

Towards Decentralised Cloud Storage with IPFS: Opportunities, Challenges, and Future Directions

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ABSTRACT

Recent data ownership initiatives such as GAIA-X attempt to shift from currently common centralised cloud storage solutions to decentralised alternatives, which gives users more control over their data. The InterPlanetary File System (IPFS) is a storage architecture which attempts to provide decentralised cloud storage by building on founding principles of P2P networking and content addressing. It combines approaches from previous research, such as Kademlia-based Distributed Hash Tables (DHTs), git's versioning model with cryptographic hashing, Merkle Trees, and content-based addressing in order to compose a protocol stack that supports both forward and backward compatibility of components. IPFS is used by more than 250k peers per month and serves tens of millions of requests per day, which makes it an interesting large-scale operational network to study. In this editorial, we provide an overview of the IPFS design and its core features, along with the opportunities that it opens as well as the challenges that it faces because of its properties. IPFS provides persistence of names, censorship circumvention, built-in file deduplication with integrity verification, and file delivery to external users via an HTTP gateway, among other properties.

1 INTRODUCTION

The General Data Protection Regulation (GDPR) of the European Union (EU) gives natural persons greater control over the storage and use of their personal information (including data related to their conduct) and requires technology services to adopt user privacy as a design principle. The prevailing baseline internet infrastructure, based on centralised cloud storage and management, lends itself to an examination of whether decentralised cloud services may provide a basic infrastructure that ultimately allows users more control over their personal data. These same goals are at the heart of emerging data protection standards in the US as well, such as the California Consumer Privacy Act (CCPA). The use of decentralised networks to achieve the aims of emerging privacy regulations is already being examined by initiatives such as GAIA-X [16]. However, the decentralised architecture of such networks may also add new challenges and types of complexity. In this editorial, we discuss these issues – both the benefits and challenges – in relation to InterPlanetary File System (IPFS), a protocol for decentralised cloud storage.

IPFS is an open-source set of protocols that combines multiple existing concepts from peer-to-peer (P2P) networking to allow participants to exchange pieces of files, similar to BitTorrent. To

simplify the retrieval of files, content on IPFS is uniquely named and addressed using the so called *multihash*, a self-describable datatype that adopts concepts from git's versioning model, cryptographic hashing, and Merkle Trees. In the resulting naming scheme, content is identified and accessed using names, rather than through location-based identifiers such as Uniform Resource Locators (URLs), as is also the case with several Information-Centric Networking (ICN) architectures [57]. In practice, IPFS integrates important components from several projects to achieve content distribution and availability in a decentralised manner. For instance, during the Catalan independence movement, replication of websites relating to the independence referendum were still available through the IPFS protocol, even after the Spanish government censored related pages [25]. Similarly, snapshots of Wikipedia were hosted on IPFS to give Turkish users access despite Wikipedia itself being blocked in Turkey [53].

Deployment figures as of 2020. The IPFS network has been gaining constant momentum over the last years, with the `ipfs.io` public gateway seeing 2M unique users and serving more than 100TBs of data in more than 100M requests per week as of 2020. IPFS gateways act as web-servers for users outside the IPFS network (i.e., users that do not participate as peers themselves) and carry out requests on behalf of those users. Thus, they provide access to content stored in IPFS over HTTP, without users having to install any extra software.

In September 2018, Cloudflare initially started hosting IPFS gateways in more than 150 of their data centers [9] (later increasing to more than 200), which are still operational and serve the IPFS network to date.

Mozilla Firefox added the `ipfs://` scheme to the list of whitelisted protocols in March 2018 [11] to support protocol handlers for browser extensions. As of January 2021, the Brave browser added native support for IPFS [5], making it possible to access `ipfs://` links directly from the browser window, similar to the native IPFS support in Opera browsers [42] since March 2020.

Regarding the clients connected to the IPFS network, Table 1 shows the numbers of nodes for the top 10 countries and Autonomous Systems (ASes), listing unique nodes that have been observed in the network over last 30 days. The numbers refer to the number of distinct nodes which are seen in the Distributed Hash Table (DHT) (see § 2), i.e., the number of publicly reachable nodes in the public IP address space, with 6.2k nodes in total as of November 25, 2020 [22]. Measurement studies [18] report similar numbers of roughly 6k publicly reachable nodes on average. Note

Table 1: Distribution of all 6,243 publicly reachable IPFS nodes seen in DHT over the last 30 days (November 25, 2020), by top 10 countries (left) and autonomous systems (right).

