Overlay Structure for Large Scale Content Sharing: Leveraging Geography as the Basis for Routing Locality

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Abstract

In this paper we place our arguments on two related issues in the design of generalized structured peer-to-peer overlays. First, we argue that for the large-scale content-sharing applications, lookup and content transport functions need to be treated separately. Second, to create a location-based routing overlay suitable for content sharing and other applications, we argue that off-the-shelf geographic coordinates of Internet-connected hosts can be used as a basis. We then outline the design principles and present a design for the generalized routing overlay based on adaptive hierarchical partitioning of the geographical space.

1 Introduction

Peer-to-peer overlay networks are nowadays envisioned as a single self-organized and decentralized substrate to be used by many different large-scale networked applications. Since inception of the concept, a large number of alternative designs for peer-to-peer overlays have been proposed to support different application needs. At some point, consensus has emerged that there is a need for a single well-defined interface to encapsulate the generic features provided by these overlays. Progress have been made in this direction and several well-understood features have been defined [10, 21].

Because the evolution of peer-to-peer research has historically depended on the content sharing applications, two fundamental functional requirements of these applications – search and transport have guided the design of general purpose overlays. Initially, the problem of search or lookup dominated the research while the transport related problems gradually emerged. Researchers then have attempted to accommodate transport related functionalities in generalized versions of the overlays that were primarily created for lookup [7]. Also, randomness was introduced in the overlay structures for several purposes such as load balancing and source anonymity [23, 24]. As a result, the conventional wisdom of routing locality in bulk data transport necessary for efficient usage of network resources has been ignored.

With the rising of complaints from the ISPs against the peer-to-peer traffic, there have been several proposals for introducing locality awareness in the overlay structures [29, 16, 20, 28, 26]. In most of the cases, localities are defined based on explicit measurements of some application level metric such as latency. This class of overlays, denoted as network aware overlays suffer from the large background overhead of the measurement.

In this paper, we argue that the geographic location of the end-hosts, at the available granularity of ISP’s points of presence, can be used as the basis of a locality-based routing overlay. The argument is founded on two observations. First, the Internet infrastructure has significant geographic clustering and hierarchical organization [13, 14], and second, the major fraction of the acquaintances in online social networking communities are dictated by geographic proximity [17]. Thus, if we expect that social interaction will dominate the cyber-traffic in near future, from sending messages, emails and blogs to sharing videos, photos and musics, geography can be used as the basis for overlay routing structure that would provide the desired locality properties.

The main contributions of this paper are the arguments in favor of our positions in two related issues – whether the overlay support for content transport should be treated separately from the content lookup, and whether the off-the-shelf geographic coordinates can be used for constructing the location-based routing overlay. In the line of our arguments, we have outlined the design principles for the transport overlay and presented an overlay design based on adaptive hierarchical partitioning of the geographical space.

In Section 2, the history of peer-to-peer research is analyzed to demonstrate the need for separation of the overlay supports for lookup and transport. Section 3 outlines the design goals of an overlay structure for large-scale content transport. Section 4 places the arguments for using geographic coordinates in a location-based overlay. Section 5 gives a brief description of the proposed overlay structure and its routing techniques. How the structure would be useful in content-sharing applications is explained in Section 6.

2 Development of P2P Overlays in Retrospect: Separation of Lookup and Transport in Content Sharing

Although many different applications have been cited that could use peer-to-peer overlays [10], the major driving force behind the design of almost all the overlays is the single most popular application of content sharing – that allows a huge number of Internet-connected end-hosts to participate in sharing of large data contents like software packages, media files or live audio/video streams.

Two related but subtly distinct necessities of this content-sharing application influenced the design of the peer-to-peer overlay networks. The first need was indexing and search – how to quickly find the physical location of a specific content when a description or a name is given. The second need was data transport – how the content can be efficiently transported when a large number of hosts show interest in the same content, either at the same time, or asynchronously over a pro-
longed period of time.

Several generic overlays attempted to provide both the lookup and transport features using the same message routing infrastructure [21, 7]. Key-based routing has been proposed as the standard service interface that can be used to derive all the necessary functions for the content sharing application [10]. It may be observed that the initial designs of the overlay structures were driven by the goal of efficient lookup. The necessity of a transport structure for concurrent or nearly concurrent transportation of content to multiple receivers came as a secondary thought. As such, the designers of the lookup overlays attempted to use the same infrastructure they created for lookup for the purpose of content routing [7].

