amortize the cost of lease renewals across multiple reads [20]. The *Volume Leases* algorithm introduces the notion of a volume, which is a collection of objects that reside on the same server. The algorithm associates a lease with each volume as well as with each object. A client's cached object is valid only if both its object lease and corresponding volume lease are valid. The Volume Leases algorithm uses a combination of long object leases and short volume leases to resolve the tradeoff with lease lengths. Short volume leases allow servers to write quickly in the face of client and network failures: since clients can't read an object when its corresponding volume lease is invalid, in the worst case the server waits only for the the short volume lease to expire before modifying an object. While the cost of renewing short volume leases is amortized across the number of objects that reside in the same volume, long object leases minimize the overhead of renewing object leases.

In the Volume Leases algorithm, a server maintains a list of unreachable clients whose volume leases expired while the server was attempting to invalidate an object lease. We call this list the *unreachable list*. After an unreachable client recovers or its network connection to the server is restored, the next time that client tries to renew its volume lease the algorithm uses a reconnection protocol to restore consistency between the client's and server's lists of current object leases.

Because the reconnection protocol is a key building block for hierarchical caching, we describe it in detail. Each server maintains an *epoch number*. Whenever a server recovers from a crash, it increments the epoch number and logs that number to stable storage before proceeding with normal operations. All messages from a server to its clients include the epoch number. When a client receives a message from a server, it records the server's epoch number. When a client sends a volume lease request to a server, it always includes the last known epoch number for that server. A server grants a volume lease only if the epoch number in the request matches its current epoch and if it has not marked client unreachable. If the client's epoch number does not match or if the client is marked unreachable, the server sends the client a reconnect request. In response to such a request, a client sends the server the list of objects it currently caches and the *version numbers* of these objects. The version number associated with an object is an integer that the server increments whenever it modifies the object. The server then compares the version numbers of the cached objects and server's objects and grants object leases to all objects whose versions match. The server invalidates all other cached objects then grants the volume lease. All these tasks can be accomplished with one message from the server to the clients. When the client finishes updating its object leases, it sends a connect message back to the server, which then removes the client from the unreachable list.

3 Algorithms

We first describe a naive algorithm based on a static consistency hierarchy and discuss its performance and fault tolerance properties. Next, we present two primitive mechanisms, split and join, for reconfiguring the hierarchy. These mechanisms can be constructed with trivial additions to the basic Volume Leases algorithm. We then describe policies that use these mechanisms to enhance the fault tolerance and performance of the basic static hierarchy.

Both the static and dynamic versions of the algorithm assume that nodes participating in the consistency service have been identified and organized into an initial hierarchy. This study does not specify a particular mechanism for doing so. For some systems, constructing the hierarchy manually suffices; for some, such as the server-proxy-client configuration in Section 4.3, automatic construction is trivial; for others, more sophisticated automatic strategies such as those described by Plaxton et. al [16] might be required. This hierarchy may be embedded on current clients and proxies, it might be coincident with a larger cache hierarchy [2] or it might be part of a separate data-location-metadata hierarchy [6, 18].

3.1 Static hierarchy

Our consistency hierarchy is a tree structure of interconnected nodes. We refer to the root as the *origin server*, to the leaves as *clients*, and to the intermediate nodes as *consistency servers*. Each node runs the standard Volume Leases algorithm; each intermediate node acts both as a client and as a server, treating its parent as its server and its children as its clients. Each node thus satisfies lease requests from its children by returning a valid lease if it has one cached, or—if it does not—by requesting a lease from its parent, caching the lease, and returning the lease to its child. Similarly, each node passes to any children that have valid leases the invalidation messages that it receives.

Such hierarchies have the potential to improve performance by reducing both server load and the latency of client lease renewals. In the Internet, a popular site might serve millions of clients, and by using a hierarchy, a server tracks and communicates with only its immediate children. This reduces memory state, average load for lease renewals, and bursts of load when popular objects are modified. In essence, the consistency hierarchy forms a multicast tree for sending invalidation message and forms a reduction tree for gathering replies. By the same token, if clients can renew leases by going to nearby intermediate consistency servers rather than to the root server, read latency and network load may be reduced.

However, the use of leases in the hierarchy is not guaranteed to reduce either server load or latency. When volumes are popular and frequently accessed, it is likely that consistency servers will hold valid leases and will respond to client requests without consulting their parents, and it is likely that the hierarchical "multicast" will achieve a large fan-out and significantly reduce server load. However, for unpopular or infrequently accessed volumes, the time between accesses to consistency nodes is likely to be longer than the volume lease, so the cached leases may often have expired when they are accessed. In these cases, many messages would traverse the entire hierarchy, increasing the average read latency without reducing server load.

A second problem with a static hierarchy is reliability. The hierarchy consists of a large number of nodes that can fail independently, and one node failure can effectively disconnect a subtree.

3.2 Join and split

The solution to both problems is to reconfigure the consistency hierarchy dynamically without breaking consistency guarantees. We propose a mechanism that uses two primitives: *join*, which removes an intermediate node from the hierarchy, and *split*, which adds an intermediate node to the hierarchy. Both primitives work on a per-volume basis—in our system different volumes can use different hierarchies.

