Stealth Distributed Hash Table: A Robust and Flexible Super-Peered DHT

Andrew Brampton, Andrew MacQuire, Idris A. Rai,
Nicholas J. P. Race and Laurent Mathy
Computing Department,
Lancaster University
{brampton,macquire,rai,race,laurent}@comp.lancs.ac.uk

ABSTRACT

Most Distributed Hash Tables (DHTs) simply consider interconnecting *homogeneous* nodes on the same overlay. However, realistically nodes on a network are heterogeneous in terms of their capabilities. Because of this, traditional DHTs have been shown to exhibit poor performance in a real-world environment. Additionally, we believe that it is this approach that contributes to a limited exploitation of peer-to-peer technologies. Previous work on super-peers in DHTs was proposed to address these performance issues, however the strategy used is often based on locally clustering peers around individual super-peers. This method of super-peering, however, compromises fundamental features such as load-balancing, resilience and routing efficiency, which traditional DHTs originally promised to offer.

We propose a Stealth DHT which addresses the deficiencies of previous super-peer approaches by using the DHT algorithm itself to select the most appropriate super-peer for each message sent by peers. Through simulations and measurements, we show the fitness for purpose of our proposal.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Distributed networks*;
C.2.4 [**Computer-Communication Networks**]: Distributed Systems

General Terms

Algorithms, Performance, Experimentation

Keywords

Distributed Hash Tables, Peer-to-Peer, Stealth DHT

1. INTRODUCTION

A common design approach for Distributed Hash Tables (DHTs) simply considers interconnecting *autonomous* and *homogeneous* nodes on the same overlay. The autonomicity of nodes arises in the sense that any node may join or leave the network, and perform any operation supported by the DHT such as *routing messages* or *putting* and *getting* data (indexed by *keys*) as they wish. On the other hand, the homogeneity of nodes assumes that nodes are equally capable devices which trust each other at the highest level.

Clearly, these assumptions are unrealistic for any practical large scale network. This is demonstrated by various measurement studies of peer-to-peer file sharing systems, which have shown a natural inequality in the capabilities and behaviour of peers [20]. This leads to DHT based systems often operating at a level of performance far below that which is expected. Indeed, lookup latencies can be seriously affected by a node that has become a routing bottleneck due to a lack of bandwidth or CPU cycles. Another example is when nodes continually join and leave the network in an unpredictable fashion, there can be tremendous increase in network overhead. This behaviour is often referred to as *churn*, severe levels of which have been shown to cause many DHTs to simply break down [8, 16, 18].

A classical approach to improving this situation is to leverage the natural heterogeneity in the system by using *super-peers* [14, 25]. However, most DHT-based super-peer proposals rely on multiple overlays (*e.g.* maintaining several rings) and suffer from a rather static binding between peers and super-peers (*i.e.* the same super-peer proxies for peers' whole sessions). This, in turn, leads to a higher maintenance overhead, as well as potentially single point of failure and load-balancing issues.

In this paper we propose a simple, yet elegant technique applicable to the majority of existing DHT systems, which enables the use of super-peers in DHT-based networks, while avoiding the deficiencies of previous super-peer approaches. Our proposal, the *Stealth Distributed Hash Table* (Stealth DHT), differs from traditional DHTs mainly in that it makes a subset of nodes effectively "invisible" to the routing and forwarding decisions on the network. Therefore, these nodes never receive any queries and thus cannot intercept nor reply to them. As they are hidden from the rest of the overlay, these nodes are referred to as *stealth nodes*. In contrast, the nodes responsible for forwarding messages in the DHT are referred to as *service nodes* (and are therefore equivalent to super-peers). Salient features of a Stealth DHT are that it maintains a single overlay, and that any source node (including stealth nodes) uses the original routing decision process found in traditional DHTs to choose the first hop of their message. In other words, the original DHT routing is used for super-peer selection on a per message basis, meaning there exists no single point of failure in the Stealth DHT approach – preserving all of the benefits of traditional DHTs whilst enabling super-peering.

Realistically, we envisage service nodes making up a relatively small percentage of nodes in the DHT, perhaps owned by a single entity as a means of service provision. It therefore follows that they should ideally be highly stable and capable machines (*e.g.* dedicated servers). Conversely, stealth nodes are expected to be heterogeneous, autonomous devices owned by end-users and are likely to connect and disconnect from the network in an unpredictable fashion.

In this paper, we focus on evaluating the performance of Stealth DHTs in comparison with a traditional DHT, both with and without churn in the DHT population. While we believe that a Stealth DHT can be created from almost any of the numerous existing algorithms to date, we chose Pastry [19] to be used in our performance evaluation, as we deemed it to be a good representation of a typical DHT. We later use both simulations and an implementation running on PlanetLab [15] to critically evaluate our approach. In particular, we show how a Stealth DHT can reduce messaging overhead, reduce object retrieval latency, provide greater resilience under churn and more, all for the cost of increased load being placed on a small number of (presumably over-provisioned) nodes.

The rest of the paper is organised as follows. In Section 2, we present a brief overview of traditional DHT concepts, then continue by discussing the details of a Stealth DHT in Section 3. We explain our evaluation methodology and go on to show a number of results in Section 4. We then discuss potential applications of the Stealth DHT work in Section 5. Work related to our proposal is elaborated upon in Section 6 and finally we conclude the paper in Section 7.

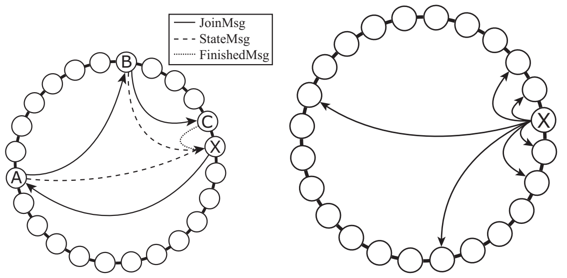
2. DHT OVERVIEW

Distributed Hash Tables (DHTs) have been shown to be a promising form of decentralised structured peer-to-peer networking, offering substantial scalability and resilience. Unsurprisingly, there exist numerous DHT systems [19, 22, 24, 17]. Primarily, DHTs serve as an object location service that can be used as a substrate for multiple large-scale distributed applications such as storage [5, 3, 10], multicast [2, 26] and load balancing systems [9, 7].

Many DHT algorithms have a similar structure, wherein each node on the network has a unique identifier (ID), randomly generated within the address space. The address space is dynamically partitioned into regions depending on the number of nodes and their addresses. Each region is then assigned to a single node.

Each key in the DHT is generated by applying a hash function to the object it represents, producing an identifier that falls within a specific region of the address space. The DHT algorithm ensures that the key is held by the node responsible for that region. In most implementations a node will maintain relatively sparse routing state spanning the entire address space, which will grow with increasing numbers of nodes in the DHT.

A reference to an object can then be retrieved by sending a request message addressed to the value of the corresponding key. The DHT routing algorithm then ensures that this message is actually delivered to the node responsible for the region of the address space where the key falls.



(a) State Gathering Phase (b) Announcement Phase

Figure 1: *Join Procedure*

When a new node joins a DHT, it must first initialise its routing table. The assumption is made that the new node will know at least one established node on the network. This *bootstrap* node can be used to route a *join* message to the region that the joining node's ID lies within.

DHTs normally provide good routing performance in terms of average overlay hops, varying slightly depending on the routing algorithm used. The actual trend will often depend on the geometry of the DHT itself. For instance, Pastry, Chord and Tapestry [19, 22, 24] are all based on the common ring structure, giving approximately $O(logN)$ hops, where N is the number of nodes in the DHT. Content Addressable Network (CAN) [17], however, is a d-dimensional space, instead giving $(\mathrm{d}/4)(\mathrm{N}^{1/d})$ hops on average.

The following section provides an overview of the Stealth DHT approach based upon Pastry.

