Efficient Batch Update of Unique Identifiers in a Distributed Hash Table for Resources in a Mobile Host

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Abstract

Resources in a distributed system can be identified using identifiers based on random numbers. When using a distributed hash table to resolve such identifiers to network locations, the straightforward approach is to store the network location directly in the hash table entry associated with an identifier. When a mobile host contains a large number of resources, this requires that all of the associated hash table entries must be updated when its network address changes.

We propose an alternative approach where we store a host identifier in the entry associated with a resource identifier and the actual network address of the host in a separate host entry. This can drastically reduce the time required for updating the distributed hash table when a mobile host changes its network address. We also investigate under which circumstances our approach should or should not be used. We evaluate and confirm the usefulness of our approach with experiments run on top of OpenDHT.

1 Introduction

A distributed system needs a way to identify computing resources that it uses. A common way to identify them is to use a URL [4], which comprises a network address for the host and a path within the host. However, some authors have argued that resource identifiers should contain little or no information, since otherwise an identifier would become invalid whenever there are changes in network locations, storage locations, naming policy, organization, etc. [3, 18, 19]

Using random numbers for resource identification avoids including such information in the identifier. It also makes it easy to allocate identifiers without having to manage the identifier space carefully, since identifier duplication is

¹In http://example.invalid/1/2/3/, for example, the network address for the host would be example.invalid while /1/2/3/ would be the path within the host.

virtually impossible with a large enough identifier space.² However, unique identifiers based on random numbers need to be resolved to actual network locations, which are often composed of a host address and a path within the host, in order for the represented resource to be used. One way to resolve such identifiers is to use distributed hash tables [1, 17]. Most distributed hash tables are scalable and are well suited for storing data indexed by random identifiers.

The most straightforward way to index a resource in a distributed hash table is to simply store an entry in the table with the resource identifier as the key and the network location of the resource as the value. However, this results in performance and latency issues when a mobile host contains many resources, since the network location in each entry must be updated independently whenever the host moves.

For data, this problem can be alleviated by using replication [5, 16]. However, there are many cases when replication is not a feasible option, some of which are listed below:

- Owners of nodes in a distributed hash table may not be willing to contribute large amounts of storage to store data for other people. For example, while they may be willing to store network locations of home videos, they may not be be willing to store the video files themselves.
- An identifier needs to identify a specific master copy of a file in a mobile
 host in order to ensure that updates to the file are immediately available
 to the host.
- The resource in question is inherently not replicable. For example, it could be a network service or sensor specific to a mobile host.

Instead of replication, an alternative approach is to use Mobile IP [12] or the Host Identity Protocol [?] to preserve the network address of mobile hosts. This requires support in the operating system and the network infrastructure. Such support is not widespread, however, so this approach may not be desirable for applications using distributed hash tables.

In this paper, we propose the use of indirect entries in a distributed hash table. An indirect entry contains a host identifier and a host-specific path. A host identifier is a random number which identifies a specific mobile host and is the key to a host entry in the distributed hash table. The network address of the mobile host is obtained from the host entry, which gives the actual network location when combined with the host-specific path. When a mobile host moves, only its host entry needs to be updated.

The remainder of the paper is organized as follows. We discuss related work in section 2. Section 3 describes our proposal and discusses the circumstances under which it should or should not be used. We evaluate it against the straightforward approach in section 4 and conclude in section 5.

 $^{^2}$ Given a 160-bit identifier space, the probability that even a single duplicate identifier would be generated over a 100-year time period with a billion identifiers being generated per second is about 10^{-12} .

2 Related work

The use of random numbers for globally unique identifiers is not uncommon, which takes advantage of the fact that the probability of two different resources being assigned the same random number is extremely low for a large enough identifier space. For example, X.667 defines random-number-based UUIDs [21], while SPKI/SDSI uses hashes of public keys, which for identification purposes are similar to random numbers [6].

Ballintijn et al. argue that resource naming should be decoupled from resource identification [2]. Resources are named with human-friendly names, which are based on DNS [10], while identification is done with object handles, which are globally unique identifiers that need not contain network locations. They use DNS to resolve human-friendly names to object handles and a location service to resolve object handles to network locations. The location service uses a hierarchical architecture for resolving object handles. This two-level approach allows the naming of resources without worrying about replication or migration and the identification of resources without worrying about naming policies.

