# A Data Locating Mechanism for Distributed XML Data over P2P Networks *

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**Abstract**

Many emerging applications that use XML are distributed, usually over the Internet or over large Peer-to-Peer (P2P) networks. A fundamental problem of XML query processing in these systems is how to locate the data relevant to the queries so that only useful data are involved in query evaluation. In this paper, we address this problem within the context of structured P2P networks, and propose a novel data locating mechanism for query shipping systems. Our approach follows the multi-hop routing approach and encodes the hierarchical information of the XML data into the overlay network, so that routing keys can be hierarchical XML path expressions. We also propose a decentralized data locating algorithm that does not employ a centralized catalog but also avoids flooding the network with XML queries. We report comprehensive experiments to demonstrate the scalability and effectiveness of the data locating mechanism.

# 1 Introduction

In recent years, Peer-to-Peer (P2P) distribution architecture has become a popular decentralized platform for many Internet-scale applications such as file sharing[1], instant messaging[2], and computing resource sharing[3]. Meanwhile, XML is being increasingly used as a data format for data exchange and storage on the Internet. Many of the XML data repositories are distributed. For example, sensor data in XML format are stored geographically close to the sensors [14], large XML documents are partitioned and allocated to distributed physical sites [11], and XML-based descriptions in WSDL [8] and SOAP [9] provide interfaces for distributed Web services. Although there exist some work on distributed XML query processing (e.g. [27]), we are faced with new challenges when XML data are deployed over large-scale P2P networks, where centralized catalogs are not available and peers may join and leave arbitrarily.

Consider, as an example, peer services in a self-organized P2P community, where services are provided such as book sharing and carpooling. We assume that each peer service publishes the information about the available books or carpooling using simple XML paths shown in Figure 1. Alternatively, Web service description languages such as WSDL and SOAP can be used, but we don't consider that approach in this paper. Another assumption of this work is that each peer is aware of the schema on which queries are executed. Note that multiple schemas (e.g. one schema for each peer service) may exist in the P2P network and XML queries can be issued at any peer. For example, the query "/PeerService/Country[@name='Canada']/Province[@name='Ontario']/City[@name='Waterloo'] /Carpooling[date = '2004 Dec.19']" can be issued by a peer in the network to retrieve all carpooling service data provided in the city of Waterloo on the specified date. Besides Web services, many other distributed XML query processing systems fit a similar computation model, e.g. distributed XML repositories [11] over P2P networks.

A fundamental problem for distributed query processing is how to locate the data relevant to the queries so that only useful data are involved in the query execution. This is crucial for large-scale network environments such as the Internet-scale P2P networks where the network communication cost of transferring data and queries dominates the performance of the system. A number of approaches to the problem have been proposed. Data may be located by looking up the information in DNS (Domain Name Service) style catalogs [14]. However, such an approach assumes DNS servers to be stable, which is not guaranteed in a P2P network

[1]Gnutella http://www.gnutella.com
[2]Skype http://www.skype.com
[3]Seti@home http://setiathome.ssl.berkeley.edu

```
Book sharing:
/PeerService[@provider='Jane']/Country[@name='United States']/State[@name='New York']
[@region='Northeast']/City[@name='Boston']/Book[@name='Road Worthy']

Carpooling service:
/PeerService[@provider='John']/Country[@name='Canada']/Province[@name='Ontario']/City
[@name='Waterloo']/Carpooling[@via='Toronto'][@date='2004 Dec.19']
```

Figure 1: Peer service descriptions

where peers may join or leave the network arbitrarily. Another approach is to fully replicate global catalog information on all peers so that each peer knows exactly where the relevant data reside for the queries [11]. Obviously, this approach does not scale in an Internet-scale distributed system. Finally, in a generalized P2P network environment, we do not assume the employment of centralized mechanisms such as superpeers employed by P2P file sharing systems, e.g. KaZaA[4].

In this paper, we design a novel data locating mechanism for distributed XML query processing over P2P networks that is based on a purely decentralized catalog service and a multi-hop routing mechanism. More specifically, to avoid a centralized catalog service, we encode the hierarchical information of the distributed XML data on each peer into a specially-designed overlay network so that each peer manages part of the catalog information. Based on the decentralized catalog information, a peer can be reached through a multi-hop routing mechanism according to the path of the data published by that peer. For simple queries targeted to one peer, the query can be sent over to the peer by routing directly, while for complex queries covering several peers, the propagation of the query is inevitable. To avoid flooding the overlay network, we first route the query to a logical rendezvous node from where it is propagated within a sub-network to locate the relevant data. This approach is similar, in some sense, to IP multicast strategy.

There are similarities between our work and structured P2P file sharing systems (e.g. Chord [26], CAN [22], Pastry [24], and Tapestry [29]), whose primary goal is to decentralize the catalog service and routing mechanism so as to locate the files efficiently over large-scale dynamic networks without flooding the network with the queries or employing specialized peers for catalog service. The main idea behind these structured P2P file sharing systems is to build overlay networks consisting of logical nodes derived from the file names and impose some relationships among the logical nodes to facilitate the file locating process. It has been proven both theoretically and experimentally that these systems are highly scalable over Internet-scale networks, and can deal with the frequent changes of the network environments, i.e. the joining and leaving of the peers. Although we exploit the idea of overlay networks and routing ideas developed for P2P file sharing systems, our work differs from them in important ways. The P2P file sharing systems only support a flat routing key (e.g. file names) rather than the hierarchically structured ones as exist in XML path expressions defined in XPath language [13] that is also embedded in XQuery [10]. For example, the query "/PeerService/Country[@name='Canada']//City[@name='Waterloo'] /Carpooling[date = '2004 Dec.19']" contains hierarchical constructs such as parent-child axis and ancestor-descendant axis. The most likely approach for P2P file sharing systems to resolve the XML data locating is to treat the whole query expression as a flat key, which means that a query can only locate the distributed XML data with an exactly matching path expression. Alternatively, P2P file sharing systems can deal with XML data locating

[4]KaZaA http://www.kazaa.com

by separating the data locating process on the flat names from the one on the hierarchical constructs [17]. Because of the separation, the matching of the queries against the distributed XML data on the hierarchical constructs still employs some centralized mechanism, which leads to performance degradation and scalability problems. To solve these problems, we integrate the matching process on the hierarchical constructs directly into the decentralized catalog management and routing mechanism by designing an overlay network where the hierarchical information of the distributed XML data is encoded. To the best of our knowledge, ours is the first design that follows this approach.

In brief, our data locating mechanism can be highlighted as follows:

1. We avoid any centralized management of the catalog and adopt a purely decentralized mechanism, where each peer keeps a part of the catalog information. Furthermore, catalog management is based on a specially designed overlay network which encodes the hierarchical structure information of all the distributed XML data. The overlay network consists of logical nodes, each corresponding to a unique XML path expression published by peers, as shown in Figure 1. The relationship among the logical nodes is built according to the hierarchical structure information contained in the XML path expressions. This novel way of encoding hierarchical information of distributed XML data into the overlay network greatly reduces the size of the catalog information. Moreover, the updates on the catalog information, which are very common in a P2P system, can now be managed in a decentralized way. Based on the decentralized catalog management, we design a multi-hop routing algorithm that can reach an arbitrary peer through the paths published by that peer (e.g. Figure 1).

2. The data locating mechanism supports a declarative query language which captures the essential navigational constructs of the XPath language. The data locating mechanism rewrites a declarative XML query into either a process of routing towards a specific logical node in the overlay network or a process of propagating the query within a limited part of the overlay network so as to locate all the peers containing the relevant data. Consequently, our approach avoids flooding the network or using DNS-style servers.

To evaluate the effectiveness of the data locating mechanism, we deploy synthetic distributed XML data over a simulated P2P network generated using NS-2 [5] in transit-stub topology, and we take measurements on several metrics related to the overlay network and different kinds of XML queries. Experimental results demonstrate good scalability.

The organization of the paper is as follows. The related work is presented in Section 2. Section 3 introduces the preliminary knowledge including the definition of the distributed XML data and the overlay network. Based on the overlay network, a decentralized catalog management and a decentralized multi-hop routing mechanism are discussed, respectively, in Sections 4 and 5. In Section 6, the data locating mechanism for declarative XML queries is addressed. In Section 7 we discuss the impact on our mechanism of the frequent joining and leaving of the peers on our mechanism. Section 8 is focused on a series of experiments for performance evaluation. Finally we conclude in Section 9.

## 2 Related Work

Galanis et al. [17] also address the problem of locating relevant data for XML queries. They propose an approach that uses a two-phase process: in the first phase, a specific element name contained in the

XML queries is used as the routing key to locate a catalog that includes the physical site information of all the distributed XML data containing the elements with that name. This phase is realized using existing structured P2P routing mechanisms (e.g. Chord) because the routing keys are just flat-structured element names. In the second phase, the path descriptions of the distributed XML data in the catalog are matched against queries, and the physical sites containing the relevant data are located. Since the catalog information is not evenly distributed among the distributed physical sites, some sites may become bottleneck when a vast number of queries are targeted at them. Another problem is that the path description information is replicated among the catalog sites corresponding to the names contained in the path descriptions, which adds extra overhead for consistency maintenance. In contrast, we encode the hierarchical structure information into the overlay network, consequently each distributed catalog can exclude the structure information and manage much less information. Furthermore, since the distributed XML data cluster according to their hierarchical structure in the overlay network, it is especially efficient to locate the relevant data for queries containing the hierarchical constructs such as ancestor-descendant axis and wild cards, which aggregate structurally similar distributed XML data.

There are other works addressing distributed XML processing. Deshpande et al. discuss distributed XML processing in a sensor database [14], where the distributed XML data are stored geographically close to sensors, and DNS-style servers are employed to locate all physical sites containing data relevant to a query. The Active XML project [1] defines a P2P framework to integrate XML-based Web services, where an Active XML document embeds calls for services distributed on different physical sites. Since the services are referenced using the physical sites' domain names or IP addresses, relevant data are located directly through DNS services on the Internet. We avoid specialized servers in our design by decentralizing the catalog information among all the peers. Similar to DNS style catalogs, XML dissemination systems (e.g. [15]) employ a technique which aggregates the routing information on several distributed brokers based on the topology of a broadcast tree. The aggregation technique is also employed by Koloniari et al. [19], where summary information on each peer is aggregated on ancestor peers following a hierarchical organization. The problem with this approach is that the routing information is replicated along the routing tree, substantially increasing the consistency maintenance cost.

