Distributed Overlay Anycast Tables using Space Filling Curves

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***Abstract*—In this paper we present the *Distributed Overlay Anycast Table*, a structured overlay that implements application-layer anycast, allowing the discovery of the closest host that is a member of a given group. One application is in locality-aware peer-to-peer networks, where peers need to discover low-latency peers participating in the distribution of a particular file or stream. The DOAT makes use of network delay coordinates and a space filling curve to achieve locality-aware routing across the overlay, and Bloom filters to aggregate group identifiers. The solution is designed to optimise both accuracy and query time, which are essential for real-time applications. We simulated DOAT using both random and realistic node distributions. The results show that accuracy is high and query time is low.**

I. Introduction

Anycast is a service that allows a host to discover a *close* host which is a **member** of a given **group**, where proximity is defined by a metric like the number of hops or the delay over the IP path. Allowing the application to locate nearby object replicas, anycast is beneficial to Content Distribution Networks[1], peer-to-peer data distribution systems and WWW replication architectures.

In anycast systems, hosts register their membership to groups with their closest anycast-enabled routers. Each group is associated with a distinct anycast address. Traffic sent to an anycast destination address is routed to the closest host registered as a member of the corresponding group. It is up to the routing infrastructure to maintain host group memberships, exchange anycast routes and route the data to the closest member host.

However, due to limitations in routing table sizes, addressing schemes and computational costs, the widespread deployment of anycast at the network layer (*Network Layer Anycast*, NLA) has been proven problematic, focusing instead on small groups of application-specific hosts, such as the root DNS servers.

[1]such as http://www.akamai.com or http://www.limelight.com

An alternative to NLA, *Application Layer Anycast* (ALA) bypasses the addressing and memory constraints in edge and core routers by delegating anycast routing functions to the hosts themselves. ALA peers organise themselves in an overlay network, where links represent peering relationships to exchange routing information and to forward messages to anycast destination hosts. Unlike NLA, ALA hosts use the overlay network only to discover anycast destination hosts, not to route their data. The latter is done separately, over the IP network. The process of discovering an ALA group member host is called ALA *querying*.

Although traditional applications can benefit from anycast, the greatest benefits from an efficient anycast service would be to those applications that require consistently low-delay interactions, including live video streaming applications [1], peer-to-peer virtual environments [2] and peer-to-peer networked games [3].

In these applications, peers need to discover other peers that are participating in the distribution of a particular stream, or in a given virtual spatial locality, and which are at the same time able to sustain low delay interactions that allow the system to maintain high responsiveness and interactivity. With anycast groups corresponding to a stream or a virtual space, a fast anycast service can be used by peer selection algorithms to improve the distribution topology and reduce the end-to-end path latencies, while at the same time minimising start-up delay.

Although there have been a number of proposals regarding the implementation of NLA and ALA, there is still a need for an anycast architecture focusing on the stringent accuracy and query resolution time requirements that this new class of real-time applications presents. To address this, we present **DOAT (Distributed Overlay Anycast Table)**, a delay-aware, application-layer anycast system designed to return accurate results in short time. In this case, accuracy is associated with the distance, measured as delay over the IP network path, between the group member discovered by DOAT and the actually closest group member. Our solution makes use of three key technologies to implement an ALA service: network coordinates, space filling curves and Bloom filters.

To estimate network delay distance, DOAT nodes use a network coordinate system to find their location on a multi-dimensional (usually two or three dimensional) *delay space*. This space is then mapped into a single-dimensional *DOAT coordinate* using a space-filling curve, in order to simplify searching operations. This coordinate is used to construct a locality-aware overlay. Scalability is addressed by aggregating group memberships using Bloom filters, and query resolution is accelerated using efficient routing.

II. Background and Related Work

Given the great implementation challenges of NLA, there have been a number of research studies on the subject. Work by Katabi [4] overcomes some of the shortfalls in NLA by using route caching techniques. Proxies [5] are proposed as a means to reduce the size of routing tables as the number of groups increases.