However, it has later been understood that the optimization objective of the transport overlay is grossly different from that of the lookup overlay [8, 18]. The lookup needs fast response while transportation needs efficient use of underlying network links. At some point, it has also been argued that, based on the current hardware capacities and the possible scale of the overlay networks in foreseeable future, the fancy designs of multi-hop structured routing overlays for the lookup service are unnecessary complexities [22]. Although there have been attempts to propose some hybrid infrastructures [8] that cover optimization objectives for both lookup and transport, we argue that they are fundamentally different, and hence it is beneficial to separate these features from the ground level of the architecture.

A common design decision taken by the designers of the overlay structures, primarily designed for the lookup service, is the randomly assigned flat identifiers for the hosts, while the overlay structures are defined in terms of the numeric properties of the identifiers. The arguments placed in favor of such randomness include load balancing, placing of replicas at uncorrelated hosts and anonymizing the source of a content. While accepting that all these features are necessary for content sharing, researchers have argued that randomized placement of hosts in the overlay structure is not the only way, nor the best way, of achieving them [30]. Moreover, our position is that emphasis on such features should not preclude the conventional wisdom of routing locality in high-volume content transportation.

Ever since the emergence of the peer-to-peer content sharing application, there have been growing complaints and consequent policing from the ISPs on the traffic generated by peer-to-peer applications. Though part of the reason of this overwhelming traffic is the sheer volume of the contents, we believe that the on-purpose randomized message routing topologies of most of the peer-to-peer overlays also shares part of the blame.

3 Design Principles for the Transport Overlay

In this paper we focus on the routing overlay that is primarily used for transport of bulk data content. The Internet Protocol is sufficiently optimized for carrying data packets between two endpoints in the network. However, in the large scale content sharing application that dominates the peer-to-peer world, the same content is transported to a large number of end-points, either at the same time or asynchronously over an extended period of time. Thus, either in strong or in loose sense, the necessity of these content sharing application is an overlay that can support construction of efficient multicast trees.

For bulk data transport, whether unicast or multicast, the primary optimization goal in choosing the transport paths is the efficient use of the network resources. Low latency path of transport is desirable and may even be necessary in some applications, although it comes secondary to the resource efficiency in case of bulk-transport applications.

The scale of the systems demands achieving these objectives through decentralized decisions of routing. The problem has been thoroughly studied in the realm of IP networks. It is understood that if some simple principles are followed in local decisions, the desired global properties emerge.

One such well-known principle is the principle of locality, which requires that the transport path between two endpoints of the same local region should remain within the region [11]. This discourages the traffic to take arbitrary detours causing unnecessary burden on the global network. The same principle also yields low latency and high reliability paths.

Another locality property that results in efficient resource usage in multicasting is the path-convergence property, which states that paths from a single source to multiple destinations in one locality should have significant portion of the path shared. The smaller the area of the locality, the larger should be the common segment. Intuitively, this can be attained, if the localities are hierarchically divided, and the traffic follows a direction towards destination, gradually resolving the destination at a deeper level of the hierarchy. Such directional routing with hierarchical resolution will be explained in further details in Section 5.

There are other design objectives that are common in all peer-to-peer overlays, to account for the sheer scale and the dynamics of overlay membership. The overlay structure should be adaptive and should easily accommodate growth and shrinkage of the membership pool. The overhead for managing the structure must be low.

4 Location Awareness: can Geography Help?

As we understand from the discussion on the overlay design principles in Section 3, the overlay must take into account the physical location of the hosts and the network links with respect to each other while routing traffic. Indeed, several structured overlays have been designed that base their routing decisions on location. They differ in the way they represent and utilize the location information.

Pietzuch et al. in [20] classify location-based overlays in two classes – proactive and reactive ones. The reactive location based overlays, such as Meridian [27], take explicit measurement of location immediately before taking each routing decision. Such measurement provides fresh and more correct information but the overhead is large when the sys-
tem is loaded. The proactive location based overlays use some background mechanism to measure the relative locations of nodes and use that information for routing decisions. Here the overhead depends on the dynamics of overlay membership rather than system usage. The location information is represented either implicitly in the choice of the overlay neighbors [4] or explicitly by placing nodes in a virtual coordinate space [26].

Positioning the Internet hosts in a virtual coordinate space, called Network Coordinates, has been an active research issue for several years, due to the perceived usefulness of such coordinates in solving several distributed system problems such as resource discovery, replica placement and efficient routing. The usual choice of the coordinate space is a multi-dimensional Cartesian space, and research shows that the Internet hosts can be mapped into a low-dimensional Cartesian space with acceptable accuracy [19]. Notable projects that approach such mappings include GNP [12] and Vivaldi [9]. Nevertheless, high background overhead inhibits the acceptability of network coordinates for many useful applications.