Bremer et al. [11] focus on a top-down design methodology of distributed XML repository systems, whereby large XML documents are partitioned and allocated to distributed physical sites. In their design, the catalog information is fully replicated to all distributed physical sites so that each one is aware of all the mapping information between the fragment data and the physical sites. We, on the other hand, require each peer to only manage a small amount of catalog information, improving scalability.

Suciu addresses the query processing problems on distributed semistructured data [27]. The queries are sent to all distributed nodes and partial query results are collected. As pointed out in the paper, this work is only targeted at a small-scale network environment consisting of dozens of distributed physical sites.

Since we employ a multi-dimensional coordinate space to encode the hierarchical structure information of the distributed XML data into the overlay network, another related work is the construction of the multi-dimensional space for an XML path expression by mapping the element names on each level of the path expression to values [20]. In addition to the element names, we treat attribute values in the same way. Furthermore, we use a secure hash function (i.e. SHA-1 [28]) for the mapping rather than a signature file [21], because SHA-1 is recognized to have good distribution properties such as the guarantee of an even distribution of the information in the overlay network [26].

# 3 Preliminaries

## 3.1 Distributed XML Data Definition

In this work, we use a simple XML path language to define distributed XML data deployed on each peer, whose formal definition is shown in Figure 2. “Label” represents valid element or attribute names in XML documents; “Number” and “String” represent numeric data and character string data respectively. For simplicity of presentation, we do not include XML text nodes in this paper and an extension is straightforward.

```
Path ::= ‘/’ Steps
Steps ::= Step ‘/’ Step
Step::=Label (‘[’ Predicate ‘]’)*
Predicate ::= NumPred | StrPred
NumPred ::= ‘@’Label [‘=’ | ‘>’ | ‘<’ | ‘>=’ | ‘<=’] Number
StrPred ::= ‘@’Label ‘=’ String
```

Figure 2: Distributed XML data definition language

There are several other definitions of distributed XML data and XML fragment in literature, some used for data exchange [16, 18], while others used for storage of distributed XML repositories [11]. Our distributed XML data definition is simpler than these and is restricted to parent-child axis and relational predicates over attributes. Our definition does not include ancestor-descendant axis, wild card, or the exclusion operation (“-”) which can calculate the difference of two fragments as a new fragment [11]. There are multiple reasons for using this simple language. First, there are existing distributed XML data that can be captured by this language (e.g. the XML sensor data [14]). Second, this restricted language is a fundamental part of any XML path language, thus it can be used as a building block of more complex definitions as in the top-down design of distributed XML processing systems [11]. Third, the simplicity of the language indicates the possibility of efficient manipulations over distributed data, which is obviously important for the overall performance of the system.

A piece of distributed XML data on a peer can be published with the path expression defined using the language, and one peer can publish multiple path expressions for different data. For example, in the peer service example, two paths about service data, i.e. “/PeerService[@provider=‘John’]/Country[@name =‘Canada’]/Province[@name =‘Ontario’]/City[@name =‘Toronto’]/Carpooling[@via =‘Toronto’][@date = ‘2004 Dec.19’]” and “/PeerService[@provider=‘John’]/Country[@name =‘Canada’]/Province[@name =‘Ontario’]/City[@name =‘Toronto’]/Carpooling[@via =‘Kingston’][@date = ‘2004 Dec.22’]” can be published by the same peer. Such path expressions can be extracted from the distributed XML data, e.g. in the peer service case, or directly deployed by the data provider, e.g. in the distributed XML repository case. For the latter case, fragments are computed by partitioning the original XML document in the repository horizontally and vertically [11], where, in the context of distributed XML repository, horizontal partitioning refers to a partition over the attribute values while vertical partitioning refers to a partition over rooted element paths. For example, an XML document (derived from [14]) is shown in Figure 3 which describes the distributed sensor data on parking lots according to their geographical status. For clarity, we ignore the data under elements “Parkinglot” because they are never referenced in the remainder. A fragmentation scheme consisting of four fragment path expressions is shown in Figure 4. This fragmentation partitions the XML document vertically on element name such as “Province” and “State”, and horizontally on attribute values such as “Canada” and “United States” for name attribute of element “Country”. Applying this fragmentation scheme over the XML document presented in Figure 3 results in four XML fragments shown in Figure 5.

Up to this point, we have discussed the fragmentation over only one document, but the same strategy can be applied to all the documents in an XML repository. Then the fragments with their path expressions are deployed over peers and each peer may contain multiple fragments.

Without loss of generality, we use the Parking lot example in the remainder of the paper. Similar data exist in the real project of IrisNet [3].

```
<Global>
  <Country name=‘Canada’>
    <Province name=‘Ontario’>
      <City name=‘Waterloo’>
        <Parkinglot id=‘1’>
          ...
        </Parkinglot>
      </City>
      <City name=‘Toronto’>
        <Parkinglot id=‘1’>
          ...
        </Parkinglot>
      </City>
    </Province>
  </Country>
  <Country name=‘United States’>
    <State name=‘New York’ region=‘Northeast’>
      <City name=‘New York’>
        <Parkinglot id=‘2’>
          ...
        </Parkinglot>
      </City>
      <City name=‘Boston’>
        <Parkinglot id=‘3’>
          ...
        </Parkinglot>
      </City>
    </State>
  </Country>
</Global>
```

Figure 3: An XML instance

## 3.2 The Overlay Network

Overlay networks are widely employed in the structured P2P file sharing systems as a substrate to implement a purely decentralized catalog service and routing mechanism. An overlay network is a virtual network consisting of logical nodes each corresponding to a coordinate in a multi-dimensional Cartesian space. The multi-dimensional space and the coordinates in it are defined based on the hierarchical structure information of the paths published by the peers; logical nodes in the overlay network are connected to each other based on their corresponding geometric relationship in the multi-dimensional Cartesian space.

The overlay network provides a basis for managing the catalog in a decentralized way while enabling a

```
Path of Fragment 1:
/Global/Country[@name =‘Canada’]/Province[@name =‘Ontario’]/City[@name =‘Waterloo’]/Parkinglot[@id =‘1’]

Path of Fragment 2:
/Global/Country[@name =‘Canada’]/Province[@name =‘Ontario’]/City[@name =‘Toronto’]/Parkinglot[@id =‘1’]

Path of Fragment 3:
/Global/Country[@name =‘United States’]/State[@name =‘New York’, @region =‘Northeast’]/
City[@name =‘New York’]/Parkinglot[@id =‘2’]

Path of Fragment 4:
/Global/Country[@name =‘United States’]/State[@name =‘New York’, @region =‘Northeast’]/
City[@name =‘Boston’]/Parkinglot[@id =‘3’]
```

Figure 4: A fragmentation scheme

```
Fragment 1:
<Global>
  <Country name=‘Canada’>
    <Province name=‘Ontario’>
      <City name=‘Waterloo’>
        <Parkinglot id=‘1’>
          ...
        </Parkinglot>
      </City>
    </Province>
  </Country>
</Global>
```

```
Fragment 2:
<Global>
  <Country name=‘Canada’>
    <Province name=‘Ontario’>
      <City name=‘Toronto’>
        <Parkinglot id=‘1’>
          ...
        </Parkinglot>
      </City>
    </Province>
  </Country>
</Global>
```

```
Fragment 3:
<Global>
  <Country name=‘United States’>
    <State name=‘New York’ region=‘Northeast’>
      <City name=‘New York’>
        <Parkinglot id=‘2’>
          ...
        </Parkinglot>
      </City>
    </State>
  </Country>
</Global>
```

```
Fragment 4:
<Global>
  <Country name=‘United States’>
    <State name=‘New York’ region=‘Northeast’>
      <City name=‘Boston’>
        <Parkinglot id=‘3’>
          ...
        </Parkinglot>
      </City>
    </State>
  </Country>
</Global>
```

Figure 5: XML fragments

routing mechanism that locates the distributed XML data according to the hierarchial structure information, rather than using the IP addresses as in IP routing. A number of proposals exist for catalog management and routing: Chord [26], CAN [22], etc. Our approach is similar to CAN, but there are important differences. CAN uses the Cartesian space to ensure the relationships among the nodes in the overlay network, but their primary goal of using the cartesian space is for the even distribution of the data in the overlay network, while our objective is to encode the hierarchical structure information of the distributed XML data in the overlay network.

To be more specific, each dimension of the multi-dimensional space corresponds to either a path level (i.e. a level of the path expression corresponding to element names), or a unique attribute name on a specific element path level. For example, ten corresponding dimensions $d_1, d_2, ...d_{10}$ for the four paths in Figure 4 are demonstrated in Table 1. It is important to note that attributes with the same name (e.g. "@name") correspond to different dimensions since they are defined on different path levels. Accordingly, the number of the dimensions is $D = d + \Sigma_{i=1}^{d} a_i$, where $d$ is the maximum depth of all the paths (depth can be measured by the number of the slashes in the path expressions), and $a_i$ is the number of the distinguished attribute names on the $i^{th}$ dimension. For this example, the number of the dimensions is 10. Accordingly, the entire coordinate space can be represented as a hyper-rectangle with dimension $D$. Each distinguished path corresponds to a logical node in the overlay network. The overall hyper-rectangle is disjointly partitioned among sub-hyper-rectangles, and each sub-hyper-rectangle corresponds to exactly one logical node whose coordinate is contained in the sub-hyper-rectangle.