Country	# Nodes	Autonomous System	# Nodes
China	2,718 (43.5%)	Shenzhen Tencent Computer Systems Company Limited	1,101 (17.6%)
United States	1,393 (22.3%)	Chinanet	826 (13.2%)
Germany	486 (7.8%)	AMAZON-02	543 (8.7%)
France	274 (4.4%)	Guangdong Mobile Communication Co.Ltd.	354 (5.7%)
Netherlands	138 (2.2%)	DIGITALOCEAN-ASN	314 (5.0%)
Canada	130 (2.1%)	CHINA UNICOM China169 Backbone	232 (3.7%)
United Kingdom	126 (2.0%)	OVH SAS	203 (3.3%)
Singapore	82 (1.3%)	Hetzner Online GmbH	152 (2.4%)
Russia	80 (1.3%)	AMAZON-AES	116 (1.9%)
Japan	75 (1.2%)	COMCAST-7922	107 (1.7%)

that Table 1 does not include the number of peers that run IPFS behind a NAT, which is estimated to be above 200k nodes per month. As presented in Table 1, most IPFS nodes operate in Asia, North America, and Europe; around 1% of the 6.2k nodes are deployed in South America, whereas only 0.1% are located in Africa. With more than 200k nodes per month and more than 100M requests per week towards all gateways (with gateways also not being accounted for in the table), the IPFS network is one of the largest permissionless and decentralised P2P storage and delivery networks in operation.

Previous work (§ 4) primarily studied IPFS as a storage mechanism for specific use cases, such as IoT and edge computing [2, 12, 26], malware [6, 43], or blockchain technology [39, 59]. In particular, IPFS already plays a significant role in paving the way for decentralised applications as the reference storage solution for hundreds of projects. However, the socio-technical impact of decentralised architectures such as IPFS have not been extensively studied yet. Towards this end, we first provide an overview of the design and building blocks of IPFS (§ 2) in this editorial. We discuss its properties with associated socio-technical opportunities and challenges (§ 3), before highlighting open questions that warranty further research (§ 5).

Note that the goal of this study is *not* to exhaustively list all applications and use cases of IPFS. Instead, the goal is to describe and discuss its technical aspects along with its opportunities and challenges in order to distill lessons learned and open research questions for future studies. We further do not focus on legal or economic aspects of IPFS; while we do discuss legal issues, we do so in the context of its technical properties.

2 BUILDING BLOCKS AND PRINCIPLES

The design of IPFS, originally described in its whitepaper from 2014 [4], is inspired by various concepts from previous work in networking and file management. It combines a set of protocols to build a distributed file system on top of a P2P network. For instance, IPFS applies concepts of ICN, using uniquely identifiable fingerprints to address and retrieve files over the P2P network rather than location-based references such as URLs or IP addresses. However, in contrast to ICN approaches, which primarily use content-centric addressing at the network layer, the fingerprint-based addressing in IPFS happens at the application layer to ease deployment and guarantee backward compatibility. The content-centric addressing leverages *Multiformats*, a set of protocols which can generate *multihashes* to act as *content identifiers* (CIDs), and allows nodes to

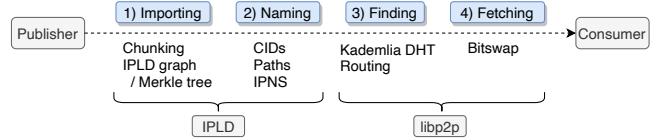


Figure 1: Outline of content publication (importing and naming) and retrieval process (finding and fetching), along with the involved IPLD and libp2p protocol stacks.

download different parts of a file from multiple peers in the network instead of a single centralised server, akin to *BitTorrent*. As content is not only addressed but also linked via unique hashes, IPFS supports file versioning through Merkle Trees similar to *Git* as well.

Moreover, IPFS implements its protocols in a stack, which means its components can be extended or replaced when required. This modularity in the design of the protocol stack is supported by a P2P networking library called *libp2p* [29], which is used as part of the IPFS protocol stack. *libp2p* is a modular, P2P networking library for *process addressing*, supporting implementations for several network and transport-layer protocols. *libp2p* also integrates protocols for content and peer routing through a DHT, a pubsub protocol, and a content exchange protocol called *Bitswap*.

The modularity and flexibility provided by *libp2p*, together with its backward-compatibility as well as future-proofing of the distributed file system it builds, are promising features that can help in decentralising Internet services such as cloud storage. IPFS also facilitates decentralisation due to its platform-independent and institution-agnostic content addressing, which avoids dependencies on (single) third parties.

2.1 Overview: Join, Find, and Transfer

Fig. 1 outlines the process of publishing and retrieving content with the involved components: A publishing peer adds a file to IPFS by first importing it into an *InterPlanetary Linked Data (IPLD)* graph (similar to a Merkle hash tree) and determining its unique name in form of a content address. In turn, this allows a consumer to find and fetch that file via this name. More details on the specific steps during the process are discussed in the following subsections.

