Monitoring Data Requests in Decentralized Data Storage Systems: A Case Study of IPFS

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Abstract—Decentralized data storage systems like the Interplanetary Filesystem (IPFS) are becoming increasingly popular, e.g., as a data layer in blockchain applications and for sharing content in a censorship-resistant manner. In IPFS, data is hosted by an open set of nodes and data requests are broadcast to connected peers in addition to being routed via a distributed hash table (DHT). In this paper, we present a passive monitoring methodology that exploits this design for obtaining data requests from a significant and upscalable portion of nodes. Using an implementation of our approach for the IPFS network and data collected over a period of fifteen months, we demonstrate how our methodology enables profound insights into, among other things: the size of the IPFS network, activity levels and structure, and content popularity distributions. We furthermore present that our methodology can be abused for attacks on users' privacy. For example, we were able to identify and successfully surveil the IPFS nodes corresponding to public IPFS/HTTP gateways. We give a detailed analysis of the mechanics and reasons behind implied privacy threats and discuss possible countermeasures.

I. INTRODUCTION

Decentralized, peer-to-peer-based data storage systems are becoming increasingly popular, especially in the context of blockchain applications and censorship-resistant data hosting. Whereas the narratives around previously conceived systems such as BitTorrent were mainly focused on performance and scalability, newer projects put a stronger emphasis on resilience and censorship resistance. This shift in narratives is also reflected in the systems' designs, e.g., in an increased usage of techniques common to unstructured overlay networks. The Interplanetary Filesystem (IPFS) is a prominent example of a newer peer-to-peer (P2P) data storage system [1]. IPFS is in active real-world use for mirroring censorship-threatened content and forms the data storage layer of various blockchainbased applications, including non-fungible token (NFT) platforms¹. As laid out by previous works [2], [3], IPFS employs a hybrid approach between a structured Kademlia overlay and broadcasting of so-called BitSwap requests for content to directly connected peers. While this combination renders IPFS reasonably robust against, e.g., eclipse attacks [4], it enables extensive monitoring, putting individual users' privacy at risk.

In this paper, with IPFS as a case study, we explore unintended consequences of these robustness-increasing design features. We present (1) a passive monitoring methodology for collecting and processing *BitSwap* data requests of a large

¹For example: https://opensea.io/

share of the network and (2) a monitoring setup as an instance of the methodology. Our system enables us to reveal *who* requested *which* data item *when*, i.e., which nodeID requested which content identifier (CID) at what timestamp. We collected measurements for fifteen months using two spatially diverse monitoring nodes, yielding traces of $2.78 \cdot 10^{10}$ data request entries in total. In this work, we use the obtained dataset to highlight possible analysis angles. Based on excerpts of our dataset, we showcase:

- estimations of the size of the network that also account for non-DHT nodes (unlike previous methods),
- analyses of activity levels and structure (e. g., geographybased usage patterns),
- the derivation of content popularity distributions, and
- the feasibility of privacy attacks, by identifying node IDs of HTTP/IPFS gateways.

An adversary with a similar setup to ours can determine (1) which nodes are interested in a given CID, (2) which CIDs were requested by a particular node, and, with negligible deniability, (3) whether a node (and hence its user) has downloaded a specific (CID-referenced) data item in the recent past. We follow up by a discussion of the design space of countermeasures to these privacy threats, highlighting promising directions for further investigation.

In summary, our main contributions are threefold:

- a methodology for monitoring and processing contentrelated activity data (Sec. IV),
- results from a measurement study based on this methodology that showcase the utility of collectable data (Sec. V),
- a discussion of privacy risks implied by our methods and potential privacy-enhancement approaches (Sec. VI).

Our work highlights privacy-related issues in the popular P2P system IPFS. While it is no secret that IPFS is not a privacy-focused network², our work demonstrates that the privacy level it offers is in some ways worse than that of the standard, "non-distributed" web. To safeguard and inform users, and in consultation with an ethics committee at HU Berlin, we have publicly committed to a privacy policy³ that describes our data collection and processing practices and limits them to the purpose of deriving general, non-personalized insights and statistics about the IPFS network.

²See, for example: https://docs.ipfs.io/concepts/privacy-and-encryption/

³https://monitoring.ipfs.trudi.group/privacy_policy.html

II. RELATED WORK

A variety of P2P systems have been measured and monitored in the past, through passive measurements, active crawling and probing, and combined approaches. Classic studies include works on the Gnutella network [5], [6] that also highlight the pitfalls of churn when measuring dynamic networks. BitTorrent [7], [8] and the KAD DHT [9], [10] have similarly been subjects of investigation. Wang *et al.* [7] highlight the importance of using more than one vantage point and discuss important considerations when combining network size estimates from crawls.

More recently, P2P networks have received renewed attention in the context of cryptocurrencies such as Bitcoin and Ethereum [11]. In a measurement setup similar to ours, Neudecker *et al.* [12] inferred the topology of the Bitcoin overlay through monitoring block and transaction distributions from several spatially diverse nodes. A similar approach is repeated in [13]. Network-level measurements for topology inference have also been conducted for the privacy-focused cryptocurrencies Monero [14] and ZCash [15]. Apart from topology inference, the latency and bandwidth of Bitcoin and Ethereum peers were measured to assess the systems' degree of centralization [16] and to assess the network health of Ethereum in general [17], [18].

IPFS, although significantly larger (in terms of node numbers) than most cryptocurrency networks [2], has received comparatively little attention so far. Previous studies have focused on the performance of data delivery [19]–[21], the performance of DTube, an application on top of IPFS [22], and the susceptibility of IPFS to eclipse attacks [23].

In our own previous works [2], [3], we investigated IPFS' overlay structure by crawling the Kademlia-based [24] DHT. We found that clients maintain an unexpectedly large number of connections, a subset of which is stored in the k-buckets of the underlying DHT and can be assessed through crawling. Instead of relying only on standard DHT searches, nodes also broadcast data request to all of their immediate overlay neighbors. This insight forms the basis of our following investigation, as we exploit IPFS' broadcasting behavior through passively collecting request messages from peers.