Note that because of the way a coordinate is generated, we do not support range-based data locating so that only those attributes appearing in equality-based predicates are considered in the definition of the dimensions. We will come back to this issue after we discuss the generation of the coordinates. The order of the dimensions should be defined for consistent mapping of paths to coordinates. For ease of explanation, we assume a fixed order for dimensions based on the path levels. Of course joining and leaving of logical nodes in the overlay network (incurred by the joining and leaving of the peers) may affect order and we discuss this issue in Section 7.

| dimension | path level | attribute name |
|---|---|---|
| $d_1$ | 0 | - |
| $d_2$ | 1 | - |
| $d_3$ | 1 | name |
| $d_4$ | 2 | - |
| $d_5$ | 2 | name |
| $d_6$ | 2 | region |
| $d_7$ | 3 | - |
| $d_8$ | 3 | name |
| $d_9$ | 4 | - |
| $d_{10}$ | 4 | id |

Table 1: Definition of the dimensions

Following the definition of the dimensions, each piece of distributed XML data with its path can be mapped to a logical node with a coordinate in the multi-dimensional coordinate space. Since the overlay network is a virtual network, all the information related to the logical node will be kept on the corresponding peer that publishes the XML data with the path[5]. Specifically, the coordinate corresponding to a node in

[5]Unless otherwise specified in the remainder, "node" will denote logical node in the overlay network.

the overlay network is a $D$-tuple $< c_1, c_2, ..., c_D >$ where each $c_i$ is computed by applying a hash function to element name or attribute value corresponding to the dimension $d_i$. In this work, we use SHA-1 [28] as the hash function. SHA-1 is one of the cryptographic message digest algorithms developed by NIST (National Institute of Standards and Technology) for secure information processing, and has been extensively used in structured P2P file sharing systems (e.g. Chord, Pastry). It has two advantages: first, SHA-1 can map each string with length $< 2^{64}$ into a 160-bit integer, so by using SHA-1 we can map the variable-length string of an element name or attribute value to a fixed length value; second, since SHA-1 is well known to be collision free with high probability, we can expect a uniform distribution of element names or attribute values on each dimension. For example, the coordinate corresponding to the path "/Global/Country[@name ='Canada']/Province[@name ='Ontario']/City[@name ='Waterloo']/Parkinglot[@id ='1']" is shown in the third column of Table 2. Note that since the dimension corresponding to the attribute '@region' on dimension $d_6$ is not defined for this fragment, the SHA-1 value of the null string is assigned to that dimension as default. Since it is unclear how to deal with range-based predicates using hash functions, in this work we only consider the attribute values appearing in equality-based predicates.

| dimension | name/value | SHA-1 (in hex) |
|---|---|---|
| $d_1$ | 'Global' | 0x5f1184f7df96c5928092ad9c6b550699bf887826 |
| $d_2$ | 'Country' | 0xd523ebbd10146cdfd39dee077f04c9d08468d0bc |
| $d_3$ | 'Canada' | 0xcd6a7b8768528485a0dbcd459185091e80dc28ad |
| $d_4$ | 'Province' | 0xf5e192238ab260a1133b26537bfff9817c2e0ef3 |
| $d_5$ | 'Ontario' | 0xf9f742e1f653a74c4cd78d7ea283b5556539b96b |
| $d_6$ | '' | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 |
| $d_7$ | 'City' | 0x4271627f4f0bef6104a95cca7bb21cda4d74503e |
| $d_8$ | 'Waterloo' | 0x5bd5a12c3d765c002e39bb392e9ac19df3197ce6 |
| $d_9$ | 'Parkinglot' | 0xc24f000070d98b24ab2767fc7a7a5b404cdefa1f |
| $d_{10}$ | '1' | 0x356a192b7913b04c54574d18c28d46e6395428ab |

Table 2: SHA-1 mapping of a path

Based on the SHA-1 hash function, each dimension of the overall hyper-rectangle has a domain ranging from 0 to the maximum 160-bit integer. As pointed out, each node corresponds to a unique sub-hyper-rectangle, so the overall hyper-rectangle is split among all the nodes. Initially during the bootstrapping of the overlay network, there is only one node corresponding to the overall hyper-rectangle; when a new node joins, its coordinate will sit within the same hyper-rectangle corresponding to the first node, so the hyper-rectangle needs to be split into two sub-hyper-rectangles, each containing only one node. The split will be done at the middle point over one dimension on which two nodes have different coordinate values. There are several candidate dimensions we can choose (e.g. the dimension on which two nodes' coordinates are the most distant as measured by the Euclidean distance, or the most dense dimension, which has the maximum number of different element names or attribute values among all the dimensions). The pseudocode in Algorithm 1 shows the splitting of the (sub-)hyper-rectangle corresponding to the *oldNode* on the most distant dimension, incurred by the joining of the *newNode*. For demonstration, a splitting of an example 2-dimensional coordinate space is shown in Figure 6(a-g), where each node is entitled a number indicating its joining order, i.e. node 1 joins first, followed by node 2, and so on. For clarity, we use a dotted line segment to link the pair of nodes involved in the splitting in each sub-figure.

To make each coordinate unambiguously belong to a unique hyper-rectangle, for each hyper-rectangle, we open its ranges on all the dimensions so that the starting points of the ranges are not included in the hyper-

**Algorithm 1** $Split_{most\_distant}(newNode, oldNode)$

$coordinate1 \leftarrow$ coordinate of the $newNode$;
$coordinate2 \leftarrow$ coordinate of the $oldNode$;
$max \leftarrow 0$;
**for all** $i^{th}$ dimension of the coordinate space **do**
    $d \leftarrow |coordinate1[i] - coordinate2[i]|$;
    **if** $d > max$ **then**
        $max \leftarrow d$;
        $sd \leftarrow i$
    **end if**
**end for**
set the sub-hyper-rectangle of $newNode$ to be the same as that of $oldNode$
$new \leftarrow$ the $sd^{th}$-dimensional value of $coordinate1$
$old \leftarrow$ the $sd^{th}$-dimensional value of $coordinate2$
$middle \leftarrow (new + old)/2$
**if** $new > old$ **then**
    (the start coordinate of the $sd^{th}$-dimension of the $newNode$'s sub-hyper-rectangle) $\leftarrow middle$
    (the end coordinate of the $sd^{th}$-dimension of the $oldNode$'s sub-hyper-rectangle) $\leftarrow middle$
**else**
    (the end coordinate of the $sd^{th}$-dimension of the $newNode$'s sub-hyper-rectangle) $\leftarrow middle$
    (the start coordinate of the $sd^{th}$-dimension of the $oldNode$'s sub-hyper-rectangle) $\leftarrow middle$
**end if**

rectangle[6]. This constraint can prevent a query from being redundantly propagated to the nodes whose hyper-rectangles share boundaries (e.g. facets, lines, and points) in the context of the query propagation (addressed in Section 6), without impacting the definition on the overlapping and adjoining relationship among the hyper-rectangles. For example, all the coordinates on the line segment ($a$, $b$) in the Figure 6(h) are not included in the hyper-rectangle corresponding to node 4, and similarly the coordinates on the line segments ($c$, $d$) and ($e$, $f$) are not included in the hyper-rectangles corresponding to node 6 and 5 respectively.

The topology of the nodes in the overlay network is decided by the geometric relationship among the hyper-rectangles corresponding to the nodes, where two node are neighbor iff their hyper-rectangles overlap on all the matching dimensions except the one on which they adjoin each other. For example in Figure 6(g), nodes 1, 2, 3 and 7 are neighbors of node 4.

Since the hierarchical structural information of the XML data is now encoded in the overlay network, we can design a catalog management system based on it, without including such information explicitly in the catalog.

# 4 Decentralized Catalog Management

Since the hierarchical structure information of all the distributed XML data has been encoded in the overlay network, a catalog based on the overlay network can ignore such information and only include routing tables and necessary metadata about the distributed XML data (e.g. URI of the XML documents), which are much smaller in size than the hierarchical structure information. More importantly, these information can be deployed among the nodes in the overlay network in a decentralized way so as to improve the scalability of the system and ease catalog management.

Each node in the overlay network keeps the catalog information about all the paths mapped to it in the form $< path, \ address >$ (in the case of a TCP/IP network, the address would be the IP address, but other kinds of physical address are also possible). To identify itself, each node also keeps the information about its corresponding coordinate and hyper-rectangle. Moreover, each node has a routing table, where each entry holds information for one neighbor as a 3-tuple $< coordinate, \ hyperrectangle, \ address >$ corresponding to a neighboring node. For demonstration purposes, the catalog information for the nodes in Figure 6(g) is given in Figure 7. Note that since the overlay network is a virtual network, the catalog information is actually stored on the corresponding peers.

The size of the routing table at each node is linear in the number of its neighbors, and experiments show that for an overlay network containing 4700 nodes, the average number of the neighbors per node can be 20 (by splitting on the most distant dimension), which indicates good scalability (see Section 8). It has been proven that the routing table size is logarithmic in the number of the nodes in structured P2P file sharing systems [26, 22]. This result is based on the assumption that the nodes are uniformly distributed in the overlay network with high probability. Unfortunately, this assumption is not necessarily true in our overlay network, because nodes corresponding to structurally similar paths cluster together. For example the paths of fragments 1 and 2 in Figure 5 are different only in the dimension corresponding to the '@name' attribute, so their corresponding nodes are neighbors in the overlay network.

[6] Except when the value of the starting point is zero, which means it is the starting point of the overall coordinate space on the corresponding dimension