Walfish et al. argue for the use of semantic-free references for identifying web documents instead of URLs [19]. The reason is that changes in naming policies or ownership of DNS domain names often result in previous URLs pointing to unrelated or non-existent documents, even when the original documents still exist. Semantic-free references are hashes of public keys or other data, and are resolved to URLs using a distributed hash table based on Chord [17]. Using semantic-free references would allow web documents to link to each other without worrying about changes in the URLs of the documents.

Distributed hash tables, also called peer-to-peer structured overlay networks, are distributed systems which map a uniform distribution of identifiers to nodes in the system [1, 17, 22]. Nodes act as peers, with no node having to play a special role, and a distributed hash table can continue operation even as nodes join or leave the system. Lookups and updates to a distributed hash table are scalable, typically taking time logarithmic to the number of nodes in the system. We experimentally evaluated our work using OpenDHT [15], which is a public distributed hash table service based on Bamboo [14].

There has also been research on implementing distributed hash tables on top of mobile ad hoc networks [8, 9]. As with Mobile IP [12] and HIP [?], hosts in mobile ad hoc networks do not change their network address with movement, so there would be no need to update entries in a distributed hash table used for resolving resource identifiers. However, almost the entire Internet is not part of a mobile ad hoc network, so it is of little help to applications that need to run on current networks.

3 Batch update for mobile hosts

The most straightforward way to map a unique identifier to an actual network location is to store a *direct entry* in the distributed hash table for each identifier,

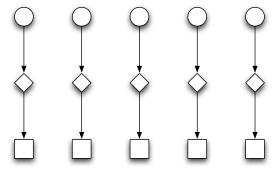


Figure 1: Representation of when identifiers are mapped directly to resources in a single mobile host. Circles denote identifiers, diamonds denote direct entries in the hash table, and squares denote network locations. All of the hash table entries must be updated whenever the mobile host moves.

with the identifier as the key and the actual network location as the value. Resolution is done by simply looking up the identifier in the distributed hash table and using the resulting network location. Figure 1 illustrates this approach.

When the network address of a mobile host changes, this approach requires that entries for every resource contained by the host be updated independently. For a distributed hash table consisting of a constant number of nodes, this requires time linear to the number of resources in the mobile host. When the host contains a large number of resources, this can result in an unacceptably large delay before identifiers can be resolved to their updated location.

Instead of storing the network location directly in a hash table entry for a resource identifier, we propose the alternative approach of storing both an location-independent identifier for the mobile host and the host-specific path in an *indirect entry*. The *host identifier* identifies the mobile host which contains the resource and are random numbers as in ordinary resource identifiers. The distributed hash table contains a host entry which maps this identifier to the network address of the mobile host. The path identifies the specific resource within the host.

In this approach, we first find the corresponding indirect entry for the given resource identifier in the distributed hash table. Once the indirect entry is found, we find the corresponding host entry for the included host identifier. We then combine the network address of the host in the host entry and the path in the indirect entry to construct the network location of the desired resource.³ This requires two lookups to the distributed hash table, compared to a single lookup required for direct entries.

However, updating the distributed hash table when a mobile host changes its network address is much more efficient when using indirect entries compared

³When network locations are given as a HTTP URL, the network address of the host would be an IP address and the port number, while the path would simply be the URL path.

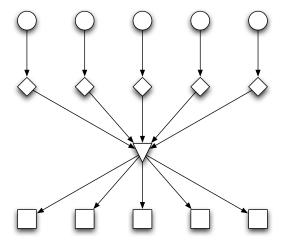


Figure 2: Representation of when identifiers are mapped indirectly to resources in a single mobile host. Circles denote identifiers, diamonds denote indirect entries in the hash table, the triangle denotes the host entry, and squares denote network locations. Only the host entry needs to be updated whenever the mobile host moves.

to using direct entries. Unlike with direct entries, where every entry must be updated independently, only a single host entry needs to be updated when using indirect entries. This can greatly reduce the delay during which resource identifiers cannot be resolved to their correct network locations. Figure 2 illustrates the approach using indirect entries.

