Bi-Dimensional P2P and MRBD Protocols to Enhance Lookup Performance

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Abstract—Chord is one of the best known lookup protocols for structured peer-to-peer (P2P) networks. Nodes in Chord can be viewed as being placed on a one-dimensional ring. In this paper, we present a novel concept of bi-dimensional P2P, in which all nodes are placed onto a square rather than a ring to enable the flexible configuration of ring(s). Diverse ring configuration schemes form a uniform protocol family called multi-ring bi-dimensional (MRBD) protocols, and Chord can be considered as MRBD-1. Different configurations of rings provide various performance to satisfy diverse user requirements. We study examples of MRBD from both theoretical analysis and simulations. The results validate the effectiveness of MRBD in improving P2P lookup performance.

I. INTRODUCTION

In recent years, there has been significant growth in the number of users in P2P (peer-to-peer) networks. To locate the desired file in a large scale network, an efficient and cost-effective lookup protocol is needed. There are several structured P2P lookup protocols available in the literature, such as Chord [1], Pastry [2] and Tapestry [3]. Chord is one of the best known structured lookup protocols because of its characteristics of load balancing, robustness and the small routing table size. Chord’s degree and network diameter are both $\log_2 N$. The average minimum number of hops per lookup request in Chord is $(\log_2 N)/2$, where $N$ is the number of nodes in the network [4].

Although some work has been done for P2P lookup protocols, most of previous work improves one aspect of the performance by degrading the other aspects of the performance. Authors of [4] propose a new P2P routing protocol that can reduce the network diameter and degree both by 21.4% compared to Chord. However, the average minimum number of hops is increased by 22.7% in [4]. F-Chord in [5] is a family of Chord-like routing protocols based on Fibonacci number. For any value of $\alpha$, the diameter of F-Chord($\alpha$) is $0.720 \log_2 N$. The average minimum number of hops of F-Chord(1) is $0.398 \log_2 N$. However the degree is $1.44 \log_2 N - 2$ in F-Chord, which is larger than that in Chord. In addition, authors of [4] give a theoretical study on the relationship between network diameter and degree in Chord-like protocols, and point out that fundamental tradeoffs exist. Their conclusion shows that none of the existing practical structured P2P protocols achieves the optimal tradeoff curve.

II. MRBD PROTOCOLS IN BI-DIMENSIONAL P2P

In this section, we first introduce the overview of structured P2P lookup protocols, then we present the novel concept of bi-

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II. MRBD PROTOCOLS IN BI-DIMENSIONAL P2P

In this section, we first introduce the overview of structured P2P lookup protocols, then we present the novel concept of bi-
A. Structured P2P Lookup Protocols

In this paper, we aim to find structured P2P lookup protocols with high efficiency and low overhead. The difference among the structured P2P lookup protocols is how the nodes maintaining their routing table to guarantee an efficient route between each pair of the nodes in the network.

In Chord, for a P2P network with the DHT key space \( \{0, 1, \ldots, N - 1\} \), assuming all nodes to be alive [4] and arranged in a ring, the routing table of the node with the address key \( n \) comprises the pairs of the addresses and address keys of nodes \( n_{(\alpha + l)} \mod N, \epsilon \in \{0, 1, \ldots, \lfloor \log_2 N \rfloor - 1\} \), where \( l \) is called the basis. In Chord, \( l = 2 \).

B. Bi-Dimensional P2P

Chord’s single ring structure can be extended to multiple ring structure by introducing bi-dimensional P2P, in which all the nodes are placed onto a \( 2^m/2 \times 2^m/2 \) square, as shown in Fig. 1. Assume that all nodes in the key space to be alive [4], and the DHT key space to be \( \{0, 1, \ldots, 2^m - 1\} \), where \( m \) is an even number. Let \( n_{i,j} \) denote the node that belongs to the \( i \)th line and the \( j \)th column in the bi-dimensional square. Fig. 2 shows the Chord ring in bi-dimensional P2P, which can be considered as a thread connecting all nodes one by one, and each node’s finger table is established along the ring with basis \( l = 2 \). However, the introduced bi-dimensional P2P allows more flexible design of the rings.

