Peer Clustering for the InterPlanetary File System

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ABSTRACT

Distributed Hash Tables (DHT) are once again attracting research interest, 20 years after their inception, as a promising solution for scalable and decentralized content storage. A prominent example is the InterPlanetary File System (IPFS), a distributed peer-to-peer storage system with more than 20K online peers, which uses the Kademlia DHT. We design and implement H-Kademlia, a hierarchical version of Kademlia for IPFS, where peers are distributed into disjoint sets of users, or clusters. Clustering can offer resilience to network partition, privacy of in-cluster content lookups, as well as improved caching, content filtering and access control. We assess the performance of IPFS over H-Kademlia via simulations that use real traces from the IPFS network. Our findings show that our design delivers the benefits of clustering, without significant performance penalties.

CCS CONCEPTS

• **Networks** → **Routing protocols**; **Network simulations**.

KEYWORDS

IPFS, Kademlia, DHT, Clustering

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1 INTRODUCTION

Serving millions of downloads daily and supporting dozens of third-party applications, the *InterPlanetary File System* (IPFS) [4] is an increasingly popular solution for decentralized storage. Under the hood, IPFS is an open-source, content-addressable *Peer-to-Peer* (P2P) content storage network. IPFS uses a *Distributed Hash Table* (DHT) for content routing, specifically, a tailored version of *Kademlia* [8]. Currently, the IPFS network is present in over 150 countries and more than 2500 autonomous systems and is growing rapidly.

Canon is a design paradigm that enables the construction of multi-level, DHT-based overlay networks, through a progressive merging of individual DHT clusters. The resulting network offers two properties: *Locality of intrA-Cluster Paths* (LACP) and *Convergence of intEr-Cluster Paths* (CECP). LACP assures that *lookups* for content located inside a cluster will never exit the cluster. This enhances content availability in case of cluster partitioning, since "local" content remains reachable, and improves user privacy, since *lookups* for local content are essentially hidden from the rest of the network. CECP assures that *lookups* for *the same* "global" content item exit the cluster from the same node. This creates chances for caching and other network optimizations (e.g., overlay mutlicast delivery trees), and also enables deploying security mechanisms, such as content filtering and access control.

In this paper, we apply the Canon paradigm to Kademlia, introducing *Hierarchical-Kademlia* (H-Kademlia), and adapt it to IPFS. Our main contributions include (i) the first technical specification of H-Kademlia, (ii) an open-source implementation of H-Kademlia for the PeerNet Simulator,[1] (iii) integration of H-Kademlia to IPFS and (iv) an evaluation of IPFS over H-Kademlia based on real IPFS traces, showing that the H-Kademlia delivers the benefits of clustering, without significant performance penalties.

The remainder of the paper is organized as follows. In Section 2, we briefly describe IPFS, Kademlia, and hierarhical DHTs. In Section 3, we detail our H-Kademlia design. In Section 4, we introduce the setup of our evaluation. In Section 5, we evaluate the performance of IPFS over H-Kademlia. Finally, in Section 6, we conclude and discuss future work.

[1] https://github.com/PeerNet/PeerNet.git

2 BACKGROUND WORK

The *InterPlanetary File System* (IPFS) is a P2P system that stores data files in a distributed, decentralized, and collaborative way. Pointers to files are replicated on multiple peers in order to provide resilience to failures. Redundancy is driven by a demand-oriented replication policy that correlates replication to popularity, thus enhancing scalability. Currently, the IPFS network consists of roughly 20K active peers.[2]

DHTs are fundamental components for many P2P systems, mapping *identifiers* (IDs) to *values* and supporting storing and looking up content in a distributed manner. IPFS uses a tailored version of the *Kademlia* DHT [8]. Every peer (and content) is assigned a unique ID of size s (256 bits in IPFS). Kademlia peers maintain s *KBuckets*, storing information about remote peers. The x^{th} KBucket of a node stores information about peers that have a common ID prefix of length $x-1$ with the node's ID.