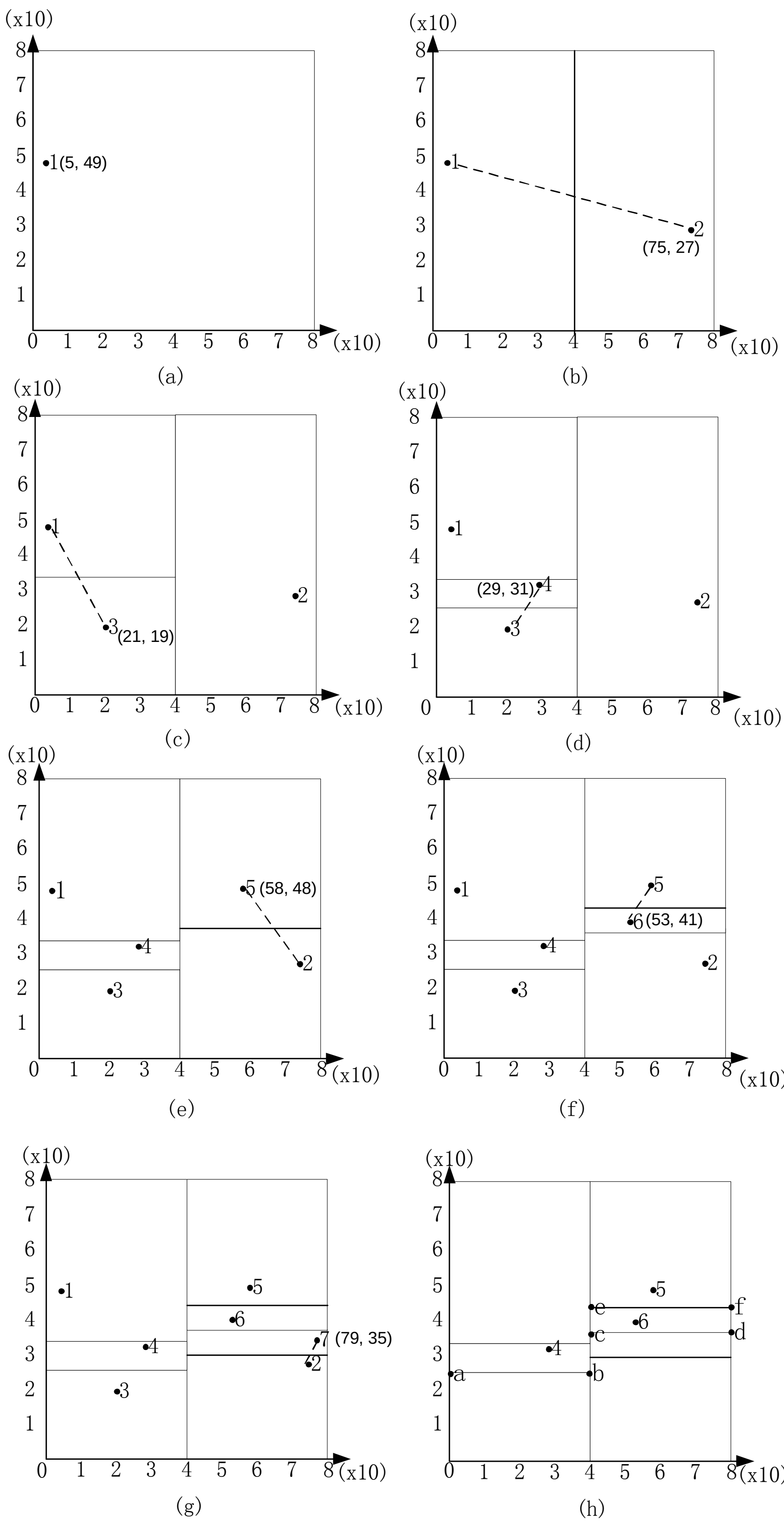



Figure 6: Split of the coordinate space

| | coordinate | start coordinate | end coordinate | physical address | neighboring node | coordinate | start coordinate | end coordinate | physical address |
|---|---|---|---|---|---|---|---|---|---|
| node1 | (5, 49) | (0, 34) | (40, 80) | address1 | node4 | (29, 31) | (0, 25) | (40, 34) | address4 |
| | | | | | node5 | (58, 48) | (40,44.5) | (80, 80) | address5 |
| | | | | | node6 | (53, 41) | (40,37.5) | (80, 44.5) | address6 |
| | | | | | node7 | (79, 35) | (40, 31) | (80, 37.5) | address7 |
| node2 | (75, 27) | (40, 0) | (80, 31) | address2 | node3 | (21, 19) | (0, 0) | (40, 25) | address3 |
| | | | | | node4 | (29, 31) | (0, 25) | (40, 34) | address4 |
| | | | | | node7 | (79, 35) | (40, 31) | (80, 37.5) | address7 |
| node3 | (21, 19) | (0, 0) | (40, 25) | address3 | node2 | (75, 27) | (40, 0) | (80, 31) | address2 |
| | | | | | node4 | (29, 31) | (0, 25) | (40, 34) | address4 |
| | | | | | node7 | (79, 35) | (40, 31) | (80, 37.5) | address7 |
| node4 | (29, 31) | (0, 25) | (40, 34) | address4 | node1 | (5 49) | (0, 34) | (40, 80) | address1 |
| | | | | | node2 | (75, 27) | (40, 0) | (80, 31) | address2 |
| | | | | | node3 | (21, 19) | (0, 0) | (40, 25) | address3 |
| | | | | | node6 | (53, 41) | (40,37.5) | (80, 44.5) | address6 |
| | | | | | node7 | (79, 35) | (40, 31) | (80, 37.5) | address7 |
| node5 | (58, 48) | (40,44.5) | (80, 80) | address5 | node1 | (5, 49) | (0, 34) | (40, 80) | address1 |
| | | | | | node6 | (53, 41) | (40,37.5) | (80, 44.5) | address6 |
| node6 | (53, 41) | (40,37.5) | (80, 44.5) | address6 | node1 | (5, 49) | (0, 34) | (40, 80) | address1 |
| | | | | | node4 | (29, 31) | (0, 25) | (40, 34) | address4 |
| | | | | | node5 | (58, 48) | (40,44.5) | (80, 80) | address5 |
| | | | | | node7 | (79, 35) | (40, 31) | (80, 37.5) | address7 |
| node7 | (79, 35) | (40, 31) | (80, 37.5) | address7 | node1 | (5, 49) | (0, 34) | (40, 80) | address1 |
| | | | | | node2 | (75, 27) | (40, 0) | (80, 31) | address2 |
| | | | | | node3 | (21, 19) | (0, 0) | (40, 25) | address3 |
| | | | | | node4 | (29, 31) | (0, 25) | (40, 34) | address4 |
| | | | | | node6 | (53, 41) | (40,37.5) | (80, 44.5) | address6 |

routing table

Figure 7: Catalog information per node

Catalog also includes metadata about the distributed XML data deployed in the P2P network. For example, in the distributed XML repository case, URI (Universal Resource Identifier) information is important to distinguish different XML documents deployed over the same P2P network. We replicate the metadata on each node by reserving for it a special dimension in the multi-dimensional coordinate space. Furthermore, as pointed out, the XML schema information used to execute queries is available on peers, which is useful for query rewriting. Since each peer only needs to know the schema in which it is interested, such metadata can be regarded as partially replicated in the network. Other useful metadata include the number of distinguished element names or attribute values on each dimension defined in the overlay network, which can be used in the splitting algorithm shown in Algorithm 1 (e.g. when choosing the dimension with the maximum number of different element names). This global statistical information can be deployed on a specific logical node (physically on the corresponding peer) whose corresponding hyper-rectangle covers the coordinate of $(0, 0, 0, ...0)$. However, for better scalability, we replicate the information on several nodes in the overlay network, e.g. the node whose corresponding hyper-rectangle covers the coordinate of $(x_i, 0, 0, ...0)$, where $x_i$ is the SHA-1 hash value of the URI corresponding to each different XML document in the distributed XML repository case. The problem of employing this information is that if peers join and leave the network very frequently, the maintenance cost will be high. Fortunately, the experiments show that the splitting algorithm based on the most distant dimension shows good scalability over thousands of nodes, so that we can choose this option to keep the catalog management in a purely decentralized manner.

Since the URI information and the schema information can be expected to be stable, little maintenance is needed. Then the biggest catalog maintenance work is on the routing tables: changes on the topology of the overlay network affect the routing tables of the related nodes. For example, if a node leaves the overlay network, its corresponding entries in its neighbors' routing tables need to be removed and new entries are then created there based on the new neighboring relationships among the remaining nodes. Since the maintenance work is distributed among all the peers, we can expect the catalog management to be scalable over large-scale P2P networks.

# 5 Routing towards peers

In the environment that is considered, XML data is distributed and stored on peers, as described above, where the data is defined by paths. A fundamental point of query processing in this environment is to efficiently match data to queries without extensive communication overhead. In this section we discuss a multi-hop routing algorithm to reach an arbitrary peer. This algorithm is the basis of the data locating mechanism described in the next section.

The routing algorithm is given in Algorithm 2, which works as follows. The target peer has a *target node* in the overlay network and we call its corresponding coordinate as *target coordinate*; during each hop, a node is reached that we call the *context node*. When a context node is reached (including the initial node), its coordinate is checked against the target coordinate. If the target node is not reached, the context node's routing table is scanned and the neighboring node whose hyper-rectangle is geometrically closest to the target coordinate is chosen as the context node for the next hop. The process continues until the target is reached. Remember that a peer may publish multiple pieces of XML data resulting in multiple overlay network nodes corresponding to that peer. So it is possible that the context node shares the same peer as that corresponding to the target coordinate. To exploit this, in each hop all the other logical nodes deployed on the peer corresponding to the context node are matched against the target coordinate for an early finding. This is reflected in lines 4 and 5 of Algorithm 2. Furthermore, by replacing the equality tests in lines 1 and 5 of the Algorithm 2 with containment tests to check whether $targetCoordinate$ is contained in the hyper-rectangles corresponding to $contextNode$ and $N$ respectively, the algorithm can route towards any peer corresponding to the nodes whose hyper-rectangle cover specific coordinates such as $(x_i, 0, 0, ...0)$ and $(0, 0, 0, ...0)$, as used by the catalog management mentioned in the previous section.

The crucial part of this routing algorithm is how to choose a neighboring node. A naive strategy is to measure the geometric distance directly using the Euclidean distance from the coordinate of a neighboring node to the target coordinate. Unfortunately this strategy does not necessarily converge, as demonstrated in Figure 8(a), where the context node is 4 and the target node is 6. Note that none of the neighboring nodes of the context node, i.e. nodes 1, 2, 3 and 7, is closer to the target node than node 4 itself (the Euclidean distance is marked in the figure). Thus if we simply choose the node with the closest Euclidean distance from the target coordinate (i.e. node 2), for the next hop, the routing will return to node 4 because now node 2 is the context node and node 4 is its neighbor with coordinate closest to the target coordinate. Thus, routing will not converge. To avoid this problem, we propose a novel approach to measure the geometric distance, where we still use Euclidean distance, but choose different coordinates in the hyper-rectangle for the measurement. We use *anchor coordinate* to denote a coordinate that is used for the measurement. Initially, the anchor coordinate is the coordinate of the context node from which the routing is issued. To choose context node and anchor coordinate for the next hop, all the distances between the coordinates of the neighboring nodes and the target coordinate are compared against the distance from the anchor coordinate. If there are some neighboring nodes with coordinate closer to the target coordinate than the anchor coordinate, the one with the closest distance will be chosen as the context node for the next hop and its coordinate is assigned to the anchor coordinate. Otherwise, we compute the intersection point between the context node's hyper-rectangle and the line segment from the anchor coordinate to the target coordinate (Figure 8(b))[7], and specify the coordinate of the intersection point as the anchor coordinate for the next hop. Correspondingly, the neighboring node whose hyper-rectangle adjoins with the context node's hyper-rectangle on the intersection point is chosen as the context node for the next hop.

The computation cost of calculating the intersection point is $O(n^2)$ where $n$ is the number of the dimensions of the multi-dimensional space, because, in the worst case, all the facets of a hyper-rectangle (totally $2n$ facets) need to be checked to see whether or not the intersection point is located inside it, and the computation on each facet involves each dimension (totally $n$ dimensions).