III. IPFS IN A NUTSHELL

In the following, we give a concise overview of the popular decentralized data storage system IPFS, based on our study of its source code and the available documentation. We focus on aspects relevant to our monitoring methodology and subsequent observations. Note that the development of IPFS and related libraries is ongoing—we focus on inherent conceptual properties here as details of the design may change over time. As a very broad overview, the design of IPFS can be summarized in the following way:

- IPFS is a permissionless system with weak identities; anyone can deploy a node on the IPFS overlay network.
- IPFS nodes are identified by the hash of their public key, $H(k_{\rm pub})$.

- Each data item on IPFS is stored and served by one or more *data providers* (nodes in the IPFS overlay).
- References to data providers are stored in a Kademliabased DHT (see [2], [3] for more details on IPFS' DHT and measurements thereof).
- Nodes are either DHT servers or DHT clients. The latter *use* the DHT but are not part of the DHT network.
- Data items are transferred from providers using IPFS' *BitSwap* subprotocol, which functions similarly to BitTorrent [8] and Bitcoin's inventory mechanism [11], [25].
- Data items are requested from *all* connected overlay neighbors and the DHT is queried for providers only *after* no neighbors were able to offer the data.
- By default, nodes cache data items they have downloaded and effectively become a data provider for them.

In the following, we give a deeper introduction into node types, data addressing, data retrieval, and the *BitSwap* subprotocol.

A. DHT Servers and DHT Clients

Release v0.5 of the IPFS software introduced the separation of nodes into two distinct types: DHT servers and DHT clients. The IPFS software decides which mode to operate in based on whether it finds itself connectable from the Internet. DHT servers are regular DHT participants: They store data that is inserted into the DHT and respond to DHT requests. DHT clients only use the DHT: They do not store DHT data or process requests, and will not be included in k-buckets of other nodes. Because of this, DHT clients cannot be enumerated using DHT crawling such as in [2].

B. Content Identifiers (CIDs) and Data Integrity

IPFS uses a form of Self-Certifying Filesystem (SFS) [26] to ensure the integrity of data throughout its delivery. To this end, each data item d is assigned a unique immutable address that is the hash of its content, i.e., $\operatorname{addr}(d) = H(d)$. Recipients can recognize whether received data was tampered with by comparing its hash with the requested address. In IPFS, an $\operatorname{addr}(d)$ is encoded as a so-called *content identifier* (CID).

Directories and files are organized as a Merkle DAG⁴. This construction differs from Merkle Trees insofar as nodes can have more than one parent and, in the case of IPFS, data on non-leaf nodes is permitted. For example, a directory on IPFS is encoded as a node containing the hashes of all entries in the directory in addition to metadata about each entry. Large files are chunked into smaller data *blocks* and encoded as multi-layered directed acyclic graph (DAG)s. This construction ultimately allows for caching and deduplication of both file contents and directory entries.

In principle, IPFS can be used to store a variety of different contents. The encoding of a data item can be derived from its CID, using a mapping known as Multicodec. Important Multicodecs for IPFS are: 1) *DagProtobuf*, which encodes nodes for the IPFS Merkle DAG. These objects usually

⁴https://docs.ipfs.io/concepts/merkle-dag/

encode files and directories on IPFS. 2) *Raw*, which are unencoded chunks of binary data or leaves of file Merkle DAGs. 3) *DagCBOR* and *DagJSON*, which are to-be replacements for DagProtobuf. They encode a generalized data model for hash-linked data, called Interplanetary Linked Data (IPLD), in different formats.

C. Content Retrieval

Data items are usually stored at multiple nodes in the network. Nodes store content because they are its original authors, because they chose to *pin* it, or because they have recently retrieved it themselves. Nodes normally serve the data items they store upon request. The nodes that store a given data item are consequently referred to as that data item's *providers*.

When an IPFS node v wishes to retrieve a data item with CID c (e. g. based on a user request), it follows a two-step strategy (cf. Fig. 1):

- 1) Ask *all* nodes it is currently connected to for *c*, using the *BitSwap* subprotocol (Sec. III-D)
- 2) If the first step fails, look up the providers P(c) for c in the DHT, then request c from members of P(c), again via BitSwap.

Peers discovered through either stage are added to a *session* S(c), which is used to scope subsequent request for data related to c. In the general case, c initially references the root of a DAG of blocks, which v subsequently requests from the peers in the session.

One of the keystones of IPFS' design is the caching and reproviding of requested blocks. By default, the IPFS node software stores up to $10\,\mathrm{GB}$ of block data, with an optional garbage collection mechanism. Users can also pin CIDs to ensure their local availability. In this case, the given CID and the DAG referenced by it is downloaded and marked exempt from garbage collection.

D. BitSwap

The *BitSwap* protocol is the main "data trading module" of IPFS. It is similar to BitTorrent's [8] inventory mechanism [11] and is used for obtaining data items from connected peers. *BitSwap* encompasses both (1) announcing interest in CIDs and discovering providers, and (2) actually requesting and receiving the referenced data. For both purposes, *BitSwap* builds upon a reliable transport layer such as TCP, QUIC, or even WebSockets.

1) Inventory Mechanism: Upon user request to download a data item d, IPFS broadcasts a BitSwap message to each connected peer. Since IPFS version v0.5, this message contains a WANT_HAVE entry for a CID $c = \operatorname{addr}(d)$, which can be understood as "I am looking for this block, do you have it?". Nodes receiving a request of this type answer with HAVE or DONT_HAVE, depending on whether they have the content or not. The latter is optional, a timeout mechanism alternatively determines absence of data. Prior to v0.5, no inventory mechanism was present—data was requested directly,

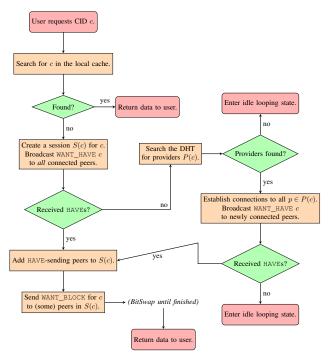


Figure 1: Content retrieval in IPFS: broadcast and then query the DHT. The "idle looping state" entails periodically re-broadcasting a request for c and re-searching the DHT.

potentially leading to a high redundancy at the receiving side [19]. The interests of connected peers is tracked in so-called want_lists, which are persisted for as long as the peer is connected. An outstanding request can be canceled with a CANCEL entry, which is done on receipt of the requested data or on user request.

