Design of a Modified Low Diameter Interest-Based Peer-to-Peer Network Architecture

Indranil Roy*, Reshmi Mitra*
Southeast Missouri State University, Cape Girardeau, MO, USA
iroy@semo.edu

Bidyut Gupta†
Southern Illinois University, Carbondale, IL, USA
bidyut@cs.siu.edu

Narayan C. Debnath‡
Eastern International University, Vietnam
NdebnathC@gmail.com

Abstract

In this work, we have proposed a modified version of the existing Residue-class (RC) based peer-to peer (P2P) network architecture. The existing RC based architecture [10] has been considered because of its two main advantages viz. (1) all peers with the same interest (or possessing the same resource type) structurally form a group of diameter one, and (2) the group heads are connected in the form of a ring and the ring always remains connected even in the presence of any churn. The diameter of the ring with n group heads is n/2 and as n increases, the latency of the existing data look-up protocols increases as well. In this paper our objective is to reduce this diameter substantially in order to reduce data look-up latency drastically. To achieve this, we have used a mathematical model using which we show that all group heads will be connected directly to each other; that is, instead of forming a ring structure of diameter n/2, it will be a network of diameter one only. Therefore, the diameter of the peer-to-peer network becomes only 3 instead of (n/2 + 2) as in [10]. This is the shortest diameter possible in such networks. It will definitely make any data look-up protocol highly efficient from the viewpoint of low latency.

Key Words: Residue Class, Interest-based P2P Network, Diameter, Capacity Constrained, Look-up Latency, Broadcast.

1 Introduction

Peer-to-peer (P2P) overlay networks have emerged as one of the most influential paradigms in the design of distributed systems, offering the ability to share computational and data resources in a scalable, self-organizing, and decentralized manner. Unlike traditional client-server models, P2P systems remove single points of failure, enhance robustness, and enable massive scalability by distributing responsibilities across all participating nodes (peers). This autonomy and flexibility make P2P overlays highly attractive for applications ranging from file sharing and content distribution to real-time communication, distributed computation, and decentralized data storage. In recent years, the paradigm has extended into emerging domains such as blockchain, federated learning, IoT integration, and decentralized social networking, where privacy preservation, scalability, and fault tolerance are paramount.

1.1 Classification of P2P Overlays

P2P overlay networks can be broadly categorized into two primary classes: *unstructured* and *structured* overlays. This classification is based on the way nodes are interconnected and how resources are indexed and retrieved. A third, increasingly relevant category includes *hybrid* and *non-DHT structured* overlays, which combine properties of the first two classes to optimize specific performance metrics.

1.1.1 Unstructured P2P Overlays

In unstructured systems [2], peers are connected in an arbitrary topology without adherence to a strict organizational structure. Resource discovery typically relies on *flooding*, *random walks*, or other probabilistic search mechanisms, which can locate resources even under high churn conditions (frequent peer join/leave events). This high resilience to churn is a defining strength of unstructured networks, enabling them to operate in highly dynamic environments.

However, these benefits come at a cost:

- **Efficiency:** Queries may require broadcasting across large portions of the network, leading to excessive message overhead and bandwidth consumption.
- **Scalability:** As network size grows, search latency and message complexity increase superlinearly, making real-time lookups challenging at scale.
- **Reliability:** Lookups are not guaranteed unless extensive replication or exhaustive search mechanisms are employed, which further increases resource usage.

Prominent examples include early systems such as Gnutella and Freenet, which demonstrated the feasibility of large-scale decentralized communication but also highlighted the limitations of unstructured search methods. Modern adaptations sometimes integrate caching and proximity-aware forwarding to improve performance, but scalability challenges remain.

1.1.2 Structured P2P Overlays

Structured overlays enforce deterministic organization of peers and resources, ensuring predictable and bounded search times. This is typically achieved by mapping resources to nodes using a globally consistent data placement strategy. *Distributed*

Hash Tables (DHTs) [18, 25, 29] form the backbone of many structured P2P systems, such as Chord, Pastry, and CAN [15, 27]. In these systems:

- Lookup operations have a worst-case complexity of $O(\log N)$, where N is the number of peers.
- The overlay is maintained through periodic updates to routing tables, ensuring consistent connectivity despite churn.
- Resource placement is uniform due to hashing, aiding load balancing across peers.

While DHT-based overlays offer strong guarantees for scalability and deterministic lookups, they incur high maintenance complexity under churn. Each join or leave event triggers reorganization of the overlay and updates to routing state, which can result in high control overhead. This is particularly problematic in mobile ad hoc networks, IoT deployments, and other environments with volatile peer availability. Furthermore, DHTs tend to be content-agnostic; while this aids uniformity, it ignores semantic locality, which can be critical for certain applications.

1.2 Hybrid and Non-DHT Structured Approaches

To address the limitations of pure DHT and unstructured systems, researchers have proposed *hybrid architectures* [5, 14, 16, 24, 28]. These architectures combine structured and unstructured elements—for example, by organizing peers into clusters connected by a structured backbone (DHT) while maintaining unstructured links within clusters. This approach seeks to inherit the benefits of both paradigms: deterministic inter-cluster lookups and churn-resilient intra-cluster communication. However, hybrid designs may also inherit drawbacks from both sides, such as DHT churn sensitivity and unstructured search inefficiency within clusters.