For content *Lookup*, the *inquiring* peer, which starts the process, sends in parallel kad_A (3 in IPFS) *FIND_VALUE* messages to the peers closest to the content's ID, until either the entire network is searched or the ID is found. When an inquired peer does not have the content, it returns the closest peers to the requested ID based on its local KBuckets, thus allowing the inquiring peer to move closer to its target. Content *Store* is based on the same recursive process. The difference is that the inquiring peer first locates the kad_K (20 in IPFS) closest peers to the content's ID and then sends a STORE message to each of them. A peer stops its search when the lists of IDs in the responses do not contain any peer IDs closer to the content ID compared to those already discovered. When a peer *Joins*, it uses a "bootstrapping peer," acquired through an out-of-band mechanism. The new peer inserts the bootstrapping peer into the appropriate KBucket, and then performs a Lookup for the new node's ID. During the Lookup process, the new peer adds to its KBuckets information about the peers with IDs closest to its own, and vice versa. When a peer *Leaves*, it does not explicitly notify anyone; Kademlia removes a peer from a KBucket after a message to it remains unanswered for a predefined period.

Canon is a design paradigm that enables the construction of multi-level DHT-based overlay networks, through a progressive merging of individual DHTs, assuming a hierarchical structure of the different peer clusters [6]. A Canon-based DHT achieves the LACP and CECP properties mentioned above. A brief discussion regarding the application of the Canon paradigm to Kademlia is presented in [6]; to the best of our knowledge, this paper is the first work to document, implement and experimentally evaluate such a design.

Hierarchical DHTs can be grouped into two categories [1, 14]: *horizontal*, in which all peers are equal, and *vertical*, in which a relatively small group of "super" peers behave as proxies that interconnect clusters. In a horizontal system, hierarchy is built by merging clusters; during this process, all peers add links to a number of peers in sibling DHTs. In a vertical system, a tree-like hierarchy is created from self-contained DHTs, where transition from a lower-level cluster to an upper-level one is realized only through super peers which are members of both clusters. A vertical design for H-Kademlia is introduced in [7]; it uses super-peers for inter-cluster communication and correlates clusters with node identifiers. That work does not delve into the implementation specifics of the protocol and only examines the design analytically. Our H-Kademlia design follows the horizontal paradigm, with cluster-independent node IDs and no super peers. This is critical for IPFS, where peers and content identifiers are cryptographically associated with specific physical peers and content items, respectively.

[2] https://trudi.weizenbaum-institut.de/ipfs_analysis.html

3 H-KADEMLIA DESIGN

Our H-Kademlia design introduces a modified KBucket maintenance process which differentiates *local* peers (from the same cluster) and *remote* peers (from a different cluster). In H-Kademlia, a peer can maintain links to *any* local peers. However, it can only maintain a link to a remote peer *if* it is the *XOR-wise closest* one to that remote peer among *all* peers in its cluster. Therefore, a peer A performs the following checks before inserting a candidate peer C in its KBuckets:

- If peer C is remote, then peer A searches for the peer in its cluster that is the closest one to C.
  - If that is *not* A, then A does *not* store a link to C.
  - Otherwise, A inserts a link to C in its KBuckets; we say that A becomes its cluster's *gateway* peer with respect to C.
- If peer C is local, then it is always added in A's KBuckets; in addition, A removes any links to remote peers that are closer to C than A itself, as C should become their new gateway peer.

Figure 1 shows the H-Kademlia operations during a Store and a Lookup, using a network of four peers in two clusters; the degree of replication (kad_K) is 2 and the degree of parallelism (kad_A) is 1. We also assume that the peers have already filled their KBuckets with peer IDs.

Figure 1(a) shows the resolution of a Store request where peer 010 wants to store some content with ID 110. The cluster's gateway peer for ID 110 is peer 111, hence only local peer 111 has a link to remote peer 110 in its KBuckets. Peer 010 starts by sending a *FIND_PEER* message to peer 111, which is the closest peer to the content ID in its KBuckets (message 1); peer 111 sends back peer ID 110 and the ID of one of the other two peers which are equally close to the content ID (message 2); peer 010 sends a request to the next closest non-inquired peer, that is, peer 110 (message 3), which finds and returns the IDs of the kad_K closest peers to the content ID (message 4). As no new peers were discovered, peer 010 concludes that the process is done and sends Stores to the closest kad_K peers, namely, peers 111 and 110.