- 2) Sessions: As shown in Fig. 1, recent versions of BitSwap operate on sessions. A session S(c) tracks the set of peers likely to have data related to a running query, based on receipt of HAVE messages and DHT searches. Future requests for blocks related to d can be directed at the relevant peers rather than flooded to all connected peers. If no progress on a download is made, IPFS attempts to extend the session with repeated broadcasts and DHT searches.
- 3) Transmitting Data: A node requests a block with a WANT_BLOCK entry for the block's CID, which similarly can be canceled with a CANCEL entry. This request type is the backwards-compatible formalization of "I am looking for this block, send it to me if you have it", which has been present in all versions of BitSwap. If the peer has the block, it responds with BLOCK containing the data. There is no negative response, a timeout tracks absence of data. Figure 2 depicts a typical procedure for obtaining a data block with CID c using both request types (node p_1 resolves c via its peers p_2, p_3, p_4).

IV. MONITORING DATA REQUESTS

Decentralized data storage systems like IPFS are inherently hard to monitor. Signaling messages and data are exchanged directly between peers, without passing through centrallycontrolled infrastructure that could form a natural vantage point.

⁵https://github.com/ipfs/go-bitswap

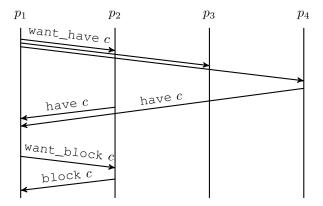


Figure 2: Obtaining a block with CID c via BitSwap.

In previous works, we demonstrated how, using crawling, the nodes and connections forming the IPFS DHT can nevertheless be made visible [2], [3]. In the following, we present a methodology for monitoring *data-related activity*—how many and which nodes request which data. Notably, this also enables the systematic investigation of stored content. In IPFS, providers only return data when asked for the correct CID, so in order to investigate stored content one must first learn about valid CIDs—which can be done by observing data requests.

This section introduces our methodology for collecting, processing, and interpreting *BitSwap* data requests in IPFS. In Sec. V we apply our methodology for conducting an exemplary measurement study that highlights the feasibility and potential of our approach. While the detailed designs and empirical results we present in this paper are focused on IPFS, our methods and conclusions are transferable to other decentralized data storage systems that share key design features, most prominently the reliance on data request broadcasts.

A. Data Collection

Data collection can conceptually be described as a twostep process, with each step leveraging different features of IPFS' design. Firstly, we *operate nodes with infinite connection* capacity. This is possible because, by design, anyone can deploy a node on the IPFS network and the number of connections a node can maintain is only limited by the IPFS software. Secondly, we collect all BitSwap messages from connected nodes. IPFS nodes send data requests to all nodes they are connected to (cf. Sec. III), and hence also to our monitoring nodes.

By collecting the BitSwap traffic of a peer, we learn which CIDs it requested, and at which times. Our monitoring nodes produce, using a modified version of the IPFS software, a list of (timestamp, node_ID, address, request_type, CID) tuples. No definite knowledge is gained about whether (1) the data d referenced by a CID c was downloaded successfully, and (2) what d is (including whether it is a file or a directory). The former can be determined by sending a request for c to the requesting peer after it has issued a CANCEL for c. The latter can be determined by downloading and indexing d.

In the presented approach, monitoring nodes are *passive*. They accept all incoming connections, but do not actively search for or connect to peers apart from usual node behavior (e.g., bootstrapping and DHT maintenance). They thereby remain indistinguishable from regular nodes in terms of connection *initiation* and generally do not send *BitSwap* requests or data. In order to collect messages from a larger portion of the IPFS network, multiple monitors with different node IDs can be used in conjunction.

Our collection methodology implies a number of limitations. While enabling low-cost and hard-to-detect monitoring, passive monitors will generally only detect requests for root hashes of a Merkle DAG, as requests further down in the Merkle DAG are scoped to that CID's session (cf. Sec. III-D). Since our monitoring nodes W do not hold any data, they are not added to any session and will therefore not receive any further requests. IPFS nodes furthermore cache downloaded data (cf. Sec. III-C). Subsequent request for the same data will be served from the local cache instead of being broadcast via BitSwap. We can therefore observe only the first requests of a node for a given data item, or requests made after its cache was purged.

B. Preprocessing

Each monitoring node produces a *trace* of *BitSwap* messages it received. If necessary, traces from multiple monitors can be unified into one global trace. If a node is connected to multiple monitors, we receive broadcast want_list entries multiple times. To filter out these duplicates, we consider want_list entries received by different monitors to be identical if their source node ID, request type, and target CID match and their timestamps differ by at most 5 s. The window size was chosen to account for most genuine duplicates, potentially delayed due to high latencies.

There are mechanisms in IPFS that cause nodes to rebroadcast want_list entries every $30\,\mathrm{s}$ if the referenced data has not been downloaded yet (cf. Sec. III-D2)⁶. These repeated broadcasts make up a significant portion of all requests (> $50\,\%$ according to our measurements), skewing the numbers for some analyses. We maintain another, larger, per-monitor window of $31\,\mathrm{s}$ to mark these duplicate messages. Note that, as nodes maintain independent re-broadcast timers for each connected peer, re-broadcast messages reach different monitors at shifted times. This can lead to a misclassification of some same-monitor re-broadcasts as inter-monitor duplicates.

While in theory a balance between the $5\,\mathrm{s}$ and $31\,\mathrm{s}$ windows must be found, in practice both are filtered out for the analyses presented here.

After data processing, we operate on a unified trace of (timestamp, node_ID, address, request_type, CID, flags) tuples, where the flags encode information about duplicate status and repeated broadcast detection⁷.

⁶These messages serve little purpose, as want_lists are persisted—they seem to have historical origins.