3. STEALTH DHT OVERVIEW

A Stealth DHT differs from a traditional DHT in that it splits the network into nodes of two differing types: *service* and *stealth*. Service nodes are expected to be highly capable, reliable machines, and they provide the routing infrastructure for the overlay. Stealth nodes are "clients" that communicate with and through service nodes only. Note however, that the assignment of role to nodes is application dependent and in no way prescribed or constrained by the Stealth DHT itself. Future work may involve automatic assignment of roles to nodes to improve the autonomicity of the system. This paper concentrates on the modifications required for a Stealth Pastry DHT, however we believe that similar simple general principles can be applied to other DHTs too.

3.1 Service Node Join

A service node is a fully-fledged DHT node and joins the (Stealth) DHT in conformance with the method prescribed by the original DHT.

It is worth noting that the join procedure in traditional DHTs conceptually has two phases: a state gathering phase at the end of which the joining node will have received enough information (routing, *etc.*) to take part in the DHT, and an announcement phase through which the joining node advertises its presence on the overlay to some of the nodes already present.

The state gathering phase in Pastry is depicted in

Fig. 1(a). Remember that a service node joins the network in the same way a typical Pastry node would. A Pastry (or a service) node X uses prior knowledge of a bootstrap (service) node A to route a join message into the DHT, destined for the (service) node closest to X's randomly generated ID. Upon receiving and forwarding the message, (service) nodes A and B send a relevant fraction of their routing table directly to X. The join message then arrives at its destination C (the closest (service) node to X's ID). C, in addition to sending routing data, informs X about neighbourhood information (*i.e.* leafset) and that finishes the state gathering phase. Node X then proceeds with the announcement phase (see Fig. 1(b)) to announce its presence and ID on the ring to some other (service) nodes. The main purpose of this announcement is to enable the presence of X in other nodes' routing tables.

3.2 Stealth Node Join

A stealth node joins the Stealth DHT by only completing the state gathering phase of the original DHT, and ignoring the announcement phase. This is illustrated in Fig. 1(a), but in this case node X is a stealth node and all other nodes depicted are service nodes. In particular, the reader should note that the node used as bootstrap node should be a service node.

The effect of not initiating any announcement phase is that no service node ever learns to route through a stealth node. In other words, a stealth node never appears in any routing table, yet a stealth node is able to route messages into the DHT using the routing information it acquired during the state gathering phase. Stealth nodes are therefore capable of injecting messages into the DHT, choosing the first hop for their messages from their routing table in the same way 'normal' DHT nodes do, but are never used to relay any message, nor will they ever receive any message on the DHT (unless a message is sent directly to them from a service node *e.g.* a reply to a query). This results in a single overlay (in our example case a single DHT ring) that accommodates both the service and stealth nodes.

From a functional point of view, stealth nodes can publish and retrieve keys in and from the DHT respectively. These operations are achieved by sending simple put or get messages. However, as stealth nodes never receive put messages, only service nodes can store keys, conferring them the status of super-peers.

As stealth nodes never appear in routing tables, several stealth nodes may inadvertently choose the same node ID without collisions being detected. Likewise, a new service node could also choose the same node ID as an existing stealth node without it being detected. The only detectable collisions involving a stealth node are those occurring when a new stealth node chooses a ID that already identifies an existing service node. This is because ID collisions are detected when the join message destination's ID is the same as the last hop's node ID. In such cases, a *collision* message is returned to the joining node instead of the *finished* message. However, because stealth nodes do not relay messages nor hold keys, their IDs are never required to locate them on the DHT ring so that unresolved node ID collisions involving stealth nodes do not pose any problem to the operation of the Stealth DHT. In essence, stealth nodes only pick a node ID to gather routing information. Of course, the detectable stealth node ID collisions can be resolved by having the stealth node select a new ID and then issue a new stealth join message.

Note that stealth nodes have no way of detecting the presence of other stealth nodes, while service nodes can only know of stealth nodes through their recent activity, hence the name of our scheme which exhibits enhanced privacy properties compared to the original DHT. A further benefit is that the lack of announcement messages cuts the overhead of joining stealth nodes significantly.

3.3 Stealth Routing State

Several observations can be made about the routing state needed by stealth nodes. Firstly, the role of the leafset in Pastry is to ensure that message routing always completes correctly [19]. However, since stealth nodes only initiate routing of messages (by selecting the first hop), it is clear that a stealth node does not need to maintain a leafset which is only used to consistently determine the last hop.

Secondly, if node IDs are represented in base 2^b, the routing table is conceptually a $log_{2^b}N \times 2^b$ array, where N is the size of the address space. This is because the entries of row n of any node Z contain references to nodes whose IDs share a common ID prefix of length n digits, and therefore it is impossible to have more than $log_{2^b}N$ digits in common. The $n+1$ ID digit corresponds to column number of the entry, and again there are only 2^b different digits.

The routing procedure for a node that needs to send / forward a message is to select the row of its routing table corresponding to its prefix match with the destination ID (the first row of the routing table is row 0 corresponding to no prefix match) and pick as a next hop the entry of the column corresponding to the value of first (non-matching) digit of the destination ID. This ensures that the next hop of the message shares a longer ID prefix with the destination than the current node does (and is therefore closer to the destination). This very concise and simplified description of the routing procedure is enough for our discussion and we refer the reader to [19] for further details of Pastry routing.

If we observe that the probability for two randomly chosen IDs not to share any prefix is $\frac{2^b-1}{2^b}$, we see that in the vast majority of cases, the initial sender of a message will use the first row of its routing table to select the first routing hop. Indeed, in the typical case where $b = 4$ (IDs in base 16), this situation occurs $15/16 = 93.75\%$ of the time. Recalling that stealth nodes are always the origin of any messages they send through the DHT, then it is obvious that reducing the routing information in stealth nodes to the first row of the routing table will have very little impact on routing performance while greatly reducing state overhead. In other words, the service nodes that handle the join message for a stealth node should only provide such node with routing information contained in the first row of their routing table (as opposed to information from the full routing table). It is natural to question the performance gain when stealth nodes use a single row routing table (with at most 2^b nodes' IDs) compared to when they have a list of a random 2^b nodes' IDs from existing service nodes. We discuss the benefits of using the former in Section 4.2.5.

Lastly, from the above description of routing, it should be clear that one column per row of the routing table contains an empty entry: this is the column corresponding to the $n+1$ digit of the ID of the node holding the routing table (*i.e.* the node itself). This is because the corresponding entry in row

n would then share a prefix of length $n+1$ with the node, and should therefore belong on the following row. For stealth nodes, which only have a single row in their routing table, this would mean that there would be no next hop entry for destinations whose IDs have the first digit equal to that of the stealth node. The only way a stealth node could then send toward such destinations would be to pick any other entry at random from their routing table and let that node (which does not share any prefix with the destination) decide on a more appropriate next hop. To avoid such sub-optimal "dog leg" routes, we require that stealth nodes do have an entry pointing to a node that share a one-digit prefix with the stealth node ID in the otherwise empty column entry. This ensures that a complete and valid routing table at a stealth node will always provide a next hop that has at least a one-digit prefix with the destination.

3.4 Stealth Routing State Maintenance

When a service node leaves the network, some stealth nodes will inevitably have obsolete information for that node in their routing tables. Complete disconnection, however, can only occur when all service nodes in a stealth node's routing table have left the DHT. Just like service nodes, a stealth node will detect a failed service node in its routing table when it attempts to send a message to that node, or through maintenance probes.