This approach ensures that the Euclidean distance from the anchor coordinate to the target coordinate decreases with each hop, thus guaranteeing the convergence of the routing algorithm.

**Theorem 5.1.** *The Euclidean distance from the anchor coordinate to the target coordinate strictly decreases with each hop.*

*Proof.* Denote the Euclidean distance from the anchor coordinate to the target coordinate to be $e$, and the Euclidean distances from the neighbors' coordinates to the target coordinate as $e_1, e_2, ..., e_m$, where $m$ is the number of the neighbors of the context node. If there exist some $\{e_i\} \subseteq \{e_1, e_2, ..., e_m\}$ that are smaller than $e, 1 \leq i \leq m$, the algorithm will choose the minimum one, say $e_{min},\ \ 1 \leq min \leq m$. It is apparent that

[7] The intersection point will be always available since a hyper-rectangle is a convex hull and one end point of the line segment, i.e. the anchor coordinate, is within the hyper-rectangle while the other, i.e. target coordinate, is outside.

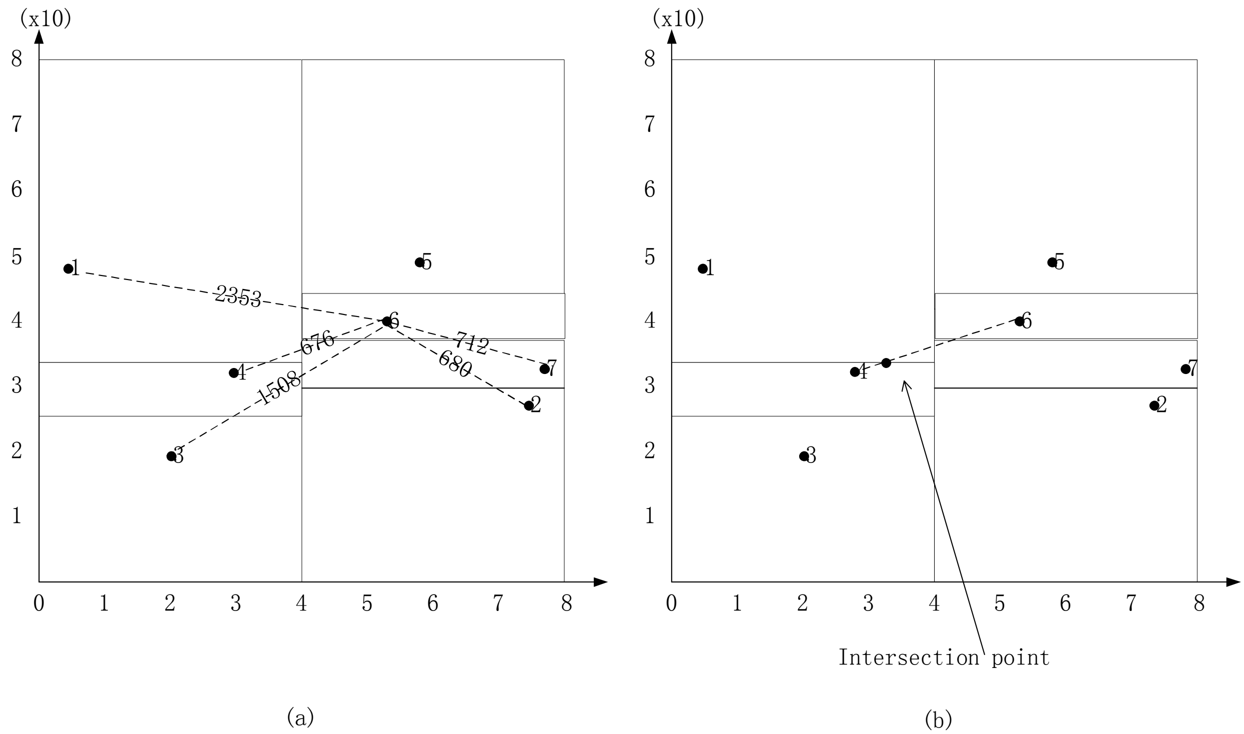



Figure 8: Measuring distance through Intersection point

**Algorithm 2** *Route*(*contextNode*, *targetCoordinate*, *anchorCoordinate*)

```
if contextNode's coordinate is equal to targetCoordinate then
  the routing succeeds and return contextNode;
else
  check all the other nodes residing on the same peer as that of contextNode
  if there is a node N whose coordinate is equal to the targetCoordinate then
    the routing succeeds and return N;
  end if
  d ← Euclidean distance from anchorCoordinate to targetCoordinate;
  min ← the smallest Euclidean distance of all the neighboring nodes using their coordinates;
  if min < d then
    nextNode ← the neighboring node corresponding to min;
    nextAnchorCoordinate ← nextNode's corresponding coordinate
    return Route(nextNode, targetCoordinate, nextAnchorCoordinate);
  else
    calculate the line segment from anchorCoordinate to targetCoordinate;
    intersectPoint ← the intersection point between the line segment and contextNode's hyper-rectangle;
    nextAnchorCoordinate ← intersectPoint's corresponding coordinate
    for all neighboring node node_i whose hyper-rectangle adjoins with contextNode's hyper-rectangle on intersectPoint do
      return Route(node_i, targetCoordinate, nextAnchorCoordinate);
    end for
  end if
end if
```

$e_{min}$ is strictly smaller than the Euclidean distance from the coordinate of the context node to the target coordinate. On the other hand, if no $e_i \in \{e_1, e_2, ..., e_m\}$ is smaller than $e$, the anchor coordinate of the next hop will be the intersection point's coordinate, which indicates a strictly smaller Euclidean distance because the intersection point is located on the line segment between the two end points, i.e. the anchor coordinate and the target coordinate. □

Our routing algorithm differs from that in the CAN system [22] in the strategy we use to find a neighboring node for the next hop. The measurement of the geometric distance directly using the coordinate of the context node, as done in CAN, works only if the coordinate space is evenly split among all the nodes so that, with high probability, there exist some neighboring nodes with coordinates closer to the target coordinate. This is not true in general and does not hold in our case, since nodes corresponding to structurally similar paths (and also data) cluster in the coordinate space. Sahin et al. develop a strategy on choosing the closest neighboring node [25], where the geometric distance from the context node's hyper-rectangle to the target coordinate is measured from the facet adjoining with a neighboring zone of the context node which covers the target coordinate. The computation cost is the same but the strategy is quite different.

# 6 Locating Relevant Data for Complex Queries

Based on the decentralized catalog management and routing mechanism described in the previous section, we design a data locating mechanism for XML queries. The queries are defined using a limited version of the XPath language, which covers the parent-child axis (i.e. "/"), the ancestor-descendant axis (i.e. "//"), the wild card for element names (i.e. "*"), and equality-based predicates over attributes. Besides absolute location path, the language also supports relative location path. The BNF definition of the language is shown in Figure 9, where "Label" represents valid element or attribute names in XML documents, "Number" and "String" represent numeric data and character string data respectively, which can also be a wild card. This query language captures the essence of the path expressions for navigating XML data. Order sensitive constructs such as "preceding-sibling", etc. are not supported since the overlay network only encodes the parent-child hierarchical information of the distributed data. Moreover, since only equality-based predicates are considered in the construction of the overlay network and range predicate operators such as "<", ">", etc. are not supported by the routing mechanism, we exclude them from the query language. These will be addressed in future work.

```
Path ::= Steps | [ '/' | '//'] Steps
Steps ::= Step ['/' | '//'] Step
Step ::= [Label | '*'] ('[' Predicate ']')*
Predicate ::= NumPred | StrPred
NumPred ::= '@'Label '=' Number
StrPred ::= '@'Label '=' String
```

Figure 9: BNF definition of the query language

Note that the query language that we use is more expressive than the language used to define distributed data (see Figure 2) in that the former includes wild card, ancestor-descendant axis and relative location path that are omitted from the latter. Since the distributed data definition language determines the definition of the overlay network and the routing algorithm, this mismatch between the two languages needs to be addressed. Briefly, the data locating for a query is transformed into a routing process towards a peer if the following two conditions are satisfied: (1) the query contains only absolute location path and parent-child axis, and (2) the query is defined on all the dimensions of the overlay network. Otherwise, for queries containing wild card or ancestor-descendant axis, and queries that are not fully defined on all the dimensions, the data locating mechanism will first locate a rendezvous node which is related to the query from where the query is propagated in a limited subnetwork. Since there is no centralized catalog providing a complete mapping of a query to candidate paths published in the network, a propagation is unavoidable. By choosing a rendezvous node first and then making a limited broadcast, we avoid the naive flooding utilized in some P2P file sharing systems. The experiments show good scalability of our data locating mechanism for all kinds of queries.

## 6.1 Queries with absolute location path and parent-child axis

As mentioned above, queries that only contain absolute location path and parent-child axis completely match the distributed XML data definition language. Thus the query path expression can be hashed to a coordinate in the same way as a path published by peers in the network. We call this the *query coordinate*.

If the path expression of a query is defined on all the dimensions of the coordinate space, locating the relevant data can be accomplished by routing the query towards the peer that publishes the same path. For example, a query can be"/Global/Country[@name ='United States']/State[@name ='New York'][@region ='Northeast']/City[@name ='New York']/Parkinglot[@id ='2']", which satisfies the above conditions. Thus the relevant data can be located by directly routing the query towards the corresponding query coordinate in the overlay network.