To illustrate the benefit of bi-dimensional P2P, we define the concept of path length:

Definition 1: For \( a, b, c \) and \( d \in \{1, 2, \ldots, 2^m/2\} \), the path length \( L_{\text{path}}(n_{a,b}, n_{c,d}) \) between \( n_{a,b} \) and \( n_{c,d} \), is defined to be the minimum number of hops for the lookup request to take, from \( n_{a,b} \) to \( n_{c,d} \), if each finger table of a node contains only one successor node along the corresponding ring.

If node \( n_{1,1} \) in Chord initiates a lookup request to node \( n_{2^m/2, 2^m/2} \), according to the definition, we can find the path length from node \( n_{1,1} \) to node \( n_{2^m/2, 2^m/2} \) to be \( L_{\text{path}}(n_{1,1}, n_{2^m/2, 2^m/2}) = 2^m - 1 \). Let \( H(L_{\text{path}}(n_{1,1}, n_{2^m/2, 2^m/2})) \) denote the minimum number of hops along the network to reach node \( n_{2^m/2, 2^m/2} \), which is also the network diameter \( D_{\text{Chord}}(m) \). Since the basis of Chord is 2, we can get \( D_{\text{Chord}}(m) = H(L_{\text{path}}(n_{1,1}, n_{2^m/2, 2^m/2}))) = \log_2(L_{\text{path}}(n_{1,1}, n_{2^m/2, 2^m/2}) + 1)=m \). If a path from the top left corner to the bottom right corner is established, we can see that the path length from \( n_{1,1} \) to \( n_{2^m/2, 2^m/2} \) in bi-dimensional P2P can be much smaller, i.e., \( 2^m/2 - 1 \), as well as the degree, which is \( \log_2(m/2) = m/2 \) with basis 2. That’s why bi-dimensional P2P may perform better than Chord.

C. Ring Configuration

The performance improvement of bi-dimensional P2P may not exists without the proper ring configuration. Since there can be various rings, a family of protocols is proposed by selecting different number of rings and the nodes to form the rings. We call this protocol family multi-ring bi-dimensional (MRBD) P2P lookup protocols. The MRBD protocol with \( i \) rings from each node is called MRBD-\( i \).

One single ring of MRBD does not necessarily contain all nodes in the network, and one node may belong to more than one rings. The ring configuration should accord with some rules to ensure that the lookup request from any nodes can reach any other nodes with limited number of hops. The ring chosen by Chord shown in Fig. 2 is one of the feasible options. In a P2P network with DHT key space \( \{0, 1, \ldots, 2^m - 1\} \), create a \( 2^m \times 2^m \) matrix \( C \) to represent the connectivity between nodes. Since node \( n_{i,j} \) is the \((i-1)2^m/2+j\)th among all the nodes, we denote \( c(n_{a,b}, n_{c,d}) \), which is the element on the \((a-1)2^m/2+b\)th row and the \((c-1)2^m/2+d\)th column in \( C \) to be connectivity between nodes \( n_{a,b} \) and \( n_{c,d} \), i.e.,

\[
c(n_{a,b}, n_{c,d}) = \begin{cases} 2 & \text{if } n_{c,d} \in F(n_{a,b}) \\ 1 & \text{if } n_{c,d} = n_{a,b} \\ 0 & \text{else} \end{cases}
\]

where \( a, b, c \) and \( d \in \{1, 2, \ldots, 2^m/2\} \), and \( F(n) \) denotes the set of nodes in node \( n \)’s finger table(s). The establishments of finger tables are described in II-C.

Theorem 1: To guarantee that the request from any node can arrive at any other node with limited number of hops, the elements of the connectivity matrix \( C \) should satisfy: for \( \forall s(1), s(2), d(1) \) and \( d(2) \in \{1, 2, \ldots, 2^m/2\} \), \( \exists n(1), n(2), \ldots, n(m) \in \{0, 1, \ldots, 2^m/2\} \), allow \( c(n(s(1),s(2)), n(n(1),n(2)), \ldots, c(n(n(m-1),n(m),n(d(1),d(2)) > 0 \).

The proof of the theorem is evident and omitted here.