Join and split can be trivially implemented using mechanisms already required by the Volume Leases algorithm. Recall that join removes a node from the hierarchy, connecting the children of the node directly to the node's parent. To implement join we augment the volume epoch number to include the parent node's identity. When a child initiates a join for a particular volume, it simply begins using its former grandparent as a parent. The volume epoch number held by the child will not match its new parent, so the new parent initiates the standard volume reconnection protocol to synchronize its state with its new child. Thus, going to a new parent in the hierarchical algorithm is no different than going to a server that has crashed and lost a client's state in the original Volume Leases algorithm. Similarly, to split the hierarchy, a child chooses a descendant of its parent and starts using the new node as its parent, again using the reconnection protocol to synchronize the state. For both split and join, the decision to use a new parent can be made by children at arbitrary times. The criteria for such decisions are a matter of policy. Children can thus decide to find new parents to improve fault tolerance or they can be told to use new parents to improve performance.

3.3 Fault tolerant static hierarchy

Using join and split, an intermediate node failure is handled as follows. If a node N cannot contact its parent P to renew a lease, it sends the renewal message to one of its ancestors A, triggering the volume reconnection protocol between N and A. Note that if A cannot send an invalidation to P, it does not try to contact N, but instead waits for the volume lease timeout; this means that parents need to know only about their immediate children, not their more distant descendents. Finally, when node P recovers, it can send hints to its list of (former) children suggesting that they split from A and join P instead.

3.4 Dynamic hierarchy configuration

For volumes with high read frequencies and many active clients, a deep hierarchy can reduce read latency and distribute load. However, for less popular objects, or for popular objects with low read frequency, intermediate hops can increase read latency without significantly reducing server load. Therefore, it is useful for different volumes to construct different dynamic hierarchies. These hierarchies can be constructed from the static hierarchy using the split and join mechanisms in response to changing workloads. Hence, a node can have different children in the static and dynamic hierarchies: we refer to the former as *static children*, and to the latter simply as *children*.

In the dynamic configuration algorithm a node N monitors the number of lease requests it receives from its children and the fraction of these requests that it can satisfy locally during time intervals of length T. Using this data, N instructs its children to join with its parent if (1) the load from its children would not cause the load on its parent to exceed a threshold value and (2) its children would receive better read latency by skipping N and going directly to the parent. N performs the latency calculation as follows.

Let $RenewCost(N)$ be the cost for a child of N to renew a lease cached at N, and let $RenewCost(P)$ be the cost for N to renew a lease cached at its parent. If the fraction of renewals that N satisfies locally is F, then the expected latency that a child of N pays to renew a lease is $RenewCost(N) + (1 - F)RenewCost(P)$. Assuming that the cost of accessing N's parent is about the same for both N and N's child, the expected cost after a join is $RenewCost(P)$. When $RenewCost(N) + (1 - F)RenewCost(P)$ is greater than $RenewCost(P)$ by some threshold, N instructs its children to perform a join unless doing so would raise the load of the parent to an unacceptable level.

Similarly, to determine when to initiate a split, a node monitors the requests from its children and initiates a split if (1) its local load exceeds some threshold or (2) connecting a set of children to a skipped node would reduce their expected read latency by some threshold.

A node N performs this read latency calculation by simulating the performance of its skipped children as follows. For each static child S, N maintains a simulated request count $ReqCount(S)$, hit count $HitCount(S)$, and volume lease expiration time $VolExp(S)$. When a child C of N contacts N to renew a lease, N updates the statistics for the skipped child S that is a static ancestor of C by (1) incrementing $ReqCount(S)$, (2) incrementing $HitCount(S)$ if the current time is before $VolExp(S)$, and (3) setting $VolExp(S)$ to the current time plus the volume lease length. Let $RenewCost(N)$ be the cost for C to renew its lease at N and $RenewCost(S)$ be the cost for C to renew its lease from the skipped child S instead. N tells C and its siblings to split from N and instead use S as their parent if $RenewCost(S) + (1 - \frac{HitCount(S)}{ReqCount(S)}) \cdot RenewCost(N) < RenewCost(N) - threshold$.

4 Evaluation

We evaluate hierarchical consistency in three different deployment configurations. First, we examine an aggressive deployment model, *generic hierarchy*, to characterize the factors that affect the behavior of the core algorithms and to determine the performance limits of our approach. Second, we examine a simple *clustered-server* configuration in which the hierarchy is used to distribute the algorithm across a LAN cluster in order to improve scalability but not latency. This configuration might be used if a service wishes to provide strong consistency for its data without relying on having consistency-enabled intermediate proxies deployed across the WAN. Third, we examine a *server-proxy-client* configuration that maps well to infrastructure that is common today.

We evaluate these algorithms using simulations. To study scalability and to evaluate how different aspects of workloads impact scalability, we first use a series of synthetic workloads. We run each of these experiments five times using different random seeds for workload generation and show the 90% confidence interval for each point. Then, to calibrate these results, we examine a smaller, trace-based workload in the context of the server-proxy-client configuration.

Based on these experiments, we reach the following conclusions:

- For the aggressive deployment scenario with flexible hierarchy configurations, static hierarchies can reduce latency compared to the flat Volume Leases algorithm for high request-rate services, but they can increase latency for low request-rate services. In contrast, the dynamic version always performs as well as the flat algorithm for low request rates and as well as the static hierarchy for high request rates.

- For workloads with modest request rates in the range of many current web services, the flat Volume Leases algorithm with a single server can scale to client populations in the tens or hundreds of thousands of nodes; distributing the consistency algorithm across a group of nodes—either in a cluster or across a WAN—via hierarchies can provide scalability to millions of clients even under aggressive workloads.

- In the server-proxy-client configuration, the simple static hierarchy performs well for our web trace workload; this configuration has the added benefit that it might also provide a controlled way to traverse firewalls in order to deliver consistency signals. The synthetic workload suggests that there may be other workloads for which the dynamic algorithm's flexibility is desirable.

