AGChain: A Blockchain-based Gateway for Permanent, Distributed, and Secure App Delegation from Existing Mobile App Markets

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ABSTRACT
Mobile app markets are emerging with the popularity of smartphones. However, they fall short in several aspects, including no transparent app listing, no world-wide access, and even insecure app downloading. To address these problems, we propose a novel blockchain-based gateway, AGChain, to bridge end users and app markets so that existing app markets could still provide services while users enjoy permanent, distributed, and secure app delegation from AGChain. To this end, we identify two previously underestimated challenges and propose mechanisms to significantly reduce gas costs in our smart contract and make IPFS (Interplanetary File System) based file storage really distributed. We also address three AGChain-specific system challenges to make it secure and sustainable. We have implemented an AGChain prototype (https://www.agchain.ltd/) on Ethereum. The evaluation shows that it achieves security and decentralization with minimal gas costs and reasonable performance.

1 INTRODUCTION
Smartphones are getting increasingly popular around the world. The popularity is (partially) driven by the large amount of feature-rich mobile apps in various app markets. Apart from the official marketplaces like Google Play and Apple Store, some third-party app markets, e.g., Amazon AppStore and Baidu Market, appeared as the important supplementary of official app markets. They provide more app options for Android users and are also popular (especially in China). Nevertheless, all these official and third-party app markets are in a centralized design, which falls short in the following several aspects (more details are listed in §2):

P1: No transparent listing or permanent access. Firstly, centralized app markets could enforce strict listing policies and delist the apps as they wish. For example, 13.7% (1,146) of the 8,359 popular apps we measured in late 2018 have been delisted (by either the market or developers themselves) after one year in late 2019.

P2: No world-wide and even censored access. Secondly, many apps on Google Play and Apple Store are available only in certain countries. Moreover, Google Play itself is being censored in some regions, causing no easy app access for the users in those affected areas.

P3: No enough security guarantee. Thirdly, we find that a significant portion of third-party Android app markets do not provide secure app downloading. For example, half of the top 14 Chinese app markets download apps via the insecure HTTP, such as the widely used Baidu and 360 app markets. Moreover, even for the markets with secure downloading, they generally have no checking of app repackaging [46] as in official markets.

While some of these problems (P1 to P3) individually look resolvable by technical means like asking users to use VPN (for P2) and forcing markets to use HTTPS (for P3), these means do not address the fundamental limitation in current app markets — the lack of permanent and distributed (and even secure) app access. Moreover, the first problem P1 is technically unresolvable except periodic backup. As a result, users have to worry that a certain app could “disappear” from the markets one day. A famous example is that the Google Play app is no longer available on Huawei phones due to the Huawei ban [13]. Even for the apps legitimately taken down by the markets, such as malicious apps, they are still useful for certain users like security researchers. Addressing P1 requires markets to guarantee permanent app access; however, this is impossible since they are a centralized entity.

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Since general users have no paid VPN and the security status of Chinese app markets would not change in a short period of time, those technical means may not work as thought.
A natural thought of tackling these problems as a whole is to build a decentralized app market from scratch, as similar to the typical blockchain-based work [36–38, 43]. However, this kind of design also brings a new problem because massive apps are already stored in existing markets. Without enough apps, a decentralized market is meaningless for end users.

In this paper, we balance all these considerations and propose a novel architecture that combines the advantages of traditional IT infrastructure and decentralized blockchain. Specifically, we propose a blockchain-based gateway that acts as a bridge between end users and app markets. We call this novel app gateway AGChain (App Gateway Chain). With AGChain, users can leverage the (permanent, distributed, and secure) delegation of AGChain for indirect app downloads if they worry about the direct app downloads from existing markets. During this process, existing markets still provide services as usual except for the apps that have been delisted. More specifically, if a user wants to delegate an app download from an existing market URL, she can input that URL to AGChain and AGChain will automatically (i) retrieve the corresponding app from its original market, (ii) upload the raw app file to a decentralized storage, and (iii) save the app file index and important metadata on chain for controlling all future downloads directly from AGChain.

After delegation, the user (and other users) can permanently download the app from AGChain in a distributed manner.

We choose to use smart contract [28] for programming our logic on blockchain and IPFS (Interplanetary File System) [26] for our decentralized storage. However, instead of straightforwardly using them as in other blockchain- and IPFS-based systems [36–38, 43], we identify and overcome two previously underestimated challenges. First, we significantly reduce gas costs by proposing a set of design-level mechanisms (as compared with code-level gas optimizations [22, 29, 31]) for gas-efficient app storing and retrieving on chain. Notably, we transform the typical in-contract data structures to transaction log-based contract storage, which reduces gas by a factor of 53 per operation (20,000 v.s. 375 Gas). Second, we surprisingly found that IPFS is not distributed by default — files stay only in the original IPFS node and are cached at IPFS gateways only when there are requests. To make IPFS really distributed, we build an IPFS consortium network that periodically caches app files at IPFS gateways and timely backup apps at crowdsourced server nodes. We also propose a mechanism to identify fast and uncensored IPFS gateways for distributed app downloading.