Several examples of ring configuration schemes that satisfy the requirement in Theorem 1 are shown in Fig. 3. For simplicity, only the rings from node \( n_{1,1} \) are illustrated in Fig. 3. Without loss of generality, the following analysis focuses on the behaviors of the node \( n_{1,1} \). Every other node maintains
its own rings and finger tables, and acts in the same manner as \( n_{1,1} \).

MRBD protocols are uniform, i.e., node \( n_{x_1,x_2} \) is connected to \( n_{x_1,x_2} \) iff \( n_l(x_1 + 1) \bmod N \cdot n_l(x_2 + 2) \bmod N \) is connected to \( n_l(x_1 + y_1) \bmod N \cdot n_l(x_2 + y_2) \bmod N \), \( x_1, x_2, y_1, y_2, x_1, x_2 \in \{1, 2, \ldots, N\} \) [4]. Consequently, the assumption that all lookup requests are initiated by \( n_{1,1} \) can be adopted in the performance evaluation. MRBD-1, MRBD-2, MRBD-3 and MRBD-4 shown in Fig. 3 all satisfy the requirements stated in Theorem 1.

In MRBD, the rings comprise the nodes on the corresponding threads. For example, for Ring 2 in Fig. 3 c and Fig. 3 d, choose one node nearest to the thread from each line to compose the ring; for Ring 3 in Fig. 3 c and Ring 4 of Fig. 3 d, choose the nearest node from each column. Consequently, the number of nodes along each ring equals \( 2^m/2 \). Ring 2 of Fig. 3 b is configured to reduce the network diameter. It makes the distance from \( n_{1,1} \) to \( n_{2^m/2, 2^m/2} \) much shorter than Chord.

The specific configurations of rings in MRBD are not limited to the examples. Flexible configurations of rings provide large space for performance improvement.

D. Finger Tables and Routing Schemes

In MRBD, the number of finger tables in one node equals to the number of rings selected, i.e., one finger table is created for every ring. Here we introduce another way to represent a node: \( n_{p,t} \) denotes the node that is the \( t \)-th nearest to \( n_{1,1} \) on Ring \( p \) from \( n_{1,1} \). With basis \( l \), the finger table of \( n_{1,1} \) corresponding to Ring \( p \) includes nodes \( n_{p,l,t} \), where \( t \in \{0, 1, \ldots, \left\lfloor \frac{1}{2} \log_2 \frac{2^m}{2} \right\rfloor \} \). The finger tables are of equal size \( \log_2 \frac{2^m}{2} \), since that the rings are of equal length \( 2^m/2 \).

Since each node in Chord maintains a finger table of size \( \log_2 2^m \), to ensure the total size of the finger tables (degree) of MRBD with \( P \) rings to be no larger than the size of Chord with the basis \( l = 2 \), the basis of MRBD-\( P \) should satisfy, \( P \times \log_2 \frac{2^m}{2} \leq \log_2 2^m = m \). So, \( l \geq 2^{P/2} \). For simplicity, let the basis be an integer, i.e.,

\[
 l = \left\lfloor \left(2^{P/2}\right) \right\rfloor. 
\]

The typical lookup steps along the rings are:

1. On receiving the lookup request to node \( n_{d(1),d(2)} \) from the user of \( n_{1,1} \), the source node searches through all its finger tables to find a node \( n_{d(1),i(2)} \) that has the minimum \( L_{path}(n_{d(1),i(2)}, n_{d(1),d(2)}) \) and satisfies the requirements \( i(1) \leq d(1) \) and \( i(2) \leq d(2) \).

2. The request is delivered to \( n_{d(1),i(2)} \).

3. \( n_{d(1),i(2)} \) will repeat the above steps until the request reaches \( n_{d(1),d(2)} \).

4. The response from \( n_{d(1),d(2)} \) goes back to \( n_{1,1} \).

III. PERFORMANCE EVALUATION

A. The Diameter and Degree Analysis of MRBD-2

The main performance of P2P lookup protocols includes network diameter, degree and average minimum number of hops. For simplicity, we first study the performance of MRBD-2 shown in Fig. 3 a.