Another line of research has focused on *non-DHT structured approaches* [3]. These designs avoid hash-based resource placement and instead rely on mathematically driven or topology-aware organization, such as hierarchical clustering, tree-based overlays, grid-based coordinate systems, or residue-class–based addressing. Non-DHT structured systems aim to:

- Preserve deterministic search performance with predictable latency bounds.
- Reduce maintenance complexity compared to DHT-based overlays by limiting reorganization scope.
- Enable more natural grouping of peers based on real-world constraints (e.g., geographic proximity, latency sensitivity, or resource similarity).

Examples include skip-graph overlays, hypercube-based routing, and tree-based hierarchical models that exploit structured locality for performance gains.

1.3 Interest-Based P2P Overlays

A particularly important subclass of non-DHT approaches is *interest-based P2P overlays*. These systems group peers into clusters or communities based on shared interests, resource types, or application-specific attributes, thereby:

- Reducing the search space and improving lookup relevance by focusing queries on semantically relevant subsets of peers.
- Supporting deterministic intra-cluster searches (often $O(1)$ latency in fully connected cluster topologies).
- Simplifying maintenance by limiting topology updates to smaller, interest-specific clusters.

Examples in the literature [1, 4, 6–13, 17, 19–23, 26] vary widely in their approaches:

- **Super-peer or popular-peer models** [4, 13, 26] designate high-capacity nodes as entry points or aggregators for peers with similar interests, balancing efficiency with robustness.
- **Gossip-based clustering** [11] uses probabilistic peer exchanges to form and maintain interest groups without centralized control.
- **Hybrid interest-aware DHTs** [8, 23] embed interest semantics into DHT routing to accelerate relevant lookups.
- **Non-DHT mathematical approaches**, such as the **pyramid tree architecture** [20], which leverages residue-class addressing to ensure complete intra-cluster connectivity and predictable routing.

While these designs have achieved notable improvements in search latency and relevance, several challenges remain open:

1. **Efficient inter-cluster routing** between geographically or topologically dispersed interest communities without excessive control traffic.
2. **Scalability** under heterogeneous workloads where cluster sizes and interest popularity vary widely.
3. **Robustness against churn** while maintaining deterministic lookup guarantees and minimizing maintenance costs.
4. **Applicability to emerging domains** such as industrial IoT, social network overlays, blockchain-based marketplaces, and federated learning systems, where low latency and context awareness are crucial.

1.4 Motivation for the Proposed Work

The present research builds upon these foundations, aiming to address the limitations identified in existing interest-based and non-DHT structured approaches. In particular, we focus on designing a scalable, mathematically grounded architecture that:

- Achieves constant-time intra-cluster lookups and logarithmic-time inter-cluster searches, ensuring predictable performance regardless of network scale.

- Handles churn with minimal restructuring overhead by localizing maintenance to affected clusters.
- Integrates seamlessly with application domains requiring high availability, semantic relevance, and low latency, such as real-time industrial monitoring, healthcare data sharing, and distributed machine learning.

By systematically analyzing existing designs and identifying their architectural strengths and weaknesses, our work proposes an improved model that advances the state of the art in interest-based P2P systems. Our proposed approach incorporates residue-class–based hierarchical organization for efficient routing, dynamic cluster adaptation for churn resilience, and semantic indexing for relevance-aware lookups, making it adaptable to a wide range of distributed computing environments.

2 Literature Survey of some Existing Interest Based P2P Architectures

In this section, we examine a set of significant interest-based peer-to-peer (P2P) systems [1,4,8,9,11,13,20,23,26], outlining their architectural principles, cluster formation strategies, and handling of peer heterogeneity. We emphasize both the similarities and the limitations of these systems, highlighting the need for more efficient, churn-resilient architectures.

2.1 Super Peer and Popular Peer Architectures

The works in [4, 13, 26] incorporate peer heterogeneity through the concepts of *super peers* or *popular peers*, which act as high-capacity nodes managing clusters.

- **[13]** adopts the super peer model, forming clusters via gossiping among peers with common interests. This creates a hierarchy where super peers maintain intra-cluster coordination.
- **[4]** proposes the *popular peer* concept, functionally similar to the super peer model. The underlying network is unstructured, meaning there is no fixed routing topology and searches may require flooding.
- **[26]** presents a hybrid system integrating a Chord-based structured overlay with unstructured peer groups, also leveraging super peers for improved routing efficiency.

2.2 Gossiping and Best-Peer Selection Strategies

In [11], gossiping is employed for interest-based cluster formation. Upon joining, a peer searches a known peer list to identify the node with the most connections and links to it, creating high-degree hubs. While this can improve connectivity, it introduces significant latency during the joining process and increases dependence on a few central nodes.

Conversely, [20] criticizes gossiping as inefficient for interest-based clustering. The authors also reject super peer/popular peer models, noting that newly joining peers could outperform existing high-capacity nodes, requiring repeated leader re-selection. This re-selection process wastes time, particularly during bursts of new peer arrivals.

2.3 Interest Community Formation Approaches

The work in [9] develops a resource location strategy that leverages collaborative information exchange to form *interest communities*. Similar peers are grouped, and relevant data is disseminated to improve search accuracy within communities.

In [8], a Pastry-based P2P e-commerce model organizes peers with shared interests into clusters, assuming direct connections among them (overlay diameter = 1). However, no mathematical basis is provided for this assumption, making scalability and resilience under churn questionable.