To further make AGChain secure and sustainable, we still need to address three AGChain-specific system challenges.

2 MOTIVATION AND BACKGROUND

In this section, we motivate the need of permanent, distributed, and secure app access by pinpointing pitfalls in existing app markets. We then present the background required for understanding our blockchain-based design.

First, to securely retrieve apps from existing app markets without the network security guarantee, we extract and validate the checksums that are potentially embedded in apps’ market pages, and also achieve alternative security when there are no checksums. Second, to avoid repackaged apps from polluting our market, we propose a mechanism that exploits a lightweight yet effective app certificate field to detect repackaged apps, and experimentally validate it using 15,297 repackaged app pairs. Third, as a monetary incentive for crowdsourced server nodes, we design a mechanism of charging upload fees to maintain the platform self-sustainability.

We have implemented a public AGChain (https://www.agchain.ltd/) on the widely-used Ethereum blockchain with 2,485 lines of code in Solidity, Python, Java, and JavaScript. To evaluate AGChain, we not only empirically demonstrate its security effectiveness (via preventing man-in-the-middle and repackaging attacks against our app delegation) and decentralization (IPFS gateways discovered in over 21 different locations worldwide), but also experimentally measure the performance and gas costs. On average, AGChain introduces 12% performance overhead in 140 app tests from seven app markets, and costs 0.00008466 Ether (around 0.085 USD) per app upload. We further provide a batch upload mechanism to save gas by a factor of between 2.02 (for a batch of 10 uploads) and 2.65 (for a batch of 100 uploads). Besides minimal gas costs for app uploads, AGChain does not consume gas for app downloads since they do not change contract state.

To sum up, this paper makes the following contributions:

- (A novel gateway design for app markets) We propose a blockchain-based gateway to enable permanent, distributed, and secure app delegation for massive apps stored in existing markets (and custom apps via GitHub URLs). Our idea of combining traditional IT infrastructure and decentralized blockchain opens a new door for better blockchain system design in the future.
- (Addressing design and system challenges) We propose mechanisms to achieve gas-efficient smart contract and distributed IPFS design. We also overcome three system challenges that are specific to AGChain.
- (Implementation and extensive evaluation) We have implemented a publicly available prototype, AGChain, on Ethereum and conducted extensive evaluation on its performance, gas costs, security, and decentralization.
2.1 The Delisted Apps on Google Play
Centralized app markets could enforce strict listing policies and delist the apps as they wish. While it is known that Google Play and Apple Store do not allow apps like third-party market apps to be listed, it is unclear how many uploaded apps were once delisted. We estimate this percentage by specifically measuring the number of delisted apps in a set of 8,359 apps that we initially collected from Google Play in November 2018. These apps are all popular, with one million installs each. We then re-crawled them in the same country after one year in November 2019 and found that as high as 13.7% (1,146) of them had been delisted in this period of time. Although some of them could be intentionally withdrawn by their developers, we believe that a considerable portion of the total 1,146 delisted apps was due to the violation of Google Play’s recent Developer Distribution policies [17].

2.2 App Cases of No World-wide Access
Besides no permanent app access, a more easily observable pitfall is that many apps on Google Play and Apple Store are available only in certain countries. For example, the TVB media app [7] and the popular Hulu app [12] are restricted within Hong Kong and US/Japan, respectively. Besides country-specific app control, many English-based apps are not available in Chinese app markets (and vice versa). As a result, users who need to download apps in other countries or languages have to switch their iTunes accounts to other countries [2] or use VPN to bypass Google Play’s checking [5]. Note that no world-wide app access is not only caused by markets’ country-specific control but also by network-side censorship. For example, Google Play itself is being censored in some regions [11], causing no app access for affected users.

2.3 Insecure App Downloading in Third-party App Markets
Lastly, an unexpected yet serious pitfall is that not all app markets provide secure app downloading as Google Play and Apple Store do. Indeed, we find that half of the top 14 Chinese Android app markets still use insecure downloading via HTTPS but provide the actual app downloading only in lightweight HTTP. We distinguish such a situation by inspecting the app downloading traffic only. As shown in Table 1, half of 14 Chinese app markets (two markets do not provide the web-based app downloading) use insecure HTTP downloading, which include markets from Internet giants (e.g., Baidu) and hardware smartphone vendors (e.g., Meizu and Lenovo), and also specialized app markets (e.g., Anzhi and App China).