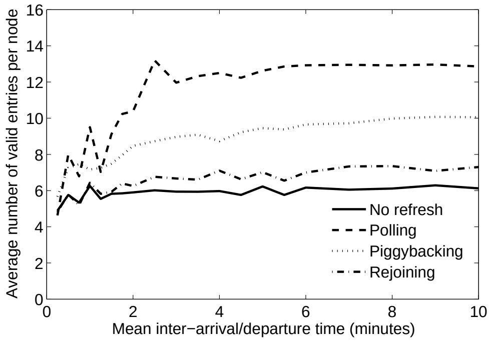
One problem that arises as a result of the isolation of stealth nodes is that their routing tables are difficult to keep up to date. To recap, stealth nodes never receive announcement messages from newly arrived service nodes as they are not addressable on the DHT. A new method is therefore required for maintaining routing state at stealth nodes. We propose several possible approaches: *rejoining*, *periodic polling* and *piggybacking*.

A stealth node could rejoin the Stealth DHT on a periodic basis. This can be done without changing its chosen node ID and can even bootstrap through any entry of its routing table.

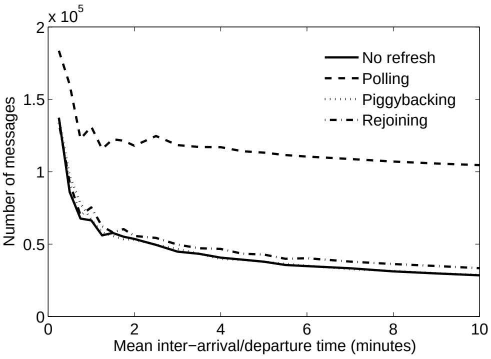
Periodic polling is a variation of rejoining where a stealth node periodically queries any of the service nodes in its routing table for its current relevant routing state (as opposed to all the nodes on the path to a service node closest to its ID).

The piggybacking approach requires service nodes to attach some additional routing state to every message it sends to a stealth node[1]. Upon receiving each message from a service node, a stealth node checks these attached IDs to see if they can be used to update its routing table. This approach allows the routing tables in stealth nodes to stay fresh whilst being updated in a passive fashion. An added benefit is that the mechanism is "self-tuning": the more active a stealth node is on the network, the fresher and more complete its routing table is.

To evaluate the respective merits of these different approaches for refreshing routing state in stealth nodes, we have run the same simulation scenario for each, with varying rates of churn (refer to Section 4 for details on the simulation setup). Fig. 2(a) shows the average number of valid routing entries in stealth node routing tables (*i.e.* one row with 2^b entries where $b = 4$), while Fig. 2(b) shows the overall number of messages observed during the scenario (*e.g.* queries, routing updates, *etc.*). Note that the period for polling was set to 100 seconds, while that for rejoining to 5 minutes.



(a) Validity of routing entries



(b) Overhead

Figure 2: *Stealth routing state refresh*

From these results, it seems clear that polling provides the best routing table maintenance, albeit at the highest cost. This is due to two messages being generated at each polling interval (the request and reply message). In contrast, the rejoining mechanism updates state 3 times less frequently than polling, but only generates $log_{2^b}N$ message per join. Overall, piggybacking appears to offer a better accuracy versus cost tradeoff, as it does not increase the number of messages (although it does slightly increase the message size) while keeping the routing table fresh.

4. EVALUATION

In order to evaluate our Stealth DHT proposal, we developed our own discrete-event packet-level simulator for Pastry and Stealth DHTs, because existing Pastry simulators did not offer all the features we required. We also implemented both Pastry and a Stealth DHT for evaluation in a real-world environment (PlanetLab). As with our simulator, we considered modifying an existing open-source project such as FreePastry or Bamboo [4, 18], but found the flexibility of creating our own implementation to be preferable.

Throughout the paper, we describe Stealth DHTs networks as *Stealth (S%)*, where $S\%$ of nodes on the DHT are stealth nodes. For example, when we discuss the performance of a Stealth (95%) DHT, it implies that 95% of the existing nodes are stealth nodes (*e.g.* on a 1,000 node DHT,

---

[1] Recall that although stealth nodes are not addressable on the DHT, a service node will communicate directly via the underlying network with a stealth node when responding to a solicitation from it.

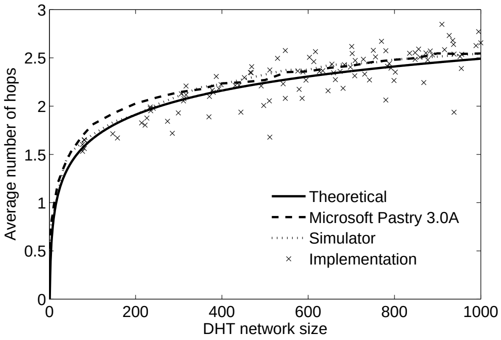


Figure 3: ***Simulator and implementation validation***

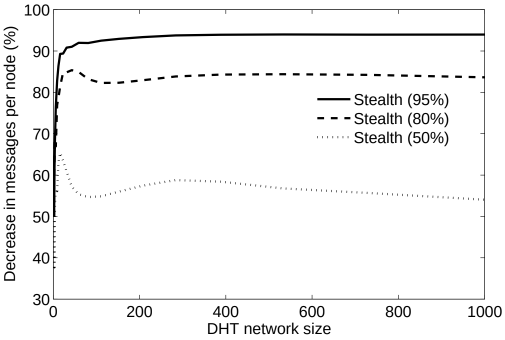


Figure 4: ***Percentage decrease in messages generated***

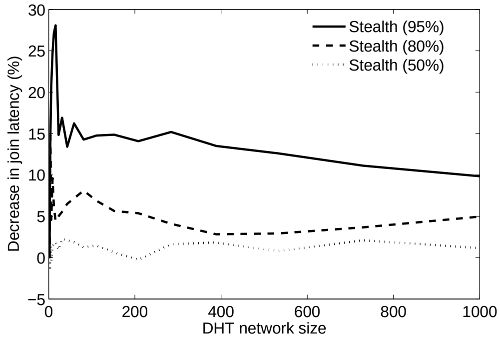


Figure 5: ***Percentage decrease in join latency***

950 stealth and 50 service nodes would exist). This is a value used repeatedly throughout the paper, as it clearly shows the differences that using a Stealth DHT can make; with lower values, results have been found to tend towards that of the corresponding Pastry DHT.

In both the simulator and the implementation, 1,000 or more randomly generated keys were initially put into the network. Each key was assigned a popularity ranking following a Zipf distribution with an α parameter of 1.2. Whenever a node performs a *get* operation, the probability of it choosing a particular key depends on this distribution, thus providing a realistic popularity function as commonly observed in web-page access, caching systems, peer-to-peer filesharing [21], etc. In all figures where the network is of a fixed size, 1,000 nodes were used, 95% of which were stealth nodes, if applicable.

4.1 Validation

In order to validate both our simulator and our implementation, we compared our results with both Microsoft's own Pastry simulator [19] (MS Pastry version 3.0A) and theoretical values. We found that they all produced similar results. As an example, each DHT was found to give hop count performance of approximately $log_{2^b}N$ as expected, where N is the number of nodes in the network; this result is shown in Fig. 3. We used the optimisation of Proximity Neighbour Selection (PNS) [19] within the two simulators and also compared lookup latency and overlay stretch on identical topologies.

4.2 Simulations

In the following sections, we explain and evaluate the simulation workloads used on a case by case basis. The exact parameters used in each simulation reflect what we believe to be a good balance between practicality and accuracy. In all cases we ran our simulations with at least 5 iterations on a 1,000 router transit-stub topology (with 4% transit nodes), generated by GT-ITM [1]. DHT nodes were then connected to this topology in a random fashion via realistic bandwidth/latency end-host links.

4.2.1 Join Performance

As explained in Section 3, stealth nodes make use of a simpler join mechanism in comparison with service or traditional DHT nodes. We therefore compare the overhead of join operations between Pastry and a Stealth DHT by first measuring the number of messages generated during the construction of the DHT. In both Pastry and the Stealth DHT, new nodes joined by contacting randomly selected existing nodes. The exact number of messages obtained is comprised of the initial join message, replies sent back to the joining node and, where appropriate, the messages sent from the joining node announcing its existence.