Here we argue that, for the purpose of overlay routing adhering to the locality principle, two dimensional geographic coordinates (latitude, longitude) of the hosts would provide sufficient location information. At present, there are a number of comprehensive databases [3, 1, 2] that resolve the geographic coordinates of Internet hosts, usually at the resolution of the point-of-presence of the ISP. Since the geographic location of hosts at this resolution is relatively stable within a session, the information can be obtained by off-the-shelf database lookup, eliminating any measurement overhead.

Studies on spatial characteristics of the Internet infrastructure show that Internet, like many other networks, have strong geographic clustering, following the geographic distribution of its users [14, 13]. Also, like hierarchical division of geographic locations made for political and administrative purposes, Internet backbone can also be roughly organized in different tiers, that serve interconnection for locations at different levels such as continent, country, state and city [25]. It is true that there are many instances of different ISPs in the same geographic location, and the ISP’s preferred route for geographically local traffic between two ISPs may not exactly follow the locality principle at fine resolution. Nevertheless, transporting the traffic between points of the same geographic location locally is arguably beneficial for the globally optimal use of Internet resources. The growth of caching proxy networks like Akamai to contain the local web traffic locally also supports the argument.

Indeed, before the advent of the peer-to-peer overlays, there has been attempts to introduce geography-directed routing in the Internet infrastructure [15]. Although the technique faced deployment hurdles in the rigid infrastructure, the applications it envisioned only became more relevant in present days. Besides resource-efficient routing, the applications include location-based information search, finding nearest services and broadcasting messages in a geographic community.

Recent growth of social networking platforms suggests that social acquaintance of network users will dictate the direction of majority of content transport in the Internet in the near future. Interestingly, a recent study shows that more than two thirds of the acquaintances in on-line social networking communities are defined by geographic locality [17]. If the general purpose routing overlay is to be used for future implementations of these social applications, the finding supports the argument that the overlay should be carefully optimized for geographically localized traffic.

5 Structure of the Overlay Interconnection

In the previous sections, we argued in favor of a location-based routing overlay for peer-to-peer applications and that geographic coordinates can serve as the basis of such location-based overlays. In this section, we present an overlay interconnection structure based on hierarchical partitioning of the geographic space, where traffic is routed towards the geographic location of the destination, successively resolving the destination at a deeper level of the hierarchy.

5.1 Structure

The universe (earth surface) is hierarchically divided into zones, sub-zones, sub-sub-zones and so on. A zone is divided into non-overlapping sub-zones and the higher-level zone completely covers all the areas of its sub-zones. The shape of the zones need to be amenable to concise memory representation and also to easy computation of whether a point belongs to a zone or not. A simple shape such as an axis-parallel rectangle may be used as zones. At the leaf level of the hierarchy are the zones that are not divided any further (denoted leaf zone). Each individual overlay node or peer belongs to a leaf zone at its deepest level, to successively larger zones at higher levels, and to the zone covering the universe at the top level. Figure 1(a) illustrates an example division of the universe and the corresponding tree representation is shown in Figure 1(b).

A routing table in each peer stores the overlay neighbors of the peer. To be able to route messages towards a destination by successively resolving the zones at finer grain, a peer need to know at least one peer in all the sibling zones at every level of the hierarchy. At the deepest level, the peer knows all other peers within its own leaf zone. The routing table may be organized in rows, each row storing the pointers to the siblings at a different level. For each pointer, the IP address of the target peer and the boundary definition of the corresponding sibling zone is stored. Also, the boundary definition of the self-zone at every level is stored at the corresponding row. Additionally, peers and zones can be uniquely identified globally, using a hierarchical name that concatenates the identifications of the zones at successive levels of the hierarchy (as shown in the figure). Such names (denoted as overlay identifier) can be stored in each entry of the routing table, besides the zone boundary definition. The overlay neighborhood of a peer is illustrated in Figure 1(b).