2.4 Relevant Technical Background
To address the pitfalls mentioned above, we propose a novel blockchain-based architecture that leverages Ethereum and IPFS. We now introduce the relevant background as follows.

Blockchain. Technically, a typical blockchain is a public and distributed ledger. It records transactions that are immutable, verifiable, and permanent [40]. Therefore, blockchain can be utilized as a decentralized database. The trust among different network nodes is guaranteed by the so-called consensus (e.g., Proof of Work) instead of the authority of a specific institution. Consensus is the key for all nodes on a blockchain to maintain the same ledger in a way that the authenticity could be recognized by each node in the network.

Ethereum. Ethereum [28] is the second largest blockchain system and is a widely-used smart contract platform. A smart contract is a contract that has been programmed in advance with a sequence of rules and regulations for self-executing. Solidity is the primary language for programming smart contracts on Ethereum. In particular, it is a Turing-complete language, which suggests that developers could achieve arbitrary functionality on smart contracts theoretically. To prevent denial-of-service attacks, users need to consume gas

| Table 1: The measurement result of app download security in the top 16 Chinese Android app markets [41]. |
|--------------------------------------------------|
| **Market Name** | **Company Type** | **Secure App Downloading?** |
| Tencent Myapp | Web Co. | HTTPS ✔ |
| Baidu Market | Web Co. | HTTP ✗ |
| 360 Market | Web Co. | HTTP ✗ |
| OPPO Market | HW Vendor | No Website Download |
| Huawei Market | HW Vendor | HTTPS ✔ |
| Xiaomi Market | HW Vendor | HTTPS ✔ |
| Meizu Market | HW Vendor | HTTP ✗ |
| Lenovo MM | HW Vendor | HTTP ✗ |
| HiApk | Specialized | Cannot Find the Website |
| Wandoujia | Specialized | HTTPS ✔ |
| PC Online | Specialized | HTTPS ✔ |
| LIQU | Specialized | HTTPS ✔ |
| 25PP | Specialized | HTTPS ✔ |
| App China | Specialized | HTTP ✗ |
| Sougou | Specialized | HTTP ✗ |
| AnZhi | Specialized | HTTP ✗ |
fees to send transactions on Ethereum. The gas fees are paid in Ethereum’s native cryptocurrency called Ether (or ETH).

**IPFS.** IPFS (Interplanetary File System) [26] is a peer-to-peer file sharing system, where files are stored in a distributed way and routed using the content-addressing [30]. IPFS was proposed because the storage of large files on blockchain is inefficient and with high costs. Specifically, all nodes in a blockchain network need to endorse the entire ledger and synchronize the files stored. As a result, unnecessary redundancy will lead to a huge waste of storage, and the latency of ledger synchronicity will also be significantly increased. To address this limitation, we can store data only in the IPFS storage nodes and keep the unique and permanent IPFS address (called IPFS hash) in the blockchain network.

## 3 THE CORE AGCHAIN DESIGN

In this section, we introduce the core design of AGChain, including its objectives, threat model, the overall design, and two major challenges we addressed.

### 3.1 Design Objectives and Threat Model

**Design objectives.** Our goal is to build a blockchain-based gateway that can provide permanent, distributed, and secure app delegation from existing app markets. Note that we do not aim to fully replace existing markets because apps on AGChain eventually also come from them\(^3\). In this way, existing app markets can still serve massive regular users, while users with security awareness or backup purposes can leverage the proxy of AGChain to securely download an app from a third-party market or permanently store an app on chain. Hence, AGChain is more like a gateway of existing app markets, instead of a standalone market. More specifically, we have the following major design objectives:

- **Permanent delegation.** Upon an app is uploaded to AGChain, we aim to achieve the permanent storage and delegation of this app. The immutable nature of blockchain makes it an ideal technology for this purpose. To utilize it for AGChain, we make these two choices. First, we leverage an existing and mature blockchain rather than build our own blockchain as in Infnote [45]. This is because mainstream blockchains, such as Bitcoin and Ethereum, have accumulated enough nodes over the years and are thus robust against many attacks. Second, to program our logic on blockchain, we write a smart contract instead of creating a virtualchain as in [23, 35, 38], since smart contract is much lightweight and also powerful in terms of Turing-completeness. Note that only for the apps once accessed via AGChain, we can provide permanent access.

- **Distributed delegation.** Since raw files are not suitable to be directly stored on blockchain due to the high storage and gas cost (see §2.4), we still need an efficient yet distributed file storage. In this paper, we employ IPFS for its feature of being both distributed and permanent, whereas centralized cloud services cannot guarantee they always exist (some are even censored, such as Google Drive and Dropbox). The basic idea of using IPFS in AGChain is to store raw app files on IPFS and keep their corresponding IPFS indexes on chain. However, we surprisingly found that IPFS does not duplicate files to other IPFS nodes if no request. To make it distributed, we build a consortium network by utilizing IPFS gateways and crowdsourced server nodes.