3.1 Using direct and indirect entries together

If a host contains only a very small number of resources or almost never changes its network address, then using direct entries would be more efficient because of the smaller lookup overhead. On the other hand, using indirect entries drastically reduces the update latency for a mobile host which contains a large number of resources and changes its network address frequently. Fortunately, both types of entries can be used simultaneously in a single distributed hash table.

Entries in the distributed hash table can be prepended by a magic number which identifies the type of entry they are. The magic numbers are used to distinguish among direct, indirect, and host entries. They also serve to prevent potential conflicts when the same distributed hash table is used for other applications besides resource identifier resolution. Table 1 shows the entry types and their contents, while figure 3 describes the resolution procedure.

Type	Content
	MD, network location
Indirect entry	MI, host identifier, path
Host entry	MH, host network address

Table 1: Entry types and their contents. MD, MI, MH are magic numbers for direct, indirect, and host entries, respectively.

- 1. Find entry indexed by the resource identifier in the distributed hash table.
- 2. If entry is direct entry, return with included network location.
- 3. If entry is indirect entry,
 - (a) Find host entry indexed by the included host identifier.
 - (b) Combine network address of host in the host entry and the path of the resource in the indirect entry to construct the network location of the resource.
 - (c) Return with the network location.
- 4. Otherwise, return that the resource cannot be found.

Figure 3: Resource identifier resolution procedure. This procedure does not treat a host as a resource (extending it so that it does is trivial).

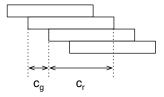


Figure 4: Types of delays during concurrent get operations. c_g is the minimum delay between the operations, while c_r is the delay due to network latency.

3.2 When to use direct or indirect entries

A host can choose whether to use direct or indirect entries for its resources depending on which approach performs better for its needs. But under which circumstances should the host choose which approach? This section discusses this in terms of lookup overhead and update latency.

Since get and put operations to the distributed hash table can be pipelined, where multiple operations may be handled concurrently as in figure 4, we will consider the time costs c_g or c_p for an individual get or put operation separately from the fixed time costs c_r or c_q due to network latency in the get or put operation, which not only comes from accessing the distributed hash table externally but also from the communication among the distributed hash table nodes. We will assume that the number of nodes in the distributed hash table is constant so that these costs are also essentially constant.

When using direct entries, all entries referencing resources in a given host must be updated independently. With n resources in a host, the migration time $c_{m,d}$ required to update all of the entries when it changes its network address is

$$c_{m,d} = nc_p + c_q \tag{1}$$

On the other hand, only a single host entry needs to be updated when using indirect entries, so the migration time $c_{m,i}$ in this case is

$$c_{m,i} = c_p + c_q \tag{2}$$

A direct entry requires only a single get operation to resolve an identifier, whereas an indirect entry requires that it get the indirect entry first and then obtain the appropriate host entry (the two get operations cannot be done concurrently since the second operation is done based on the result from the first operation), so the respective lookup times $c_{l,d}$ and $c_{l,i}$ are

$$c_{l,d} = c_g + c_r$$

$$c_{l,i} = 2(c_q + c_r)$$

If there are r_l lookups per unit time and r_m migrations per unit time, then the overall time costs C_d and C_i per unit time when using direct and indirect entries, respectively, are

$$C_d = r_l c_{l,d} + r_m c_{m,d} = r_l (c_g + c_r) + r_m (nc_p + c_q)$$

$$C_i = r_l c_{l,i} + r_m c_{m,i} = 2r_l (c_q + c_r) + r_m (c_p + c_q)$$

When minimizing the overall time cost, it is better to use indirect entries when

$$C_i < C_d$$

$$r_l(c_g + c_r) < r_m(n-1)c_p$$

$$\frac{r_l}{r_m} < \frac{(n-1)c_p}{c_g + c_r}$$

One may also wish to give more weight to reducing migration times or lookup times. If we set the weights w_m and w_l by how much importance we attach to reducing migration times or lookup times, respectively, we can compute the weighted time costs as