The beauty of the overlay structure lies in its flexibility to grow and retract with the membership dynamics, and its ability to manage this in a completely decentralized way. When
Figure 1. Routing overlay by hierarchical zoning

Algorithm 1 RouteToAllPeers(msg, area, level)

1: if peer.coordinate falls in area then
2: Delivered msg to peer
3: end if
4: if level ≤ deepest level d then
5: for Each entry e in row d of the routing table do
6: if e.coordinate falls in area then
7: Send new RouteToAllPeers(area, d + 1, msg) to e.IP Address
8: end if
9: end for
10: end if
11: for r = d − 1 down to level do
12: for each entry e in row r of the routing table, except
13: for the one denoting self zone do
14: if e.zone boundary intersects area then
15: Send new RouteToAllPeers(area, r + 1, msg) to e.IP Address
16: end if
17: end for

the number of peers in a leaf zone grows beyond a threshold,
new sub-zones are created by dividing the zone according to
geographical clusters of peers. Note that all peers in a leaf
zone are neighbors to each other in the overlay. So any peer,
knowing coordinates of all other peers in the same leaf zone
can perform the partitioning and inform all others of the new
boundaries and identifiers. Similarly, when it is discovered
that the number of peers in a leaf zone is below a threshold,
the leaf zone can initiate a merge with one of its siblings.
When new sub-zones are created based on geographic clus-
tering, an area of the previous leaf zone that does not be-
long to any of the clusters, is also considered a sub-zone and
is denoted as remainder-leaf-zone. The remainder-leaf-zone
always serves as a suitable merger siblings for the other leaf
zones. Details of the adaptation techniques in response to
membership dynamics can be found in [5].

5.2 Routing

The overlay is able to route messages towards a geo-
graphic location. The target may be all or any peers in the
specified area, or the nearest or a nearby peer of a specified
point. Messages may also be routed to a particular peer spec-
ified by the overlay identifier.

To forward a message targeted to an area, a peer uses the
RouteToAllPeers method defined in Algorithm 1. A peer for-
wards the message to its contacts in all sibling zones at all
levels of the routing table, whose zone-area intersects with
the target area (Lines 11-17) and to all peers within the leaf
level self-zone that fall in the target area (Lines 5-9). To re-
member the levels of hierarchy already resolved, the level
parameter is used, which is set to 1 at the peer that initiates
the routing.

Routing a message to a peer at or near a specified point
can be performed by the same algorithm with minor modifi-
cations. The algorithm will have a point as the third param-
eter instead of an area. The condition in Line 13 will check
if the point falls in the zone and the loop in Lines 11-17 will
terminate as soon as a match is found. The loop in Lines 5-9
will forward the message to the peer in the self zone closest
from the target.

If precisely the peer nearest to a specified point is sought,
it can be done by first reaching the peer that is closest to the
peer within the zone that holds the point, and then sending a
query message towards a circular area with the target point at
its center and the current peer at the perimeter, to figure out
if any other peer closer to the target exists.

By construction, it is observable that the overlay routing
adheres to both the locality and the path convergence princi-
ple outlined in Section 3. An illustration of the routing paths
in Figure 1(a) demonstrates both the properties.

6 Application of the Routing Overlay

Focusing back to the origin of peer-to-peer research, i.e.
the large scale content sharing application, we argued in Sec-
tion 2 in favor of separation of its search and transport ser-
VICES. The generalized routing overlay is designed having
in mind mainly the requirements for the high-volume data transport to a large number of recipients. Here we explain how the overlay may be used for multicasting and proactive caching.

A request for the content is sent to the source directly. Because there is a separate service for lookup, the IP address of the source of a desired content can be known from there. The routing overlay is used for efficient delivery of the content once the request is received. Knowing the overlay identifier of the requester, the source is able to explore the overlay route towards the requester. Due to its locality and path convergence properties, this route can be used to create an efficient delivery tree for live streaming content, when there are many requests for the same content [6].

For non-live contents that are shared among many users during an extended period of time, replicas of the fragments of the content can be stored along the overlay route. This helps to serve multiple requests originated in the same geographic locality from the nearest replica without causing unnecessary traffic burden on the long distance links.

Besides multicast transport, the routing overlay can be used for several geography related applications, such as, finding the nearest service or looking up services in a geographic range from a location, or broadcasting some message or command to the hosts in a specific geographic region [5].

7 Conclusion

In this paper, we raised the issue of separating the transport from lookup in the design of overlays for peer-to-peer content sharing, and explained how geographic coordinates of the hosts can be used to create a location-based overlay that yields efficiency of resource usage in bulk transport. Whether such generalized overlay will be useful for other unforeseen applications, can only be examined in the future.