- **Secure delegation.** A practically desirable objective is to achieve secure app download delegation for apps from the markets without HTTPS downloading (called unprotected markets thereafter) because this can immediately benefit millions of Chinese market users (see §2.3). Specifically, we need to securely retrieve apps from existing app markets without a dedicated and trusted network path. Besides the download security, we also need to guarantee apps uploaded to AGChain are not repackaged [46] in their original markets.

3As mentioned in §1, AGChain also supports uploading custom apps not available in any app markets, by asking users to list them via GitHub URLs.
3.2 The Overall System Design

Architecture. Figure 1 presents AGChain’s high-level design. As highlighted in the green color, it has four components as follows:

- **Smart contract.** The most important component is a novel (gas-efficient) smart contract, which stores all app metadata on chain and duplicates them on most of Ethereum nodes worldwide. With these data (including IPFS file indexes) and their programmed storing and retrieving logic, this smart contract is the actual control party of AGChain’s entire logic.

- **IPFS network.** Another core component is an IPFS (consortium) network, which stores raw app files in a distributed manner. The stored apps then can be automatically routed and retrieved through IPFS’s content-addressing [18]. Note that with the smart contract and IPFS components, we guarantee the permanent and decentralized app access in AGChain.

- **Server nodes.** To achieve app download security and repackaging checking, we also need server(s) to retrieve apps from existing markets, inspect their security, and schedule their uploading as these tasks cannot be performed in blockchain. Since any machine with our server code could be a server node, we propose an incentive mechanism (details in §4.3) to motivate servers to join AGChain. These crowdsourced server nodes further enhance the decentralization.

- **Front-end.** Finally, we provide a front-end web interface to help uploaders and downloaders interact with AGChain. Note that for app downloading, our front-end directly communicates with smart contract and IPFS without the server.

Upload workflow. Figure 1 also shows the overall workflow of AGChain. As shown in left part, Alice wants to securely download an app (e.g., Alice is a security-sensitive user) or permanently store an app on chain for future usage (e.g., Alice is a developer or a user who wants to backup the current version of an app). She then acts as an app uploader:

1. Alice just needs to input the original app page URL and clicks the “upload” button in the front-end. AGChain automatically finishes all the remaining steps.
2. The front-end transfers the URL to one server node.
3. After knowing the URL, the server analyzes the corresponding app page to obtain the download URL that points to the actual APK file (the file format used by Android apps), and retrieves it from its original market.
4. For the app markets using insecure app downloading (e.g., those seven markets in Table 1), AGChain performs one more step to check whether the retrieved file has been tampered with during network transmission.
5. For all third-party markets, we conduct repackaging checks to prevent repackaged apps [46] from polluting AGChain. We propose a lightweight yet effective certificate ID based mechanism; see details in §4.2. During this process, we also parse the APK file to extract its package name and version (besides the certificate ID).
6. The server then uploads the raw APK file to IPFS and obtains its corresponding IPFS hash (i.e., the file index).
7. Finally, the server invokes the smart contract to store all app metadata and IPFS hash on chain. We choose the widely-used Ethereum as our underlying blockchain.
8. To avoid Alice from waiting a long time for blockchain transaction confirmation (typically 9–13 seconds, according to our tests), AGChain simultaneously returns the result of package name, app version, and IPFS hash.

Download workflow. As shown in the right part of Figure 1, Bob acts as an app downloader to download apps (e.g., the app uploaded by Alice) that are already in AGChain:

a) Bob inputs (or browses) the package name and version of the app that he wants to download in the front-end.
b) The front-end then automatically invokes the smart contract to retrieve the corresponding IPFS hash.
c) The front-end further locates the nearest IPFS network node to download the APK file and returns it to Bob.

Major challenges. In the course of developing AGChain, we identify two previously underestimated challenges:

C1: How to minimize gas costs in the smart contract? Since each app upload initializes a blockchain transaction and costs gas fees, it is critical to minimize such costs in our smart contract. While there were some code-level gas optimizations [22, 29, 31], they are still far from enough. In §3.3, we propose design-level optimizations to significantly reduce gas costs by a factor of 18.

C2: How to make IPFS storage distributed? As mentioned in §3.1, we surprisingly found that IPFS files stay only in the original IPFS node and are cached at IPFS gateways only when there are requests. Once the original node goes offline, the entire IPFS network can no longer access the file (availability gets restored when one node adds the same content back). To make IPFS storage distributed in the first place, we build an IPFS consortium network (§3.4) that timely asks IPFS gateways and crowdsourced server nodes to backup files.