Fig. 4 shows the percentage decrease in the number of generated messages per node[2] as a function of network size in comparison with Pastry. The figure clearly illustrates that for DHT networks of identical size, the Stealth DHT has a consistently lower join overhead than Pastry in terms of messages. As an example, we see that for a Stealth DHT with 95% Stealth nodes, approximately 90% fewer messages are generated than the equivalent Pastry network. A major factor in the lower join overhead in the Stealth DHT is that stealth nodes do not have to announce their presence on the network. A further contributing factor is that a Stealth DHT by its very nature has fewer nodes performing routing operations. This means that messages will travel fewer hops on average, which in turns means that fewer nodes will send joining nodes routing state, as this is performed on a per-hop basis. Finally, and although not shown in Fig. 4 (which deals exclusively in DHT messages), service nodes and traditional DHT nodes have to periodically send keep-alive messages to their close neighbours (leafset) to ensure correct routing; as stealth nodes do not route messages, this is unnecessary, leading to another reduction in overhead.

The second metric we use to analyse join performance is

---

[2] We define percentage decrease as $100\times(1-\frac{M_{Stealth}}{M_{Pastry}})$, where M represents the performance metric in question.

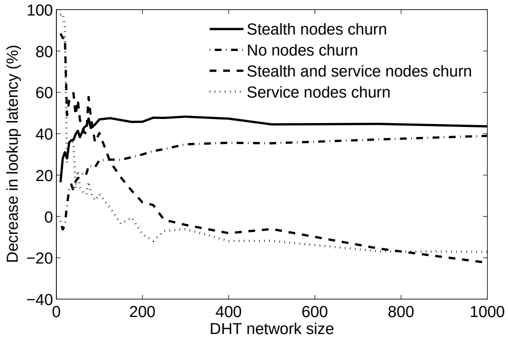


Figure 6: ***Percentage decrease in lookup latency relative to Pastry***

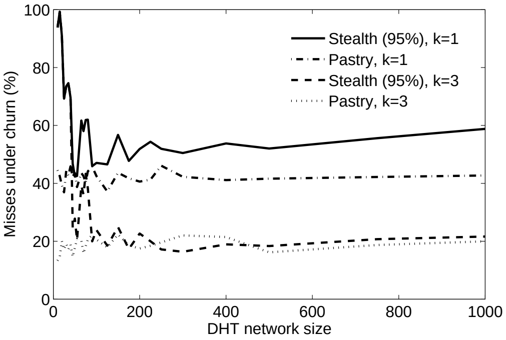


Figure 7: ***Percentage of misses under churn***

join latency, defined here as the time elapsed between a node sending its initial *Join* message and it receiving a *JoinFinished* message from the recipient. It therefore represents the time taken for a node to receive its routing state, but not the time taken for other nodes to also be able to route to it. This therefore allows for a fair comparison between Pastry and a Stealth DHT, as stealth nodes send no announcement messages.

Fig. 5 shows the percentage decrease in join latency relative to Pastry. It shows that for a 95% stealth node DHT, nodes can expect to join 10-15% faster than the equivalent Pastry DHT. As a Stealth DHT provides a lower hop count per message on average, it has a correspondingly lower end-to-end overlay latency. Accordingly, as the number of service nodes tends towards that of Pastry's overall nodes, the join latency also tends towards that of Pastry. Of course, if announcement messages were also taken into account, we would expect to see a trend more favourable to Stealth DHTs for larger network sizes.

4.2.2 Storage and Retrieval

If a DHT is viewed purely as a black-box system, then two of the most important performance metrics are how quickly keys can be retrieved, and how likely a given key is to be retrievable when network conditions are unstable.

We therefore begin by defining *lookup latency* as the time elapsed between a node performing a *get* for a specific key in the DHT and it receiving a reply. Fig. 6 shows the percentage decrease in lookup latency relative to Pastry for a Stealth DHT with 95% stealth nodes. Each line on the figure represents a different level of stability in the network, as in this simulation (and several other simulations throughout the paper), we churn selected sets of nodes whilst performing *get* operations. Both the get request rate and inter-arrival/departure time are dictated by an exponential distribution with a mean of six minutes unless otherwise specified.

The figure clearly shows that even without churn on moderately sized networks, the Stealth DHT provides over a 30% decrease in lookup latency. When both stealth and Pastry nodes churn, however, the decrease in latency relative to Pastry is significantly higher, providing a reduction of between 40% and 50%. The reason for this is churning stealth nodes have a minimal effect on the routing efficiency of the Stealth DHT, whereas in Pastry, churn causes much poorer routing due to the number of invalid routing entries that result.

As we expect service nodes to be highly stable machines, we believe that the comparisons without churn and with stealth node churn to be the most important. However, for completeness, we also examined the effect of exclusively churning service nodes, as well as churning both service and stealth nodes. Fig. 6 shows how both cases have an understandably detrimental effect on the Stealth DHT, resulting in performance which is approximately 20% worse than Pastry for larger networks. Interestingly, when both stealth and service peers churn, the average performance is slightly improved over when service nodes alone churn. We attribute this to the fact that the churning stealth nodes are getting fresher routing tables when they rejoin than the persistent stealth nodes whose routing tables become increasingly stale.

It is important to note that the reply to a lookup may be simply to inform the requesting node that the data associated with the requested key was not found in the DHT. All service or traditional DHT nodes are obliged to reply to these requests, regardless of whether they have the data in question or not. This behaviour explains why, in Fig. 6, when service nodes churn for very small networks there is a tremendous reduction in latency relative to Pastry. It follows that if very few service nodes exist, the time taken to receive a response will be greatly decreased, regardless of the fact that it may not contain the requested data. Accordingly, we refer to the case when a node successfully retrieves a given object as a *hit*, and otherwise as a *miss*.

As stealth nodes do not store keys, it follows that the average number of keys per service node on a Stealth DHT is increased compared with nodes on a normal Pastry network of similar size. Unfortunately, this means that when a service node is disconnected, a larger fraction of keys on the network are also lost. To reduce the impact of such an event, keys can be replicated amongst several service nodes (of course, this can equally be done amongst traditional DHT nodes).

Fig. 7 shows the result of simulating object retrieval under churn both with and without replication in Pastry and a Stealth DHT. The Stealth DHT consisted of 95% stealth nodes, wherein only the nodes holding keys churned.

In our simulations there existed three cases when the percentage of misses was always 0% (*i.e.* gets are always successful): Pastry with no churn, a Stealth DHT with no churn and a Stealth DHT with only stealth nodes churning. Thus, these results confirm that the stability of stealth nodes has no impact on key availability.

We show that by replicating keys just twice (*i.e.* $k = 3$), the percentage of misses that occur are decreased significantly. Obviously, for very small network sizes (*e.g.* 2 service nodes for 23 stealth nodes), a Stealth DHT performs poorly if the service nodes churn. Once sufficient service nodes exist, however, the Stealth DHT manages to match the performance of an equivalent Pastry DHT, despite it having significantly fewer nodes holding keys. In this case, both Pastry and the Stealth DHT have a miss rate of approximately 20% under churn. Again, we use an exponentially distributed inter-arrival/departure time with a mean of 6 minutes; it remains important to note that we envision service nodes as being much more stable machines, and that this result is shown for completeness only.

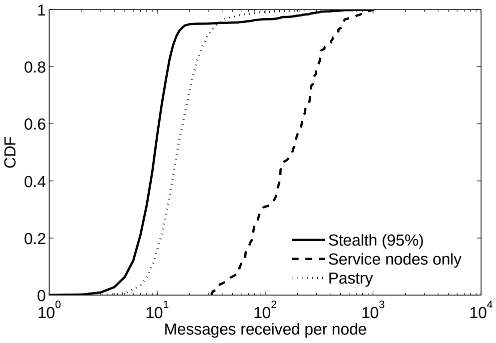
4.2.3 Load-Balancing

As already mentioned, in a Stealth DHT all storage and routing responsibilities are placed on the service nodes alone. We therefore studied the message overhead per node and the corresponding number of packets per link on the underlying network in order to assess the impact of these alterations on load-balancing.