Figure 1(b) shows the resolution of a Lookup request where peer 000 searches for content ID 110; the gateway peer for content ID 110 is peer 111. If peer 000 does not find a locally stored copy of the content, it sends a *FIND_VALUE* request to the closest peer to that content ID in its KBuckets, peer 111 (message 1). Peer 111 searches locally for the content, and if the search fails it replies with the IDs of the kad_K closest peers in its KBuckets (message 2). Peer 000 sends a request to peer 110 (message 3), which satisfies the request.

These examples illustrate the two properties of the Canon paradigm. First, all requests that concern a non-local peer ID exit the

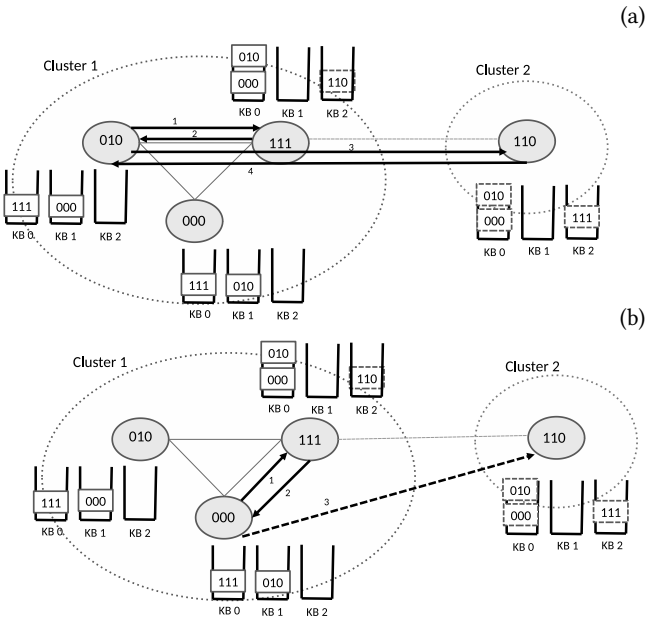

Figure 1: H-Kademlia resolving (a) a Store and (b) a Lookup request in a network of four peers (circles) in two clusters (dotted circles). The lines indicate overlay links, the arrows indicate messages and the numbering shows the sequence of the messages.

cluster through the same gateway peer (CECP). Second, all requests that can be resolved locally, never exit the cluster (LACP). Both properties arise due to the decision to only store a link to a remote peer at the peer closest to it.

Peers need a mechanism to decide whether other peers are local or remote. This can be an out-of-band mechanism, such as an online service, or a distributed procedure that each peer can perform . This mechanism is intertwined with the clustering scheme, which is orthogonal to the H-Kademlia design; different clustering approaches can favor different mechanisms. For a fixed clustering method, e.g., based on the peer's country of origin, an out-of-band bootstrap mechanism can assign cluster IDs to the new peers and respond to cluster ID queries. For a dynamic clustering method, e.g., based on inter-peer latency, the peers should exchange clustering-specific messages in order to infer and share changes in network topology. Without loss of generality, we assume that each peer knows the cluster it belongs to and shares this information with other peers by including it in Kademlia messages.

Caching can deliver an additional performance gain to hierarchical DHTs by resolving requests within a cluster. In our system, each peer opportunistically stores the traffic it forwards. Without loss of generality, we assume a *First In First Out* (FIFO) replacement policy. Responses from remote peers are also cached at the gateway peer for their content ID; future requests for the same content will always flow through the gateway peer, due to the CECP property.

Even though it is orthogonal to the design of H-Kademlia, the clustering policy determines the attributes of the resulting IPFS network. In our experiments, clusters were based on the peer's country of origin. This policy is appropriate for supporting security mechanisms and access control policies for multi-level DHTs. For example, due to international content distribution agreements, content availability can be restricted within a country; the LACP property ensures that these requests will be satisfied locally. Alternatively, by forming clusters based on trust metrics, rather than topology-based metrics, H-Kademlia can provide resilience against *Denial-of-Service* (DoS) attacks, where attackers refuse to forward or respond to a query [5]. Such a trust-based clustering approach can also be used as a building block for a query privacy mechanism [2]: in H-Kademlia a query is initially routed through intra-cluster (trusted) peers and only if no result is found, it exits the cluster through the gateway peer, which can act as an obfuscation point.