A more complicated case is that some dimensions are not defined in the query. For these missing dimensions, we assign SHA-1 hash value of the null string as default values, denoted as "#" for convenience. For example, based on the dimensions defined in Table 1, the query coordinate of the query "/Global/Country[@name ='Canada']/Province[@name ='Ontario']/City" is shown in the third column of Table 3, which has four default values corresponding to the missing dimensions (i.e. Province region, City name, Parkinglot, and Parkinglot id). Such a query can not be rewritten into paths published in the P2P network without a centralized catalog. We solve this problem by propagating the query within a limited part of the overlay network. In principle, all the nodes in the overlay network matching the query should be covered by a *sub-coordinate-space* that is defined by the query coordinate. Specifically, on the dimensions that the query is defined, the sub-coordinate-space takes the point values of the query coordinate as its ranges (i.e. range with single value); otherwise on the dimensions that the query is not defined, the sub-coordinate-space takes the full range of the overall coordinate space (i.e. 0 to the maximum of 160-bit integer). For demonstration, the sub-coordinate-space corresponding to the query coordinate in the third column of Table 3 is shown in the fourth column. Note that we set the range corresponding to the missing dimensions to be the whole domain of the dimension so as to cover all the possible values on it. There are still two problems: (1) how to choose a starting point for the propagation, and (2) how to propagate the query so that all the relevant logical nodes are exhausted. The answer to the first question is that we can start from any node in the overlay network whose hyper-rectangle intersects with the sub-coordinate-space. The answer to the second question is that we can propagate the query to all of its neighbors in the overlay network whose hyper-rectangles intersect with the sub-coordinate-space. Here, the intersection between a hyper-rectangle and a sub-coordinate-space means that the hyper-rectangle contains some coordinates belonging to the sub-coordinate-space. Our strategy is based on the intuition that all the nodes whose hyper-rectangle intersects with the sub-coordinate-space are interconnected with each other by neighboring relationship.

| dimension | name/value | query coordinate (SHA-1 value in hex) | sub-coordinate-space (SHA-1 value in hex) |
|---|---|---|---|
| $d_1$ | 'Global' | 0x5f1184f7df96c5928092ad9c6b550699bf887826 | 0x5f1184f7df96c5928092ad9c6b550699bf887826 |
| $d_2$ | 'Country' | 0xd523ebbd10146cdfd39dee077f04c9d08468d0bc | 0xd523ebbd10146cdfd39dee077f04c9d08468d0bc |
| $d_3$ | 'Canada' | 0xcd6a7b8768528485a0dbcd459185091e80dc28ad | 0xcd6a7b8768528485a0dbcd459185091e80dc28ad |
| $d_4$ | 'Province' | 0xf5e192238ab260a1133b26537bfff9817c2e0ef3 | 0xf5e192238ab260a1133b26537bfff9817c2e0ef3 |
| $d_5$ | 'Ontario' | 0xf9f742e1f653a74c4cd78d7ea283b5556539b96b | 0xf9f742e1f653a74c4cd78d7ea283b5556539b96b |
| $d_6$ | '' | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 (i.e. #) | [0, 0xffffffffffffffffffffffffffffffffffffffff] |
| $d_7$ | 'City' | 0x4271627f4f0bef6104a95cca7bb21cda4d74503e | 0x4271627f4f0bef6104a95cca7bb21cda4d74503e |
| $d_8$ | '' | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 | [0, 0xffffffffffffffffffffffffffffffffffffffff] |
| $d_9$ | '' | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 | [0, 0xffffffffffffffffffffffffffffffffffffffff] |
| $d_{10}$ | '' | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 | [0, 0xffffffffffffffffffffffffffffffffffffffff] |

Table 3: Query coordinate with undefined dimension and corresponding sub-coordinate-space

**Theorem 6.1.** *All the nodes in the overlay network whose hyper-rectangles intersect with the sub-coordinate-space are, recursively, neighbors of each other in the overall coordinate space.*

*Proof.* According to the definition of the intersection relationship between a hyper-rectangle and the same sub-coordinate-space, if two arbitrary hyper-rectangles both intersect with the sub-coordinate-space, their ranges must overlap on the dimensions on which the sub-coordinate-space has point values. Then the remaining dimensions (with full range from 0 to maximum of 160-bit integer) can correspond to a space with reduced dimensions, which we call *reduced space* in the remainder. If we use *intersection zone* to represent the intersection space between a hyper-rectangle and the *reduced space*, two intersection zones will be neighbors of each other if and only if their corresponding hyper-rectangles are neighbors, based on the neighboring relationship defined in Section 3. Since the *reduced space* is continuous, it is straightforward, from a geometric perspective, that the intersection zones are recursively neighbors of each other. This leads to the conclusion that their corresponding hyper-rectangles are also recursively neighboring to each other. □

Theorem 6.1 excludes the possibility that some nodes relevant to the query have to be reached via other nodes whose hyper-rectangles are disjoint from the sub-coordinate-space, so as to ensure propagation in a limited overlay network. In this work, we simply choose the node whose hyper-rectangle covers the query coordinate as the starting point (thus, the hyper-rectangle intersects with the sub-coordinate-space), and the propagation proceeds recursively until all the nodes whose hyper-rectangles intersect with the sub-coordinate-space are exhausted. The propagation algorithm is shown in Algorithm 3.

Finally, during the propagation, a node may be visited via different neighboring nodes. To avoid redundant checks, each node keeps a log which contains all the queries that have been propagated to it, so that a revisit can be terminated.

## 6.2 Queries with absolute location path and wild card

The wild card in a query path expression matches an arbitrary element name and attributes at a specific path level. Since the XML schema information for the queries is available on peers, we can always transcribe

**Algorithm 3** $Propagate(contextNode, subVectorSpace, relevantNodeList)$

```
1: if contextNode is covered by the subVectorSpace then
2:    append contextNode into relevantNodeList
3: end if
4: for all neighboring nodes of contextNode do
5:    if the neighboring node node_i's hyper-rectangle intersects with the subVectorSpace then
6:       Propagate(node_i, subVectorSpace, relevantNodeList)
7:    end if
8: end for
```

a query containing a wild card into several subqueries, each taking a possible element name and its corresponding attribute names defined on that path level, with the attribute values not specified. For example, if we assume that either *State* or *Province* can appear at the path level below the path level of *Country*, the query "/Global/Country[@name ='Canada']/*/City[@name ='Waterloo']/Parkinglot[@id ='1']" can be rewritten into two subqueries, i.e. "/Global/Country[@name ='Canada']/Province[@ name = '*']/City[@name ='Waterloo']/Parkinglot[@id ='1']" and "/Global/Country[@name ='Canada'] /State[@name='*'][@region='*']/City[@name ='Waterloo']/Parkinglot[@id ='1']". The problem with this approach is that when the numbers of candidate element names and attributes are large, there will be too many subqueries. Even worse, when there are multiple wild cards in the query, the number of the subqueries will increase exponentially. Another problem is that the attributes attached with the element names cannot be estimated since schema information only provides data types of the attributes rather than exact values. Thus we specify wild cards as the attribute values in the subqueries, which implicitly indicates a propagation for each subquery. So instead of rewriting the query into subqueries according to the possible elements and attributes defined by the schema, we take an alternative approach to generate the subqueries by simply assigning wild cards to all the dimensions not defined in the query, covering both element names and attributes. Then we apply the same data locating mechanism as before. This approach eases each peer from the task of generation of the subqueries, and also makes the data locating less dependent on the schema information. For example, consider a query "/Global/Country/*/City[@name = 'Waterloo']/*", which queries parking lot data for all cities with the name "Waterloo". Its query coordinate (shown in the third column of Table 4) is located first and then all the hyper-rectangles intersecting with the sub-coordinate-space (shown in the fourth column in Table 4) are reached, among which those nodes whose coordinates covered by the sub coordinate space are retrieved and corresponding peers will be contacted for the relevant data.

## 6.3 Queries with relative location path and parent-child axis

According to the query definition language, a query can be a relative location path expression, e.g. "Country[@name ='Canada']/Province[@name ='Ontario']/City[@name ='Waterloo']/Parkinglot[@id ='1']". According to the schema, the query can be directly transcribed into the absolute location path query "/Global/Country [@name ='Canada']/Province[@name ='Ontario']/City[@name ='Waterloo']/Parkinglot[@id ='1']". Since the problem on the number of the subqueries described in Section 6.2 still exists, in this work we rewrite the query into $(n - m + 1)$ subqueries, each starting from a different level and leaving the previous path levels with wild cards, where $n$ is the maximum depth of the path (only containing parent-child axis) allowed by

| dimension | name/value | query coordinate (SHA-1 value in hex) | sub-coordinate-space (SHA-1 value in hex) |
|---|---|---|---|
| $d_1$ | 'Global' | 0x5f1184f7df96c5928092ad9c6b550699bf887826 | 0x5f1184f7df96c5928092ad9c6b550699bf887826 |
| $d_2$ | 'Country' | 0xd523ebbd10146cdfd39dee077f04c9d08468d0bc | 0xd523ebbd10146cdfd39dee077f04c9d08468d0bc |
| $d_3$ | '' | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 (i.e. #) | [0, 0xffffffffffffffffffffffffffffffffffffffff] |
| $d_4$ | * | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 | [0, 0xffffffffffffffffffffffffffffffffffffffff] |
| $d_5$ | '' | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 | [0, 0xffffffffffffffffffffffffffffffffffffffff] |
| $d_6$ | '' | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 | [0, 0xffffffffffffffffffffffffffffffffffffffff] |
| $d_7$ | 'City' | 0x4271627f4f0bef6104a95cca7bb21cda4d74503e | 0x4271627f4f0bef6104a95cca7bb21cda4d74503e |
| $d_8$ | 'Waterloo' | 0x5bd5a12c3d765c002e39bb392e9ac19df3197ce6 | 0x5bd5a12c3d765c002e39bb392e9ac19df3197ce6 |
| $d_9$ | * | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 | [0, 0xffffffffffffffffffffffffffffffffffffffff] |
| $d_{10}$ | '' | 0xda39a3ee5e6b4b0d3255bfef95601890afd80709 | [0, 0xffffffffffffffffffffffffffffffffffffffff] |

Table 4: Query coordinate corresponding to queries with wild cards and its sub-coordinate-space

the schema, and $m$ is the number of the path levels of the query. In this way, we bound the number of the subqueries and can further use the schema to prune the invalid subqueries.

Take an example about a personal contact list, whose simple XML schema tree is shown in Figure 10(a). Note that the element *person* is defined at two different path levels. If we consider a simple relative location path query, i.e. "person", it will be initially transcribed into five subqueries, and after pruning the invalid ones based on the schema, two are left (see Figure 10(b)).

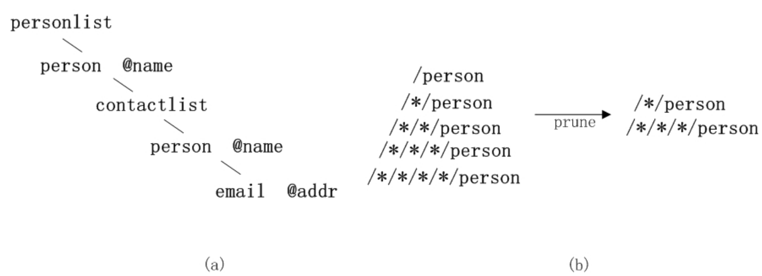



Figure 10: Rewriting a query with wild card

All the valid subqueries are issued simultaneously from the peer posing the query, and relevant data are located using the strategies discussed in the previous subsections since all the subqueries contain only absolute path and wild card.