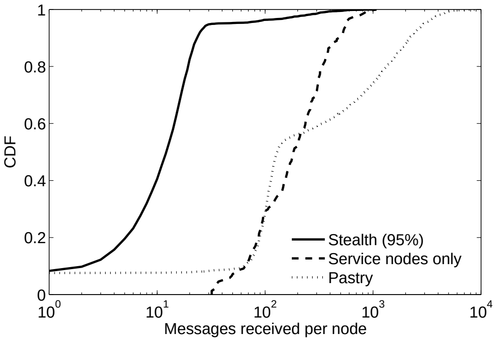
In the following simulations, DHTs consisting of 1,000 nodes were created for both Pastry and a Stealth DHT with 95% stealth nodes. 10,000 get requests were sent through the course of the simulation, randomly divided amongst all the nodes on the DHT; each node would therefore send approximately 10 requests. The exact key that each node requests is again dependent on a Zipf distribution, as outlined in Section 4.

Figs. 8 show the cumulative distribution function (CDF) of received messages per node both with and without churn for Pastry, a Stealth DHT with 95% stealth nodes, and the Stealth DHT's service nodes alone. We first note that the distribution of messages per node for the Stealth DHT exhibits the same expected non-uniformity for the network both with and without churn with only 5% of the nodes handling between 20 and 1,000 messages, and 95% of nodes receiving less than or equal to only 20 messages. In this simulation, only stealth and Pastry nodes churned. The CDF of received messages per service node is also shown on the figure, showing a slightly more uniform distribution for received messages for service nodes than for all nodes. This shows that a Stealth DHT retains the ability to balance load amongst its service nodes.

In contrast with the Stealth DHT, Figs. 8 also show that the distribution of messages for Pastry without churn differs from that with churn. For the case without churn, the CDF of messages shows a gentler slope and a smoother curve than for the Stealth DHT, with Pastry nodes receiving between around 1 to 1,000 messages, as with the Stealth DHT. The steepness of the curve indicates the expected uniform distribution of messages amongst the nodes for Pastry. As seen in Fig. 8(b), the distribution of messages among nodes in Pastry *under churn* is, unexpectedly, not uniform. We observe that the variation of messages per node is significantly higher for Pastry between 1 and 10^4 compared to 30 and 10^3 for service nodes. Thus, under churn service nodes actually experience less load than a typical Pastry node due to the fewer maintenance messages required.



(a) *Without churn*



(b) *With Churn*

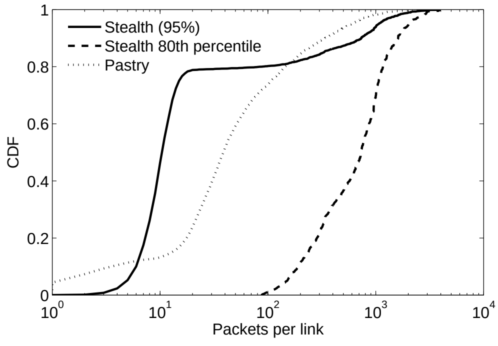
Figure 8: *Distribution of received messages per node*

Figs. 9 show the CDFs of packets per physical link for Pastry, a Stealth DHT with 95% stealth nodes, and the 80^{th} percentile of links in a Stealth DHT, for cases with and without churn. Packets per link is also known as link *stress*. Similar trends to Figs. 8 are shown for both Pastry and a Stealth DHT when there is no churn. Expectedly, around 80% of the links in the Stealth DHT handle less than or equal to 20 packets, and the remaining 20% of links handle between 20 and 4×10^3 packets. The resultant performance is near-identical regardless of churn. Of interest is the stress performance difference between Pastry with and without churn. We observe from Fig. 9(b) that under churn, the distribution of packets per link in Pastry varies highly, causing a small percentage of links to handle significantly more packets compared to when there is no churn.

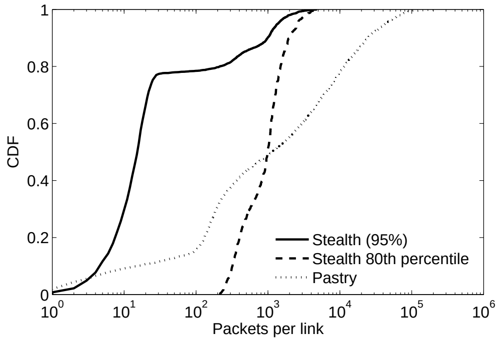
To verify that no link was uniquely overloaded in the Stealth DHT, we plotted the CDF of packets for the 80^{th} percentile of packets per link, which is observed to be quite uniform and unaffected by churn (see Figs. 9).

We further compared the performance of Pastry and a Stealth DHT with 95% stealth nodes in terms of the average and maximum stress as a function of network size, both with and without churn. These results are shown in Figs. 10. Expectedly, links in the Stealth DHT experience higher average and maximum stress performances than links in Pastry when there is no churn. This is because packets in a Stealth DHT are more likely to follow similar paths than in Pastry due to a smaller number of routing service nodes (only 5% of all nodes).

Fig. 10(b) shows the stress performance under churn. The results show that links under Pastry experience much higher average and maximum stress than links in the Stealth DHT.

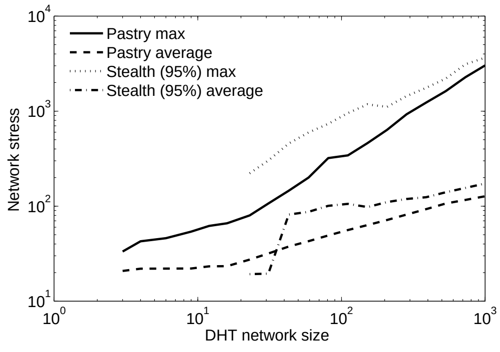


(a) *Without Churn*

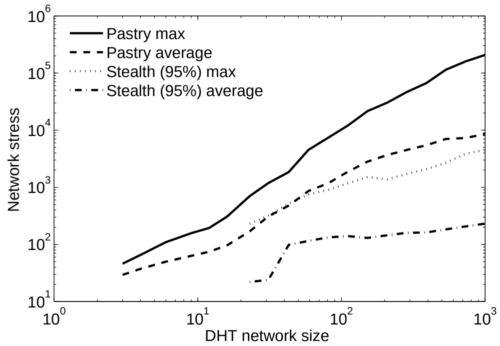


(b) *With Churn*

Figure 9: ***Distribution of packets per link (Stress)***



(a) *Without churn*



(b) *With Churn*

Figure 10: ***Number of packets handled per link as a function of network size***

Take a network of 1,000 nodes for example, Pastry results in average and maximum stress of 10^4 and 2×10^5 compared to average and maximum stress for the Stealth DHT of only 200 and 4×10^3 respectively.

To sum up, Figs. 8 and Figs. 9 show that Pastry under churn distributes load less effectively between its nodes than a Stealth DHT does amongst its service nodes. Whereas Figs. 10 shows that Stealth DHTs lead to higher maximum stress than Pastry, while actually providing lower average and maximum stresses when under churn. We attribute the unbalanced load and the increase stresses in Pastry to the many messages generated when a node churns. The combination of the *join* and the *announcement* messages causes each Pastry node to see approximately an order of magnitude more messages than a Pastry node not under churn. Since stealth node on the other hand do not use *announcement* messages, service nodes see much less messages than their Pastry counterparts.