2.4 Proximity-Aware and Hybrid DHT Approaches

The system in [23] is a DHT-based structured P2P network that considers both *physical proximity* and *common interest*. Initially, clusters are formed among physically close peers, and then sub-clusters are created for interest alignment. While this improves local search efficiency, it fails to address inter-sub-cluster lookups across geographically distributed clusters sharing the same interest, leaving a critical gap in scalability.

2.5 Social Network-Influenced Architectures

In [1], the Chord architecture is adapted to support social network characteristics. Peers establish *interest links* dynamically based on prior communication patterns. An efficient routing algorithm exploits these links to improve lookup performance without abandoning the structured overlay.

2.6 Residue Class-Based Non-DHT Approach

The Pyramid Tree architecture proposed in [20] takes a fundamentally different path, avoiding DHT structures altogether. It applies modular arithmetic (residue class) to form clusters where:

- Each interest-based cluster is a complete graph, ensuring an intra-cluster search latency of $O(1)$.
- The overall network diameter is $2d+2$, where d is the number of pyramid tree levels. Inter-cluster search latency is $O(d)$, with d being small compared to total peers since only cluster-heads populate the tree.
- Cluster size is unrestricted, and churn handling is simplified since the complete graph topology remains unchanged by peer joins/leaves.
- New cluster-heads for novel resource types are always placed at the leaf level, ensuring predictable growth.

This approach addresses many shortcomings of prior work, including inefficiencies in gossiping, unstructured search, churn sensitivity in DHTs, and incomplete inter-cluster communication handling.

We have presented the above works in a comparative summary table as shown in Table 1.

Problem Statement

The existing two-level residue class-based (RC-based) peer-to-peer (P2P) architecture [10] has been considered in this work due to its several distinctive advantages. It is an *interest-based* system, meaning that peers are logically grouped according to shared interests or resource types, which improves the relevance and efficiency of resource discovery. Two of the most prominent features relevant to our study are:

1. **Clustered organization with minimal intra-group diameter:** All peers with the same interest (or possessing the same resource type) structurally form a group of *diameter one*. This ensures constant-time intra-group lookups and eliminates unnecessary routing within the group.
2. **Churn-resilient backbone:** The group heads are connected in the form of a logical ring. This ring structure guarantees connectivity among groups even under churn, as each group head maintains at least two persistent connections to its immediate neighbors in the ring.

Under this design, the overall diameter of the P2P network is computed as the *diameter of the ring backbone* plus *twice the group diameter*. Since each group has a diameter of one, the total network diameter is given by:

$$\text{Diameter}_{\text{RC}} = \frac{n}{2} + 2$$

where n is the total number of groups (or group heads). This low diameter has been shown to be beneficial for achieving low-latency data lookups compared to many unstructured or DHT-based overlays.

However, upon closer examination, we observe that the network's lookup latency is heavily dependent on the ring diameter, which is $\frac{n}{2}$ in the worst case. As n grows, this term becomes the dominant factor in lookup delay. While the original RC-based design offers good scalability and churn resilience, its performance under high values of n can be further improved by optimizing the inter-group backbone topology.

Proposed Modification. In the research presented in this paper, we propose a modified architecture in which *all group heads are directly connected to each other*, thereby transforming the backbone from a ring topology into a fully connected graph. This change reduces the backbone diameter from $\frac{n}{2}$ to **1**. Consequently, the overall network diameter becomes:

$$\text{Diameter}_{\text{Proposed}} = 3$$

This is derived as follows: (1) one hop from the source peer to its group head, (2) one hop directly between the source and destination group heads, and (3) one hop from the destination group head to the target peer. This represents the **shortest possible diameter** achievable in such multi-group P2P systems while maintaining the interest-based grouping.

Advantages and Implications. The proposed architecture offers several key benefits:

- **Reduced worst-case latency:** Lookup operations complete in at most three hops, independent of n.
- **Improved throughput:** Shorter paths reduce intermediate forwarding load and congestion.
- **Enhanced fault tolerance:** Fully connected group heads provide multiple alternate shortest paths, eliminating single-path dependencies.

The remainder of this paper is organized as follows: Section 3 presents relevant preliminaries. Section 4 details the proposed modified architecture. In Section 5, we describe the broadcast protocols for the proposed network, both with and without capacity constraints. Section 6 concludes the paper with final remarks and outlines potential future research directions, particularly in the area of secure and efficient communication over the proposed topology.

3 RC Based Topology

We first state briefly the architecture of the RC-based network, followed by the STAR topology.

3.1 RC Based architecture [10]

Definition 1. *We define a resource as a tuple* $< R_i, V >$, *where* R_i *denotes the type of a resource and* V *is the value of the resource.*

A resource can have many values. For example, let R_i denote the resource type 'movies' and V' denote a particular actor. Thus $< R_i, V >$ represents movies (some or all) acted by a particular actor V'.

Definition 2. *Let* S *be the set of all peers in a peer-to-peer system. Then* $S = \{P^{Ri} \mid 0 \leq i \leq n-1\}$, *where* P^{Ri} *denotes the subset consisting of all peers with the same resource type* R_i, *and the number of distinct resource types present in the system is* n. *Also, for each subset* P^{Ri}, *we assume that* P_i *is the first peer among the peers in* P^{Ri} *to join the system. We call* P_i *the group-head of group* G_i *formed by the peers in the subset* P^{Ri}. *For each subset* P^{Ri}, *we assume that* P_i *is the first peer among the peers in* P^{Ri} *to join the system. We call* P_i *the group-head of group* G_i *formed by the peers in the subset* P^{Ri}.