## 6.4 Queries with ancestor-descendant axis

Similar to the case of the relative location path queries (Section 6.3), we can also rewrite a query with ancestor-descendant axes into multiple subqueries containing only wild cards and parent-child axes. Since ancestor-descendant axis can appear at any level of a query path expression, we consider all the combinations of the rewriting of ancestor-descendant axis using wild cards. Again, we use the maximum depth of a path allowed by the schema to constrain the number of the subqueries. For example, based on the schema shown in Figure 10(a), a query "//person" can be expanded into five subqueries, while another query "//person/email" can be expanded into only four subqueries shown in Figure 11, which also depicts the pruning of the invalid ones.

Finally, since all the subqueries only contain wild cards and parent-child axes, the data locating mecha-

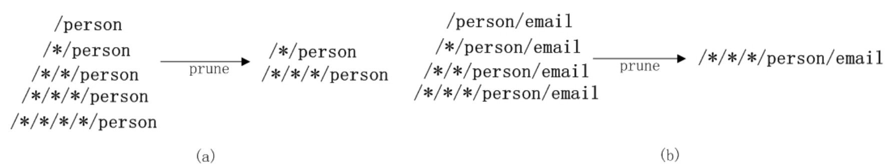



Figure 11: Rewriting a query with ancestor-descendant axis

nism is the same as discussed before.

### 6.5 Pre and post-processing for more complex queries

As pointed out before, our query language is a limited subset of XPath so that we need to resolve the unsupported constructs and operators by pre and post-processing.

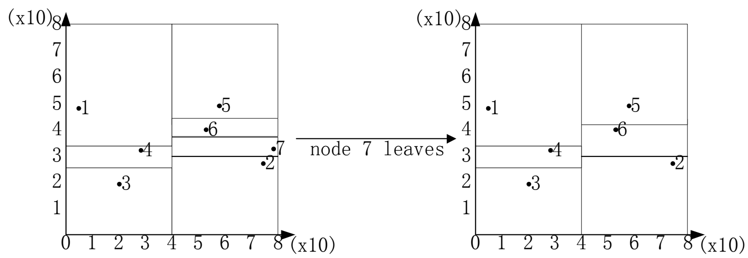
- For queries with predicates involving existence test of child elements, e.g. "/Global/Cou-ntry//City[Parkinglot[@id = 4]]", the pre-processing transcribes the query into two subqueries, i.e., "/Global/Country//City" and "/Global/Country//City/Parkinglot[@id = 4]"; and post-processing joins the result data located by the two subqueries for the final answer.
- For queries containing range-based relational predicates, e.g. "/Global/Country//City[@ name = 'Waterloo']/Parkinglot[@id $<$ 4]", when such a query is issued, we suppress the range-based relational predicate and locate the relevant data for a transcribed version of the query without any range-based relational predicate. Then, during a post-processing we impose the range-based relational predicates over the returning data for a finer retrieval.

Other unsupported constructs and operators can also be resolved by certain pre and post-processing, but obviously they are not ideal solutions for these complex queries. We plan to design new routing mechanism to support these constructs and operators in the future work.

## 7 Dealing With the Dynamic Environment

In a P2P network, peers may join and leave arbitrarily, which may affect the published data in the network and further impact the definition of the multi-dimensional space. Since the dimensions may increase or decrease with the change of the nodes in the overlay network, it is impractical to fix the order of the dimensions beforehand. Instead, we encode the order of the dimensions into the pair of $<$ *path level*, *attribute name* $>$, where the *path level* represents the levels corresponding to element names. If the attribute name is null, the pair will correspond to elements at the path level, otherwise to attributes. Thus a set of such pairs uniquely defines the dimensions of the coordinate space. Accordingly, each coordinate is redefined as a set of SHA-1 values together with the $<$ *path level*, *attribute name* $>$ information. Consequently, the operations over the coordinates also need to be adjusted.

As pointed out in Section 4, the joining and leaving of nodes in the overlay network affect the content of the routing tables. When a peer joins with new data, new nodes will be added to the overlay network. Since the topology of the overlay network changes, the routing tables of the related nodes will be updated accordingly. Similarly, the departure of a peer causes deletion of its data or their transfer them to other peers (according to some prior agreements). If data are deleted, the corresponding nodes in the overlay network will be removed accordingly, causing their neighboring nodes to remove the related entries from their routing tables. Furthermore, hyper-rectangles corresponding to the departing node need to be merged with the remaining neighboring nodes, and new entries are added based on the updated neighboring relationships among the remaining nodes. If the departing peer transfers its data to others, the hyper-rectangles will not change, but the physical addresses in the routing table entries of the related nodes need to be updated. Specifically, an example is shown in Figure 12(a) to demonstrate the leaving of node 7. In this work, to make the coordinate space split as evenly as possible, we merge the hyper-rectangle corresponding to a departing node with its neighbor whose hyper-rectangle has the smallest area, e.g. node 6 in this example. Then the routing tables of the neighboring nodes need to be changed, and in the Figure 12(b) we show the routing tables of node 1, 2, 3, 4, and 6, which are the original neighbors of node 7.




(a)

| | coordinate | start coordinate | end coordinate | physical address | neighboring node | coordinate | start coordinate | end coordinate | |
|---|---|---|---|---|---|---|---|---|---|
| node1 | (5, 49) | (0, 34) | (40, 80) | address1 | node4 | (29, 31) | (0, 25) | (40, 34) | address4 |
| | | | | | node5 | (58, 48) | (40,44.5) | (80, 80) | address5 |
| | | | | | node6 | (53, 41) | (40,31) | (80, 44.5) | address6 |
| node2 | (75, 27) | (40, 0) | (80, 31) | address2 | node3 | (21, 19) | (0, 0) | (40, 25) | address3 |
| | | | | | node4 | (29, 31) | (0, 25) | (40, 34) | address4 |
| | | | | | node6 | (53, 41) | (40,31) | (80, 44.5) | address6 |
| node3 | (21, 19) | (0, 0) | (40, 25) | address3 | node2 | (75, 27) | (40, 0) | (80, 31) | address2 |
| | | | | | node4 | (29, 31) | (0, 25) | (40, 34) | address4 |
| | | | | | node6 | (53, 41) | (40,31) | (80, 44.5) | address6 |
| node4 | (29, 31) | (0, 25) | (40, 34) | address4 | node1 | (5 49) | (0, 34) | (40, 80) | address1 |
| | | | | | node2 | (75, 27) | (40, 0) | (80, 31) | address2 |
| | | | | | node3 | (21, 19) | (0, 0) | (40, 25) | address3 |
| | | | | | node6 | (53, 41) | (40,31) | (80, 44.5) | address6 |
| node6 | (53, 41) | (40,31) | (80, 44.5) | address6 | node1 | (5, 49) | (0, 34) | (40, 80) | address1 |
| | | | | | node2 | (75, 27) | (40, 0) | (80, 31) | address2 |
| | | | | | node4 | (29, 31) | (0, 25) | (40, 34) | address4 |
| | | | | | node5 | (58, 48) | (40,44.5) | (80, 80) | address5 |

(b)

Figure 12: Node leaving the overlay network

# 8 Experiments

## 8.1 Simulation Environment

We run tests on a physical network with Transit-Stub (TS) topology, which uses a two-level hierarchical architecture consisting of transit domains and stub domains, where the former interconnect the latter. We use GT-ITM [2] to generate a TS network containing 100 peers, which has one transit domain containing four transit nodes, and eight stub domains each containing three stub nodes on average. The average inter-node latency of the physical network is 1.0192s, which is measured by simulating TCP/IP traffic on the network using Network Simulator-2 [5]. Network environments containing more peers are generated in a similar way.

## 8.2 Average hop length and routing table size for the overlay network

Although there are a number of XML query benchmarks, they do not address distributed XML query processing. Following the parking lot example discussed earlier, we derive an XML data set from the World Geographic Database at the University of Washington repository [7], from which we extract distinguished paths each representing a city (e.g. shown in Figure 13). Note that the paths in the example demonstrate some heterogeneity since different element names and attributes on defined on same path levels. We synthesize parking lot id information into the paths by adding a path level with element name "Parkinglot" and attribute name "id" at the end. Following a uniform distribution function, each city can receive up to four parking lot ids. Altogether there are 4700 synthetic paths with parking lot id information, and some examples are shown in Figure 14.

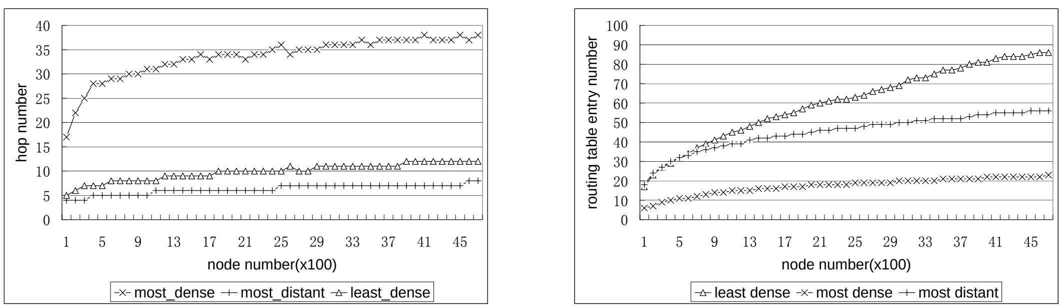
```
....
/Global/Country[@name='Canada']/Province[@area='1068582'][@name='Ontario']/City[@name='Kitchener']
....
/Global/Country[@name='China']/Province[@name='Jiangsu']/City[@population='2500000'][@name='Nanjing']
....
/Global/Country[@name='United States']/State[@name='New York']/City[@name='Boston']
....
```

Figure 13: Extracted XML paths

```
....
/Global/Country[@name='Canada']/Province[@area='1068582'][@name='Ontario']/City[@name='Kitchener']/Parkinglot[@id='1']
....
/Global/Country[@name='Canada']/Province[@area='1068582'][@name='Ontario']/City[@name='Kitchener']/Parkinglot[@id='4']
....
/Global/Country[@name='China']/Province[@name='Jiangsu']/City[@population='2500000'][@name='Nanjing']/Parkinglot[@id='1']
....
```

Figure 14: Parking lot data set

To demonstrate the scalability of the overlay network, we deploy the parking lot data uniformly over the P2P network and measure the average inter-node hop length of the overlay network and the average routing table size per node. Results on these metrics are shown in Figure 15. Since there are several candidate dimensions for splitting hyper-rectangles during the construction of the overlay network, we compare three of them: the dimension on which two nodes' coordinates are most distant using the Euclidean distance (i.e. the most distant), the dimension with the maximum number of different element names or attribute values (i.e. the most dense), and the dimension with the minimum number of different element names or attribute values (i.e. the least dense). It is clear that the overlay network obtained by splitting hyper-rectangles on the most distant dimension gets the minimum average hop length and also gets a medium average routing table size. Intuitively, splitting on the most distant dimension leads to a more even space that results in shorter paths towards target nodes, but increases the size of the routing table per node. Another advantage of splitting on the most distant dimension is that no global statistics (e.g. dimension density, which measures the number of the element names or attribute values on each dimension) is required.