4.2.4 The Effect of Increasing Churn

While we assume that service nodes are stable machines, it is important to know what to expect if, for some reason, they become unstable. We therefore examined how a Stealth DHT with 95% stealth nodes performed under increasing levels of churn.

Fig. 11 shows the percentage of misses as a function of decreasing churn rate. From the figure we can see that as mean inter-arrival/departure time decreases, the percentage of misses increases steadily, climbing increasingly rapidly for the highest rates of churn. It is also clear from the figure that regardless of the rate of churn, replication provides a significant improvement in key availability.

4.2.5 Improvement Over Random Selection

As mentioned in Section 3.3, one may argue that the complexity of using a routing table with a single row is unnecessary, if randomly selecting a first hop from a set of 2^b randomly obtained service nodes offers similar performance. However, by simulating both scenarios with 1,000 nodes (95% stealth) we show that this is not the case.

Fig. 12(a) shows the percentage increase in end-to-end latency when randomly selecting a first hop relative to using a single row routing table. Clearly, we observe that both approaches exhibit similar performance for small networks (fewer than 20 nodes), whereas as network size increases above 20, we see that a random selection results in higher latencies with increasing discrepancy as a function of network size. For example, for a network of 1,000 nodes, a random selection produces a 30% increase in end-to-end latency.

The improved performance observed for a single row routing table is due to the fact that the first hop under random selection makes little or no progress towards the message destination. In particular, while DHT paths are made up of a series of hops of exponentially decreasing length, the first random hop potentially adds a long hop to the path; thus seriously degrading the quality of the overall end-to-end path.

Fig. 12(b) shows the CDF of messages received per service node for both scenarios. We first observe that the number

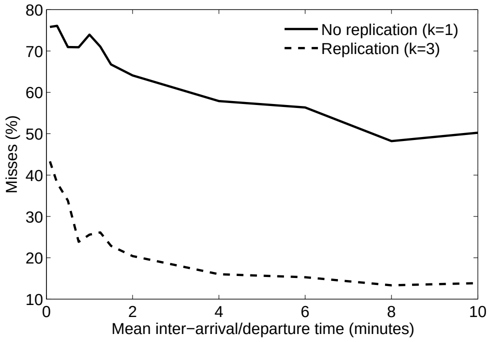
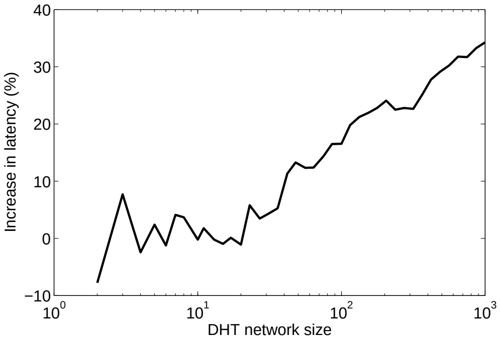
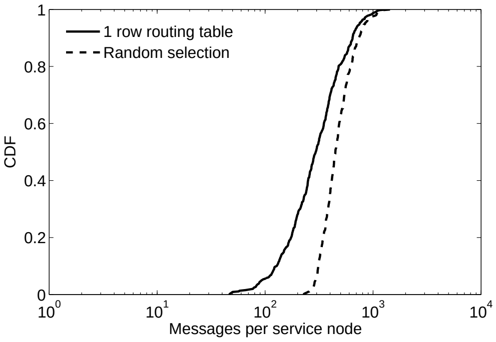


Figure 11: ***Percentage of misses under decreasing churn***

of messages per node is higher if nodes select their first hop randomly. For instance, around 40% of the service nodes in the Stealth DHT receive fewer than 200 messages, whereas if the first hop is randomly selected then all nodes receive more than 200. This shows that random selection also results in a larger average number of messages than if a single row routing table is used. The percentage of nodes that receive a large number of messages is similar for both cases, and is caused by the combined effect of the Zipf popularity for the keys, as used in the simulations, and normal DHT routing behaviour. Indeed, this similarity is to be expected, as the set of nodes chosen as the first hop in the Stealth DHT case is the same as the set of nodes chosen as the second hop in the random case.



(a) Percentage increase in end-to-end latency



(b) Number of messages received per service node

Figure 12: ***Comparison between the use of a single row routing table and random selection***

4.3 Implementation

In addition to simulations we also created and deployed an implementation of a Pastry-based Stealth DHT onto PlanetLab [15]. This section compares the performance of Stealth DHT to that of Pastry while running on a real-world platform. PlanetLab provides roughly 600 nodes, but at any time roughly only 400 of these were active. Every implementation run we used a randomly selected set of nodes from the pool of 400. Each node ran four instances of our implementation, thus when we have results for 1200 nodes, this actually represents 300 physical machines, each hosting four nodes. When we used the Stealth DHT portion of the implementation, we randomly selected which nodes would be service nodes and which would be stealth nodes from the pool of available nodes. However, we ensured that at most one instance of a service node would be run on any physical machine. The nodes would then use a random *bootstrap* node from the set of joined service nodes, thus providing a uniformly distributed load during join.

While using PlanetLab we encountered some limitations in the use of our implementation, these were the common problems of timing and unpredictable node failures. Given the number of physical nodes used and their geographical diversity, it is perhaps to be expected that many would have their clocks incorrectly set and/or be prone to occasional failure. We therefore examined all retrieved data carefully, discarding results where necessary.

We first examine the overhead caused by joins. This was also looked at within the simulator in Section 4.2.1, but in Fig. 13 we verify if these overheads hold true in the real-world. Here we plot the number of messages generated on average when a single node (service or stealth) joins the network as a function of network size. This includes the initial join message, the state sent back to the node and also the announcements sent back into the network. Pastry nodes consistently generate between 30 and 50 messages for each join; the majority of these are the announcement messages, and messages sent to nodes' leafsets. In the case of Stealth DHTs, when a stealth node joins these announcement and leafset messages are not generated, thus producing values between 5 and 15 messages per join (for the considered network sizes of 50%, 80% and 95% stealth nodes).

Fig. 14 shows the average number of hops a *get* message takes to get to its destinations for differently sized networks. Lines of best fit are also plotted for clarity. These results show the same trends as the simulation results, as well as the expected results. However, in all cases they exhibit slightly more hops than the anticipated values: 15% for Pastry and between 10% and 12% for the stealth DHT lines. These increased hop counts can be explained by Fig. 15.

While running our implementation on PlanetLab, we found that there were a significant number of nodes with non-transitive connectivity (*i.e.* a node A may be able to contact B, B may be able to contact C, but C cannot contact A) [6]. Fig. 15 shows the percentage of messages that experience at least one failed hop between source and destination. This does not indicate that the message failed to be delivered, just that the optimal path failed and a alternative route was taken. When an alternative route is taken this adds to the end-to-end delay of the message, as well as de-

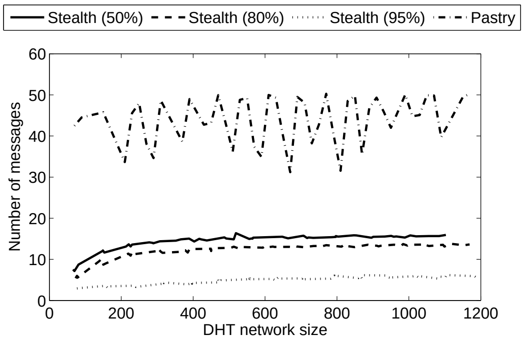


Figure 13: ***Average number of messages generated per node during a single join***

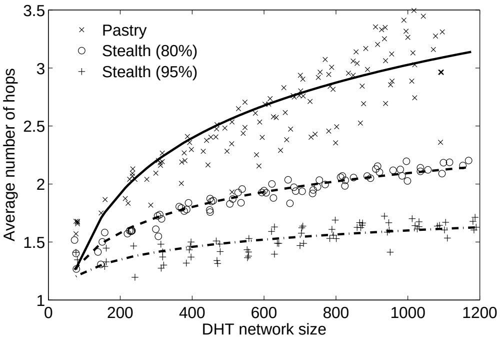


Figure 14: ***Average DHT hops for get message in varying sized Pastry and Stealth networks***

grading DHT network performance. The results for Stealth DHTs are excluded from the plot for clarity but have similar points with similar trend lines.