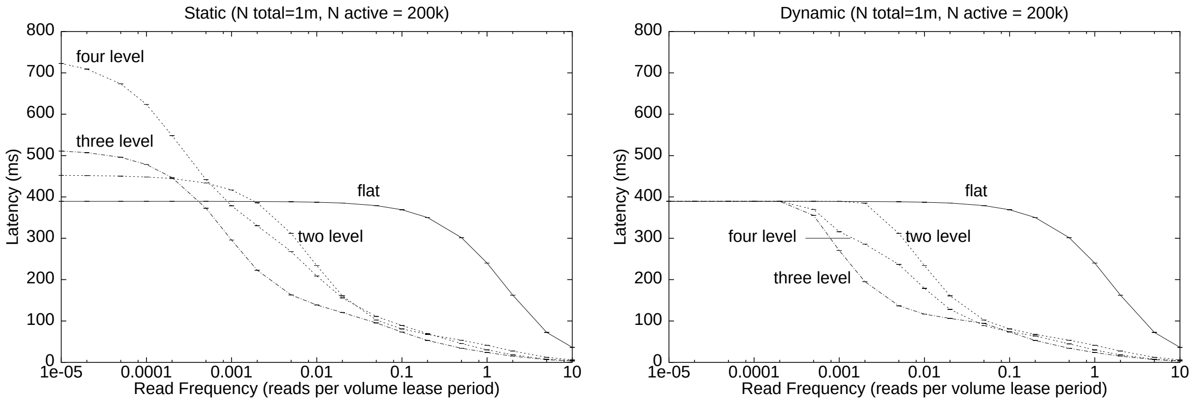
Our methodology makes several significant assumptions and simplifications. For our latency estimates, we do not simulate network or server contention. We use a simple network topology and delay model to make our analysis tractable. Finally, our default synthetic workloads simulate one object per volume. This may understate the apparent benefit of hierarchies because long-lived object leases are much easier to cache in the hierarchy than short volume leases; furthermore, the small number of objects per volume may also hurt the relative performance of the static algorithm.

4.1 Generic hierarchy

Our Generic Hierarchy configuration represents a system with few constraints on deployment. We examine this configuration to understand the behavior of the core algorithms as we vary several key parameters. This configuration also models an aggressive deployment strategy such as might be employed within a large cache service or in a system where collections of servers and cache systems coordinate to provide consistency.

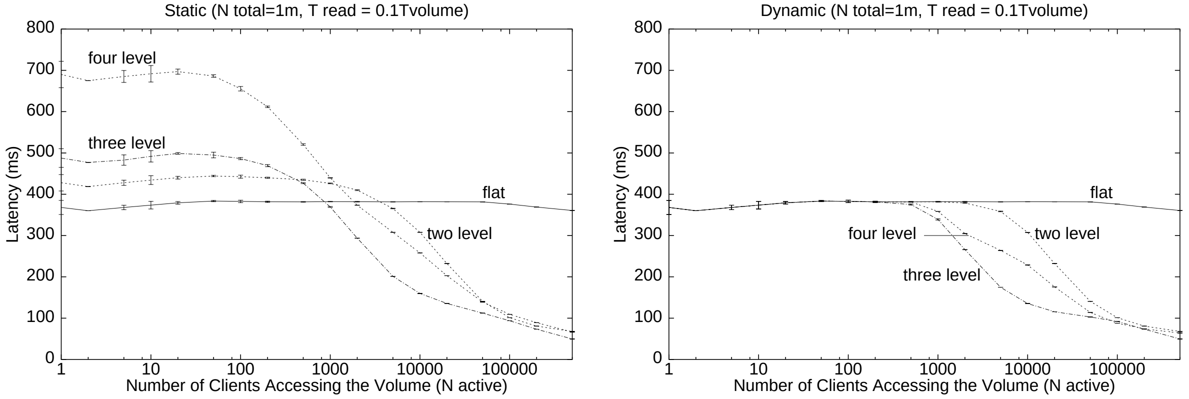
The consistency hierarchy is a tree with one server at its root, C clients at its leaves, and $l - 1$ levels of intermediate nodes. We designate the server to be the level 0 node of the consistency hierarchy. For simplicity, we assume that at all levels of the tree the degree d is the same, with $d^l = C$. We defer the evaluation of hierarchies with different fan-out at different levels for future work. We use a simple cost model for accessing consistency servers. First, we assume that all leaf nodes and internal nodes within a subtree experience the same latency when they renew a lease with the root of that subtree. Second, we assume that the latency experienced within a subtree increases with the number of leaves in the subtree as follows: subtrees with 100 or fewer leaves have a latency of 30 ms, subtrees with 10,000 leaves have a latency of 100 ms, and subtrees with more than 100,000 leaves have a latency of 400 ms; latencies for subtrees with 100-10,000 nodes and 10,000 to 100,000 nodes are estimated through interpolation. These latencies are meant to be suggestive of department-, enterprise-, and Internet-scale delays, but do not represent any specific system.

We use a synthetic workload and compute the average read latency and server load when we simulate the accesses of a collection of clients to a single volume. Out of N_{total} clients, we choose a subset of clients of



(a) Static (b) Dynamic

Figure 1: Average read latency as the per-client read frequency is varied for a hierarchy of one million clients, of which 200,000 access the volume in question.