According to (1), the degree of MRBD-2 with \( l = 2 \) is

\[
 S_{MRBD-2}(m, 2) = 2 \log_2 \frac{2^m}{2} = m,
\]

which is the same as Chord.

For \( \forall i, j \in \{1, 2, \ldots, 2^m/2\} \), we can get \( \arg \max (L_{path}(n_{1,1}, n_{i,j})) = (2^m/2, 2^m/2) \). Consequently, the node with the largest \( L_{path} \) is \( n_{2^m/2, 2^m/2} \). We can also know that, \( \arg \max (H(L_{path}(n_{1,1}, n_{i,j}))) = (2^m/2, 2^m/2) \), because, to reach \( n_{2^m/2, 2^m/2} \), the request from \( n_{1,1} \) has to come to \( n_{1,2^m/2} \) first and then \( n_{2^m/2, 2^m/2} \) or \( n_{2^m/2, 2^m/2} \) first and then \( n_{2^m/2, 2^m/2} \). Both steps in both options take the largest minimum number of hops along every single ring. That is to say, the diameter of the MRBD-2 network is \( D_{MRBD-2}(m, 2) = 2 \log_2 \frac{2^m}{2} + \log_2 \frac{2^m}{2} = m \), which is also the same as Chord.

MRBD-2 with basis 2 provides the same performance of degree and diameter compared to Chord. However, there exist redundant routing paths from the source to some of its destinations. MRBD-2 enables the source node to create two request packets that can be forwarded along different rings to decrease the lookup failure rate. Such a characteristic provides better robustness when nodes suddenly fail or leave from the P2P network. However, if the redundant path is used, heavier overload is introduced at the same time.

B. The Diameter and Degree Analysis of MRBD-3

MRBD-3 provides a direct path that is the farthest node if Chord is utilized. The direct path from \( n_{1,1} \) to \( n_{2^m/2, 2^m/2} \) will surely reduce the network diameter. We first illustrate how to get the path length from \( n_{a,b} \) to \( n_{c,d} \).

**Lemma 1:** In MRBD-3, for \( \forall a, b, c \) and \( d \in \{1, 2, \ldots, 2^m/2\} \), and \( a \leq c, b \leq d \), \( L_{path}(n_{a,b}, n_{c,d}) = \max((c-a), (d-b)). \)

It's straightforward to verify Lemma 1 by considering three cases: a) \( c-a = d-b \), b) \( c-a < d-b \) and c) \( c-a > d-b \).
Based on the path length, we can evaluate the network degree with the theorem as follows:

**Theorem 2:** In MRBD-3 with basis $l$, given $L_{path}(n_{a,b}, n_{c,d})$, the minimum number of hops from $n_{a,b}$ to $n_{c,d}$ satisfies

$$H_{min}(L_{path}(n_{a,b}, n_{c,d})) \leq (l - 1)|\log L_{path}(n_{a,b}, n_{c,d})| + 1.$$  

(2)

**Proof:** The theorem is to be proved by induction:

Step 1: For $L_{path}(n_{a,b}, n_{c,d}) = 1$, $L_{path}(n_{a,b}, n_{c,d}) = 2$, \ldots, $L_{path}(n_{a,b}, n_{c,d}) = l$, (2) is satisfied obviously.

Step 2: We will prove that, for any given positive integer $k \leq \frac{m}{2\log l} - 1$, if $L_{path}(n_{a,b}, n_{c,d}) = 1$, $L_{path}(n_{a,b}, n_{c,d}) = 2$, \ldots, $L_{path}(n_{a,b}, n_{c,d}) = 1^k$ satisfy (2), $L_{path}(n_{a,b}, n_{c,d}) = 1^{k+1}$, $L_{path}(n_{a,b}, n_{c,d}) = 1^k + 2$, \ldots, $L_{path}(n_{a,b}, n_{c,d}) = 1^k + l$ satisfy (2) too. The proof is described as follows:

Through the study of the finger tables of the rings, we know that in MRBD-3 with basis $l$,

$$H_{min}(L_{path}(n_{a,b}, n_{a,b+i^k})) = H_{min}(L_{path}(n_{a,b}, n_{a+b^k})) = H_{min}(L_{path}(n_{a,b}, n_{a+b^k+i^k})) = 1.$$  