3.1.1 Two level P2P architecture

It is a two-level overlay architecture and at each level structured networks of peers exist. It is explained below.

1. At level-1, it is a ring network consisting of the peers P_i $(0 \leq i \leq n-1)$. The number of peers (i.e., group heads) on the ring is n, which is also the number of distinct resource types. This ring network is used for efficient data lookup and so it is named the transit ring network [10].

Table 1: Comparison of Selected Interest-Based P2P Architectures

Ref.	Architecture Type	Clustering Method	Churn Handling	Overlay Diameter	Main Limitations
[13]	Unstructured w/ Super Peers	Gossip-based	Moderate (depends on super peers)	Variable (depends on flooding)	Inefficient gossiping; reliance on super peers
[4]	Unstructured w/ Popular Peers	Interest-based peer selection	Moderate	Variable	Similar to super peer issues; unstructured search overhead
[26]	Hybrid (Chord + Unstructured)	Super peer-based clusters	Moderate (DHT churn impact)	$O(\log N)$ for DHT part	Complexity of hybrid maintenance
[11]	Unstructured	Gossip + best-peer selection	Low	Variable	Joining delay; centralization risk
[9]	Unstructured	Collaborative interest community	Low	Variable	Scalability issues; no proximity consideration
[23]	Structured DHT	Proximity + interest clustering	Moderate (DHT churn)	$O(\log N)$ intra-cluster; unknown inter-sub-cluster	Incomplete inter-cluster routing
[8]	Pastry-based	Interest community (1-hop assumption)	Low	1 hop (assumed)	Unrealistic assumption; no churn resilience
[1]	Chord-based DHT	Dynamic interest links	Moderate	$O(\log N)$	Churn maintenance overhead
[20]	Non-DHT Pyramid Tree	Residue class clustering	High (simple)	1 (intra), $2d+2$ (inter)	None significant; assumes accurate interest identification

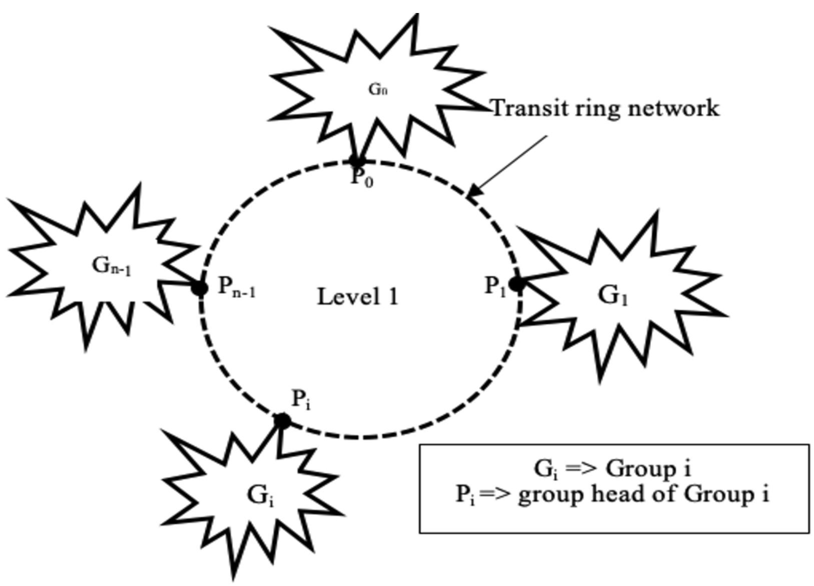

Figure 1: An RC-based 2-level P2P network

2. At level-2, there are n completely connected networks (groups) of peers. Each such group, say G_i, is formed by the peers of the subset P^{Ri} $(0 \leq i \leq n-1)$, such that all peers ($\in P^{Ri}$) are directly connected (logically) to each other, resulting in a network diameter of 1. Each G_i is connected to the transit ring network via its group-head P_i.
3. Any communication between a peer $p'_i \in G_i$ and $p'_j \in G_j$ takes place only via the respective group-heads P_i and P_j.

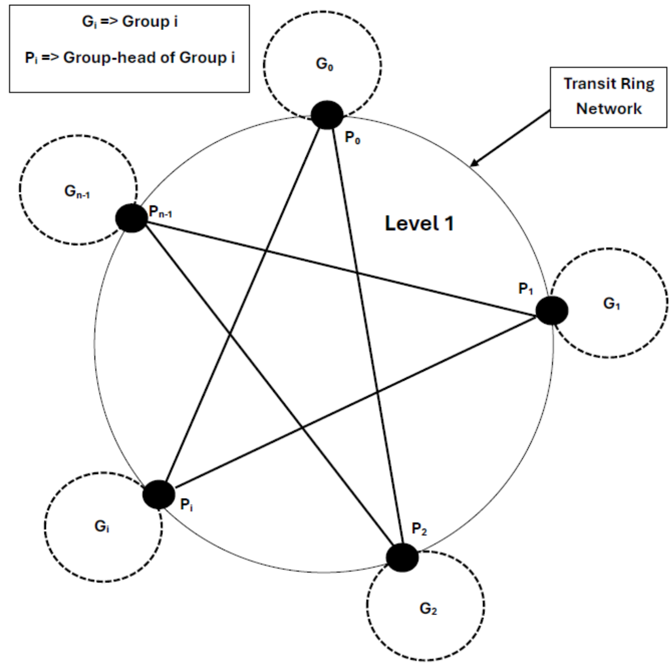

Figure 2: The modified RC-based 2-level P2P architecture with a complete network at Level-1