(a) Static (b) Dynamic

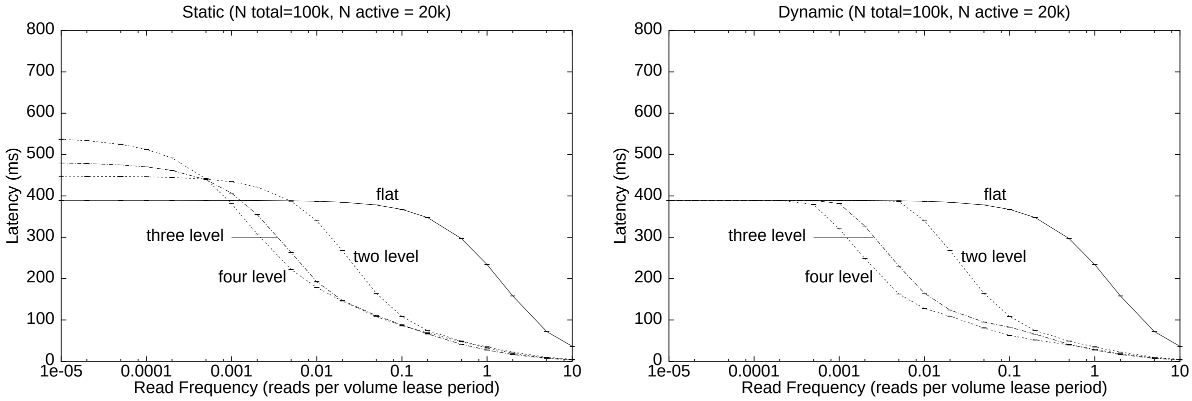
Figure 2: Average read latency as the number of active clients varies for a hierarchy of one million clients, each issuing requests to a volume at a rate of 0.1 requests per volume lease period.

size N_{active} that access the volume with per-client inter-access times determined using an exponential distribution around an average value t_{read}, which is expressed as a ratio of the average inter-access time to the volume lease renewal time. In our initial experiment, each volume contains a single object; we relax this assumption later in this section.

Read Frequency A server's read frequency has a large impact on the performance of hierarchical consistency. The higher the collective read frequency of the clients below a proxy, the more often the proxy holds the lease. Hence, if the read frequency is high the lease hit ratio will be high and the proxy can reduce read latency. Otherwise, if the collective read frequency is low, then the lease hit ratio will be low.

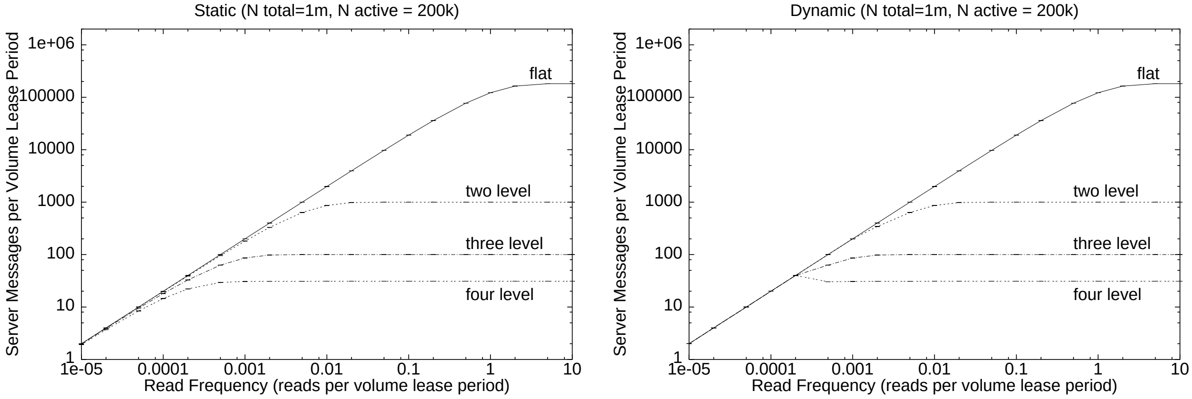
Figure 1 shows the average lease renewal latency as the per-client read frequency is varied. Figure 2 shows lease renewal latency as the fraction of clients that access the volume in question is varied. The graphs compare the performance of a flat, 2-level, 3-level, and 4-level consistency hierarchy with part (a) of each figure showing performance for the static algorithm and part (b) showing performance for the dynamic algorithm. Figures 1 and 2 have the same general shape because as one moves to the right along the x axis the total request rate increases in both sets of graphs. But, these graphs represent different dimensions of the design space. Read latency generally decreases as read frequency increases. For high request rates, the read latency falls even for the flat configuration because a client issues multiple reads within the period the client's volume lease is valid.

To interpret these graphs it is helpful to consider where different classes of services might lie or where a single service might lie under different workloads. For example, a weather service that is visited by an average client once a day for one minute and that uses a 10-second lease period would correspond to a read frequency of less than 0.001 reads per volume lease period per client. Similarly, a news service whose typical users visit for 5 minutes during the 8-hour working day would correspond to a volume renewal frequency near 0.01 per volume lease period per client. The read frequency of that same ser-



(a) Static (b) Dynamic

Figure 3: Average read latency as the per-client read frequency is varied for a hierarchy of 100,000, of which 20,000 access the volume in question.



(a) Static (b) Dynamic

Figure 4: Average server load for handling renewal requests as the per-client read frequency is varied for a hierarchy of one million clients, of which 200,000 access the volume in question.

vice might jump above 0.1 or even near 1 for periods of time during news events of widespread interest as clients constantly monitor the news for new developments. Similarly, emerging program-driven applications might span a wide range of the parameter space.