In addition, H-Kademlia can be used as a defense mechanism against some common DHT threats. For example, due to the LACP, H-Kademlia guarantees that Lookup requests for locally stored content will always succeed, even when the DHT network is under an external *Eclipse* attack [11], i.e., an attacker "eclipses" some peers by "poisoning" the routing protocol. H-Kademlia is resilient to this type of attack since routing entries for "local" peers have higher priority.

4 EVALUATION SETUP

We have implemented Kademlia and H-Kademlia on *PeerNet*, a well-established simulator for P2P networks, using real IPFS traces to drive the evaluation. We selected the following metrics to explore the performance of H-Kademlia:

- Path length (*hops*): the distance that a request travels until it reaches its destination, in *overlay* hops.
- Latency (*ms*): the time between the emission of a request and its completion, that is, when one peer is found for a Lookup, or all peers are found for a Store.
- Success ratio (%): the ratio of Lookups that are successfully resolved.
- Routing state (*peers*): the number of peers that are maintained in the KBuckets.
- Store receivers (*peers*): the number of peers that are selected to store a content item in a Store.
- Inter to Intra-Cluster Ratio: the ratio of inter-cluster to intra-cluster messages in Lookups and Stores.

To evaluate the performance of H-Kademlia under realistic conditions, we started with traces of actual IPFS network traffic provided by Nebula, an IPFS crawler.[3] We analysed the traces and inferred the value distributions of the parameters critical to our evaluation. These distributions allowed us to simulate diverse scenarios, rather than the specific scenarios provided by the traces. As the generation of the input parameters was stochastic, we tested multiple input data sets and we present the average measurements.

Churn. To describe churn, we consider three peer session parameters: the overall up-time, the number of sessions (or re-connections) and the down-time between sessions. We infer the up-time distribution from [9] (Fig. "peer classification"). The traces in [12] (Fig. "inter-arrival time") depict the CDF of the unavailability period (between

[3] https://github.com/dennis-tra/nebula

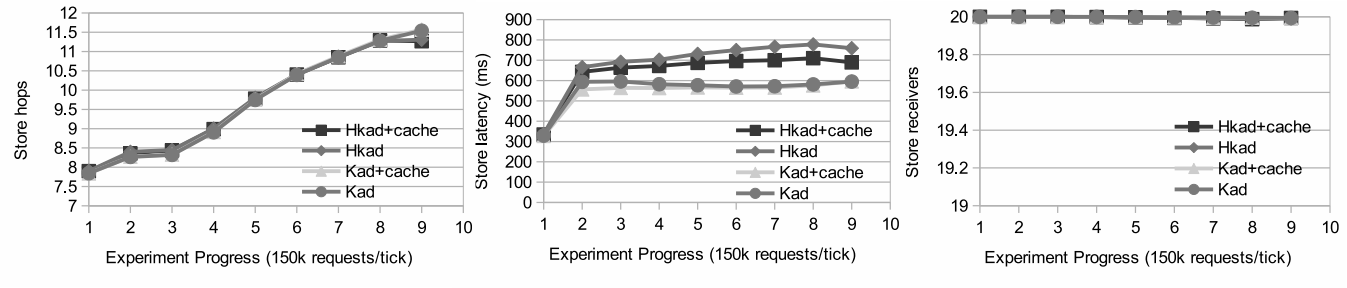

Figure 2: Performance comparison of H-Kademlia and Kademlia: Store requests.

two consecutive sessions) in the IPFS network. From the same traces, we determined the number of sessions that the peers conducted within the trace period. For the simulations, we generated a random churn profile for each peer according to these distributions.[4]

Network topology. Network topology determines peer location and the latency of overlay links. We infer the peer location distribution from [10] (Fig. "geolocation of on peers"). Then, we synthesize a link-latency matrix at the country level (for scalability) based on publicly available global RTT measurements made by cloud providers.[5] By combining the location distribution and the latency matrix, we approximate the latency between every pair of peers.

Network size. We determine the number of *unique* peers from the number of *up* peers and the mean up-time of peers. The number of up peers is 10K to 12K [12] (Fig. "crawl time series"). The mean up-time of peers in [9] (Figs. "peer classification" and "reliability") suggests a 3.7 ratio of active to up peers, hence our simulations use 37K unique peers; this is consistent with the 54K unique peers in 7 days from [12].