3.3 Gas-Efficient Smart Contract for App Metadata Storing and Retrieving

In this subsection, we propose a set of mechanisms to minimize gas costs for app metadata storing (i.e., app uploads), eliminate gas costs for metadata retrieving (i.e., app downloads), and achieve a whitelist mechanism for preventing misuse of our contract functions. These design-level optimizations are much more efficient than code-level optimizations [22, 29, 31] and can guide future smart contract design. Minimizing gas costs via log-based contract storage.

We found that a major source of gas inefficiency comes from data storage in the smart contract. Like many other smart contracts, AGChain needs to store app metadata as a structure defined in the contract. However, such data storage operation, via the SSTORE instruction in Ethereum Virtual Machine (EVM), changes the internal block states and Ethereum’s world state [4]. Therefore, it is expensive, costing 20,000 Gas per operation [44]. Since numerous app metadata records will be stored in AGChain, it would cost a large amount of gas fees if we use the traditional contract structure. Fortunately, we identify a logging interface in the EVM, which can be used to permanently log data in transaction receipts via the LOG instruction [44]. Since it changes only the block headers and does not need to change the world state, only 375 Gas is consumed per operation. The underlying logging mechanism is complicated, and we refer interested readers to the Ethereum yellow paper [1, 44] for more details. While log-based contract storage significantly reduces gas fees, it has no structure information. We thus ask our server nodes to recover the app metadata structure, which includes the app package name, app package version, app certificate serial number, the original market page URL, the repackaging detection result, and the important IPFS hash.

Offloading on-chain duplicate check to server nodes.

Another major source of gas costs originates from the duplicate check, which checks duplicated app metadata before storing it on chain. Originally, we deployed such a check in the smart contract, but we found that it is costly since each check needs to iterate over the entire app metadata structure. Moreover, an in-contract structure has to be maintained, which causes the first log-based optimization unadaptable. Therefore, we offload this on-chain duplicate check to server nodes, which query the latest app metadata from the smart contract before uploading any records. If a duplicate exists, the uploading will stop.

Further reducing gas costs via batch uploads. With the above two default optimization mechanisms, we significantly reduce gas costs by a factor of 15.75 (0.001347 v.s. 0.0000855 Ether, before and after the optimization). We further reduce the costs by providing a back-end interface of

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6 The gas cost/fee is the product of gas price (or Gwei) and the Gas consumed.
batch uploads. Our experiment shows that by batching 10 uploads together, we save gas by a factor of 2.02 (compared with 10 times of normal uploads). This factor increases to 2.65 for a batch upload of 100 records. These suggest that for a large number of app uploads (e.g., a company uploads all its apps), we can use batch uploads to minimize gas costs.

Eliminating gas costs for all app downloads. While app uploading certainly consumes gas, we find a way to eliminate gas costs for all app downloads. For a normal contract data structure, we originally used the view function modifier to describe the data retrieving contract function since it does not change any contract state. Invoking such a view-only function (even by external parties) will not initiate any blockchain transaction, and thus no gas fee is needed. However, since we have switched to log-based contract storage, we create a bloom filter [1, 3] to quickly locate the block headers containing our data logs, regenerate the original logs, and extract IPFS hashes from them. Since this task is performed only at the server side via the web3 Python APIs [21], the contract side will not cost any gas.

Achieving a whitelist mechanism for access control. Since smart contract has no access control mechanism, a contract function can be invoked by anyone. This implies that an adversary can invoke our storeApp() function to upload any app in our scenario. To prevent malicious uploads from interfering AGChain’s data, we implement a lightweight whitelist mechanism that consists of two function modifiers, onlyOwner(address caller) and onlyWhitelist(address caller), where the parameter address is the invoking party’s Ethereum account address. By enforcing the onlyWhitelist modifier to check the caller of storeApp(), we can guarantee that only an account in the whitelist can upload apps. We also implement two contract functions to add or delete an account address from the whitelist, and they are enforced by the onlyOwner modifier. Note that the owner is our contract creator, and we gradually add each authorized server node into the whitelist. By designing such a hierarchical whitelist, we can achieve effective access control to avoid malicious data injecting into AGChain.

3.4 IPFS Consortium Network for Distributed File Uploading and Downloading
To address the challenge C2, AGChain leverages IPFS gateways and crowdsourced server nodes to cache or backup apps so that they are really distributed in the IPFS network. With these gateways and servers, AGChain essentially forms an IPFS consortium network for distributed app access.

Periodically caching app files at IPFS gateways. As mentioned in the challenge C2, an IPFS file stays only in the original IPFS node and is routed for access through content-addressing [18]. Once this node goes offline, the entire IPFS network can no longer access the file. Fortunately, our experiment found that an IPFS gateway would cache the file for a certain period of time when there is a file access through the gateway. We thus leverage this observation to intentionally mimic normal user requests for caching apps at IPFS gateways. Specifically, we deploy a script in the server to send file requests through various IPFS gateways. These requests are periodically sent before the IPFS garbage collector cleans our app files. In this way, we guarantee that a copy or multiple copies of app files are always available in IPFS gateways.