⁷The corresponding tools and documentation are maintained at https://github.com/mrd0ll4r/ipfs-tools

C. Estimating the Network's Size

The data we gather through our monitoring methodology can be used for estimating the total size N of the IPFS network. For example, using two monitors m1 and m2, and with the simplifying assumption that each monitoring node selects peer sets P_{m1} and P_{m2} uniformly and independently from the whole node population, we can estimate the size of the network as:

$$N_E = \frac{|P_{\text{m1}}| \cdot |P_{\text{m2}}|}{|P_{\text{m1}} \cap P_{\text{m2}}|},\tag{1}$$

where N_E is an estimation for N. This can be derived by considering the population of N nodes as black balls in an urn, $K:=|P_{\mathrm{ml}}|$ of which are turned red through connections through m1. Then, the connections of m2 can be seen as sampling $n:=|P_{\mathrm{m2}}|$ balls without replacement—yielding a hypergeometric distribution with $k:=|P_{\mathrm{m1}}\cap P_{\mathrm{m2}}|$ successes. A maximum likelihood estimate of N with the Stirling approximation ($\ln n! = n \ln n - n$) gives us $N_E = \frac{nK}{k} = \frac{|P_{\mathrm{m1}}| \cdot |P_{\mathrm{m2}}|}{|P_{\mathrm{m1}} \cap P_{\mathrm{m2}}|}$.

The general case of r monitors can be handled through modeling the system as a coupon collectors problem with group drawings, also referred to as committee occupancy problem [27]. In this setting, peers correspond to cards and are numbered $1, \ldots, N$. Assume each monitor has w connections, then a monitor is a group drawing of w cards/peers without replacement from the total set of peers—hence, there are no duplicates within a drawing but only between them. We furthermore assume these drawings to be independent from one another. Typically, the question modeled is "What is the probability that we have m distinct cards/peers after r draws of size w?". Let X be the number of distinct peers after r draws of size w, then this probability is given by [27]:

$$\mathbb{P}[X=m] = \binom{N}{w}^{-r} \binom{N}{m} \sum_{k=w}^{m} (-1)^{m-k} \binom{m}{k} \binom{k}{w}^{r}. \quad (2)$$

In our setting, we know m (the size of the union over all monitors' peer sets), and N is the quantity to be estimated. Hence, as for eq. (1), we can turn the probability density into a maximum likelihood estimation of N. Given m, r, w, we (numerically) solve the following equation for N:

$$N - N\sqrt[r]{1 - \frac{m}{N}} - w = 0. (3)$$

The accuracy of our estimation formulas is influenced by a number of factors. Most prominently, due to various aspects of IPFS' peer selection logic, peer sets might not represent a uniform and independent draw from the whole node population. The selection of peers is biased based on node IDs, with node IDs close (in XOR metric) to the node ID of m1 being more more likely to be connected to m1 than nodes further away (e.g., m2). Our measurements (presented in Sec. V-C) indicate that this is *not* an important factor in our setup: For longrunning nodes with a high number of peers the distribution of peers' node IDs is approximately uniform.

Our monitors' selection of peers might also be biased based on more nuanced node characteristics. Our monitors never evict peers and do not actively search for peers beyond IPFS' periodic DHT refresh. Consequently, we observe that the majority of our monitors' connections are inbound and that their peers are more likely to be client nodes and popular gateway nodes, i.e., nodes that acquire new peers more frequently. Therefore, stable, long-living nodes that seldom initiate data requests will be underrepresented in peer draws, which can lead to estimation errors.

In theory, our estimates can also be influenced by effects resulting from the combination of observations from multiple monitoring nodes. For example, a node already connected to m1 has one less slot for forming new connections and is therefore minimally less likely to be connected to m2 as well. As IPFS nodes establish anywhere between 600 and 900 connections on average, the effect of occupied capacities is limited. With respect to our r>2 estimator, it must be pointed out that w is not the same for all monitors, as they slightly differ in the number of connections. Due to the small difference, explicitly modeling a heterogeneous w would significantly increase the complexity of the model with questionable benefits. Based on our empirical observations, neither of these two factors seem to have a significant impact in practice.

It is noteworthy to remember that 1) the IPFS network consists of DHT servers and clients (see Sec. III-A), and that 2) it has an unusual topology (see [2]): Although it is, in principle, constructed on top of a Kademlia DHT, participating nodes hold *additional* connections not present in their k-buckets. These are, for example, connections that were opened during a DHT search or download. DHT clients are *not* present in k-buckets and cannot be enumerated using traditional DHT crawling. They do, however, appear as peers to our monitoring nodes due to these additional connections. As such, DHT crawls can observe the core of the network, and our monitoring nodes can observe the entire network, albeit as of now with some bias due to their passive peer selection. In Sec. V-C we apply our network size estimators in practice and compare the results with numbers obtained through DHT crawls.

D. Content Popularity

Collected traces of BitSwap requests can be used to deduce the relative popularity of CIDs, and hence the content they reference. Knowledge of this popularity distribution is, e.g., an important building block for the formal analysis of cache hit ratios (especially relevant for IPFS gateways) [28]. It furthermore allows for more realistic network simulations and user models. To this end, we define two different popularity scores, one for capturing IPFS' behavior "on the wire" and one for approximating user behavior. For the former, we define a CID's raw request popularity (RRP) as the total number of requests received for a particular CID over a given period. This number is of interest to simulation studies and for improving the performance of BitSwap. For approximating user behavior, we consider unique request popularity (URP), the number of distinct peers that requested a respective CID in the given time period. The motivation behind URP is that requests for a CID

coming from distinct peers indicate the corresponding data item's popularity among distinct users.

V. EXAMPLE MONITORING STUDY

We implemented our monitoring methodology and have been collecting data from the public IPFS network since March 2020. In the following, we describe our setup and present exemplary observations that it has allowed us to make, showcasing the feasibility and utility of our approach.

A. Monitoring Setup

Our setup consists of a small number of monitoring nodes W, which function as outlined in Sec. IV-A. They are deployed on publicly reachable servers, i.e., not behind a NAT. For this paper, $|W|=r=2^8$, with one node situated in Germany and one in the United States. The nodes were running a modified version of the IPFS client, which was kept up-to-date within a few weeks of every new stable release of IPFS.