$$C'_{d} = w_{l}r_{l}c_{l,d} + w_{m}r_{m}c_{m,d}$$
$$C'_{i} = w_{l}r_{l}c_{l,i} + w_{m}r_{m}c_{m,i}$$

and then indirect entries should be used when

$$\frac{w_l}{w_m} \cdot \frac{r_l}{r_m} < \frac{(n-1)c_p}{c_q + c_r} \tag{3}$$

Assuming a large n, with W denoting the relative importance of reducing lookup times compared to migration times and R denoting how often lookups occur compared to migrations, equation (3) can be approximately rewritten as

$$WR < \frac{nc_p}{c_g + c_r} \tag{4}$$

Equation (4) agrees with our intuition that direct entries should be used when migration times do not matter or when migrations are rare, and that indirect entries should be used when migration times do matter and happen often for mobile hosts with a large number of resources. It also gives a concrete forumula for deciding whether to use direct or indirect entries.

4 Evaluation

In order to evaluate how using direct and indirect entries perform in a real network, we conducted experiments on OpenDHT [15]. OpenDHT is a public distributed hash table service which runs on about 200 nodes in PlanetLab [?]. We used the service by selecting a single gateway to the distributed hash table and accessing it with the XML-RPC [20] interface throughout our experiments. Here the mobile host is not part of the distributed hash table, similar to how clients are separate from the distributed hash tables in SFR [19] and CoDoNS [13].⁴ Figure 5 illustrates our experimental setup.

⁴In cases where mobile hosts are part of the distributed hash table, the overhead for updating the routing tables should also be considered.

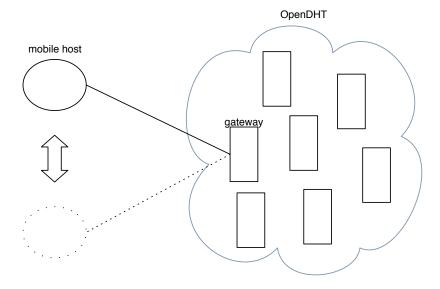


Figure 5: Experimental setup. The mobile host, which can move around and change its network address, accesses OpenDHT through a gateway which is one of the nodes in the distributed hash table.

	Lookup time (s)
Direct	0.53 ± 0.63
Indirect	1.13 ± 0.60

Table 2: Lookup times and their standard deviations.

We compared lookup times and migration times when using direct entries and indirect entries for a single host. The host, a 2.16 GHz Intel Core 2 Duo with 1GB of memory connected to the Internet via Ethernet, was migrated between two network addresses. Resource identifiers were mapped to URLs that point to files. A URL was stored directly in a direct entry, while only the URL path and a host identifier was stored in an indirect entry, with the IP address of the host being stored in a host entry.

We first measured the lookup times for resolving an identifier to a URL. Since lookup for a direct entry requires exactly a single get operation and lookup for an indirect entry requires exactly two get operations, lookup times do not depend on the number of resources in a host.⁵ Thus we measured the average lookup times required by direct and indirect entries by first inserting entries for 5000 resource identifiers into the distributed hash table and then resolving randomly selected identifiers 2000 times for each case. As expected, the average lookup time for indirect entries was roughly twice that of direct entries as can be seen

⁵The time for a get operation should be constant for a distributed hash table with a fixed number of nodes, since network latency dominates the time.

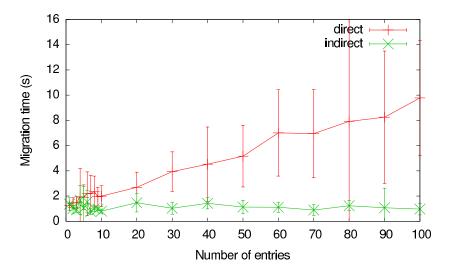


Figure 6: Migration times for up to 100 resources in the mobile host. The error bars denote the standard deviation for each case.

in table 2.

Next, we measured the migration times when using direct or indirect entries with varying numbers of resources in the host. For each number of resources, we first put in the entries for each resource into the distributed hash table. We then migrated the host 100 times and measured the average migration time.