References

[1] Geobytes. http://www.geobytes.com/.
[2] Ip2location. http://www.ip2location.com/.
[3] Maxmind. http://www.maxmind.com/app/ip-location.
[4] I. Abraham, A. Badola, D. Bickson, D. Malkhi, and S. M. S. Ron. Practical Locality-Awareness for Large Scale Information Sharing. In 4th IPTPS, Feb. 2005.
[5] S. Asaduzzaman and G. V. Bochmann. GeoP2P: an Adaptive and Fault-tolerant Peer-to-peer Overlay for Location Based Search. In The 29th IEEE ICDCS, 2009. submitted for review.
[6] S. Asaduzzaman, Y. Qiao, and G. V. Bochmann. CliqueStream: An Efficient and Fault-resilient Live Streaming Network on a Clustered Peer-to-peer Overlay. In 8th IEEE P2P ’08, pages 269–278, Sep. 2008.
[7] M. Castro, P. Druschel, A. Kermarrec, and A. Rowstron. Scribe: A Large-Scale and Decentralized Application-Level Multicast Infrastructure. IEEE JSAC, 20(8):1489–99, 2002.
[8] N. Cruces, R. Rodrigues, and P. Ferreira. Pastel: Bridging the Gap between Structured and Large-State Overlays. In IEEE CCGrid, pages 49–57, 2008.
[9] F. Dabek, R. Cox, F. Kaashoek, and R. Morris. Vivaldi: A Decentralized Network Coordinate System. In ACM SIGCOMM’04, Aug. 2004.
[10] F. Dabek, B. Y. Zhao, P. Druschel, J. Kubiakowicz, and I. Stoica. Towards a common api for structured peer-to-peer overlays. In 2nd IPTPS, pages 33–44, 2003.
[11] P. J. Denning. The Locality Principle. Communications of the ACM, 48(7):19–24, 2005.
[12] T. S. Eugene-Ng and H. Zhang. Predicting Internet Network Distance with Coordinates-Based Approaches. In 21st IEEE INFOCOM, pages 170–179, 2002.
[13] M. T. Gastner and M. E. J. Newman. The Spatial Structure of Networks. The Eur. Phy. Journal B, 49:247–252, 2006.
[14] S. M. Greenstein. The Economic Geography of Internet Infrastructure in the United States. In Handbook of Telecommunications Economics, volume 2, chapter 8. Elsevier, 2005.
[15] T. Imielinski and J. C. Navas. GPS-Based Geographic Addressing, Routing, and Resource Discovery. Communications of the ACM, 42(4):86–92, 1999.
[16] H. Le, D. Hong, and A. Simmonds. A Self-Organising Model for Topology-Aware Overlay Formation. In IEEE ICC, volume 3, pages 1566–1571, May 2005.
[17] D. Liben-Nowell, J. Novak, R. Kumar, P. Raghavan, and A. Tomkins. Geographic Routing in Social Networks. Proc. National Academy of Sciences, 102(33):11623–11628, 2005.
[18] I. Margasimski and M. Pioro. A Concept of an Anonymous Direct P2P Distribution Overlay System. In 22nd IEEE AINA, pages 590–597, 2008.
[19] P. Pietzuch, J. Ledlie, and M. Seltzer. Supporting Network Coordinates on PlanetLab. In 2nd USENIX WORLDS’05, pages 19–24, Dec. 2005.
[20] P. Pietzuch, J. Ledlie, and M. M. M. Seltzer. Network-Aware Overlays with Network Coordinates. In 26th IEEE ICDCS Workshops, Jul. 2006.
[21] S. Rhea, B. Godfrey, B. Karp, J. Kubiakowicz, S. Ratnasamy, S. Shenker, I. Stoica, and H. Yu. OpenDHT: a public DHT service and its uses. ACM SIGCOMM Computer Communications Review, 35(4):73–84, 2005.
[22] R. Rodrigues and C. Blake. When Multi-hop Peer-to-Peer Lookup Matters. In 3rd IPTPS, pages 112–122, Feb. 2004.
[23] A. Rowstron and P. Druschel. Pastry: Scalable, Decentralized Object Location, and Routing for Large-Scale Peer-to-Peer Systems. In IFIP/ACM Intl. Conf. on Distributed Systems Platforms, pages 329–350, 2001.
[24] I. Stoica, R. Morris, D. Karger, M. F. Kaashoek, and H. Yu. A Scalable Peer-to-Peer Lookup Service for Internet Applications. In ACM SIGCOMM’01, pages 149–160, Aug. 2001.
[25] L. Subramanian, S. Agarwal, J. Rexford, and R. H. Katz. Characterizing the Internet Hierarchy from Multiple Vantage Points. In IEEE INFOCOM 2002, Jun. 2002.
[26] M. Waldvogel and R. Rinaldi. Efficient Topology Aware Overlay Network. ACM SIGCOMM Computer Communications Review, 33(1):101–106, 2003.
[27] B. Wong, A. Slivkins, and E. G. Sirer. Meridian: A Lightweight Network Location Service without Virtual Co-ordinations. Technical Report CMU-CS-03-160, Aug. 2001.