NLA has no access to metrics such as server load and available bandwidth, which might be important for certain applications. Since ALA resides above the network layer, it can monitor both network conditions and application-layer metrics. Bhattacharjee et. al [6] propose the use of *anycast domain names* (ADNs) with ADN resolvers maintaining a database of metrics, such as server load. These metrics are useful only if they accurately reflect the current state of the network, and thus, techniques are needed to accurately propagate them. Work presented by Zegura [7] provides a hybrid server push technique for the maintenance of the metrics database, and shows that lower response times can be obtained when compared with randomly chosen servers. Early work done on ALA [6], [8] assumes that groups remain small and have low levels of churn. This last assumption is rarely justified in peer-to-peer overlays [9]. [10] proposes a solution suitable for large groups, assuming however only a small number of groups, and loose requirements for accurately routing to the closest group member.

Although DOAT resembles a Distributed Hash Table (DHT), its function is fundamentally different. As in a DHT, DOAT peers form an overlay network where data (membership entries) can be registered and searched with a given key (group identifier). However, in DOAT there is no one-to-one mapping between the key space and the overlay nodes. Group members associated with the same key register in arbitrary locations, and assignment of group membership data to overlay nodes is based on location, and not key to node identifier mapping, thus allowing for localised searches.

III. Architecture

In NLA there is a natural separation between hosts that make use of the anycast routing capability of the system and the routers that actually implement it. In the same way, in DOAT not all hosts that use the anycast service need to act as anycast routers. We distinguish between a) *group members*, that register their membership to a group with the anycast system in order to receive anycast messages, b) *DOAT nodes*, who participate in the overlay acting as anycast routers, and c) *query senders*, that send queries to the ALA system in order to discover the closest member of their group of interest.

Every group member registers its membership with its closest DOAT node. DOAT nodes discover their neighbour nodes and exchange information to establish routes to group members. Every query sender is associated with its closest DOAT node, which will forward its queries into the DOAT overlay, following the established routes until the closest group member is found. The corresponding protocols are detailed in the following section.

IV. Protocols

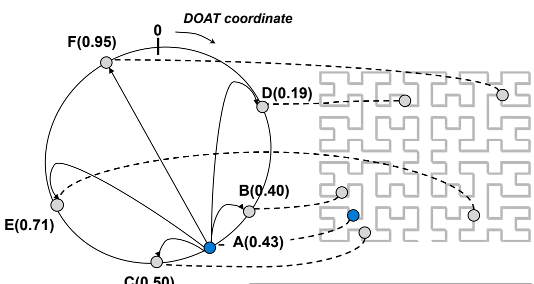
DOAT uses coordinates to obtain a measure of proximity. In the rest of the paper, we assume network delay coordinates, however, coordinates with more rich semantics like *load-aware network coordinates* [11] are also possible. In order to minimise query time, DOAT operates on the principle of creating paths with logarithmically decreasing distances to the destination, a technique similar to [12]. This principle underlies the protocols for establishing connections between the overlay nodes, for exchanging routing information and for forwarding queries for a particular group.

A. Overlay Topology Construction

Before connecting to the overlay, a node determines its position using a distributed coordinate system such as [13]. This allows the node to calculate its coordinates in a multi-dimensional delay space $\mathcal{X}$ where metric distance between peers in the space is directly correlated with network delay between the peers in the network. Thus, short metric distances imply low delay.

Coordinates in $\mathcal{X}$ are mapped to a single-dimensional *DOAT coordinate* which becomes the identifier of the node, used to determine its neighbours in the overlay. The DOAT coordinate has the property that, if two nodes are "close" in it, then they are close in $\mathcal{X}$. Note that the opposite is not true: closeness in $\mathcal{X}$ does not guarantee closeness in the single dimensional DOAT space. This has the drawback that the closest node in the single-dimensional space might not be the closest node in the multi-dimensional space, but coarser locality information will be preserved.

The mapping from $\mathcal{X}$ to a single-dimensional space is done by first using a linear transform to map $\mathcal{X}$ coordinates into the unit square, and then mapping the unit square to a single-dimensional coordinate using a number of iterations of a space filling curve. The curve used here is the *H-curve* [14], which is known to have good locality preserving properties. The obtained single-dimensional coordinate is a wrapping coordinate in the range of $[0, 1)$, that positions the nodes in a ring (see figure 1). For the purpose of this paper we will treat $\mathcal{X}$ as a two-dimensional space, note however that the *H-curve* trivially generalises to the multi-dimensional space.