(3)

According to Lemma 1 and the assumption of step 2, because for $\forall i, j \in \{1, 2, 3, \ldots, l^k\}$,

$$H_{min}(L_{path}(n_{a+b^k+i^k+j}, n_{a+b^k+i^k+j})) \leq (l - 1)|\log L_{path}(n_{a+b^k+i^k+j}, n_{a+b^k+i^k+j})| + 1$$

$$\leq (l - 1)|\log L_{path}(n_{a+b^k+i^k+j}, n_{a+b^k+i^k+j})| + 1$$

$$\leq (l - 1)|\log L_{path}(n_{a+b^k+i^k+j}, n_{a+b^k+i^k+j})| + 1$$

(4)

so,

$$H_{min}(L_{path}(n_{a,b}, n_{a+b^k+i^k+j})) \leq (l - 1)|\log L_{path}(n_{a,b}, n_{a+b^k+i^k+j})| + 1$$

$$\leq (l - 1)|\log L_{path}(n_{a,b}, n_{a+b^k+i^k+j})| + 1$$

(5)

Moreover, since

$$H_{min}(L_{path}(n_{a,b}, n_{a+b^k})) = H_{min}(L_{path}(n_{a,b}, n_{a+b^k+i^k})) = H_{min}(L_{path}(n_{a,b}, n_{a+b^k+i^k})) = H_{min}(L_{path}(n_{a,b}, n_{a+b^k+i^k})) = 2,$$

(7)

and (by the same method as (4),

$$H_{min}(L_{path}(n_{a,b}, n_{a+b^k+i^k+j})) \leq (l - 1)|\log L_{path}(n_{a,b}, n_{a+b^k+i^k+j})| + 1$$

(8)

we can get:

$$H_{min}(L_{path}(n_{a,b}, n_{a+i^k+b^k+j})) \leq H_{min}(L_{path}(n_{a,b}, n_{a+i^k+b^k+j}))$$

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$$H_{min}(L_{path}(n_{a,b}, n_{a+i^k+b^k+j})) \leq (l - 1)k + 1 + 2,$$

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(9)

By the same method as (3) - (6) and (7) - (9), we know that, for integers $g$ and $h$ that satisfy $0 \leq g, h \leq l$,

$$H_{min}(L_{path}(n_{a,b}, n_{a+h^k+b^k+j})) = H_{min}(L_{path}(n_{a,b}, n_{a+h^k+b^k+j}))$$

$$H_{min}(L_{path}(n_{a,b}, n_{a+h^k+b^k+j})) \leq (l - 1)k + 1 + 1 + 2.$$  

Note that $i, j \in \{1, 2, 3, \ldots, l^k\}$. Hence, for integers $e$ and $f$ that satisfy $0 \leq e, f \leq l + 1, H_{min}(L_{path}(n_{a,b}, n_{a+e^k+b^k+f^k})) \leq (l - 1)k + 1 + 1.$

That is to say, for $\forall u, v \in \{1, 1, 2, 2, 3, \ldots, l^k+1\}, H_{min}(L_{path}(n_{a,b}, n_{a+u^k+b^k+v^k})) \leq H_{min}(L_{path}(n_{a,b}, n_{a+u^k+b^k+v^k})) + 1 + 1 = (l - 1)|\log L_{path}(n_{a,b}, n_{a+u^k+b^k+v^k})| + 1.$

The proof of step 2 is finished. Consequently, by induction, Theorem 2 is proved.

In MRBD-3 with $2^m$ nodes, the node farthest from node $n_{1,1}$ is $n_{2^m/2,2^m/2}$. Therefore, the network diameter is:

$$D_{MRBD-3}(m, l) = (l - 1)|\log L_{path}(n_{1,1}, n_{2^m/2,2^m/2})| + 1$$

$$= (l - 1)|\log L_{path}(n_{1,1}, n_{2^m/2,2^m/2})| + 1$$

$$\leq (l - 1)|\log L_{path}(n_{1,1}, n_{2^m/2,2^m/2})| + 1 \leq \frac{m(l-1)}{2} \log 2 + 2.$$  

To compare with Chord, we guarantee that the degree of MRBD-3 to be no larger than Chord, according to (1), $l = \lceil 2^{1/2} \rceil = 3$. Therefore, $D_{MRBD-3}(m, 3) \leq m \log 2$, $2 \approx 0.63m + 2$. The degree $S_{MRBD-3}(m, 3) = 3 \times \text{floor}(\log_3 2^m/2) \leq \frac{3m}{2} \log_2 3 \approx 0.946m$.