Timely backing up apps at crowdsourced server nodes. To achieve really distributed app storage, we ask each crowdsourced server to serve as an IPFS storage node and timely backup apps in our IPFS consortium network. Each server node first uses the ipfs daemon command to run as an IPFS node. It then runs a consortium synchronization script, which gets a list of IPFS hashes of the apps in AGChain and retrieves raw app files from the IPFS network. To avoid being collected by the IPFS garbage collection, the script pins these raw apps locally using the ipfs pin command. In this way, we increase the data redundancy in AGChain and improve the distribution of app storage.

Identifying fast IPFS gateways for app downloading. Besides distributed app uploads, we also propose a mechanism to make app downloading distributed and fast. Specifically, AGChain’s front-end tests the RTT (Round-Trip Time) of public IPFS gateways, chooses the gateway with the lowest RTT, and downloads the raw app file from it. This not only improves the performance of app downloading in IPFS but also prevents potential censorship of some IPFS gateways.

4 MAKING IT SECURE & SUSTAINABLE
So far, we have designed AGChain to be permanent and distributed through contract-based distribution and IPFS-based storage. However, to make it secure and sustainable, we still need to address three AGChain-specific system challenges:

C3: How to securely retrieve apps from the app markets without network security guarantee? Recall that our server needs to retrieve apps from existing markets before uploading them to IPFS. This is straightforward for markets with HTTPS but difficult for those using insecure HTTP (see §2.3) because there is no underlying network security guarantee. To address this, we propose two modes of secure app retrieval in §4.1.

C4: How to avoid repackaged apps from polluting our market? Addressing challenge C3 guarantees that the retrieved app is the same as the one in its original app market. However, if the market is a third-party app market, the app might be already repackaged before our (secure) retrieval. Hence, we need a mechanism, as
proposed in §4.2, to detect repackaged apps [46] that are different from their official Google Play versions.

4.1 Secure App Retrieval from (Existing) Unprotected Markets

In this subsection, we present two methods that collectively achieve secure app retrieval even for those unprotected markets, e.g., seven markets using HTTP downloading in Table 1.

Secure app downloading via checksums. We find that although those seven markets use HTTP to download apps, most of them allow users to browse app pages via HTTPS (e.g., https://zhushou.360.cn/detail/index/soft_id/95487) and also allow us to extract app APK file checksums (e.g., MD5) from those pages’ HTML source code. For example, three app markets (Baidu, 360, and AppChina) directly embed the checksums in their app download URLs. One app market, Lenovo MM, embeds the checksum in its app HTML page’s `<script>` data section. Hence, by analyzing these markets’ app HTML pages, we can securely obtain app checksums and further compare them with the calculated checksums of app APK files we retrieve via HTTP. If they match, we conclude that the retrieved app is not replaced by adversaries. Furthermore, although Sogou market does not provide the checksum information, we find that its HTTP download URL can be directly transformed into an HTTPS version. As a result, we can achieve guaranteed app download security for five out of a total of seven unprotected markets.

Alternative security with no checksums. For the remaining app markets that contain no checksums, e.g., Meizu and Anzhi, we propose a mechanism to achieve alternative download security. The basic idea is to check the Google Play counterpart of each downloaded app. Specifically, by leveraging the AndroZoo app repository [24] that contains over ten million apps from Google Play, we can check if a downloaded app is in this repository. If it is, we conclude that the downloaded app from a third-party market is not compromised during the download process. Furthermore, even if an app is not in the repository, we can extract its developer certificate and check whether it is from a Google Play developer. Since the AndroZoo repository keeps evolving with Google Play, we have high confidence that most apps could be covered by either our app- or develop-level checking. For minimal apps that still miss, AGChain will give a warning that these apps might not be securely retrieved.

4.2 Exploiting App Certificate Info for Repackaging Detection

In this subsection, we present a mechanism of exploiting app certificate to accurately detect repackaged apps that might be uploaded to AGChain from third-party app markets.

Unlike traditional app repackaging detection [33, 46], the identifier of uploaded apps to AGChain, i.e., app package name, is fixed. We can leverage this package name identifier to locate a corresponding official app on Google Play. We then just need a mechanism to differentiate these two versions of apps, and more specifically, whether they are from the same developer. We thus investigate the app certificate data structure, which includes the certificate serial number, issuer, subject, and X509v3 extensions. Among these fields, we find that serial number (e.g., 0x706a633e) is the most lightweight metric that adversaries cannot manipulate (because they do not have developers’ app signing key). In contrast, other fields like issuer and subject are manipulatable, and X509v3 is more complex than the serial number.