5. APPLICATIONS OF STEALTH DHT

The Stealth DHT approach has several noteworthy features that make it appealing for a number of applications. As one might expect, any application that can make use of a traditional DHT could also be implemented on top of a Stealth DHT, often leveraging the additional properties offered to provide greater functionality and performance. The benefits, such as scalability, resilience, improved performance and so forth should be common to all applications built upon the Stealth DHT foundation.

A good example of where nodes may have low capabilities and a short lifetime is a mobile environment. The nature of mobile communications means that these nodes are particularly likely to cause churn, which causes serious problems for traditional DHTs [8]. It is also important that such nodes be able to join the network quickly and efficiently, otherwise the time taken connecting to the network may dominate their lifespan. A Stealth DHT therefore provides an ideal solution by supporting mobile nodes as stealth nodes as discuss in [13].

Commercial applications such as content delivery networks could also make good use of a number of specific features. By using identification and authentication (*e.g.* digital certificates) in conjunction with a Stealth DHT, a

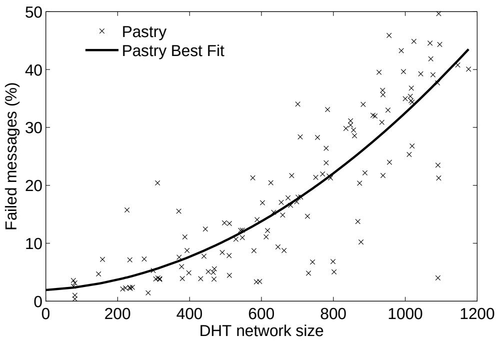


Figure 15: ***Percentage of messages that experience at least one failed hop on their path as a function of network size***

(DHT) service provider can control which operations nodes are allowed to carry out. For example, an announcement message (see Section 3.1) can be discarded and ignored by service nodes if it does not carry proper credentials, ensuring that only authorised nodes join as service nodes. In the same manner, a DHT service provider could control who publishes what on its network as well as using the authentication information provided to trace content publishers if need be, whilst being able to guarantee to clients (stealth nodes) that they will only talk to trusted nodes (service nodes). These are by no means an exhaustive list of the powerful control a DHT service provider can regain through the combined use of Stealth DHT and authentication. Such control would, in turn, allow the service provider to repel some of the major common security issues present in peer-to-peer networks, such as sniffing, man-in-the-middle, pollution and some denial-of-service attacks, while still benefiting from the scalability and resilience of these networks. We also discuss this topic further in [12].

Certain applications may also require that the source of messages be addressable on the DHT. As no state regarding stealth nodes is stored in service nodes, this is impossible without an extension to the Stealth DHT.

Recall that service nodes deliberately avoid keeping any state on stealth nodes as a means of improving performance and security. It is therefore important to design addressability mechanisms for stealth nodes that do not jeopardise these basic design principles. We propose two application-specific solutions to this issue: *Registration* and *Encapsulation*.

Registration, as the name suggests, involves stealth nodes registering their existence with the service node closest to their IDs in the address space, by simply sending a registration message towards their own ID. The corresponding service node can then record the registering stealth node's ID and pertinent other details in what we refer to as a *Addressing Table*[3]. The registration method therefore allows the service node with which a stealth node registered to forward the appropriately addressed DHT messages to it. Registration information can also be used to detect collisions between stealth node IDs (see Section 3.2) and take appropriate remedial action.

In request-response circumstances, where service nodes

---

[3] The information in an addressing table should be maintained using an appropriate soft-state mechanism.

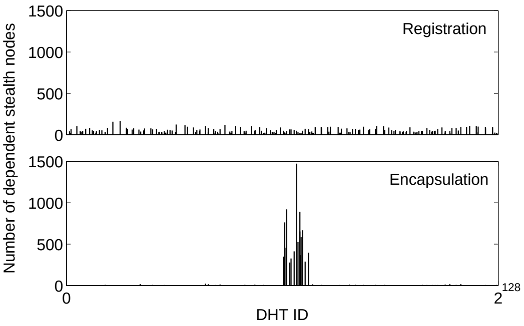


Figure 16: ***Stealth nodes addressability: service nodes overhead***

only need to be able to reply to stealth nodes via the DHT rather than direct unicast, then our encapsulation method may provide a better solution. In encapsulation, the service node which happens to be the first hop of a stealth node's message records information about this message for a limited time, and forwards it on as though the message was sent by the service node itself. The message also contains a local identifier associated with the message[4]. Note that stealth node ID collisions may not be a problem with this method, as the information held in message records can include differentiating information such as the stealth nodes' IP addresses. Collisions would then be resolved as different local identifiers.

Fig. 16 shows the number of dependent stealth nodes per service node for a DHT with 10,000 stealth nodes and 200 service nodes. For registration, each stealth node registered, while for the encapsulation example, each stealth node sent a message to the same service node. The more uniform repartition of stealth nodes among service nodes is obviously explained by the fact that both service and stealth nodes are uniformly distributed across the overlay and registration information is kept at the service node closest to the corresponding stealth node. The apparent concentration of state on just a few service nodes in the encapsulation case is caused by the routing strategy which, in essence, divides the DHT ring into 2^b equal regions and always strives to find a first hop within the region where the destination lies (in our case this destination is unique). The observant reader will have noticed that with encapsulation, service nodes outside this restricted region also hold a small amount of encapsulation state. This is caused by incomplete or invalid entries in some stealth node routing tables, forcing these nodes to pick a first hop at random.

The choice of stealth node addressability mechanism is application dependent and the results above are provided solely to guide such a choice.

6. RELATED WORK

A number of previous works have also proposed improving DHT performance by separating network nodes into groups of more and less capable nodes, wherein the more capable nodes are often referred to as *super-peers*. Indeed, the notion of incorporating such a strategy into traditional DHT algorithms is seemingly similar to that of our Stealth DHT proposal. However, we should stress that there are a number of key differences in our approach.

Mizrak *et al.* [14], and Zhu *et al.* [25], suggested similar architectures that utilised a dual overlay DHT where one overlay exists for the super-peers, and another for the normal peers. In these approaches peers will forward onto the super-peer overlay first via their nearest super-peer, which continues forwarding towards the destination super-peer. In turn the destination super-peer moves the message back onto the normal overlay. The problem with this approach is that each normal peer is associated with a single super-node, which results in a single point of failure, and also requires each super node to retain a large amount of state. In our system, stealth nodes are connected to the DHT itself, albeit without appearing to other nodes. The advantage of our approach is that a stealth node is not reliant on any one service node for connectivity; in the event of a failure, the DHT algorithm will automatically ensure that a suitable replacement can forward any data that a stealth node wishes to send without extra overhead. In addition, as stealth nodes decide their own first hop we achieve slightly improved levels of routing performance.

Xu *et al.* [23] suggest a DHT where nodes are only added into the routing tables after the node has appeared on the network for a given length of time. This allows the more stable nodes to be identified and used in preference. However this technique requires continuous probing of newly joining nodes to calculate their stability. They claim that this additional overhead is less than the maintenance overhead required when there is churn, however they have left their evaluation as future work.

The topic of how churn affects DHTs has also been widely discussed. Rhea *et al.* [18] demonstrated how many DHT implementations simply break under high levels of churn, especially with high levels of background traffic. As a consequence, any attempt to use a traditional DHT with unstable nodes (mobile clients, for example), is unlikely to yield acceptable performance. While there have been several efforts to solve this issue[8], they still involve placing unstable nodes into the DHT itself whilst using complex algorithms to attempt to lessen the effect of churn. Our system takes a simpler approach in that as stealth nodes are not allowed to forward data, their transient nature does not affect the routing performance of the network.