With respect to lease renewal latency as a function of read frequency, the main observations are as follows:

- Hierarchies can significantly reduce latency for active and popular services.
- The dynamic hierarchy succeeds in matching the latency of the flat Volume Leases algorithm for less active or less popular services while matching the performance of the static hierarchy for busier services. Relative to flat Volume Leases, the static hierarchy can hurt latency for less active or less popular services but can help latency for active and popular services.
- The dynamic hierarchy appears to be a good default choice for this configuration. If a service's access patterns are known and if these access patterns do not change much, then either flat Volume Leases or a static hierarchy may be reasonable, depending on the workload.

Finally, note that the variations among different depths of underlying static trees depend both on interactions between the number of clients under each level of a subtree and on our assumptions on the network distances between subtrees as a function of subtree size. Hence, this experiment should not be used for general comparisons between the number of levels that should be used in the underlying hierarchy.

Figure 3 shows similar experiments but with 100,000 total clients (20,000 of them active) rather than 1,000,000. Comparing these results to those with more clients provides intuition about the effects of scaling the client population, which may help predict system behavior for populations larger than the 1,000,000 that we are able to simulate.

- As expected, increasing (decreasing) the total number of clients decreases (increases) the per-client request rate for which hierarchies begin to pay off rel-

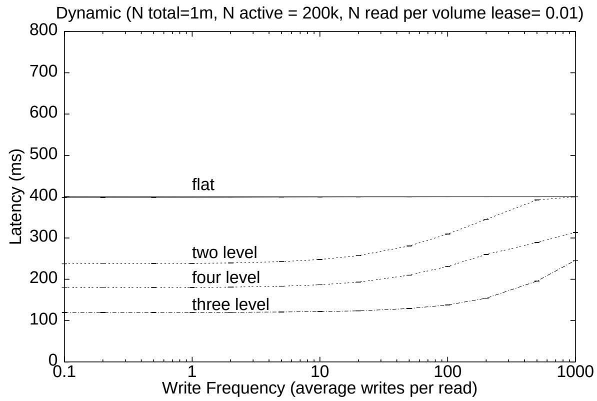


Figure 5: Average read latency under the dynamic algorithm as the write frequency for 10 objects in a server volume is varied. Average read frequency per client is fixed at 0.01 read per client per volume lease period.

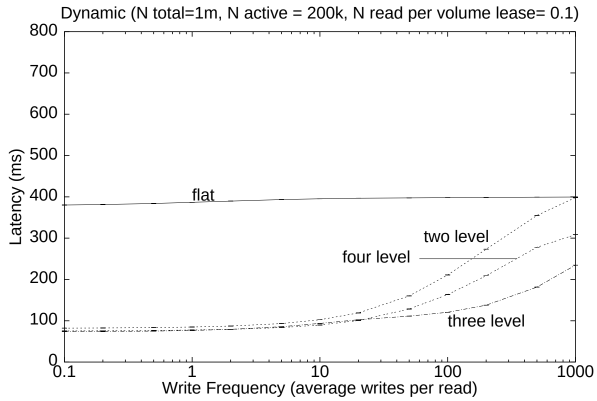


Figure 6: Same as Figure 5, except that the read frequency is 0.1 read per client per volume lease period.

ative to the flat Volume Leases configuration. We observe similar results when we vary the number of active clients (graph omitted).

Figure 4 shows how server load varies with client request rate hierarchies spanning one million clients. (Results for varying the number of active clients or simulating a universe of 100,000 clients are omitted, but are qualitatively similar). Assuming that a server can handle a few thousand requests per volume lease period, we conclude:

- The flat Volume Leases algorithm scales to tens of thousands of clients under workloads corresponding to a range of reasonable web access patterns.
- The addition of hierarchies supports scalability to many millions of clients under nearly arbitrary workloads because it bounds the rate of requests at the root to one request per volume lease period per immediate child of the root.

Writes to multiple-object volumes To make simulating a large scale hierarchy feasible, we have so far considered only the cost of renewing volume leases. We have not examined the cost of renewing or invalidating object leases. This simplification affects our results in two ways. First, it causes us to understate average read time because in reality clients will sometimes have valid volume leases but still need to fetch object leases. This effect should be modest because object leases are much longer than volume leases. Second, this simplification may cause us to understate the benefit of consistency proxies, particularly when read frequency is low, because consistency proxies can cache long object leases more effectively than short volume leases. To calibrate the effect of object leases for popular servers, we run several simulations with multiple object leases per volume. The results are illustrated in Figures 5 to 10. Due to space constraints, we show the graphs for the dynamic hierarchy algorithm and omit those for the static algorithm; the static results differ little from the dynamic ones.

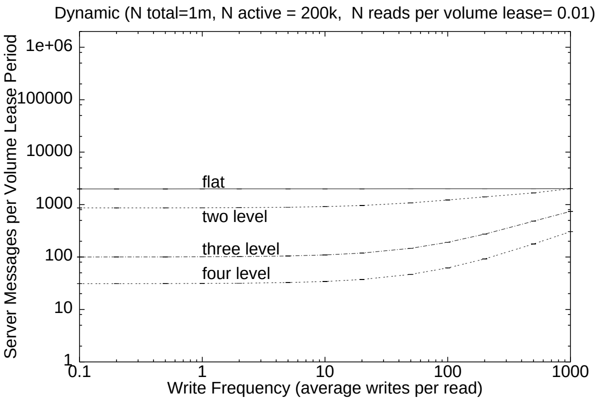


Figure 7: Average server messages per volume lease period under the dynamic algorithm as the write frequency for 10 objects in a server volume is varied. Average read frequency per client is fixed at 0.01 read per client per volume lease period.