Distance	Coordinate	Next-Hop	Bloom Filter
0.00	0.43	A	BF.local
0.03	0.40	B	BF.B
0.07	0.50	C	BF.C
0.24	0.19	D	BF.D
0.28	0.71	E	BF.E
0.48	0.95	F	BF.F

Fig. 1. DOAT Topology Construction using Space Filling Curve

After obtaining its DOAT coordinate, a node establishes peering connections with other DOAT nodes to exchange routing information. Following the principle of logarithmically decreasing distances, a node first connects to the furthest neighbour (closest to the opposite point of the ring at 0.5 distance), then to the two at half distance (0.25) in either direction of the ring, and so on. This process terminates when the immediately closest node is found at each direction.

To connect to a neighbour n_2 at a given distance and direction on the ring, a DOAT node n_1 calculates a target coordinate for n_2. For example, from n_1 at 0.43, the neighbours at a distance of 0.25 have target coordinates of 0.68 (clockwise) and 0.18 (anti-clockwise). Node n_1 then sends a message with the target coordinate n_2 to any known DOAT node n_3 , which then forwards the message to its neighbour that is closest to the target coordinate n_2. This is done recursively, until the message reaches the actual DOAT node n_2' that is closest to the target coordinate n_2. This is the node that has no neighbour closer to n_2 than the node itself.

B. Registering Membership and Updating Routing Tables

When a host becomes a member of a group, it has already calculated reliably its position in $\mathcal{X}$. It then sends a registration message to any known DOAT node, which converts the position of the new group member to the corresponding DOAT coordinate. The registration is then forwarded to the DOAT neighbour node which is closest to this DOAT coordinate, until it reaches the DOAT node which is closest to the DOAT coordinate of the new group member. This node installs the new membership entry at its local registry.

Each DOAT node maintains a routing table to forward queries for groups with no members in its local registry. The routing table contains one entry for the local registry, and one entry for each of its neighbours. Each entry includes information on the identity of the next hop (neighbour DOAT node), the distance to the next hop along the DOAT ring, and the set of groups reachable through it. Routing entries are sorted in ascending order of distance to the next hop, with first the entry corresponding to the local registry. Figure 1 shows the routing table of the node at DOAT coordinate 0.43.

The group identifiers cannot be inherently aggregated as it is the case with, for example, IP addresses. To preserve the scalability of routing tables and routing update messages, group identifiers are aggregated using Bloom filters.

A route announcement from a node n_1 to one of its neighbours n_2 contains the groups present in the local registry of n_1, and the groups that n_1 can reach through other DOAT nodes n_i, where the distance between n_1 and n_i is less than the distance between n_1 and n_2. In other words, the node announces all the anycast groups for which there are member hosts in its local area, to nodes further away. The area Bloom filter sent to each neighbour n_i is the aggregate of the Bloom filter that corresponds to the local registry, and the Bloom filters received from all the neighbours which are closer than n_i, i.e. appearing before n_i in the routing table. When a new group is registered with the node n_1, the latter sends an update to all its neighbours. When the node n_1 forwards a routing update received from another neighbour n_2 then it propagates the update only to these nodes further away than n_2.

To reduce the message overhead, a DOAT node may not send routing updates synchronously with local changes. Instead, a minimum interval may be enforced between two consecutive updates sent to a neighbour. There is an accuracy penalty incurred by delaying updating the neighbours (see Section V-D). Additionally, instead of sending the entire Bloom filter every time, a node may send only the difference since the last update and other compression techniques are possible.

A routing update message also contains the immediately closest neighbour of the node in both directions. These DOAT nodes can be used as alternative neighbours in case the node fails and does not follow the procedure of gracefully removing itself from the overlay.

C. Query Forwarding

When a DOAT node receives a query, it will either return the appropriate group member IP address if the group appears in its local registry, or forward the query to another DOAT node, according to the Bloom filter matches on its routing table.

To determine the next hop to forward the query, the DOAT node will iterate its routing table in increasing distance order, attempting to match the queried group identifier with the Bloom filters at each step. The next hop will be the first neighbour whose Bloom filter returns a positive match with the group identifier. The query is then forwarded to the associated next hop neighbour. Because the routing table is sorted in ascending order of distance to the next hop, this is the nearest next hop that has announced a route for this group. The process is repeated at each hop until a node with group members in its local registry is found.