3.2 Assignments of overlay addresses

Consider the set S_n of nonnegative integers less than n, given as $S_n = \{0, 1, 2, \ldots, (n-1)\}$. This is referred to as the set of residues, or residue classes (mod n). That is, each integer in S_n represents a residue class (RC). These residue classes can be labelled as $[0], [1], [2], \ldots, [n-1]$, where $[r] = \{a : a \text{ is an integer}, a \equiv r \pmod{n}\}$.

For example, for $n = 3$, the classes are:

$$[0] = \{\ldots, -6, -3, 0, 3, 6, \ldots\}$$
$$[1] = \{\ldots, -5, -2, 1, 4, 7, \ldots\}$$
$$[2] = \{\ldots, -4, -1, 2, 5, 8, \ldots\}$$

A relevant property of residue class is stated below.

Lemma 1. *Any two numbers of any class r of S_n are mutually congruent.*

The architecture [10] is shown in Figure 1.

Assume that in an interest-based P2P system there are n distinct resource types. Consider the set of all peers in the system given as $S = \{P^{Ri}\}, 0 \leq i \leq n-1$. Also, as mentioned earlier, for each subset P^{Ri} (i.e., group G_i) peer P_i is the first peer with resource type R_i to join the system. This first peer P_i is the group-head of group G_i.

The assignment of overlay (logical) addresses to the peers at the two levels and the resources happens as follows:

1. At level-1, each group-head P_r of group G_r is assigned with the minimum nonnegative number (r) of residue class $r \pmod{n}$ of the residue system S_n.
2. At level-2, all peers having the same resource type R_r will form the group G_r (i.e., the subset P^{Rr}) with the group-head P_r connected to the transit ring network. The first peer to form the group is assigned the overlay address r. Each new peer joining group G_r is given the group membership address $(r + j \cdot n)$, for $j = 1, 2, \ldots$, where these addresses are the consecutive positive integers starting with r belonging to residue class $\{r\}$. Based on Lemma 1, all these addresses are mutually congruent. According to the research work reported in [10], any two peers in a group with assigned logical addresses that are congruent to each other will be directly connected to each other via an overlay link. Therefore, all peers in any group are directly connected to each other. That is, the network of peers belonging to any group has a diameter of 1.
3. Resource type R_r possessed by peers in G_r is assigned the code r which is also the logical address of the group-head P_r of group G_r.
4. Each time a new group-head joins, a corresponding tuple $\langle$Resource Type, Resource Code, Group Head Logical Address$\rangle$ is entered in the global resource table (GRT).

Definition 3. *Two peers P_i and P_j on the ring network are logically linked together if $(i+1) \bmod n = j$.*

Remark 1. *The last group-head P_{n-1} and the first group-head P_0 are neighbors based on Definition 3. It justifies that the transit network is a ring.*

Definition 4. *Two peers of a group G_r are logically linked*

Algorithm 1 A Non-capacity constrained approach

Group-head P_i broadcasts the query $\langle p', a_r \rangle$ to all other group-heads of the P2P network ▷ one hop communication
Some Group-head P_r finds the resource type r in its group G_r
if the group-head P_r has the answer a_r to the query **then** ▷ Group-head P_r executes data look-up in its group
    it unicasts a_r to the requesting peer p'
    search ends ▷ search ends with success
else
    P_r broadcasts the query $\langle p', a_r \rangle$ to peers in G_r ▷ diameter of any cluster is one hop
    if $\exists\, p^*$ with a_r in G_r **then**
        peer p^* unicasts a_r to p'
        search ends ▷ search ends with success
    else
        search fails and ends
    end if
end if

together if their assigned logical addresses are mutually congruent.

Lemma 2. *Diameter of the transit ring network is $n/2$.*

Lemma 3. *Each group G_r forms a complete graph.*

4 Modified Architecture

In the proposed modified architecture, the only change occurs at level 1: we replace the ring-based topology with a fully connected (complete) network composed exclusively of group-heads. This ensures that each group-head can communicate directly with every other group-head at the same level, reducing lookup latency and improving fault tolerance.

As detailed in Section 3, at level 1 each group-head P_r of group G_r is assigned a unique identifier equal to the smallest nonnegative representative of its residue class $r \bmod n$ in the residue system S_n. Equivalently, the overlay (logical) addresses of the n group-heads are assigned in consecutive order:

$$0, 1, 2, 3, \ldots, (n-1).$$

These are logical identifiers used for overlay routing and resource discovery (not physical network addresses), yielding a uniform and deterministic mapping across all group-heads within the complete level-1 network.

Consider the following series (sequence) of nonnegative integers:

$$i, i+d, i+2d, i+3d, \ldots, i+kd, \ldots$$

We observe that this is an AP (Arithmetic Progression) series with first term i and common difference d. This series may be finite or infinite.