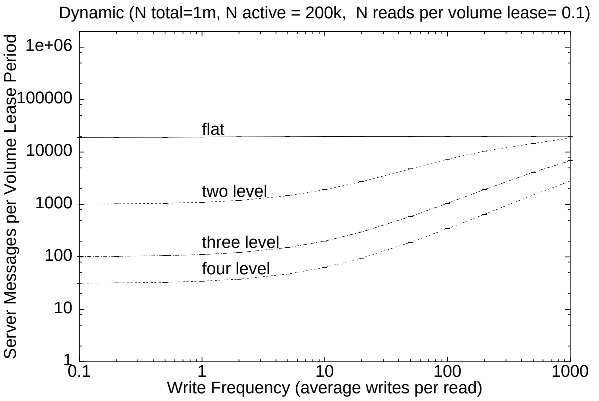


Figure 8: Same as Figure 7, except that the read frequency per client is 0.1 read per client per volume lease period.

In these experiments, the server volume contains 10 objects. Each object is modified independently with average write frequency varying from 0.1 writes to 1000 writes per client read. We illustrate performance for

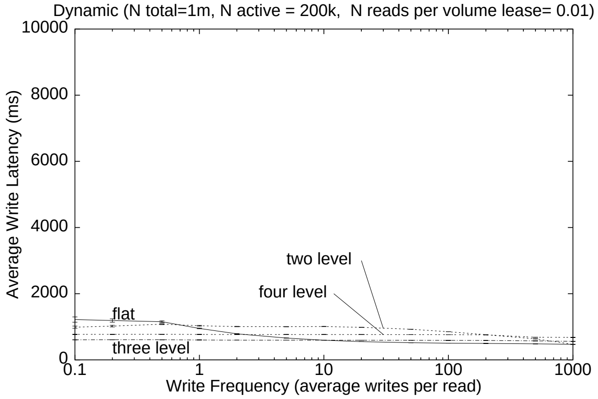


Figure 9: Average write latency seen by server for the dynamic algorithm as the write frequency for 10 objects in a server volume is varied. Average read frequency per client is fixed at 0.01 read per client per volume lease period.

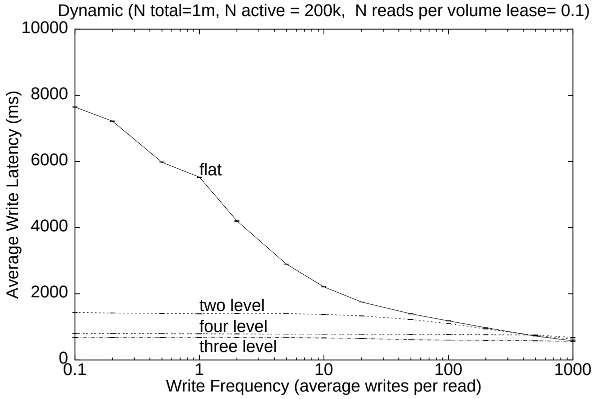


Figure 10: Same as Figure 9, except that the read frequency per client is 0.1 read per client per volume lease period.

servers that have average 0.01 read and 0.1 read per volume lease per client. For example, a system with 30 second volume leases, 3000 seconds between client reads, and 300 seconds between writes would correspond to the *Write Frequency = 10* point in Figure 5.

Figure 5 shows the average read latency as the write frequency changes. Each client issues an average of 0.01 reads per volume lease period. When write frequency is between 0.1 to 10 writes per client read, the results closely match our simplified experiment. Only after write frequency gets higher than 10 writes per client read does the read latency increase become noticeable. Figure 6 is similar to Figure 5, except the read frequency is set to 0.1 reads per volume lease period instead of 0.01. Figures 7 and 8 show the average server load under the same workload as Figures 5 and 6.

Figures 9 and 10 show the average write latency as the write frequency changes. We calculate the write latency by finding the critical path from when the server sends its first invalidation until it receives the final reply. At each node, N, of the hierarchy, we charge $writeCost(N) = nValidChildren(N) \cdot costPerChild + latencyToChild(N) + \max_{\forall c|c \in children(N)}(writeCost(c))$ where $nValidChildren(N)$ is the number of N's direct children that have valid volume leases. Note that by using the *delayed invalidation* optimization [20], the sending of invalidation messages to nodes whose volume leases have expired can be removed from the critical path. The latency to a child is determined by the topology according to our standard formula, and the cost per child is set to 1 ms.

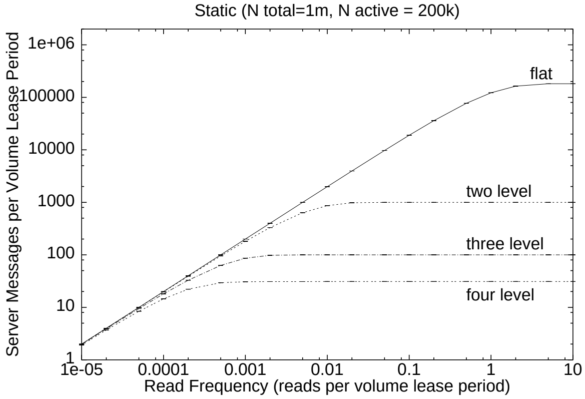


Figure 11: Server lease renewal load as the per-client read frequency is varied for a static server cluster hierarchy serving one million clients, of which 200,000 access the volume in question.