When updating direct entries, 100 entries were updated concurrently, which is much faster than updating each entry one by one. Using significantly larger amounts of concurrency was problematic because the gateway to OpenDHT had problems handling the number of connections.

Also, we selected the entry with the largest remaining time-to-live value when retrieving entries from OpenDHT. This entry is the one that is most up-to-date since we used a fixed TTL value for all entries. We did not have to worry about individual entries becoming large enough to skew the results⁶ since we alternated the host between only two network addresses.

Our results for the migration times are shown in figures 6, 7, and 8, where the host contained up to 100, 1000, and 5000 resources, respectively. We can see that migrating direct entries takes time linear to the number of entries in the host, as is expected from equation (1). On the other hand, the time required for updating indirect entries is essentially constant, as is expected from equation (2).

While migration with indirect entries took only about a second, migration with direct entries took over 4 minutes and a half with 5000 resources contained in the host. Even with only 10 resources, it took about 9 seconds longer to update direct entries compared to the one second it takes to migrate with indirect entries, which can be a significant difference for interactive applications.

⁶OpenDHT returns all unexpired values that have been associated with a key.

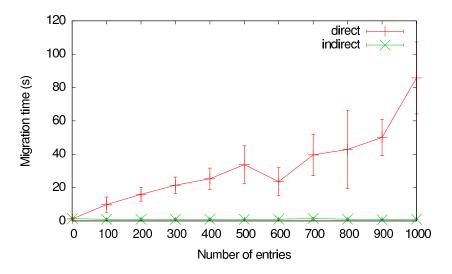


Figure 7: Migration times for up to 1000 resources in the mobile host. The error bars denote the standard deviation for each case.

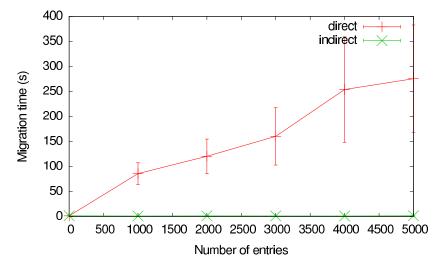


Figure 8: Migration times for up to 5000 resources in the mobile host. The error bars denote the standard deviation for each case.

Mobile hosts could contain even more resources than what was tried in our experiments. For example, the home directory in a personal machine of one of the authors contains more than 60,000 files. A straightforward extrapolation from our results suggests that this case would require almost an hour for migration when using direct entries.

These results show that the drastic reduction in migration time by using indirect entries over direct entries can be worth the small increase in lookup time required when resolving indirect entries.

5 Conclusions

When identifying resources in a distributed system using identifiers based on random numbers, the most straightforward way to resolve identifiers with a distributed hash table is to store the network location directly in the entry keyed by the identifier. However, when a mobile host which contains multiple non-replicable resources changes its network address, all of the associated entries in the distributed hash table must be updated.

When the number of resources in the mobile host is large, updating all of the entries so that remote hosts can properly use resources in the mobile host can take a long time. Therefore we proposed an alternative approach, where the entry keyed by the resource identifier contained only a host identifier and host-specific path for the resource, and the host identifier itself is a key to a host entry containing the actual network address for the mobile host.

With our proposed approach, only the host entry needs to be updated when the mobile host changes its network address. This can drastically reduce the delay during which its resources cannot be resolved to their current network locations, as was shown theoretically and experimentally. However, there is a small increase in the time required for resolving identifiers with our approach, so we also discussed under which circumstances it should not be used.

In our work, we only consider whether to use direct or indirect entries given static lookup and migration rates. It would be interesting to see how an adaptive system could dynamically adjust the approach used in order to achieve optimal performance with changing lookup and migration rates, since such a system would also have to consider the overhead for switching between the two.

It may also be possible to apply system-specific optimizations to our approach. For example, while our approach can be applied to any type of distributed hash table, it could be possible to reduce the lookup overhead when it is applied on top of OpenDHT by taking advantage of the ReDiR framework.

We plan to apply our approach in a decentralized and unified naming system we are developing, where it would improve performance for identifying resources such as files and network services located inside mobile devices in a persistent and location-independent manner.

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