The IPFS network is permissionless (similar to BitTorrent), which means that peers can freely join the P2P network to start sharing files by running an IPFS node, which is identified by a public/private-key pair. One of the main content routing systems used by IPFS (although not the only one) is *libp2p*'s DHT. New peers connect to bootstrap nodes to get initial connections for their routing tables. The list of bootstrap nodes is pre-defined, although it can be arbitrarily modified when required [21]. The DHT is inspired by Kademlia [34] as well as Coral DHT [15]. It allows peers to lookup the unique hash identifier of an object (§ 2.2), a so called *Content Identifier (CID)*, in order to retrieve a list of peer IDs that hold replicas of the object. These lookups provide information about ways to connect to the peers, for instance their IPv4 or IPv6 addresses along with the transport protocol and port number. This information is included in *libp2p*'s *multiaddresses* [30], which express connectivity primitives for peers to connect to other peers.

Any object added to the IPFS network is converted to an IPLD graph (essentially a Merkle tree, see § 2.2 for details), which means that the object is chunked into smaller pieces (each chunk with its own CID) on which a hash tree is built, in addition to a root CID for the whole graph; the CID of any node in the graph can then be announced as part of *want lists*. Object requests are then sent to the different peers which store the chunks to initiate file exchange using IPFS' exchange protocol called *Bitswap*. Once the transfer is complete, the integrity of the pieces and the whole file can be verified using the content's hash fingerprints by reconstructing the IPLD graph. From that point on, the requesting node caches the retrieved file and becomes a temporary provider for that file (§ 2.4). Unlike BitTorrent, IPFS does not adopt the concept of trackers, as content is globally named and addressed using linked cryptographic hashes instead.

2.2 File Processing and Naming

Any data item added to the network is chunked into blocks of 256 kB (default block size). Each block is named and addressed individually by a unique IPFS CID. These blocks are arranged as leaf nodes in a Directed Acyclic Graph (DAG) to build an IPLD graph: The root of this hash-linked graph is the unique IPFS CID for the specific input file, which allows peers to easily verify the integrity of a file through the hash-chained DAG (cf. Merkle tree). As each block is uniquely identified, IPFS provides random access to files, i.e., blocks can be addressed and exchanged independent of the file as a whole. Further, a hash can refer not only to a chunk or file but also to more complex structures such as subgraphs or other graphs for instance, with each vertex being individually addressable.

The identifier of each block is a self-describing *multihash*. In addition to only containing the actual hash digest of the input, it further denotes the type of hash function that was used, together with digest length, by prepending both to the digest value. The whole construct is then encoded in `base58` to avoid similar looking characters and to obtain alpha-numeric characters exclusively for unambiguous identifiers. Due to `SHA-256` being the standard hash function (assigned to hash type `0x12`) and digest length being 32 bytes (i.e. `0x20`), IPFS fingerprints commonly start with `Qm...` when encoded in `base58`. Files that are hashed with other hash functions can be easily identified and processed accordingly.

After processing the file in this manner, a node announces the local storage of each block to the DHT in order to allow other peers to retrieve the content. In particular, peers that store some content in the IPFS network produce *provider records*, which they publish on the content routing system (the DHT in this case). Provider records bind the content address to a location address (cf. DNS) and are placed at nodes whose `peerID` is close to the published object's CID in XOR space, as instructed by Kademlia. Due to blocks being identified by their multi-hashes, even smallest modifications will lead to substantially different digest values to allow for file integrity verification. That said, mutable content is not supported by the hash-based representation of content in IPFS.

2.3 Pathnames and IPNS

IPFS adopts a pathname scheme with a global namespace similar to the Self-certifying File System (SFS) [35]. Once the objects are

named, they can be navigated using regular path syntax as commonly employed in file systems or Web URLs. Towards this end, `/ipfs/` is added as a prefix to the object multi-hash to denote that IPFS is used. Following the fingerprint, regular path syntax can be added, such as `/ipfs/<multi-hash>/foo/bar.baz` for instance.

To avoid having to replace links in cases of file modification and keep the name of content consistent, IPFS supports a naming system called *InterPlanetary Name System (IPNS)*. The IPNS fingerprint is derived from a node's public key, which means that each node can only create a single IPNS identifier. While the identifier itself is static to allow sharing, the CID it refers to can be modified arbitrarily by the publishing node, which enables "mutability" for the IPFS object behind the static IPNS identifier. These IPNS identifiers use the `/ipns/` prefix instead of the `/ipfs/` prefix in their pathname to distinguish themselves (see § 2.3). Alternatively, if clients have access to DNS records and can modify them, it is also possible to store the IPFS or IPNS identifier in a DNS TXT record and update it whenever required: A user can publish a DNS TXT record for their domain, e.g. `domain.name`, containing `dnslink=/ip[f|n]s/<multi-hash>` to link the domain to a specific IPFS or IPNS identifier. When accessing a file using `/ipns/domain.name`, IPNS resolves the respective `domain.name` suffix using DNS and replaces it with the stored fingerprint to access the content.

2.4 Content Storage and Caching

When adding content to the IPFS network as a node, the content is only made available to other peers but *not replicated*. By default, content is only replicated when it is explicitly requested and retrieved by another peer, who then caches it locally, with the caching behavior and duration being configurable. As such, IPFS does not force peers to cache arbitrary content (which they are not interested in themselves for instance) on behalf of other peers. In other words, peers cache content that they have requested, following a strict pull model. Among other reasons, this is done to avoid legal implications for the hosting node.