B. Data Collection

We collected *BitSwap* traces continuously for fifteen months, yielding over 3.5 TB of compressed traces. We maintained only one monitoring node for the first two months of our observations. The remaining time was surveyed with two nodes. Since beginning the data collection, our monitors underwent minor configuration and version changes as well as some outages. We classify these as minor (>5 s) and major (>1 h)outages and count the number of days during which they occurred. The us monitor in the U.S. was running for a total of 450 days, 17 days out of which it experienced one or more major outages and an additional 15 days out of which it experienced one or more minor outages. The de monitor in Germany was running for a total of 385 days, 18 days out of which it experienced one or more major outages and an additional 5 days out of which it experienced one ore more minor outages. We observed more than 806 million unique CIDs over the entire fifteen months on one monitor.

The remainder of this section showcases analyses possible with our collected data, and with data collectible using our monitoring methodology in general. We present results for:

- Estimating the size of the IPFS network.
- Assessing the level and structure of data-related activity.
- Investigating the popularity of content stored on IPFS.

We leave further analyses on the "file system" layer of IPFS that are enabled through the learned CIDs, e.g., of the structure of IPFS' data graph, for future works.

While presenting analysis results, we will mostly focus on an excerpt of our collected data that corresponds to the week from April 30th to May 6th 2021. Focusing our discussion on a single week allows us to highlight more fine-granular results and perform more complex analyses.

 $^8 \mbox{While a higher } r$ might result in a larger portion of the network's requests being recorded, we found that the intersection over union of $\it BitSwap$ -active peers (whose messages we record) between our two nodes is, on average, >70%.

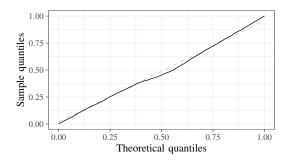


Figure 3: Quantile-quantile plot of the IDs of peers connected to the us monitor in comparison to a uniform distribution (straight dashed line).

C. Monitoring Coverage and Network Size

In the following, we take a closer look at traces collected in the week from April 30th to May 6th 2021. Over this period, our two monitors saw 78011 and 81423 unique peers in total, respectively, for a union of 99147 peers. The monitors were connected to an average number of, respectively, 7132.56 and 7798.82 peers, with the size of the union of unique peers being 9628.67 on average. Notably, averages and weekly totals differ significantly from each other, which is in line with previous observations about churn in the IPFS network [2]. Only a small portion of the nodes we monitored in the above period were actively engaging in the *BitSwap* protocol, sending at least one request or cancel. The two monitors saw, respectively, 6080 and 6247 unique *BitSwap*-active peers during the studied period, with a union of 7520 unique *BitSwap*-active peers.

These results allow us to estimate the network's size using the methods we propose in Sec. IV-C. We first investigate whether the assumption of uniform peer selection can reasonably be made. We exemplarily gathered all connected peers of the us monitor on the 4th of May⁹, totaling 8171 peers. The comparison of the distribution of these node IDs to a standard uniform distribution is depicted in Fig. 3 as a quantile-quantile plot, with the straight dashed line corresponding to the uniform distribution. It can be observed that the distribution of node IDs is surprisingly close to uniformity.

We then apply our network size estimation formulas from Sec. IV-C. Doing so yields an estimated average network size of 10561 (std. dev. 390) with eq. (1) and 10250 (std. dev. 395) with eq. (3) (setting w as the average of connections of both monitors). While deriving a ground truth for this estimate is inherently challenging [29], we can compare our results with alternative indicators for the IPFS network's size. Existing measurement infrastructure from previous works [2], [3] can be used to generate insights into the portion of the network reachable through crawls of the IPFS DHT¹⁰. Based on crawls of the IPFS network during the discussed period, a total of 52463 unique peers were found, with an average network size of 14411.42 peers per crawl. This hints at the fact that our method might in fact underestimate the current network size,

⁹Other points in time yield similar results.

¹⁰See also: https://trudi.weizenbaum-institut.de/ipfs_crawler.html.

as speculated in Sec. IV-C. However, measuring the size of the IPFS network based on DHT crawls has limitations on its own. For example, crawled IPFS nodes also propose DHT nodes to the crawler that are in fact offline [23]. Such nodes are still counted by the crawler, as even online nodes might be unreachable if they reside behind NAT or other restrictive middleboxes. On the other hand, our DHT crawler doesn't enumerate client-only nodes that are part of the IPFS network but not part of the DHT, which potentially explains why our monitors saw more unique node IDs over the discussed week than the aforementioned crawler (99147 vs. 52463). As hinted at in our discussion in Sec. IV-C, the crawler and our monitors seem to be biased towards different parts of the IPFS overlay, with monitors discovering more edge nodes (that naturally generate more data request traffic) and the DHT crawler a larger part of the core network. Research opportunities remain for deepening the investigation of both approaches, their biases and combination possibilities. Still, the available estimations already enable a ballpark assessment of the number of nodes in the IPFS network.

We can use the available network size estimates to gauge the *coverage* of our monitoring approach. We use the crawling-based estimation of the network's size in the following, being the larger of the two and therefore more likely to underestimate our coverage. At any given time, our monitoring nodes us and de were thereby connected to, and hence receiving BitSwap messages from, $54\,\%$ and $49\,\%$ of the network, respectively. The joint setup combining traces from both nodes had an average monitoring coverage of $67\,\%$. Notably, we achieved this coverage using only two passive monitoring nodes. The monitoring coverage can be further increased by adding more monitoring nodes or, complementary, by implementing a more active peer discovery mechanism.

D. Level and Structure of Data-Related Activity

Showcasing the potential of our methodology for monitoring the level and structure of data-related activity, Fig. 4 depicts the view of monitor us on the number of requested CIDs per day and entry type, for the period from mid-March to the end of August 2020. Requests are classified into the older WANT_BLOCK entry type and the WANT_HAVE type officially introduced in IPFS v0.5. Missing values indicate incomplete data due to outages. We observe a willingness of users to upgrade their clients. The large spike at the beginning of August was registered by both of our nodes, but we did not investigate further.

We also analyzed the collected CIDs for the Multicodec they reference. The Multicodec describes what type of data is referenced by a CID, as outlined in Sec. III-B. The results of our analysis over the entire fifteen months are presented in Table I. Over this duration, we collected a total of $2.78\cdot 10^{10}\,$ data requests from both monitors. We only count requested entries, not CANCELs, and derive the data from raw, unprocessed traces of the two monitors. We can see that, from the perspective of our monitoring infrastructure, IPFS is used mostly for file storage.