We further experimentally validate our detection idea. Specifically, we use a dataset [33] of 15,297 repackaged Android app pairs (i.e., each pair contains an original app and a repackaged app) as our ground truth. We also develop a script that automatically extracts the package name and serial number from a given app APK file. This script leverages the popular Androguard library to parse APK files. Note that this script has been integrated into AGChain’s server code. By running our script on 15,297 app pairs, we find a total of 2,270 pairs with the same package name each, and no single pair has the same serial number. For the other 13,027 repackaged pairs, every pair of their package names is different. This experiment shows that our serial number based mechanism is 100% accurate.

4.3 Charging Upload Fees to Maintain the Platform Self-Sustainability

In this subsection, we design a mechanism of charging app upload fees to pay crowdsourced server nodes in AGChain so that the entire AGChain platform is sustainable.

We thus revise the original design of AGChain to charge upload fees just before each server node invokes (IPFS and) smart contract. More specifically, we add two more steps between step 5 and 6 in Figure 1. The first step is to send an estimated transaction fee to our smart contract, for which we add one more function called DonateGasFee() in our smart
Table 2: A breakdown of LOC (lines of code) in AGChain.

| Component | Front-end (F) | Server (S) | Contract (C) | IPFS (I) | AGChain |
|-----------|---------------|------------|--------------|---------|---------|
| JavaScript| 781           | (302 in F)*| (80 in F)    | 781     | 781     |
| Java      | 849           | (36 in S)  | 849          | 849     | 849     |
| Python    | 723           | (445 in S) | 723          | 723     | 723     |
| Solidity  | 51            |            | 51           | 51      | 51      |
| CSS       | 81            |            | 81           |         | 81      |
| Sum       | 862           | 1,572      | 51 + (747)   | (116)   | 2,485   |

*This means that 302 lines of code in front-end are related to smart contract. Other brackets, such as (445 in S) and (80 in F), are similar.

We now explain how our JavaScript code estimates the gas fee and how the server verifies the payment transaction. To calculate a gas fee at the user side, we invoke a web3 JavaScript function called `estimateGas()` to estimate the required gas of executing the transaction in the EVM. For the transaction verification at the server, we first query the transaction according to its ID, and then determine (i) whether the destination address of this transaction is our smart contract, (ii) whether the upload fee exceeds our estimated gas, and (iii) whether this transaction is never used before. Only when the three conditions are all satisfied, the server then continues the actual app uploading to IPFS and Ethereum.

5 IMPLEMENTATION

We have implemented a public AGChain prototype (https://www.agchain.ltd/) on the Ethereum blockchain. Figure 2 shows a screenshot of its front-end homepage. In this section, we summarize AGChain’s implementation details.

Our current AGChain prototype consists of a total of 2,485 LOC (lines of code), excluding all the library code used. Table 2 lists a breakdown of AGChain’s LOC across different components and programming languages.

**Front-end.** We implement the front-end user interface using the React web framework [16]. Hence, the HTML and CSS code is minimal, and some HTML contents are dynamically generated using JavaScript. Besides user interfaces, we write 302 JavaScript LOC on top of the web3.js library [20] to query our smart contract for retrieving IPFS hashes. To execute IPFS commands in JavaScript for app downloading, we write additional 80 JavaScript LOC based on the js-ipfs library [14]. Totally, the front-end is implemented in 862 LOC.

**Server node.** We implement our server code in a total of 1,572 LOC and run it on the AWS (Amazon Web Services). Specifically, we write 849 Java LOC to handle requests from the front-end, securely download apps from existing markets, perform repackaging checks, and upload APK files to IPFS. Moreover, we write 445 Python LOC to leverage web3 Python APIs to interact with smart contract. Lastly, to parse APK files (used in repackaging checks), we leverage the Androguard library [8] and write 278 Python LOC on top of it.

One major task of the server node is to retrieve apps from the market URLs specified by users. However, such URLs are often only the page URLs (e.g., https://shouji.baidu.com/software/11569169.html) instead of direct download URLs. To automatically extract download URLs, we leverage the insight that each market has a fixed transition pattern from a page URL to a download URL. Hence, we can pre-analyze those markets to obtain their download URL patterns. Most markets’ download URLs can be directly extracted from their HTML tags, e.g., the aforementioned Baidu market example. A few markets, e.g., Meizu and AnZhi, require to calculate URLs from its JavaScript code. In our current prototype, we have analyzed the download patterns of all seven markets that need AGChain’s secure app download delegation.