Cached content is periodically removed locally by the automatic garbage collection. In order to become a "permanent" provider of some content item, IPFS includes a mechanism called *pinning*, which allows nodes to mark files as permanent in local storage, i.e., not have them removed by garbage collection. This means that unpopular content, unless explicitly pinned, will eventually disappear from the network. Popular content, on the other hand, will be constantly re-cached by peers and will therefore be disseminated through the network, which additionally improves availability. Due to garbage collection and churn of nodes, IPFS therefore only provides best-effort storage without any guarantees for availability.

2.5 IPFS Public Gateways

In traditional P2P networks, users that are interested in retrieving information from the network or using its offered services are required to join and participate in the network. In many cases, this may not be a feasible option, as devices may be resource-constrained, for instance. Thus, peers in IPFS have the option to act as a gateway for external users who can access the IPFS content using HTTP(S) instead. It is worth noting that any user in

the IPFS network can run a public IPFS gateway, as long as they have a publicly reachable IP address. IPFS gateways serve as a web-server for clients and as a DHT server for the IPFS network, making access to content seamless. An example for one of these gateways is `ipfs.io`, which can be given either an IPFS or an IPNS multi-hash to request the content. A regular user would then navigate to `https://ipfs.io/ip[f|n]s/<multi-hash>` with their browser to request the object with the respective multi-hash from the `ipfs.io` gateway. If not already cached, the gateway retrieves the content from peers in the IPFS network. After retrieving all chunks from the network, the gateway then serves the file to the requesting user HTTP(S).

Note that gateways are not essential building blocks by design: they are intended to support the network by providing another way of retrieving files from IPFS, in particular to assist clients which are behind NATs, resource-constrained, or cannot participate as a peer. However, gateways can also lead to centralisation and dependencies (cf. supernodes [32] in traditional P2P networks), along with free-rider problems (see § 3.4).

3 PROPERTIES OF IPFS

The usage of IPFS for file storage in existing solutions can bring a multitude of benefits, such as built-in integrity checks or content-based addressing, which decouples file retrieval from specific locations. At the same time it presents special characteristics owing to its decentralised and permissionless nature that need to be considered when integrating IPFS into a project or application for decentralised storage. In particular, this is due to the IPFS being an application-layer *protocol* (communication between peers by building on top of IPLD and libp2p; see § 2), which simultaneously also manages file storage and, thus, acts as a P2P file sharing *application*. As such, developers using IPFS need to carefully take its inherent properties into account and accommodate them within the remit of their application.

3.1 Persistence of Names and File Integrity

Identifying content by a unique multi-hash rather than a location address gives more flexibility to the network in different ways: resources can be used more efficiently since duplicate files, and even duplicate blocks of files, are assigned the same identifier and can therefore be handled, linked, and re-used appropriately to not waste additional resources. In traditional host-based addressing, duplicate files usually end up being stored redundantly due to having different file names and different location-based identifiers, for instance. Explicit content-based addressing also facilitates on-path and in-network caching, as the integrity of blocks of files can be verified using the multi-hash. Hence, there is no need to trust third parties to point to, or deliver the correct file pieces, which circumvents potential centralisation by removing dependency on a single content provider.

One property of the persistence of content-based names in IPFS is that content identifiers change when the content itself is updated, e.g., in case of dynamic content. This is in contrast to the current HTTP-based model, where the URL remains when the body of the content it represents changes. Persistence of content names is a desirable property in the design of IPFS as a protocol, which creates

the need for additional mechanisms to deal with dynamic content. The InterPlanetary Naming System IPNS (see § 2.3) or libp2p’s pubsub protocols, which allow peers to create pubsub channels between each other to dynamically broadcast and listen to events have to be used in order to update content published on IPFS.

There are a few examples of applications on top of IPFS that support dynamic and mutable data: For instance, *Textile* provides a set of developer tools and focuses on data ownership, allowing applications to make use of the data the users “bring with them”, e.g., through so called Buckets, which resemble dynamic personalised cloud storage services based on IPFS and libp2p. Another similar SDK is *Fission*, which facilitates the publication of frontend apps via built-in backend solutions that handle (user) data management over IPFS. *QRI* builds an overlay P2P network on top of IPFS and allows its users to share datasets among each other and track changes through version control features, essentially providing a dynamic, distributed database. Another example for a serverless, decentralised database is *OrbitDB*, which provides eventual consistency through conflict-free replicated data types (CRDTs). Similarly, *Ceramic* uses smart documents which leverage IPFS and other decentralised approaches, such as Decentralised Identifiers (DIDs) and blockchains, to store mutable content (referred to by unique and immutable identifiers) in a censorship-resistant network.