Compared with Chord’s diameter and degree $m$, MRBD-3 provides lower diameter and degree by approximately $37\%$ and $54\%$ respectively, in large scale networks with a large enough $m$. F-Chord(1)'s diameter and degree are $0.72021m$ and $1.44042m - 2$. That is, MRBD-3 with basis 3 reduces the diameter and degree by $12.4\%$ and $34.3\%$ respectively.

To compare with the protocol proposed in [4], let $l = 4$, so $D_{MRBD-3}(m, 4) \leq 0.75m + 2$. The degree $S_{MRBD-3}(m, 4) = 3 \times \log_4 2^m/2 = 0.75m$, i.e., MRBD-3 with basis 4 performs better than the protocol proposed in [4] whose degree and diameter are both $0.786m$.

The same thing is true in MRBD-2 and MRBD-3 that allow the source node to choose the routing path(s) among the optimal paths, which improves the robustness of the lookup process.
C. The Performance Comparison

Equation (1) also gives the basis of MRBD-4, MRBD-5, etc., to guarantee the degree to be no larger than Chord. According to the basis, the degree can be calculated as follows:

\[
\begin{align*}
S_{MRBD-4}(m) &= 4 \times \lfloor \log_2 (2m^2/3) \rfloor \\
S_{MRBD-5}(m) &= 5 \times \lfloor \log_2 (2m^2/3) \rfloor \\
S_{MRBD-6}(m) &= 6 \times \lfloor \log_2 (2m^2/3) \rfloor \\
S_{MRBD-7}(m) &= 7 \times \lfloor \log_2 (2m^2/3) \rfloor \\
S_{MRBD-8}(m) &= 8 \times \lfloor \log_2 (2m^2/3) \rfloor \\
\end{align*}
\]

The degrees of MRBD-5 and MRBD-7 are about 3.3% and 2.4% smaller than Chord, respectively. The evaluation of the degree in MRBD-\(r\) with larger \(r\) is similar.

The simulation results of the main performance of Chord, F-Chord and MRBD are shown in Fig. 4, Fig. 5 and Fig. 6. It is shown that MRBD still always performs best.

In Fig. 5, MRBD-3 with basis \(l = 3\) provides the minimum network diameter. This is because that its basis 3 is the smallest within the protocols that contain direct paths to the farthest destination. The diameter of MRBD-3 with \(l = 3\) is about 37% lower than that in Chord. MRBD-5 has larger diameter than MRBD-3, even the rings in MRBD-5 incorportate the ones in MRBD-3. The reason is that, to guarantee similar degree, MRBD-5 has to choose a larger basis. Diameters of all the MRBD protocols are lower than those of Chord, and some are lower than those of F-Chord(1) whose degree is much larger than MRBD, as illustrated in Fig. 4. MRBD-3 with \(l = 3\) also has the least average minimum number of hops as shown in Fig. 6. For simplicity, these figures don’t include the protocol proposed in [4] whose degree, diameter and average minimum number of hops are \(0.786 \log_2 N\), \(0.786 \log_2 N\) and \(0.694 \log_2 N\)m respectively. MRBD-3 with \(l = 3\) also outperforms that protocol.

IV. CONCLUSIONS

In this paper, the concept of bi-dimensional P2P was presented to enable flexible ring configurations. Furthermore, based on bi-dimensional P2P, MRBD protocol family was proposed. Chord can be viewed as MRBD-1. By selecting proper rings and basis, MRBD can perform much better compared to existing Chord-like protocols, and realize the tradeoffs among different aspects of the main performance. We also gave the examples of ring configurations, and evaluated the main performance. Theoretical derivation and simulation results showed the effectiveness of the proposed protocols.

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