Because of the neighbour selection and route forwarding mechanisms, the path the query follows is composed by hops of exponentially decreasing distances, starting with a maximum of 0.5 on the DOAT coordinate, i.e. the maximum network delay between any two DOAT nodes.

D. Node Insertion and Deletion

The DOAT nodes may be statically appointed hosts, operated by a single administration. However, the system is designed to work in a peer-to-peer environment, where any *stable* peer (high uptime, stable network delay coordinates, considerable storage, bandwidth and processing resources) can be elected to become a DOAT node [2] (more elaborate methods can be adopted to minimise churn [16]).

Not every peer becomes a DOAT node and a peer does not decide in isolation to become a DOAT node. When the load on a DOAT node increases beyond a locally defined threshold, it chooses the most stable peer in its local area and sends a DOAT invite message.

When a node leaves the system it informs all its neighbours with a message that also includes its direct neighbours in both directions. This way, all its neighbours can automatically substitute the removed neighbour with one of its direct neighbours. Routing updates also carry this information, in case the node fails without warning. When a node detects that a neighbour has failed, it can immediately forward queries and routing updates to the replacing neighbour of the failed node.

Node removal and re-insertion can be also triggered by network coordinate drift [17], or by changes in the prevailing network congestion and delay patterns. As the position of a node in the overlay is dependent on its DOAT coordinate (which itself is calculated from the its network coordinates), if it moves too far away from its original position, the node will remove itself from the DOAT and re-insert itself in the new position. This is necessary because network delay changes that are not reflected in the DOAT coordinate can reduce the accuracy of the closest group member discovery (see Section V-E for an evaluation of the impact of coordinates accuracy on the DOAT accuracy).

V. Evaluation

The performance of the DOAT system for a single anycast group is evaluated using a discrete event simulator. The number of anycast groups affects only the size of the Bloom filters in the routing tables and the routing update messages.

A number of nodes is generated, with each node assigned to a two-dimensional coordinate in the network delay space $\mathcal{X}$. We used a uniform distribution to generate coordinates in the range of $[-100, 100]$ for each dimension, creating a Euclidean space with average delay of around 104 milliseconds. Three sets of 500, 1000 and 3000 nodes were generated. Additionally, we used a set of coordinates for 1740 hosts and an average

[2] We assume that peers participate in DOAT altruistically or that there is an incentives mechanism in place [15].

delay of around 145 milliseconds, generated by applying the Vivaldi algorithm [13] to the delays of the King data set [18].

Nodes join the DOAT system one by one, calculate their DOAT coordinate and connect to neighbours. A number of hosts, specified as a percentage over the total number of DOAT nodes, register as group members. This percentage represents the *density of the group* and affects the average distance to the closest group member.

We distinguish between the synchronous and asynchronous update methods. In the synchronous update, all group members are registered at once, and queries are generated from all the DOAT nodes. In the asynchronous update case, each time a group member registers, queries are generated from 10% of the nodes, thus recording each of the intermediate states of the system.

For each query, the following metrics are evaluated:

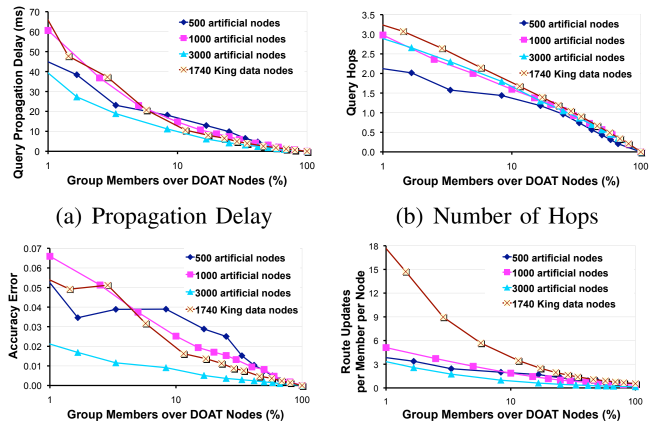
- *query time*: the sum of the propagation delay along the overlay query forwarding path,
- *accuracy error*: the difference in distance of the discovered from the actual closest group member; it is is calculated as: $\frac{R-C}{D}$, where R is the delay from the querying host to the member host discovered by DOAT, C is the delay from the querying host to the actual closest member host, and D is the average delay in the simulated two-dimensional delay space.