Theorem 1. *Any two numbers in the series are mutually congruent.*

Proof. Without any loss of generality, let us consider the mth and rth numbers of the series. Let these be N_m and N_r. These numbers can be written as:

$$N_m = i + (m-1)d \quad \text{and} \quad N_r = i + (r-1)d$$

Now,

$$\frac{N_m - N_r}{d} = \frac{(i+(m-1)d) - (i+(r-1)d)}{d} = \frac{(m-r)d}{d} = (m-r)$$

Since $(m-r)$ is an integer, $\therefore N_m \equiv N_r \pmod{d}$.

Since the congruence relation is symmetric, $\therefore N_r \equiv N_m \pmod{d}$.

Hence, any two numbers N_m and N_r of the series are mutually congruent with respect to modulus d. □ □

Corollary 1. *Any two numbers of the series $0, 1, 2, 3, \ldots, (n-1)$ are mutually congruent.*

It may be noted that the series considered in the above corollary is a finite AP series with first term 0 and common difference 1.

Observation 1. *Since the respective overlay (logical) addresses of the n number of group-heads are $0, 1, 2, 3, \ldots, (n-1)$, hence at level-1 group-heads are pairwise directly connected to each other via overlay links (Corollary 1). Therefore, at level-1, it is a complete network of group-heads with diameter* 1.

Corollary 2. *Network of peers belonging to any group has a diameter of* 1. *Hence, the diameter of the two-level Residue Class-based peer-to-peer network is* 3.

The modified architecture is shown in Figure 2. Note that the level-1 is a complete network.

5 Data Look-up Protocols

The proposed architectural modification involves only the level-1 portion of the P2P network [10]. Hence the data look-up protocols inside the groups do not need any modification.

Algorithm 2 Capacity-Constrained Group-Head Discovery

1: Group-head P_i broadcasts the query $\langle p', a_r \rangle$ to c number of group-heads in increasing sequence of their ids ▷ overlay address of a group-head is its id
2: **if** a receiving group-head P_r finds the resource type r in its group G_r **then**
3: P_r executes Step 3 of the 'non-capacity constrained approach'
4: **else**
5: P_r broadcasts the query $\langle p', a_r \rangle$ to a second set (in sequence) of c number of group-heads
6: **end if**
7: Step 2 is repeated until the search fails ▷ P_r executes at most n/c number of sends ▷ maximum number of hops (repetitions) is n/c

However, data -look-up in the whole P2P network needs some modification. Same is true for the whole network-wide broadcast of any information.

5.1 Data Look-up in the whole P2P network

Let a peer p' in group G_i look for some instance a_r of a resource type r and it is not present in the group. The query is denoted as $\langle p', a_r \rangle$. The group-head P_i executes the following as shown in Algorithm 1:

Remark 2. *The maximum number of hops required in the non-capacity constrained approach is* $[1(step1)+2]$.

In Step 1 of the above non-capacity constrained approach, peer heterogeneity has not been considered, especially from the viewpoint of the capacity (upload bandwidth) of a peer [22]. Below we present a capacity-constrained query look-up scheme initiated by the group-head P_i. Let its capacity be c. The algorithm is shown in Algorithm 2.

Remark 3. *The maximum number of hops required in the capacity constrained approach is* $[\frac{n}{c}+2]$.

5.2 Broadcast in the whole P2P network

This section introduces the broadcast algorithms tailored to address both non-capacity-constrained and capacity-constrained configurations in the system.

5.2.1 A non-capacity constrained approach

In this section state broadcast scheme only at the level-1 of the network. At level-2 existing schemes [10] apply. The algorithm is shown in Algorithm 3.

Algorithm 3 A non-capacity constrained approach

1: Given: Group-head P_i wants to broadcast some information I_{info} to all other group-heads of the network
2: P_i broadcasts I_{info} to all group-heads of the Federation ▷ One hop communication

5.2.2 A capacity constrained approach

In this section we present the broadcast scheme only at the level-1 of the network. At level-2 existing schemes [10] apply. The algorithm is shown in Algorithm 4.

Algorithm 4 Capacity-Constrained Broadcast at Level 1

1: Group-head P_i broadcasts the information I_{info} to c number of group-heads in increasing sequence of their ids ▷ One hop communication
2: Repeat Step 1 with a new set of c number of group-heads (in sequence) until all group-heads have received the broadcast information I_{info} ▷ P_i executes at most n/c number of sends

Remark 4. *The number of overlay hops required in the capacity constrained approach at Level 1 is* $\frac{n}{c}$.

6 Conclusions

In this work, we have presented a *modified* version of the existing Residue-Class (RC) based peer-to-peer (P2P) network architecture. The primary design objective of this modification is to reduce the network diameter to the smallest possible value without compromising the intrinsic advantages of the RC-based approach. The existing RC-based architecture [10] was chosen as the baseline for our work because of two key strengths: (1) all peers sharing the same interest or possessing the same resource type are structurally organized into a group (or cluster) of diameter one, thereby enabling *constant-time* intra-group lookups, and (2) the group heads are connected in the form of a logical ring, ensuring that the inter-group backbone remains connected even under churn conditions, thereby preserving network stability and routing guarantees.

Despite these strengths, the ring topology inherently imposes a network diameter of $\frac{n}{2}$ for the n group heads in the worst case. Consequently, the overall P2P network diameter becomes $\left(\frac{n}{2}+2\right)$ hops, where the additional two hops account for traversals between a peer and its group head at both ends of the communication path. As n grows, this diameter significantly affects lookup latency, particularly in time-critical or real-time applications such as industrial IoT monitoring, distributed learning, or telemedicine data retrieval.