The data indicate three main effects:

- When write frequency increases, the benefit of hierarchy for reads is eroded.
- As write frequency decreases, the write latency increases. This is because the number of valid leases that accumulate between writes, and thus must be invalidated, increases.
- For a frequently accessed popular server, flat volume leases can introduce significant write delays, but hierarchies can remedy this problem.

4.2 Server cluster

The hierarchical consistency mechanisms can be used not only to distribute consistency algorithms across a WAN, but also to split a consistency service across a clustered web server on a local area network (LAN) or system area network (SAN). Although an algorithm optimized for splitting consistency state and load across a cluster with a fast network might marginally outperform our more general mechanisms, such an algorithm must solve the same basic problems of fault tolerance, distributing invalidations, gathering acknowledgments, and partitioning state that our algorithm handles, so the simplicity of using a single framework for both LAN and WAN distribution appears attractive.

Figure 11 shows the load on the server in the server cluster hierarchy where the server and all of the internal nodes of the consistency hierarchy are located in a tightly-coupled cluster, and the lowest internal nodes in the hierarchy communicate across a WAN with the clients. This configuration is not designed to improve latency, just load-scalability. As a result, read latency cannot be affected significantly by modifying the consistency structure. Hence, it is not necessary to build a dynamic hierarchy in this circumstance.

Based on this experiment, we conclude:

- For the server-cluster configuration, the static hierarchy (with split and join for fault tolerance) provides a simple mechanism to scale the flat volume leases algorithm by distributing it across a group of nodes in a cluster; dynamic configuration to minimize latency is not required.

4.3 Server-proxy-client

Figures 12 and 13 show the latency and load measurements when the hierarchy algorithms are run on the server-proxy-client underlying hierarchy with one million clients grouped into 100 proxy-groups of 10,000 clients per group. This experiment suggests two points:

- For low read frequencies, the dynamic hierarchy where clients may contact servers directly has a modest advantage over the static hierarchy.

- At high read frequencies both the static and dynamic configurations significantly outperform the flat configuration.

Figure 14 shows latency for several selected volumes under a trace workload. The workload is the DEC trace [4], and we configure the system with all clients under a single proxy. We map each server in the trace to a different volume. We present results for 8 selected servers: the 4 most popular ones and 4 of medium popularity.

- The trace workloads include multiple objects per volume, and long object leases are easier to cache in a hierarchy. As a result, the static hierarchy begins to pay dividends even with relatively low access rates.

This suggests that for many current web workloads, the simple static hierarchy using the simple server-proxy-client hierarchy may be a reasonable deployment option. This configuration might also provide a practical way to traverse firewalls to deliver consistency signals.

5 Related work

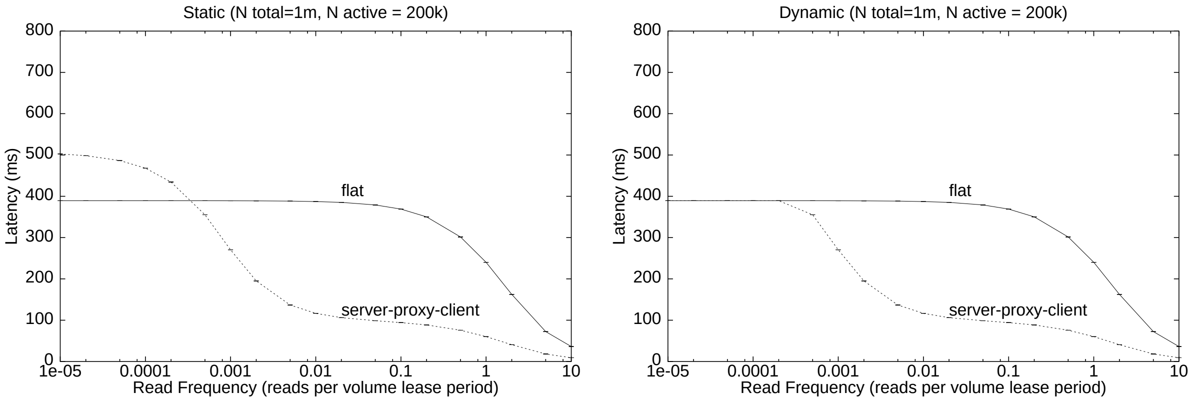
In previous work, we compared non-hierarchical consistency algorithms based on volume leases to traditional callback and polling algorithms. We found that algorithms based on volume leases could both (i) significantly outperform traditional callback or object lease algorithms for a given maximum tolerable server write delay; and (ii) could provide stronger consistency guarantees with performance competitive with callback-based algorithms. Earlier studies by Gwertzman and Seltzer [8] and by Liu and Cao [13] also compare callbacks to polling. Liu and Cao find the performance of the two approaches to be competitive. Gwertzman and Seltzer find that polling with adaptive timeouts can outperform callbacks, but that to gain this advantage the polling algorithm may return stale data more than 4% of the time.

Worrell [19] compares callback and polling protocols in a hierarchical caching system and concludes that the callback algorithms have performance competitive with polling for reasonable time-out values.

Yu et. al [21] independently develop a consistency scheme based on hierarchy, leases, and volumes; this proposal shares many properties with ours, but it differs from ours in three main ways. First, it places a bound on object staleness, whereas our algorithm can be used either to provide strong consistency or to bound staleness [20]. Second, its reconnection protocol requires a client that becomes disconnected to discard all volume and object leases and renew them individually. Third, its consistency servers periodically multicast volume lease renewals and recent object invalidations to their children. Compared to client-initiated volume lease renewal, their approach "pushes" renewals to clients that are not currently accessing a volume; it may thus improve read latency while increasing network traffic and client overheads. Beyond these algorithmic differences, the experimental focus of the study complements ours. Yu et. al primarily focus on comparing the performance of hierarchical invalidation to polling, whereas we focus on understanding the scalability properties of hierarchies.