For each experiment, we evaluate *overhead* as the number of routing messages exchanged per DOAT node, for each registered group member. The trade-off between accuracy and overhead is investigated in the asynchronous case. An *update interval* is set to constrain the frequency of updates a DOAT node can send to any of its neighbours. The update interval is specified as multiplies of new group member arrival intervals. By reducing the number of routing updates overhead is reduced. However, there is a penalty in accuracy, as the routing tables are not always up to date with routes to reach all the members registered in the system.

Finally, we evaluate the impact of the accuracy of the network delay coordinates on the accuracy of the DOAT query results. The experiment progresses as in the synchronous case; however, upon evaluating the accuracy, we alter the coordinates of the nodes for a random value around an average *coordinate offset value*.

A. Query time

Figures 2(a) and 2(b) show the average query delay and number of hops for the artificial and the King data sets, for different values of the ratio of members over DOAT nodes. The average query delay to discover the closest member is below the average delay between any two nodes, even for the smallest groups, and decreases rapidly for larger groups. As the number of DOAT nodes increases, the routing tables become more fine-grained, with more neighbours in smaller distances. This results in query paths with more hops of smaller delays, as can be seen by comparing the values between the 500, 1000 and 3000 artificial data sets. Also, comparing the uniform delay distribution and the realistic distribution of the King data set, we see that the impact is very small in both the delay and the number of hops.



(a) Propagation Delay (b) Number of Hops

(c) Accuracy (d) Overhead

Fig. 2. Query Time and Accuracy

B. Accuracy

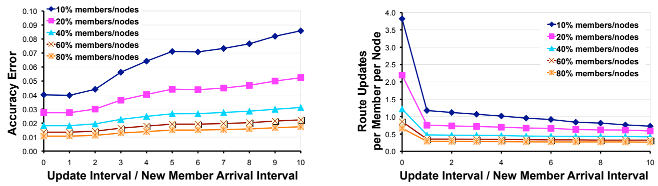
In Figure 2(c) we see the accuracy for the discovery of the closest group member. Even for small groups and small-sized DOAT overlays, the accuracy error is below 10%. For larger DOAT overlays and/or groups the error becomes negligible. One factor that contributes in the DOAT accuracy error is the error introduced by the space filling curve as there might be neighbours which are actually closer in the network delay space $\mathcal{X}$, but appear to be further away in the DOAT coordinate space.

C. Overhead

In Figure 2(d) we can see the number of routing update messages exchanged per node for each new member. When there are few members, routing updates have to reach all DOAT nodes but as soon as groups start growing, messages are only propagated in small regions reducing the impact in the overlay.

D. Accuracy and Message Overhead Trade-Off

In Figure 3 we can see the trade-off between overhead and accuracy with the King data. Even with a small



(a) Accuracy (b) Overhead

Fig. 3. Accuracy and Message Overhead Trade-Off

update interval the overhead is significantly reduced, without significantly increasing the accuracy error.

E. Sensitivity to Coordinates Accuracy

Network delay coordinates do not represent the network delay with accuracy [17], or in a static way. To evaluate sensitivity to coordinates accuracy, we alter the DOAT node coordinates during the course of the experiment by a given offset distance, and we measure the impact on the accuracy against the results obtained with static accurate coordinates.

In Figure 4 one can see a linear relationship between $\mathcal{X}$ accuracy and DOAT accuracy. This is considered acceptable, as there are studies in the literature [19] which address the problem of stabilising network delay coordinates, enhancing their accuracy on the same time.

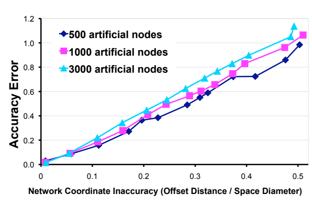


Fig. 4. Effect of Coordinates Accuracy

VI. Conclusions and Future Work

We present a structured overlay system that implements Application Layer Anycast. The system is designed to support a large number of small to very large anycast groups, with high locality accuracy while minimising the query time. We show through simulations in artificial and realistic conditions, that these objectives are achieved.

One of the future directions is to prove the validity of these early results through a prototype implementation. This work could then be applied to large scale systems like the World Wide Web, extending HTTP to work with replicated pages. This will substantially improve performance and allow small content providers to cope with flash crowds and high volumes of hits.

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