Content Popularity and Request Rate. Content popularity in IPFS is assessed in [3], which reports the total number of Lookups received for a particular content item over a given period; this study indicates that the IPFS network handles roughly 10M requests daily. Hence, we generate a traffic workload with size equal to the overall requests, i.e., 20M for 2 days, and roughly 20K individual content items. Due to computational and memory constraints, each experiment simulates 1.5M requests (3.6 hours of IPFS operation). We are not aware of any studies characterizing Stores for IPFS or similar P2P networks, hence we also use the distribution of [3] for Stores, assuming an 1:4 ratio of Stores to Lookups.

Our setup does not consider the correlation between different input parameters, e.g., different churn rates for different countries; peers are randomly assigned location, reliability and other parameters. The configuration parameters of (H-)Kademlia are those used in IPFS: 128 bit IDs, kad_A=3 and kad_K=20. The error detection timeout is 2s and we explore four different IPFS modes: Kademlia, Kademlia with caching, H-Kademlia and H-Kademlia with caching.

[4]As we combine the results of crawls with different timespans, we scale them down to a two-day duration, the minimum one among the crawls.

[5]https://learn.microsoft.com/azure/networking/azure-network-latency

5 PERFORMANCE EVALUATION

5.1 Store requests

In Fig. 2 we present the metrics related to Stores: *path length*, *latency* and *store receivers*. All figures show the evolution of the metrics as the 1.5M requests are being issued. Hierarchy and caching only seem to affect latency. Since path lengths are nearly identical in all cases, we infer that the latency overhead of H-Kademlia is due to more re-transmissions. The hierarchical design reduces the number of acceptable peers in the Kbuckets (see also Fig. 4, where the KBucket size in hierarchical mode is consistently lower), making it harder to locate 20 peers under node churn. To verify our inference, we ran the experiment without churn and found that H-Kademlia and Kademlia present the same Store latency.

Fortunately, caching noticeably reduces H-Kademlia latency. Caching reduces the length of Lookups, hence the overall distance to discovered peers is reduced; the discovered network "shrinks" around the reference peer and, in turn, Stores are delivered faster to peers. This assumption is supported by the inter-to-intra cluster ratio of messages sent during Stores, shown in Fig. 4 for H-Kademlia, where caching reduces the number of inter-cluster messages, thus favoring "shorter" intra-cluster links. Overall, the results reveal that Stores are slower with the hierarchical peer organization, but caching helps reduce the gap over the flat organization.

5.2 Lookup requests

In Fig. 3 we present the metrics related to Lookups: *path length (in hops)*, *latency* and *success ratio*. The results indicate that the number of hops grows by approximately 0.5 hops with H-Kademlia, but is reduced by roughly 0.2 hops with caching. These differences are too small to affect latency. On the other hand, the success ratio is affected: H-Kademlia has an approximately 5% lower success ratio; caching increases this success ratio by approximately 3% (and a bit less for plain Kademlia).

Caching only has a minor effect on the Lookup performance of H-Kademlia for two reasons. First, Lookups are sent in parallel to kad_A=3 "one-hop-away" peers, therefore content can be found at two other local peers besides the gateway peer, hence caching cannot greatly exploit the CECP property. Second, the cached responses in our experiments comprise roughly 23% of the successful Lookups, but they are only shorter by around 0.5 hops (compared to the origin peer). Caching will have more prevalent effects on larger networks, but since in Kademlia path length grows logarithmically

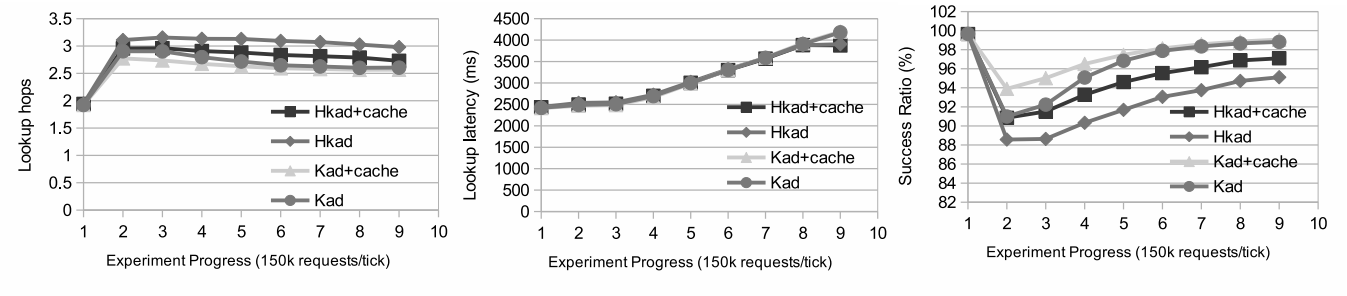

Figure 3: Performance comparison of H-Kademlia and Kademlia: Lookup requests.

to the network size, only very large networks would show clear benefits.