3.2 Censorship Resistance, Privacy and Data Auditability

One area where IPFS embodies “privacy by design” principles more closely than HTTP is in allowing more precise and comprehensive auditability of stored data. For example, in the context of attempting to delete a subject’s personal data after consent has been revoked, a difficulty faced in using HTTP is determining whether all copies of a given piece of data had been deleted from an entity’s servers. Under IPFS, the persistent nature of content identifiers allows users to know with much greater certainty and thoroughness where various files that include associated personal data are stored. Thanks to how merkle-linking works, one can verify whether an asset is stored in some location by scanning for the asset’s content fingerprint. While those content fingerprints themselves are immutable, the actual data can be deleted when needed, such as to comply with a data subject’s deletion request. This combination – mutability of data with immutability of certain metadata – has the potential to provide a more usable basis for applications built on IPFS to comply with both the specific provisions, and the broader aims, of GDPR.

At the same time, content cannot be explicitly censored in IPFS, given it operates as a distributed P2P file system with no central indexing entity. Since peers are not organised in a hierarchy, there is no authority node in the network that can prohibit the storage and propagation of a file, or delete a file from other peers’ storage. Consequently, censorship of unwanted content cannot be technically enforced, which represents an opportunity for users that are suppressed in their freedom of speech, for instance. Note that censorship of unwanted content within the borders of an oppressive state, for instance, is different to a globally applicable legal request to remove content. IPFS was previously used to circumvent censorship during the Catalonian independence movement [25] or for the replication of Wikipedia when Turkish authorities prohibited

access to the site [53]. The censorship resistance that IPFS offers is achieved by replicating content among different peers that have requested it, which makes it difficult to censor the provider nodes altogether. Moreover, any public IPFS gateway can also retrieve and deliver the specific content to users, adding further censorship resistance, especially when hosted by larger Content Delivery Network (CDN) providers such as Cloudflare; users can simply use another gateway in case one gateway is being taken down. More sophisticated censorship approaches also take more advanced information patterns, such as traffic fingerprinting, into account, which has not been extensively studied for IPFS yet. Nevertheless, due to the modularity of IPFS in terms of supported/used protocols and possibility to provide content from a large number of peers, selective censorship is made more difficult over IPFS.

On the other hand, a lookup of a fingerprint to find out which peer stores the file in question can also reveal their IP address, meaning that those peers can still be identified. There are two important points to stress here:

- (1) As any permissionless, public P2P network, IPFS is a globally distributed, public server for the data published in the network. That said, IPFS's primary current use-case is providing storage and access to public data, e.g., datasets, websites. Given the modularity and wide range of applications that IPFS envisions to be able to support, it would be limiting to integrate a specific privacy design at the protocol layer. Instead, the design of IPFS allows for multiple approaches to be applied on top. Modular approaches to enhance privacy and at the same time support a wide range of applications remains an open research problem at the time of writing.
- (2) IPFS peers can control what they share with others in the network. A peer by default announces to the network every CID in its cache, that is, content that they have either published, or have requested and fetched previously. A peer that prefers to keep their request history private can always refrain from re-providing content that they have requested. The peers can still fetch and consume content, as well as keep it in their local cache for later consumption, but they do not serve the content when asked (e.g., through Bitswap) and neither do they let the network (e.g., the DHT) know that they have the particular piece of content locally. Local node configuration¹ allows each peer to control what they share with the network.

3.3 Access Control

The JSON Object Signing and Encryption (JOSE) format is an IETF standard [33], which can be used as an IPLD codec (`dag-jose`) to put authenticated and encrypted data in IPFS [7]. The `dag-jose` IPLD codec allows for creating data structures that are linked and signed, which provides a form of access control in IPFS.

Furthermore, libp2p allows for the creation of private networks.² If none of the above methods is used, then access control would require parties to exchange shared secrets out-of-band to encrypt their files before publishing them to the file system. However, an

¹<https://github.com/ipfs/go-ipfs/blob/master/docs/config.md#reprovider>

²See <https://github.com/libp2p/specs/blob/master/pnet/Private-Networks-PSK-V1.md> for details.

attacker could still download the files and attempt offline attacks to decrypt them at a later point in time, potentially compromising forward secrecy. Although, due to the encryption scheme being unknown to the attacker, the difficulty of such an attack is increased.

3.4 Incentives for Participation

IPFS was designed as a permissionless, best-effort, decentralised P2P network and as such it does not integrate incentive schemes. The operation of an IPFS node incurs costs for infrastructure maintenance in terms of bandwidth, storage, and power. After retrieving the desired objects, there is no incentive for a user to keep the node running, resulting in short sessions and high churn in the network as observed by measurements of the IPFS network [18]. (Free-riding) Consumers may also retrieve the desired objects conveniently over HTTP through an IPFS gateway instead, which does not require participation in the network at all. This poses an open research question whether gateways (and similarly supernodes) arise naturally in a P2P network as a result of trying to support all clients in combination with a lack of incentives. Nevertheless, incentivisation for consistent and continuous participation (and ultimately a sustainable IPFS network) need to be considered by the application to avoid centralisation around gateways and super nodes. *Pinning services*, which are third parties that pin files to provide improved/guaranteed availability for a monetary return, alleviate the problem of lacking incentives, as peers can contribute disk space and receive a share of the pinning service's compensation. Another way to address the lack of incentives is to provide exclusivity (i.e., content or features that are not available elsewhere); however, this is difficult to achieve, as user convenience and experience are more unpredictable with the best-effort storage approach of IPFS in comparison with centralised infrastructures, which may lead to difficulties in gaining critical mass.