(a) Average hop length

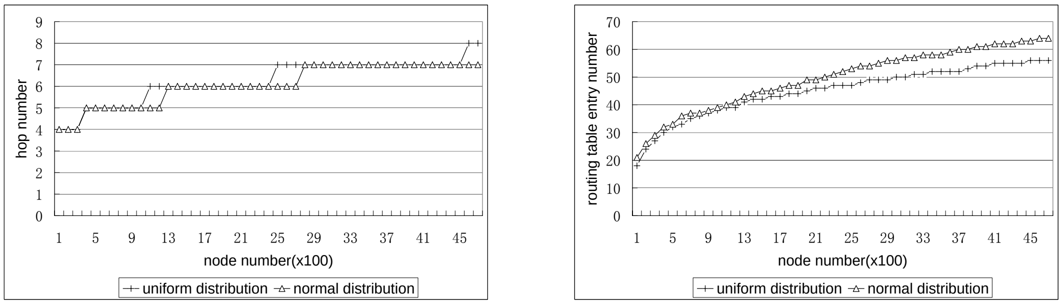
(b) Average routing table size

Figure 15: Average hop length and routing table size

Since different data distributions may affect these metrics, we deploy the data among peers using the standard normal distribution and measure the average hop length and routing table size of the overlay network, with the most distant dimension as the dimension for splitting hyper-rectangles. The comparison result shown in Figure 16 indicates that distribution functions have little impact on these metrics.

## 8.3 Stretch

*Stretch* is one of the important metrics to measure the latency difference between the overlay network and physical network, which is widely used in the performance evaluation of structured P2P systems [23]. In this work we define stretch as the ratio of the average inter-node latency on the overlay network to that on the physical network. Figure 17 shows the results on three TS physical networks containing 100, 300, and 600 peers respectively. The stretch values tend to become close to 1, which means, under our simulation environment, that the topology of the physical network has little effects on the overlay network latency little.




(a) Average hop length

(b) Average routing table size

Figure 16: Comparisons under uniform and normal data distribution

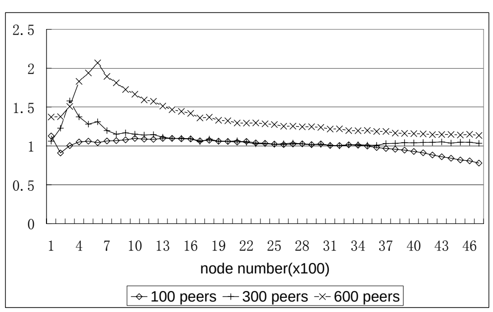



Figure 17: Stretch

## 8.4 Average hop length for queries

In this section we primarily test the average hop lengths for queries with wild card and ancestor-descendant axis. We don't consider simpler queries, e.g. queries with only parent-child axis and fully defined on all dimensions, because the metric for these queries are reflected in the measurement of the overlay network shown in Figure 15(a).

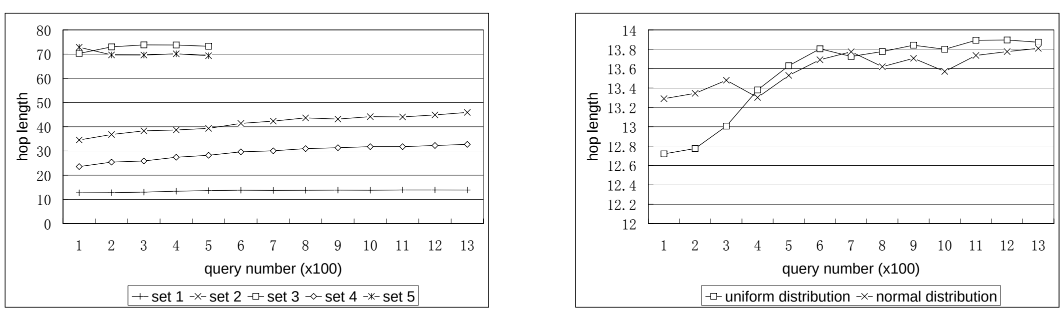
### 8.4.1 Queries with wild card

We generate five sets of queries containing wild card based on the first synthetic data set (i.e. parking lot data). Each set assigns wild cards at different path levels. The size of the query sets and examples are shown in Table 5.

| query set | query type | number | example |
|---|---|---|---|
| set 1 | /Global/*/*/City/Parkinglot | 1300 | /Global/*/*/City@name=‘Kitchener’]/Parkinglot[@id=‘1’] |
| set 2 | /Global/Country/*/City/* | 1300 | /Global/Country[@name=‘Canada’]/*/City[@name=‘Kitchener’]/* |
| set 3 | /Global/Country/Province/*/* | 500 | /Global/Country[@name=‘Canada’]/Province[@name=‘Ontario’]/*/* |
| set 4 | /Global/*/Province/City/* | 1300 | /Global/*/Province[@name=‘Ontario’]/City[@name=‘Kitchener’]/* |
| set 5 | /Global/*/Province/*/Parkinglot | 500 | /Global/*/Province[@name=‘Ontario’]/*/Parkinglot[@id=‘1’] |

Table 5: Test queries with wild cards

The results on the average hop lengths are shown in Figure 18(a), where queries with wild cards close to the root level of the query path expression (e.g. set 1: /Global/*/*/City/Parkinglot) outperform those with wild cards close to the bottom (e.g. set 3: /Global/Country/Province/*/*), because the sub-coordinate-spaces corresponding to the latter queries are normally larger than those corresponding to the former, so that the propagation for the latter queries costs more hops.




(a) Average hop length for queries with wild card

(b) Comparison between uniform and normal query distribution

Figure 18: Measuring queries with wild card

We also deploy the query set 1 among the peers using standard normal distribution. The comparison on the average hop length between uniform and normal query distribution is shown in Figure 18(b), which indicates that different distribution functions make little impact on the average hop length for the queries.

### 8.4.2 Queries with ancestor-descendant axis

We use ToxGene [6] to synthesize a data set consisting of 5953 XML paths about personal contact information, in which the same element *person* can appear on two different path levels (see Figure 19 for example). Based

```
....
/personlist/person[@name='McCluskey']/contactlist/person[@name='Koshimzu']/email[@addr='sunysb.com']
/personlist/person[@name='McCluskey']/contactlist/person[@name='Gerbe']/email[@addr='labs.com']
....
/personlist/person[@name='Csuros']/contactlist/person[@name='Tretkoff']/email[@addr='imag.fr']
....
```

Figure 19: Synthetic personal contact list

on this data set, we generate a query set containing ancestor-descendant axis, as shown in Table 6. We do not consider relative location path queries since they are equivalent to queries with an ancestor-descendant axis at the root path level.

| query set | number | example |
|---|---|---|
| /personlist//person | 1100 | /personalist//person[@name='McCluskey'] |

Table 6: Test queries with ancestor-descendant axis

The result on the average hop length is shown in Figure 20, where the average hop lengths are large. As pointed out, to constrain the number of the subqueries, we use a naive algorithm to rewrite the queries with ancestor-descendant axis into subqueries containing many wild cards, resulting in broad propagations. In the future work, we plan to improve the rewriting process by exploiting more schema information.

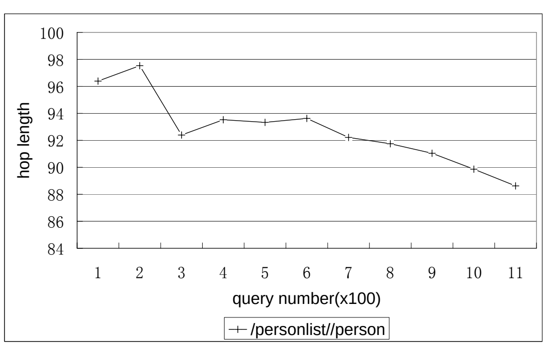



Figure 20: Average hop length for queries with ancestor-descendant axis

# 9 Conclusion

We discussed the design of a novel data locating mechanism for distributed XML query processing over P2P network. The primary problem we address is how to locate distributed XML data relevant to XML queries without any centralized mechanism or flooding the network. To deal with these problems, we follow the multi-hop style of the structured P2P file sharing systems, but is different in that we encode the hierarchical information of the XML data into the overlay network, so that hierarchical routing keys (i.e. XML path expressions) are supported. Furthermore, our data locating mechanism does not employ any centralized catalogs. To avoid flooding the network with XML queries, we use a technique that propagates queries within a limited sub-network to improve the performance.

Certain limitations exist in the current design. Since we use SHA-1 to map element names and attribute values into the coordinate space, the data locating mechanism can not deal with range queries. Moreover, order sensitive constructs in the XPath language are not defined in either distributed XML data definition language or query definition language, so they are not supported in this work. These will be addressed in follow-up work.

Furthermore, in this work we constrain each path for the published distributed XML data to only contain parent-child axis. To support data with more heterogeneity (e.g. twig patterns [12]), a more complicated distributed XML data definition language is needed. If we avoid a naive approach to decompose twig patterns into parent-child and ancestor-descendant axes, the overlay network needs to be redesigned to encode more complicated hierarchical structure information.

Finally, the experiments conducted in the simulated network environment show the effectiveness of our approach. However, we plan to do more performance evaluation on real network environment (e.g. Planetlab testbed [4]).

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