5.3 Topology awareness and clustering

In Fig. 4 we present metrics related to topology awareness and clustering: *KBucket size* and *Inter:Intra-cluster ratio* for Stores and Lookups. The routing state (KBucket size) is consistently smaller for H-Kademlia; there are roughly 20 fewer peers compared to Kademlia. Although this issue does not severely challenge operation, it can be related to the small performance disadvantages of H-Kademlia shown in previous experiments. If we had no churn and peers had complete topology awareness, the number of peers in KBuckets would be 200 peers, hence the churn observed in the IPFS traces penalizes the topology awareness of the peers by 20% to 30%.

For the "Inter:Intra-cluster" message ratio for Lookups and Stores, note first that the clustering for plain Kademlia is virtual; the network is flat, so the metrics are estimated a posteriori based on the clustering used in the equivalent H-Kademlia experiments. We observe that H-Kademlia singificantly increases message locality for both Stores and Lookups, respectively. Specifically, for H-Kademlia the ratio of inter-cluster to intra-cluster messages is 1.15 and 0.6 for Stores and Lookups, respectively, compared to 1.55 and 1.4 for flat Kademlia, thus a significant portion of traffic is confined within the cluster.

5.4 Discussion

Our evaluation suggests that H-Kademlia offers the benefits of clustering to IPFS at a negligible performance cost. Even though the parallelism and extensive content replication of Kademlia reduce the performance gains promised by the CECP property, the LACP property is prevalent in H-Kademlia. In the following, we summarize these effects:

- H-Kademlia can be used by security mechanisms that protect DHTs against common security attacks.
- The routing state of H-Kademlia is lower, since the inter-cluster peers are filtered.
- The latency of Stores and the success ratio of Lookups are slightly worse for H-Kademlia, which is more challenged by churn due to its reduced routing state.
- The path length of Lookups is slightly longer for H-Kademlia due to routing through the gateway peer.
- Locality is significantly increased by H-Kademlia, for both Lookups and Stores.
- Caching is effective in H-Kademlia only for Store latency and Lookup success ratio.
- Our findings show similar trends with the actual measurements of IPFS in [13], i.e., timeouts due to unresponsive peers penalize the latency of Stores while Lookups are handled rather effectively.

6 CONCLUSIONS AND FUTURE WORK

This paper introduced H-Kademlia, a hierarchical DHT design based on Kademlia and the Canon paradigm. We designed, implemented and evaluated H-Kademlia via PeerNet, as a candidate DHT for the growing IPFS network. In our simulations, we considered real IPFS traces that capture user activity in terms of user location, churn, and content requests. Our findings validate that in the case of IPFS, H-Kademlia can enhance the locality of requests, reducing the cost of inter-cluster traffic and facilitating the implementation of several security mechanisms, at the cost of a minor performance loss in Store latency and Lookup success ratio.

Due to space limitations, we did not consider alternative clustering approaches. To enhance performance, a fine-tuned clustering policy that leverages Kademlia's parallelism and content replication could deliver better results. To enhance security, clustering mechanisms based on peer profiles, i.e., white lists and cryptography support, can instead be considered. Finally, an important topic for future work is the incremental deployment of H-Kademlia on IPFS and the properties of the network when only some peers support H-Kademlia.

REFERENCES

[1] Marc Sanchez Artigas, Pedro Garcia Lopez, and Antonio F. Skarmeta. 2007. A Comparative Study of Hierarchical DHT Systems. In *32nd IEEE Conference on Local Computer Networks (LCN 2007)*. 325–333. https://doi.org/10.1109/LCN.2007.79

[2] Michael Backes, Ian Goldberg, Aniket Kate, and Tomas Toft. 2012. Adding query privacy to robust DHTs. In *7th ACM Symposium on Information, Computer and Communications Security*. 30–31.