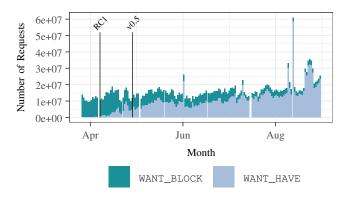


Figure 4: Number of data requests collected in 2020 by monitor us over time, classified into the WANT_BLOCK and newer WANT_HAVE request types. X-axis ticks mark the beginning of the indicated month.

Codec	Count	Share (%)
DagProtobuf	23983048867	86.21
Raw	3734468407	13.42
DagCBOR	101649452	0.37
GitRaw	616657	< 0.01
EthereumTx	163714	< 0.01
Others (8)	382982	< 0.01

Country	Share (%)
US	45.65
NL	13.85
DE	12.72
CA	7.61
FR	6.64
Others	< 13.60

Table I: Share of data requests by Multicodec. (March 2020–June 2021)

Table II: Share of data requests by country. (April 30th–May 6th 2021)

Our collected traces also allow insights into the geographic patterns of IPFS usage. We examined IP addresses from our unified, deduplicated dataset over the period between April 30th and May 06 2021. and resolved them via the MaxMind GeoIP2 database¹¹. Table II shows the share of observed *BitSwap* data requests per origin country. We see that nodes residing in the US account for almost half of the observed activity and the top three countries together for roughly 70 % of all observed activity during this period.

E. Content Popularity

Applying the popularity scores we defined in Sec. IV-D to the collected traces for the April 30th to May 6th 2021 period allows us to calculate the distribution of CID popularities. We compute both popularity metrics on the unified traces of both monitors, the resulting empirical CDFs (ECDF) are shown in Fig. 5. It can be seen that the majority of CIDs in both distributions have a low popularity score, e.g., over 80 % of CIDs were only requested by one peer, as depicted in Fig. 5b. Although the distributions differ, both seem highly skewed with few highly-requested CIDs and a majority of "unpopular" ones. In contrast to other works on item popularity reporting heavy-tailed, Zipf-like distributions [28], fitting a power-law distribution to our measured scores (Fig. 5) as laid out in [30] yields a p-value < 0.1, both for RRP and URP, regardless of the choice for a cut-off value x_{\min} . We therefore conclude that the power-law hypothesis has to be rejected, i.e., that the measured popularity data does likely not follow a power-law distribution.

It has to be noted that popular data items according to RRP are often not resolvable, i.e., the data block the CIDs

¹¹https://dev.maxmind.com/geoip/geoip2/geolite2/

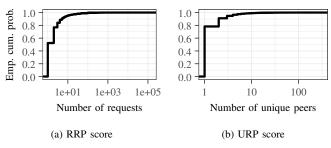


Figure 5: ECDFs of content popularities (from April 30th to May 6th 2021).

are pointing to cannot be found. This observation may stem from different factors. First, *BitSwap* periodically re-broadcasts requests for CIDs it cannot resolve (cf. Sec. IV-B). Furthermore, some peers issue an unexpectedly high number of requests for the same data item—hinting at configuration errors or non-standard usages of IPFS.

The ten most popular CIDs according to URP are resolvable. These most popular CIDs contain (1) various data related to the decentralized exchange Uniswap¹² (e.g., their logo and config files), (2) JSON files related to running Ethereum nodes through the dAppNode-project¹³ and (3) a HTML page stating "Unavailable for legal reasons".

VI. PRIVACY RISKS

The monitoring of data requests in IPFS provides useful insights for assessing the network's level of use, identifying key usage scenarios, and tuning performance. However, our monitoring techniques can also be used for tracking the behaviour of individual users, implying latent privacy risks. In the following, we flesh out these risks by proposing a series of specific attacks on the privacy of IPFS users. As a demonstration, we uncover the (normally hidden) node identifiers corresponding to public IPFS/HTTP gateways and successfully track requests initiated through these gateways. We also discuss countermeasures, highlighting that the identified attacks are in part enabled by core aspects of IPFS's design, and that remedying them is a hard challenge when other desirables from a decentralized data storage system are taken into account.

A. Privacy attacks on IPFS

We define three specific attack vectors that can enable adversaries to learn about the current and past data request behaviour of IPFS nodes: *Identifying Data Wanters* (IDW), *Tracking Node Wants* (TNW), and *Testing for Past Interests* (TPI). In the standard usage mode, IPFS users access and distribute data via IPFS nodes under their own control. Consequently, learning what data a node is or has been interested in allows for direct conclusions about the (likely private) preferences of its human

operator¹⁴. We discuss the alternative, (public) gateway-based usage mode of IPFS in Sec. VI-C.

- 1) Identifying Data Wanters (IDW): The goal of the IDW attack is to discover nodes that are interested in a given CID-identified data item. The setup of the attack is identical to our monitoring setup. In fact, our deployed monitoring infrastructure already collects the necessary information for listing node IDs that have requested a given CID. By deploying more monitoring nodes or using an active, crawling-like peer discovery approach, an adversary can increase the number of nodes to which he maintains a direct connection and from which he receives CID messages. Already with one monitoring node, however, we were able to monitor more than 45% of the public IPFS network (cf. Sec. V-C).
- 2) Tracking Node Wants (TNW): The TNW attack revolves around tracking which data items a given target node is interested in. With the current implementation of the IPFS node software, nodes broadcast CID requests to all of their connected peers (cf. Sec. III-D, [2]). It is therefore sufficient for the adversary to maintain a connection to the target node and collect the requests it broadcasts. From a practical standpoint, a more challenging aspect of the TNW attack is to firstly determine the node ID of the target This is also possible by again leveraging IPFS itself: the IDW attack can be used to discover nodes that are requesting some CID only the victim is likely to know or be interested in . In Sec. VI-B, we demonstrate the effectiveness of this approach on well-known public gateway nodes on the IPFS network.
- 3) Testing for Past Interests (TPI): In the TPI attack, the adversary seeks to confirm that a given node has recently accessed a given data item. The attack leverages the fact that IPFS nodes *cache* previously requested data items locally and serve them to interested parties (cf. Sec. III-C). This caching mechanism is a cornerstone to the scalability and censorshipresistance of IPFS. However, in its current form it also enables any adversary capable of joining the IPFS network to test whether a given target node has previously requested a given CID—by sending a request to the target node. The target node will answer if the sought data item is in its cache, and the data item will only be in the target node's cache if it was either requested or initially uploaded via the target node based on a user request. Like for the TNW attack, the TPI attack can be mounted with negligible resources on part of the adversary, given the node ID of the target is known.