In Section 3.2, we discussed that one of the benefits of stealth DHTs is that it is relatively inexpensive in terms of the number of messages generated to join a stealth node to the network. Nodes on a traditional DHT, however, often exchange substantial numbers of messages when a new node joins. Making this process more efficient has been discussed previously [23], however Li *et al.* [11] point out that a number of DHT studies do not look at all the parameters, such as the amount of bandwidth consumed.

7. CONCLUSIONS

We have proposed a simple, yet elegant method to support super-peering in DHTs. Our stealth DHT proposal accommodates both super-peers (service nodes) and other peers (stealth nodes) in a single overlay structure. Furthermore, Stealth DHTs provide for the isolation of stealth nodes, therefore avoiding numerous security and privacy issues as well as providing non-negligible performance improvement.

---

[4] Original message fields and the local identifier may be encoded as optional header field

Straightforward extensions to Stealth DHTs have also been shown to support applications that may require to communicate with all peer nodes using the overlay routing. From a scalability, resilience and robustness perspective, a Stealth DHT exhibits the same properties as the original DHT, because stealth nodes use the original routing mechanism to choose the first hop for their messages on the DHT, and therefore does not exhibit single points of failures even in the presence of service node churn, whilst preserving a direct route to the destination. Furthermore, as service nodes actually act as fully-fledged DHT nodes, a Stealth DHT with no stealth nodes would behave like the original DHT.

When coupled with identification and authentication, Stealth DHTs can confer a level of control to the super-peers that is unprecedented in today's peer-to-peer networks. Indeed, such control can equal that provided by traditional server-based solutions, but without compromising the many advantages afforded by the distributed DHT solution. In essence, the Stealth DHT concept goes a long way towards the best of both worlds.

Finally, despite their simplicity, the principles underlying Stealth DHT can be seen as a major enabler of more commercial exploitation of DHT technology, therefore unleashing the true potential of structured peer-to-peer technologies.

8. REFERENCES

[1] K. Calvert and E. Zegura. Georgiatech internetwork topology models.

[2] M. Castro, P. Druschel, A.-M. Kermarrec, and A. Rowstron. SCRIBE: A large-scale and decentralised application-level multicast infrastructure. *IEEE Journal on Selected Areas in Communications (JSAC)*, 20(8), 2002.

[3] F. Dabek, M. F. Kaashoek, D. Karger, R. Morris, and I. Stoica. Wide-area cooperative storage with CFS. In *Proc. of ACM SOSP*, October 2001.

[4] P. Druschel, E. Engineer, R. Gil, Y.-C. Hu, S. Iyer, A. Ladd, A. Mislove, A. Nandi, A. Post, C. Reis, A. Singh, and R. Zhang. Freepastry implementation.

[5] P. Druschel and A. Rowstron. A large-scale, persistent peer-to-peer storage utility. In *Proc. of the Eigth Workshop on Hot Topics in Operating Systems*, pages 75–80, May 2001.

[6] M. J. Freedman, K. Lakshminarayanan, S. Rhea, and I. Stoica. Non-transitive connectivity and DHTs. In *Proc. of USENIX WORLDS 2005*, December 2005.

[7] P. B. Godfrey and I. Stoica. Heterogeneity and load balance in distributed hash tables. In *Proc. of IEEE INFOCOM*, March 2005.

[8] H.-C. Hsiao and C.-T. King. Mobility churn in DHTs. In *Proc. of the 1st International Workshop on Mobility in Peer-to-Peer Systems (MPPS'05)*, pages 799–805, June 2005.

[9] D. R. Karger and M. Ruhl. Simple efficient load balancing algorithms for peer-to-peer systems. In *ACM Symposium on Parallelism in Algorithms and Architectures*, pages 36–43, June 2004.

[10] J. Kubiatowicz. Oceanstore: An architecture for global-scalable persistent storage. In *Proc. of the ASPLOS 2000*, November 2000.

[11] J. Li, J. Stribling, R. Morris, M. F. Kaashoek, and T. M. Gil. A performance vs. cost framework for evaluating DHT design tradeoffs under churn. In *Proc. of IEEE INFOCOM*, Miami, FL, March 2005.

[12] A. MacQuire, A. Brampton, I. A. Rai, and L. Mathy. Authentication in Stealth Distributed Hash Tables. In *Proc. of the 32nd Euromicro Conference on Software Engineering and Advanced Applications*, August 2006.

[13] A. MacQuire, A. Brampton, I. A. Rai, and L. Mathy. Performance analysis of Stealth DHT with mobile nodes. In *Proc. of the 3rd IEEE International Workshop on Mobile Peer-to-Peer Computing*, Pisa, Italy, March 2006.

[14] A. T. Mizrak, Y. Cheng, V. Kumar, and S. Savage. Structured superpeers: Leveraging heterogeneity to provide constant-time lookup. In *Proc. of the Third IEEE Workshop on Internet Applications (WIAPP'03)*, pages 104–111, 2003.

[15] L. Peterson, D. Culler, T. Anderson, and T. Roscoe. A blueprint for introducing disruptive technology into the Internet. In *Proc.of the 1st Workshop on Hot Topics in Networks (HotNets-I)*, October 2002.

[16] H. Pucha, S. M. Das, and Y. C. Hu. How to implement DHTs in mobile ad hoc networks? In *Proc. of the 10th ACM International Conference on Mobile Computing and Networks*, September 2004.

[17] S. Ratnasamy, P. Francis, M. Handley, R. Karp, and S. Shenker. A scalable content-addressable network. In *Proc. of ACM SIGCOMM*, August 2001.

[18] S. Rhea, D. Geels, T. Roscoe, and J. Kubiatowicz. Handling churn in a DHT. In *Proc. of the USENIX Annual Technical Conference*, June 2004.

[19] A. Rowstron and P. Druschel. Pastry: Scalable, distributed object location and routing for large-scale peer-to-peer systems. In *Proc. of the 18th IFIP/ACM International Conference on Distributed Systems Platforms (Middleware)*, pages 329–350, Nov. 2001.

[20] S. Saroiu, P. K. Gummadi, and S. D. Gribble. A measurement study of peer-to-peer file sharing systems. In *Proc. of MMCN*, 2002.

[21] K. Sripanidkulchai. The popularity of gnutella queries and its implications on scalability. In *OReillys http://www.openp2p.com*, Feb. 2001.

[22] I. Stoica, R. Morris, D. Karger, F. Kaashoek, and H. Balakrishnan. Chord: A scalable peer-to-peer lookup service for Internet applications. In *Proc. of ACM SIGCOMM*, pages 149–160, August 2001.

[23] Z. Xu, R. Min, and Y. Hu. Reducing maintenance overhead in DHT based peer-to-peer algorithms. In *Proc. of Peer-to-Peer Computing (P2P03)*, 2003.

[24] B. Y. Zhao, L. Huang, J. Stribling, S. C. Rhea, A. D. Joseph, and J. Kubiatowicz. Tapestry: A resilient global-scale overlay for service deployment. *IEEE Journal on Selected Areas in Communications*, 22(1):41–53, 2004.

[25] Y. Zhu, H. Wang, and Y. Hu. A super-peer based lookup in structured peer-to-peer systems. In *Proc. of the 16th International Conference on Parallel and Distributed Computing Systems (PDCS'03)*, 2003.

[26] S. Q. Zhuang, B. Y. Zhao, A. D. Joseph, R. H. Katz, and J. D. Kubiatowicz. Bayeux: An architecture for scalable and fault-tolerant wide-area data dissemination. In *Proc. of NOSSDAV*, June 2001.