In the proposed architecture, we replace the ring-based backbone with a fully connected inter-group head topology. Each group head maintains a direct link to all other group heads, effectively transforming the inter-group overlay from a diameter of $\frac{n}{2}$ to a diameter of one. Consequently, the overall network diameter is reduced to three hops:

1. One hop from the source peer to its local group head.
2. One hop directly between the source group head and the destination group head.
3. One hop from the destination group head to the target peer within its group.

This reduction is mathematically optimal for such architectures and represents the shortest possible diameter in a multi-group P2P system while maintaining structural separation of interest-based clusters.

The impact of this modification is substantial. By minimizing the maximum path length, we not only reduce the worst-case lookup latency but also decrease message forwarding overhead, improve throughput, and increase responsiveness under high query loads. Furthermore, the complete connectivity among group heads enhances fault tolerance—if a direct link fails, multiple alternative shortest paths still exist without affecting the network diameter.

Immediate future work will focus on designing secure and efficient data communication protocols tailored for this low-diameter RC-based architecture. Specifically, we aim to investigate:

- Lightweight cryptographic schemes to ensure confidentiality, integrity, and authenticity during inter-group communication without introducing significant latency.
- Trust verification mechanisms between group heads to prevent routing manipulation or malicious data injection.
- Adaptive maintenance strategies to dynamically manage backbone connections in large-scale deployments.

Through these enhancements, the proposed architecture is expected to provide a foundation for high-performance, secure, and scalable P2P systems applicable to diverse domains such as real-time distributed analytics, federated learning, and privacy-preserving healthcare networks.

References

[1] L. Badis, M. Amad, D. Aissani, K. Bedjguelal, and A. Benkerrou. Routil: P2p routing protocol based on interest links. In Proc. 2016 Int. Conf. Advanced Aspects of Software Engineering, pages 1–5, Constantine, 2016.

[2] Y. Chawathe, S. Ratnasamy, L. Breslau, N. Lanham, and S. Shenker. Making gnutella-like p2p systems scalable. In Proceedings of ACM SIGCOMM, Karlsruhe, Germany, August 2003.

[3] Shiping Chen, Baile Shi, Shigang Chen, and Ye Xia. Acom: Any-source capacity-constrained overlay multicast in non-dht p2p networks. IEEE Transactions on Parallel and Distributed Systems, 18(9):1188–1201, September 2007.

[4] Wen-Tsuen Chen, Chi-Hong Chao, and Jeng-Long Chiang. An interested-based architecture for peer-to-peer network systems. In 20th International Conference on Advanced Information Networking and Applications - Volume 1 (AINA'06), pages 707–712, Vienna, 2006.

[5] P. Ganesan, Q. Sun, and H. Garcia-Molina. Yappers: A peer-to-peer lookup service over arbitrary topology. In Proc. IEEE INFOCOM, volume 2, pages 1250–1260, San Francisco, USA, March 30–April 1 2003.

[6] Bidyut Gupta, Nick Rahimi, Henry Hexmoor, Shahram Rahimi, Koushik Maddali, and Gongzhu Hu. Design of very efficient lookup algorithms for a low diameter hierarchical structured peer-to-peer network. In Proc. IEEE 16th Int. Conf. Industrial Informatics (INDIN), Porto, Portugal, July 2018.

[7] Bidyut Gupta, Nick Rahimi, Shahram Rahimi, and Ashraf Alyanbaawi. Efficient data lookup in non-dht based low diameter structured p2p network. In Proc. IEEE 15th Int. Conf. Industrial Informatics (INDIN), pages 944–950, Emden, Germany, July 2017.

[8] M. Hai and Y. Tu. A p2p e-commerce model based on interest community. In 2010 International Conference on Management of e-Commerce and e-Government, pages 362–365, Chengdu, 2010.

[9] M. He, Y. Zhang, and X. Meng. Gossip-based resource location strategy in interest community for p2p networks. Chinese Journal of Electronics, 24(2):272–280, April 2015.

[10] Swathi Kaluvakuri, Koushik Maddali, Nick Rahimi, Bidyut Gupta, and Narayan Debnath. Generalization of rc-based low diameter hierarchical structured p2p network architecture. International Journal of Computer Applications, 27(2):74–83, June 2020.

[11] Mujtaba Khambatti, Kyung Ryu, and Partha Dasgupta. Structuring peer-to-peer networks using interest-based communities. In Lecture Notes in Computer Science, 1st International Workshop, DBISP2P 2003. Berlin, 2003.

[12] S. K. Khan and L. N. Tokarchuk. Interest-based self organization in cluster-structured p2p networks. In Proc. 6th IEEE Consumer Communications and Networking Conf, pages 1–5, Las Vegas, 2009.

[13] S. K. A. Khan and L. N. Tokarchuk. Interest-based self organization in cluster-structured p2p networks. In 2009 6th IEEE Consumer Communications and Networking Conference, pages 1–5, Las Vegas, NV, 2009.

[14] M. Kleis, E. K. Lua, and X. Zhou. Hierarchical peer-to-peer networks using lightweight superpeer topologies. In Proc. IEEE Symposium on Computers and Communications, pages 1–6, 2005.

[15] D. Korzun and A. Gurtov. Hierarchical architectures in structured peer-to-peer overlay networks. In Peer-to-Peer Networking and Applications, pages 1–37. Springer, March 2013.