3.5 Network Partition Tolerance

Due to being a decentralised P2P network with no essential central components, IPFS can still operate in cases of network partitions or in offline scenarios. While some components such as denylists can potentially not be retrieved or updated, partitions do not fully impair the content publication and retrieval process. Thus, as long as the requested objects are available within the same subgraph and the providing peers are reachable, IPFS is tolerant against partitions and does not require full Internet connectivity. Further, private IPFS networks among a set of machines can be built using *IPFS Cluster* [20], which allows deployment of IPFS in local networks.

4 IPFS IN RESEARCH STUDIES AND EXISTING APPLICATIONS

Considering the presented properties of IPFS, it has gained attention and usage in both academic and industrial projects. We provide an overview of previous research studies and existing applications to highlight use cases of IPFS, which shall also motivate future work.

4.1 Research Studies

Several studies investigated and built on top of IPFS as a main component of their proposal for various purposes, with the primary

use case being an off-chain storage for blockchain and other decentralised applications. We provide a brief review of the published literature in order to motivate further research on applications and areas that have not been covered yet. For instance, most approaches rely heavily on distributed ledger technologies to implement access control and trust mechanisms, whereas other properties of IPFS such as the best-effort storage have not been addressed yet at all.

Linked Data and Semantic Web. Studies [10, 47] proposed the publication of Linked Data on top of IPFS as an extension to the Semantic Web. Objects in IPFS are structured and linked in a DAG, which translates well to the graph structure of linked data, as the relationships between objects allow machines to read and semantically process data.

Storage for IoT applications. IoT devices generate large volumes of data, which usually are sent and processed in cloud and edge infrastructure. Previous studies [2, 12, 26] presented approaches in which IPFS is used as storage for IoT applications. As lookups in the DHT, are slow, in particular the global IPFS DHT, studies [12] showed how reducing the number of lookups by building local clusters or even replacing the DHT with a tree-based structure can result in locating stored objects in less than 15 ms. Other studies [2, 26] suggested to incorporate IPFS and blockchains into IoT storage solutions in order to add trust, access control, and confidentiality. However, there is a performance tradeoff, as adding trust increases delays by up to a few seconds or even minutes [26].

Reducing blockchain size. Due to the append-only nature, the size of a blockchain can only increase over time. Proposed models [39, 59] outsource the transaction and smart contract data to IPFS, while the blockchains only hold the IPFS hashes in order to reduce the size of appended blocks. The stored hashes can then be used to retrieve the respective data from IPFS, e.g., for transaction validation or contract execution.

Wisdom of the crowd. IPFS was used in conjunction with Ethereum to build a decentralised online social network [56]: Videos and images were stored on IPFS, whereas the main features of the system ran on top of Ethereum smart contracts. Similarly, another study [52] presented a prototype for a decentralised scientific publication process on top of IPFS and a blockchain, where IPFS is used to openly access the papers. On the other hand, the blockchain represents a reputation and incentive system for the reviewers, while also enabling transparency and accountability in the review process. A framework for a Q&A system was presented in [51] (cf. *StackOverflow*). The proposed framework includes search agents to discover questions and answers among the IPFS nodes; a decentralised search engine for IPFS was similarly proposed in [24]: it builds a search-index which consists of hashes of keywords, with the associations of keywords being integrated into the DHT to enable decentralised searches.

Healthcare systems. In medical environments, the integrity of healthcare records is an essential property for patient treatment, along with confidentiality, access control, and authorisation. Several studies [27, 50, 55] aim to build systems that allow distribution of medical records (e.g., between physicians) in a secure manner. To achieve this, they leverage permissioned blockchains and encryption schemes stored on IPFS to guarantee that only authorised parties have access to patient and medication data. This further allows traceability and integrity checks for the stored data.

Access control, auditing, and supply chains. Various studies [28, 40, 41, 49] develop access control and authorisation mechanisms for IPFS storage in combination with blockchain solutions. One proposal builds on top of smart contracts and access control lists [49], while another one [41] leverages blockchain tokens to achieve access control. A proposed authority management framework [28] allows to trace access supply chain data, which is outsourced to IPFS to reduce the blockchain size. Similarly, blockchains can be used to provide distinct audit trails for files within a private IPFS network [40], logging every access to the file to allow tracing back to its original author among other properties; a related approach leverages IPFS and blockchains to provide integrity checks and access logs for data on cloud storage [17].