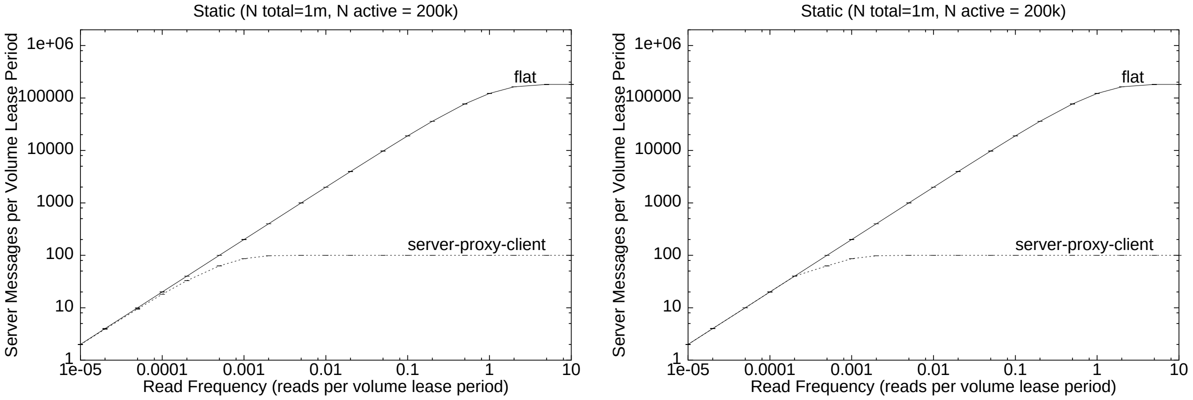
Cohen et. al [3] study the use of volumes for prefetching and consistency. The consistency algorithms they examine are best-effort algorithms based on client polling. Some of their prefetching techniques might also be useful for "prefetching" volume lease renewals in our system. We speculate that adding such prefetching to our system would reduce the read latency cost of hierarchies but magnify the value of hierarchies in reducing server load. Exploring this combination appears to be an interesting area for further study.

Krishnamurthy and Wills [12] examine ways to improve polling-based consistency by piggy-backing optional invalidation messages on other traffic between a client and server. Our volume-based approach allows *de-*



(a) Static (b) Dynamic

Figure 12: Average read latency as the per-client read frequency is varied for a server-proxy-client hierarchy of one million clients, of which 200,000 access the volume in question. In the server-proxy-client hierarchy the internal nodes in the consistency hierarchy are all proxies serving 10,000 clients each.



(a) Static (b) Dynamic

Figure 13: Server lease renewal load as the per-client read frequency is varied for a server-proxy-client hierarchy serving one million clients, of which 200,000 access the volume in question.

	Med 1			Med 2			Med 3			Med 4		
	flat	static	dyn	flat	static	dyn	flat	static	dyn	flat	static	dyn
Latency (ms)	160.5	129.4	135.4	99.0	89.5	92.1	55.6	61.2	57.3	276.3	297.0	279.7
Load (server msgs/read)	0.41	0.23	0.27	0.25	0.16	0.20	0.14	0.12	0.14	0.69	0.57	0.64

(a) Trace results for four medium-loaded volumes.

	Large 1			Large 2			Large 3			Large 4		
	flat	static	dyn	flat	static	dyn	flat	static	dyn	flat	static	dyn
Latency (ms)	84.1	30.8	30.7	123.2	51.1	51.2	133.0	46.7	46.7	68.9	39.3	39.6
Load (server msgs/read)	0.21	0.03	0.03	0.31	0.05	0.05	0.33	0.03	0.03	0.18	0.06	0.07

(b) Trace results for four heavily-loaded volumes.

Figure 14: Average read latency and fraction of renewal requests sent to the server for the four medium-loaded and four heavily-loaded volumes from the DEC trace workload under a server/proxy/client hierarchy in which the internal node in the consistency hierarchy is the proxy serving the DEC clients.

layed invalidations [20] where servers delay object invalidation messages to clients whose volume leases have expired. Combining delayed invalidations with piggybacking may be another useful optimization.

Cache consistency protocols have long been studied for distributed file systems [9, 15, 17]. Several aspects of Coda's [11] consistency protocol are reflected in our algorithms. In particular, our notion of a volume is similar to that used in Coda [14]. However, ours differ in two key respects. First, Coda does not associate volumes with leases, and relies instead on other methods to determine when servers and clients become disconnected. Second, because Coda is designed for different workloads, its design trade-offs are different. For example, because Coda expects clients to communicate with a small number of servers and it regards disconnection as a common occurrence, Coda aggressively attempts to set up volume callbacks to all servers on each hoard walk.

Our reconnection protocol in which clients help servers recover the state they need is based on the server crash recovery protocol in Sprite [1].

Finally, we note that Volume Leases on the set of all objects provided by a server can be thought of as providing a framework for the "heartbeat" messages used in many distributed state systems.

6 Conclusions

In this paper we have shown that the Volume Leases algorithm can provide strong consistency for Internet services with hundreds of thousands of clients. We have also shown how the Volume Leases can be applied to hierarchical caches to perform well for workloads with millions of clients. The key mechanisms, join and split, can be implemented using a simple extension of the Volume Leases algorithm. Finally, we have evaluated a number of hierarchy configurations, and our results show that a dynamically configurable hierarchy provides tremendous amounts of scalability.

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