B. Proof of Concept: Tracking Gateway Requests

IPFS offers a bridge to access the IPFS network and hosted content through HTTP. While every node offers this translation locally by default, there are also a number of *public gateways* available on the regular HTTP-based web, maintained by the developer community and a number of organizations. Public gateways are a convenient way to access IPFS and aim to boost adoption of IPFS, showcase examples, and enable access

¹²https://uniswap.org/.

¹³https://github.com/dappnode/DAppNode, a project devoted to simplifying the process of running full nodes in various P2P networks.

¹⁴Note that even if data items have been encrypted before being placed on IPFS, metadata such as request behaviours and approximate data sizes can still be learned by an adversary.

to the network in situations when running nodes locally is infeasible. Public gateways also allow us to test privacy attacks in a realistic setting without threatening individual users. In the following, we outline a methodology that combines the IDW attack with a tailored probing step for linking well-known public gateway nodes (identified by their DNS names) to IPFS nodes (with node IDs and sometimes different IP addresses than the associated HTTP endpoints). We apply the TNW attack on the identified nodes and briefly discuss the results of this investigation, which might be of independent interest. The success of the presented experiment underlines the viability of the proposed attacks and the latent privacy risks they imply for IPFS users.

- 1) Gateway Probing Methodology: We build upon our monitoring methodology (Sec. IV), extending it by a probing step. We generate a unique block of random data, yielding a unique CID c^{15} . We then launch a IDW attack on c, adding our monitoring nodes W as providers for c to the IPFS DHT. Subsequently, we ourselves request c through the HTTP-facing side of a public gateway and wait for BitSwap messages to arrive. The received BitSwap request for c enables us to uniquely identify the IPFS side of the probed gateway. Since c refers to a block of randomly generated data, it is unlikely that any other user on the network would request c, yielding a large confidence in the measured results.
- 2) Gateway Probing Results: We applied our gateway probing method to a list of public gateways curated by the IPFS project¹⁶. We repeated the measurements two times, on May 31st and June 8th 2020 from two distinct hosts situated in Germany and the U.S., respectively. From August 2021 we began searching for gateways regularly from the German monitor. For each search and gateway we used a different random seed so that c is unique in each trial. The number of functioning gateways varies over time, as does the list of public gateways. However, our results with regard to gateway functionality were always in line with the public list¹⁶. Using our probing method, we were able to discover node IDs for all functional public gateways, receiving relevant BitSwap messages from them at least once. We also discovered node IDs for some of the non-functional gateways, i.e., our HTTP requests to them did not succeed but we still received relevant BitSwap messages. We suspect a misconfiguration on the HTTP end of those gateways.

After collecting data through our probing step, we cross-referenced the discovered IPs and overlay IDs with recent peer lists from our monitoring nodes W, focusing on discovering nodes that share IP addresses and node IDs associated with multiple IP addresses. The repeated probing and cross-referencing uncovered that several public gateways in above list were in fact associated with not just one but multiple nodes on the IPFS network. We contacted the operators of one prominent gateway with 13 associated IPFS nodes, who confirmed that we correctly identified all of their nodes. In total, we discovered 93

node IDs corresponding to well-known public gateways. This number is growing over time as operators add new gateways to the public list, or regenerate their node IDs. Because we perform gateway probing regularly based on the public list, we are able to track both changes to the list as well as changes to the individual gateways.

3) Public Gateway Requests: After successfully discovering the IPFS nodes associated with well-known public gateways, we can launch a TNW attack on these gateways. In the following, we discuss results collected from April 30th to May 6th 2021. Figure 6 depicts the number of BitSwap requests per second that our two monitors received during this period. We unified and deduplicated the traces from the two monitors as per Sec. IV-B. We plot both gateway and non-gateway ("homegrown") request rates, illustrating that we can successfully track the requests sent by a target node population. We find that a significant portion of gateway traffic is due to a single public gateway operator—Cloudflare—and mark Cloudflare traffic explicitly in our results.

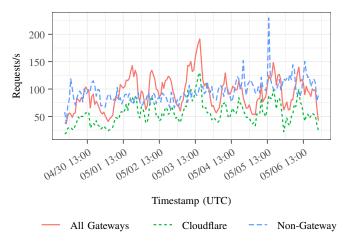


Figure 6: Deduplicated *BitSwap* request rate by origin group. The rate is calculated over one-hour slices of the unified, deduplicated trace (cf.Sec. IV-B).

As can be seen, we in fact received a similar number of requests from both non-gateway nodes and gateway nodes. This observation indicates that gateway usage is a significant part of total IPFS usage. Furthermore, public gateways cache requested data at least as aggressively as regular nodes—if data requested via HTTP is already cached, no BitSwap request is generated and we thus cannot learn of this request. Cloudflare states that their IPFS gateway has a cache hit ratio of 97%, i.e., only 3% of requests are forwarded immediately as BitSwap requests to the network However, content is re-validated when its time-to-live expires which will potentially trigger a BitSwap request for the respective content. This implies that our monitors are able to observe even cached CIDs but are unable to infer their inter-request-time distribution.

¹⁵Obtaining a CID duplicate is improbable due to the fact that CIDs are based on cryptographic hashes of the data (s.a. Sec. III).

¹⁶https://ipfs.github.io/public-gateway-checker/

¹⁷In a keynote at the DI2F workshop at IFIP Networking 2021.

¹⁸Back-of-the-envelope calculations based on the discussed data suggest that Cloudflare's gateways might be processing more than an order of magnitude more requests per second than the entirety of all monitored non-gateway nodes.