Performance and topology measurements. To study the performance of IPFS, a study performed measurements from local and remote nodes [45]. The authors found that read and write performance of clients is related to access patterns, in particular request size, since IPFS uses different strategies for different I/O requests. They also showed that for remote reads, resolving (lookups, routing) and downloading operations can both be performance bottlenecks.

A study on the IPFS topology [18] used a modified IPFS node, which accepted unlimited connections from other peers, to collect passive measurements of the P2P network. They further repeatedly scraped the DHT in order to actively measure the number of connected nodes; both measurement approaches yield on average roughly 40–45k nodes in the whole IPFS network. They found that most probes are run by private users behind symmetric NATs, with short-lived sessions, which indicates that most clients join the IPFS network on an as-needed basis.

Other use cases. IPFS was further used to enable a variety of other applications and use cases, which we cannot discuss in detail for the sake of brevity. Instead, we provide a brief list of other use cases/studies (in no particular order) which have built on top of IPFS: alternative storage schemes for IPFS [8], verifiable voting systems [44], collaborative document editing with version control [38], land record management [36], digital right management [1, 37, 46], content retrieval marketplaces [3], training of federated learning models [31], exchange of decentralised transfer learning models [54], software integrity and delivery frameworks [48], bug bounty system [19], biological data migration [58], among others.

4.2 Existing Applications Built on IPFS

Various applications build on top of IPFS in order to decentralise the application storage and to avoid having to trust a single storage provider. The complexity of the applications and the role of IPFS within the projects differ based on the use cases, which range from using IPFS as infrastructure for file sharing and asset storage (e.g., for Web applications) to supply chain networks and data aggregation platforms, among others. These projects leverage the strengths of IPFS regarding content addressing (for deduplication and integrity checks) as well as P2P storage in particular. We present a few selected examples to showcase the versatility of IPFS in decentralised applications.

Web Tools: Building, Hosting, Deploying on IPFS. Textile³ and Fleek⁴ build tools on top of IPFS, which facilitate moving or migrating Web content and applications towards a decentralised Web. The provided interfaces, integrations, and pipelines allow developers to easily move their website or Web service from a local development branch to a deployment environment based on IPFS: Instead of deploying a site on a centralised host, a site and its assets are stored and deployed on the decentralised IPFS network, which in return provides the properties discussed in § 3.

Data Management and Archival. The content-addressed naming scheme of IPFS provides inherent deduplication and links between related IPFS object pieces, along with built-in integrity validation. These properties are leveraged by data management systems, as offered by Qri⁵ or OrbitDB⁶, which build decentralised databases. Based on IPFS, these databases provide versioning, logging, synchronisation, and sharing of data in a decentralised manner, which is particularly useful for decentralised applications.

Another project that leverages IPFS' file system properties is the InterPlanetary Wayback (IPWB) [23]. Contrary to its centralised “counterpart” of the Wayback Machine, IPWB distributes the archived content among multiple peers in the P2P network, which uses the deduplication properties of IPFS to reduce the amount of space required for Web archival.

Pinning Services. As mentioned in § 3.4, pinning services such as Pinata⁷ or Temporal⁸ run dedicated IPFS nodes that keep content persistent in the IPFS network, typically in exchange for a fee. This improves the availability of the pinned objects, as the pinned content will be less affected by churn or other losses of connectivity thanks to the distributed replication of the pinning services. As such, these services can be used as a complement or alternative to cloud hosts or CDNs for purposes of data storage and retrieval.

E-Commerce and Marketplaces. In the OpenBazaar⁹ P2P network, sellers host online shops on IPFS to store shop assets and product information. The properties of IPFS also allow sellers to have full control over which items they decide to list, i.e., what information they would like to publish. Buyers can connect to sellers directly, meaning that no platform fees are charged by a centralised third party. The IPFS network assists in caching content among users, so shops can continue to function while the main seller's IPFS node is offline. Different search engines (which the user can freely choose) enable the discovery of items, allowing users to find items by searching for keywords provided by the sellers. The payment system is based on cryptocurrencies; users can act as trusted moderators on the network, i.e., they can resolve potential disputes between buyers and sellers (e.g., refunding payments that were transferred to an escrow account), for which the moderator receives a fraction of the transaction fee after solving the dispute. Similar concepts are adopted by Origin¹⁰ and Filehive¹¹.

³<https://textile.io/>

⁴<https://fleek.co/>

⁵<https://qri.io/>

⁶<https://orbitdb.org/>

⁷<https://pinata.cloud/>

⁸<https://temporal.cloud/>

⁹<https://openbazaar.org/>

¹⁰<https://www.originprotocol.com/e-commerce>

¹¹<https://filehive.app/datasetmarketplace>

Arbol¹² builds a risk marketplace for weather-related risks on top of IPFS and blockchain-based contracts. The Arbol platform aggregates longitudinal weather data from multiple sources and stores them on IPFS. These datasets can then be used as reliable information to verify contracts between weather-dependent stakeholders concerning protection agreements; for instance, the platform minimises the risks for farmers or other agricultural entities which are not able to harvest the agreed upon amounts of products due to bad weather conditions, which can be proven by the decentralised data and transparent contract.