[16] Z. Peng, Z. Duan, J. J. Qi, Y. Cao, and E. Lv. Hp2p: a hybrid hierarchical p2p network. In Proc. Intl. Conf. Digital Society, pages 86–90, 2007.

[17] N. Rahimi, K. Sinha, B. Gupta, and S. Rahimi. Ldepth, a low diameter hierarchical p2p network architecture. In Proc. IEEE 14th Int. Conf. Industrial Informatics (INDIN), pages 832–837, Poitiers, France, July 2016.

[18] A. Rowstron and P. Druschel. Pastry, scalable, distributed object location and routing for large scale peer-to-peer systems. In Proc. FIP/ACM International Conference on Distributed Systems Platforms (Middleware), pages 329–350, 2001.

[19] Indranil Roy, Bidyut Gupta, Banafsheh Rekabdar, and Henry Hexmoor. A novel approach toward designing a non-dht based structured p2p network architecture. In EPiC Series in Computing, volume 63, pages 121–129, 2019. Proceedings of 32nd Int. Conf. Computer Applications in Industry and Engineering.

[20] Indranil Roy, Swathi Kaluvakuri, Koushik Maddali, Ziping Liu, and Bidyut Gupta. Efficient communication protocols for non dht-based pyramid tree p2p architecture. WSEAS Transactions on Computers, 20:108–125, July 2021. (Invited paper).

[21] Indranil Roy, Koushik Maddali, Swathi Kaluvakuri, Banafsheh Rekabdar, Ziping Liu, Bidyut Gupta, and Narayan Debnath. Efficient any source overlay multicast in crt-based p2p networks - a capacity-constrained approach. In Proc. IEEE 17th Int. Conf. Industrial Informatics (INDIN), pages 1351–1357, Helsinki, Finland, July 2019.

[22] H. Shen, G. Liu, and L. Ward. A proximity-aware interest-clustered p2p file sharing system. IEEE Transactions on Parallel and Distributed Systems, 26(6):1509–1523, June 2015.

[23] H. Shen, G. Liu, and L. Ward. A proximity-aware interest-clustered p2p file sharing system. IEEE Transactions on Parallel and Distributed Systems, 26(6):1509–1523, June 2015.

[24] K. Shuang, P. Zhang, and S. Su. Comb: resilient and efficient two-hop lookup service for distributed communication system. Security and Communication Networks, 8(10):1890–1903, 2015.

[25] R. I. Stocia, R. Morris, D. Liben-Nowell, D. R. Karger, M. Kaashoek, F. Dabek, and H. Balakrishnan. Chord: A scalable peer-to-peer lookup protocol for internet applications. IEEE/ACM Transactions on Networking, 11(1):17–32, February 2003.

[26] Z. Tu, W. Jiang, and J. Jia. Hierarchical hybrid dve-p2p networking based on interests clustering. In 2017 International Conference on Virtual Reality and Visualization (ICVRV), pages 378–381, Zhengzhou, China, 2017.

[27] M. Xu, S. Zhou, and J. Guan. A new and effective hierarchical overlay structure for peer-to-peer networks. Computer Communications, 34:862–874, 2011.

[28] M. Yang and Y. Yang. An efficient hybrid peer-to-peer system for distributed data sharing. IEEE Transactions on Computers, 59(9):1158–1171, September 2010.

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

Indranil Roy (photo not available) is an Assistant Professor in the Department of Computer Science at the Southeast Missouri State University. He received his MS and Ph.D. degrees in Computer Science from Southern Illinois University, Carbondale in 2018 and 2022, respectively. His current research interest includes the design of architecture and communication protocols for structured peer-to-peer overlay networks, security in overlay networks, and Blockchain.

Reshmi Mitra (photo not available) is an Associate Professor in the Department of Computer Science at the Southeast Missouri State University. She received her MS and Ph.D. degrees in Electrical and Computer Engineering from the University of North Carolina at Charlotte in 2007 and 2015, respectively. Previously she has worked at the National Institute of Technology India, Advanced Micro Devices Austin, and Samsung Austin R&D Center. Her research interests include Security and Performance issues in IoT, Cloud Computing, and Blockchain.

Bidyut Gupta (photo not available) received his M. Tech. degree in Electronics Engineering and Ph.D. degree in Computer Science from Calcutta University, Calcutta, India. At present, he is a professor at the School of Computing (formerly Computer Science Department), Southern Illinois

University, Carbondale, Illinois, USA. His current research interest includes design of architecture and communication protocols for structured peer-to-peer overlay networks, security in overlay networks, and block chain. He is a senior member of IEEE and ISCA.

Narayan Debnath (photo not available) earned a Doctor of Science (D.Sc.) degree in Computer Science and also a Doctor of Philosophy (Ph.D.) degree in Physics. Narayan C. Debnath is currently the Founding Dean of the School of Computing and Information Technology at Eastern International University, Vietnam. He is also serving as the Head of the Department of Software Engineering at Eastern International University, Vietnam. Dr. Debnath has been the Director of the International Society for Computers and their Applications (ISCA) since 2014. Formerly, Dr. Debnath served as a Full Professor of Computer Science at Winona State University, Minnesota, USA for 28 years (1989-2017). Dr. Debnath has been an active member of the ACM, IEEE Computer Society, Arab Computer Society, and a senior member of the ISCA.