C. Privacy enhancement for decentralized data storage systems

The feasibility and relevance of the IDW, TNW, and TPI attacks are due to a number of inherent characteristics of IPFS:

- Long-lasting node identifiers—as connections must be maintained, nodes retain their node ID and IP address(es) for extended periods of time.
- 2) No connection limits—there are no mechanisms in place that can reliably prevent a small set of (adversary or monitoring) nodes from maintaining connections with nearly all nodes in the network, or a single adversary node from connecting to specific victim nodes.
- CID request broadcasts—as part of the BitSwap protocol, nodes broadcast data requests to all nodes they are connected to.
- 4) Plaintext CIDs—all recipients of data request learn the CIDs of requested data, not just nodes that can actually provide the data.
- 5) Cooperative caching—nodes cache downloaded data and cooperatively serve it to other interested nodes.
- 6) Single-user nodes with no cover traffic—users accessing the IPFS network via a locally installed IPFS client are represented in the network as a node that relays only their own and actual requests.

The weakening of these attack enablers poses a significant challenge for designers of decentralized data storage systems. Naive countermeasures can easily result in a significant deterioration of performance, censorship-resistance, or peer-to-peer scalability. For example:

- 1) Node identifiers can be cycled more frequently and an additional anonymization layer for IP addresses can be used. The effective cycling of node identifiers (i.e., existing connections need to be torn down) essentially increases churn. Using an established IP address anonymization service like Tor [31] limits the performance of the data storage system to that of the anonymization service. It is an open question how to best integrate IP address anonymization functionality into IPFS itself and what the performance impact of such a change would be. Parallels can be drawn to the design of privacy-centric systems such as Freenet [32], [33].
- 2) Systems like IPFS thrive on their openness, on allowing anyone to join the network and provide a node. Attempts to limit the amounts of connections a single node can maintain are difficult to design and limited in effect as adversaries can easily split their connections between multiple Sybil [34] nodes. Introducing per-connection costs, e.g., by requiring continuous Hashcash-like [35] proofs of work from peers, will likely also result in a decreased population of honest nodes while being of uncertain effect against determined adversaries with access to cloud computing resources.
- 3) Nodes could request data items only from nodes found via DHT queries, rather than from their whole overlay neighborhood. However, this would reduce IPFS's robustness against censorship attacks [23] while being of limited

- effect as (Sybil) adversaries can also place themselves at key locations in the DHT. On the opposite end, extending *BitSwap* to support multi-hop requests or even flooding might not be sufficient to confuse dedicated adversaries either, as the identification of messages' sources is provably feasible even in decentralized flooding-based networks [12].
- The BitSwap protocol could be extended so that data requests contain only salted cryptographic hashes of CIDs together with the used salt value. Recipients of data requests would then need to calculate a salted hash for each CID they store in order to determine if they are a provider for the sought data. This approach would prevent adversaries from linking requests for data for which they do not know the CID. However, it would also induce additional computational overhead at providers and open up an effective amplification angle for denial-of-service attacks¹⁹. The described solution furthermore protects only the *BitSwap*-part of content retrieval in IPFS (recall Fig. 1): plaintext CIDs would still need to be included in DHT queries in order for DHT routing to work correctly. Lastly, publicly-known CIDs, for example CIDs inferable from ipfs:// URLs found on the Web, can still be tracked by adversaries even if CID hashing is used.
- 5) Users can manually remove problematic items from their node's cache or configure their node to not reprovide downloaded items. While both measures are helpful against TPI attacks, they require manual user action and have no effect on IDW and TNW attacks. Disabling the reprovision of downloaded items would furthermore deteriorate censorship resistance of the network.
- 6) Adding realistic cover traffic to add plausible deniability to one's genuine data requests is hard—in order for fake data requests to be effective they must be directed at actually existing CIDs and follow realistic popularity distributions. Lists of existing CIDs and their popularity distribution might be obtainable for monitoring operators (cf. Sec. V-E), but is not usually the case for regular users.

Users could also use IPFS via a public gateway (cf. Sec. VI-B). While this measure is both highly effective in terms of privacy-protection and already in active use by a large part of the IPFS user base (cf. Sec. VI-B3) it arguably weakens the benefits of IPFS as a *decentralized* data storage system. Namely, by accessing content on IPFS without participating in the IPFS network, users do not contribute to the network's scalability and censorship resistance.

Turning the gateway strategy on its head, regular IPFS users could also *provide* gateway services, thereby both strengthening the IPFS network and adding natural cover traffic to requests they themselves send via their node. For increasing the use of smaller gateway services, changes to the IPFS software are necessary so that the selection of a gateway is handled

¹⁹The processing of data requests at providers would, without additional measures, induce a significantly higher workload at providers than at the nodes sending the requests.

automatically. The solution can be expanded towards a form of onion routing [31], with data requests being routed through several gateways and only the last gateway in the chain performing an actual DHT- and BitSwap-based search, or other deniability-increasing approaches like AP3 [36].

We leave the in-depth investigation of this and other potentially promising privacy-hardening approaches for future works. On a side note, providing gateway services to other (anonymous) users leads to some legal uncertainties. Gateway nodes can be led into caching data the mere possession of which might be considered a criminal act. Depending on jurisdiction, providers of hosting services are often exempt from direct liability as long as they quickly remove problematic data upon obtaining knowledge or awareness of its existence (see for example [37, Art. 14]) and it is plausible that such safe harbor rulings would extend to small-scale IPFS gateways.

VII. CONCLUSION

We presented a novel monitoring methodology for observing data-related activity in IPFS, a highly popular decentralized data storage system. Leveraging inherent features of IPFS' design, we are able to maintain connections with large portions of the node population at low cost, and receive indicators for all CIDs that connected-to nodes request and look for. We tested our methodology in a fifteen month measurement study and discuss exemplary results about the IPFS network. For a studied 7-day period, roughly 70 % of activity can be attributed to just three countries and the popularity of content items does not follow a power-law distribution. Despite its potential for generating informative insights about the IPFS network, the effectiveness of our monitoring approach also paints a troubling picture with regard to user privacy. We describe how our methodology can be extended for realizing privacy attacks that ultimately enable low-resource adversaries to surveil the current and past data requesting behavior of node-operating users. While we demonstrate the practical viability of our attacks, we also map directions for hardening IPFS and similar systems without significantly impacting other core features.

Last but not least, the collected data opens up avenues for further research, e. g., in-depth investigations into the filesystem layer of IPFS and the content stored on the network.

VIII. ACKNOWLEDGMENTS

This work was funded in part by grant PL-RGP1-2021-054.

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