Digital Content Sharing. In order to provide decentralised music streaming, Audius¹³ combines IPFS and blockchain to give music artists full control over their content. The metadata and audio files are stored and delivered through the decentralised IPFS network, whereas the blockchain is used for content registration and access management through a token economy. Artists use content nodes to publish (encrypted) content on the IPFS network along with a smart contract on the blockchain, which listeners can unlock through a smart contract mechanism. The encrypted content can be retrieved from IPFS at any time, however, conditions for unlocking the content can be defined by the artist (e.g., by payment or by proving the possession of sufficient tokens of the artist). After the conditions are met and proven to the content node (operated or trusted by the publishing artist), the content node derives a re-encryption key specific to the requesting listener, with which the listener can locally re-encrypt and finally decrypt the requested segment of a music track for streaming. The ledger provides transparency to both artists and other listeners regarding listening behavior.

Similarly, LikeCoin¹⁴ represents a digital publishing infrastructure that operates on decentralised registries and rewards. Content pieces and their metadata, which includes their IPFS content addresses, are assigned a unique identifier (cf. ISBN) that is stored on a blockchain. The use of IPFS for content storage and retrieval makes the content immutable, verifiable, and censorship-resistant. Consumers that “like” the (freely available) content will provide rewards (LikeCoin tokens) to the publishers.

5 FUTURE DIRECTIONS

The presented properties of IPFS (§ 3) along with its application and investigation in previous research and existing applications (§ 4) highlight various opportunities for future directions. One project that is closely related and attempts to solve the lack of incentives along with an improvement of its best-effort content storage is *Filecoin*.

5.1 Filecoin

Filecoin [13] is an incentivised P2P network for the storage and retrieval of objects that builds on top of IPFS. Its goal is to provide distributed storage which is cheaper than centralised cloud storage solutions. Filecoin uses the same building blocks (§ 2) as IPFS, with the content addressing via CIDs at its core. Unlike IPFS, which does not replicate content at other peers unless those peers explicitly

¹²<https://www.arbolmarket.com/>

¹³<https://audius.org/>

¹⁴<https://like.co/>

request the content, Filecoin provides cryptoeconomic incentives to its participants: storage and replication of content in the network are rewarded with cryptocurrency tokens in order to facilitate higher availability, faster retrieval, and to counteract node churn. In exchange for a fee, peers can close storage deals between each other to provide persistent storage (cf. service level agreements), which is provable through proof-of-replication and proof-of-spacetime (see [14]). Thus, Filecoin improves IPFS's best-effort storage and delivery service; while aforementioned IPFS pinning services (§ 3.1) can also improve IPFS's best-effort approach, Filecoin does not require trust between the parties of a contract due to its decentralised, blockchain-based foundations. Filecoin is under on-going development to incorporate advanced designs and make its performance comparable to traditional, centralised cloud storage approaches. As such, further work on its design principles are necessary to obtain a better understanding of its behaviour and performance.

5.2 Concluding Remarks

We provided an overview of IPFS and its core features, presenting how its combination of multiple networking protocols and P2P concepts build a foundation for decentralised cloud storage. Its building blocks (§ 2) enable peer-assisted file distribution and delivery in order to move away from centralised cloud storages by providing persistence of names, deduplication, and integrity-checks for files through Content Identifiers (CIDs), censorship resistance, network partition tolerance, and ultimately decentralisation, among other properties (§ 3). Previous studies (§ 4) use IPFS for a variety of proposals, especially as decentralised storage for blockchain or IoT applications. Nevertheless, IPFS has yet to overcome challenges such as access control, participation incentives, or persistent availability and replication of content. Future directions, such as the integration of IPFS and Filecoin (§ 5), aim to overcome some of IPFS' challenges with regard to incentives and content availability. Together with the native support of IPFS in the Opera [42] and Brave [5] browsers as well as the whitelisting of the `ipfs://` scheme in Mozilla Firefox [11], these are important steps in stimulating the growth of the network and moving towards a more decentralised Internet in the future. The performance of these decentralised solutions is a very timely research topic, which we encourage the community to undertake. As such, future work on distributed storage in general should consider both opportunities and challenges of IPFS in order to develop suitable decentralised storage systems for the Future Internet and its applications. In particular, we identified several open research questions with respect to IPFS and distributed storage: How does P2P-based content storage and retrieval compare to traditional cloud storage or CDNs technologies? How can availability, retrieval, and delivery of content be improved? How can we achieve full user anonymity when fetching and retrieving content in permissionless P2P networks? How can the use and adoption of such decentralised technologies be incentivised?

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