[3] Leonhard Balduf, Sebastian Henningsen, Martin Florian, Sebastian Rust, and Björn Scheuermann. 2021. Monitoring Data Requests in Decentralized Data Storage Systems: A Case Study of IPFS. *arXiv preprint arXiv:2104.09202* (2021).

[4] Juan Benet. 2014. IPFS-content addressed, versioned, p2p file system. *arXiv preprint arXiv:1407.3561* (2014).

[5] Miguel Castro, Peter Druschel, Ayalvadi Ganesh, Antony Rowstron, and Dan S Wallach. 200f2. Secure routing for structured peer-to-peer overlay networks. *ACM SIGOPS Operating Systems Review* 36, SI (200f2), 299–314.

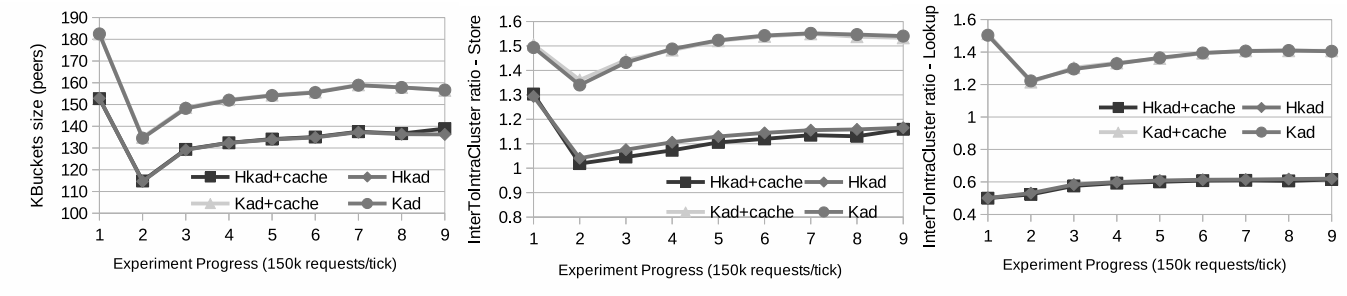

Figure 4: Performance comparison of H-Kademlia and Kademlia: Topology awareness and clustering.

[6] Prasanna Ganesan, Krishna Gummadi, and H. Garcia-Molina. 2004. Canon in G major: designing DHTs with hierarchical structure. In *24th International Conference on Distributed Computing Systems*. 263–272.

[7] Isaias Martinez-Yelmo, Ruben Cuevas, Carmen Guerrero, and Andreas Mauthe. 2008. Routing Performance in a Hierarchical DHT-based Overlay Network. In *16th Euromicro Conference on Parallel, Distributed and Network-Based Processing (PDP 2008)*. 508–515.

[8] Petar Maymounkov and David Mazieres. 2002. Kademlia: A peer-to-peer information system based on the XOR metric. In *International Workshop on Peer-to-Peer Systems*. Springer, 53–65.

[9] Zhenyang Shi. 2021. Nebula Crawlings. https://github.com/wcgcyx/nebula-crawler/tree/812f33515342321461e39b17ac02a91858926e14.

[10] Zhenyang Shi. 2021. Nebula Crawlings. https://github.com/wcgcyx/nebula-crawler#6-correlation-between-uptime-and-geolocation.

[11] Emil Sit and Robert Morris. 2002. Security considerations for peer-to-peer distributed hash tables. In *International Workshop on Peer-to-Peer Systems*. Springer, 261–269.

[12] Dennis Trautwein. 2021. Nebula Crawlings. https://github.com/dennis-tra/nebula-crawler-reports/blob/main/2021/calendar-week-44/ipfs/README.md.

[13] Dennis Trautwein, Aravindh Raman, Gareth Tyson, Ignacio Castro, Will Scott, Moritz Schubotz, Bela Gipp, and Yiannis Psaras. 2022. Design and evaluation of IPFS: a storage layer for the decentralized web. In *ACM SIGCOMM 2022 Conference*. 739–752.

[14] Peng Wang, Julong Lan, Yuxiang Hu, and Shuqiao Chen. 2015. Towards locality-aware DHT for fast mapping service in future Internet. *Computer Communications* 66 (2015), 14–24.