**Smart contract.** We implement the smart contract with 51 LOC in the Solidity language, which was reduced from
Table 3: Average processing time introduced by AGChain.

| Market ID | APK Size (Mb) | Normal Download Time (ms) | Checksum | Repackaging | IPFS Upload | Overall Upload % |
|-----------|---------------|----------------------------|----------|-------------|-------------|------------------|
| 1         | 20.09         | 71063.2                    | 820.1    | 377.1       | 340.7       | 2.16%            |
| 2         | 27.26         | 10105.5                    | 917.0    | 433.8       | 429.1       | 17.61%           |
| 3         | 20.87         | 14819.2                    | 1203.3   | 408.6       | 415.8       | 13.68%           |
| 4         | 20.63         | 20090.9                    | 1328.0   | 355.8       | 387.4       | 10.31%           |
| 5         | 30.52         | 13854.8                    | 990.1    | 444.9       | 393.2       | 13.20%           |
| 6         | 25.29         | 21875.8                    | 1870.7   | 369.8       | 396.1       | 12.05%           |
| 7         | 23.86         | 17345.3                    | 1013.0   | 414.3       | 432.7       | 10.72%           |

128 LOC in the earlier version since we no longer define in-contract data structures (see §3.3). Therefore, our smart contract mainly describes a list of functions, e.g., `storeApp()` for uploading app metadata to the blockchain. In particular, to avoid the smart contract being misused by unauthorized parties, we set that only whitelisted server nodes can invoke the `storeApp()` function by adding a function modifier of checking the transaction sender. However, this also prevents the front-end’s `estimateGas()` web3 API from estimating gas (see §4.3). To address this issue, we create an additional function called `storeApp_estimate()` that duplicates `storeApp()`’s functionality but does not execute data push operations. This function will be executed by the EVM instead of AGChain transactions.

**IPFS module.** Since we do not modify the IPFS network, IPFS-related code is implemented in other components. For example, we write 80 JavaScript LOC for the front-end to download apps from IPFS and 36 Java LOC (without counting Java file operation code) for the server node to upload apps to IPFS. Additionally, we need to activate the IPFS node on the server by running the `ipfs daemon` command.

6 EVALUATION

In this section, we first experimentally evaluate the performance and gas costs of AGChain, and then empirically demonstrate its security effectiveness and decentralization.

6.1 Performance

To fairly evaluate additional time introduced by AGChain, we use our server code to record both normal downloading time (part of step 3 in Figure 1) and AGChain’s processing time (the rest of step 3 and steps 4 to 6; see Figure 1). Note that we do not count step 8 as part of AGChain’s overhead, because we simultaneously return results to users without waiting for the transaction to be confirmed. Totally, we test 140 different apps from seven markets (20 tests each) that require secure delegation. Moreover, we perform these tests in different days.

Figure 3: CDF plot of gas fees per uploading transaction.

Table 3 lists the average results of each tested market. We first see that normal downloading time simply relies on the network quality between app markets and our AWS server instead of APK file sizes. On top of this, AGChain introduces three steps of additional processing times, including (i) about one second (or 1s) of extracting and validating checksums; (ii) ∼0.4s of performing repackaging checks; and (iii) ∼0.4s of uploading apps to IPFS. With these, the overall overhead introduced by AGChain is from 2.16% to 17.61%, with the median and average of 12.05% and 11.39%, respectively. We thus conclude that AGChain’s performance overhead is 12%, a reasonable performance cost for a blockchain-based system.

6.2 Gas Costs

During the 140 performance tests, we also collect their corresponding gas fees in Ether (tested in the Ethereum Rinkeby network). One Ether is around 1,000 USD (at the historically high range) at the time of our submission.

Figure 3 shows the CDF (cumulative distribution function) plot per app uploading in AGChain. We can see that over 95% gas fees are in the range of 0.00008245 Ether (0.082 USD) and 0.00008773 Ether (0.088 USD). Only four tests consumed a gas fee over 0.0001 Ether, ranging from 0.00010374 and 0.00012461 Ether. The average of all 140 gas fees is 0.00008466 (0.085 USD). Since only uploads in AGChain costs gas and one upload can serve all future downloads, we believe that such a gas cost is acceptable. To further reduce gas in the future, we will explore other smart contract platforms (e.g., the gas-free EOS [27] and Hyperledger Fabric [25]) beyond the currently widely-used Ethereum.

6.3 Security

Since there are no real-world attacks against AGChain, we mimic a MITM (Man-In-The-Middle) attack and a repackaging attack to demonstrate AGChain’s security effectiveness.
Table 4: IPFS gateways identified in 21 different locations.

| Gateway Domain               | IP Address      | Location            | RTT (s) |
|------------------------------|-----------------|---------------------|---------|
| ipfs.jbb.one                 | 47.52.139.252   | Hong Kong SAR       | 0.04    |
| ipfs.smartsignature.io       | 13.231.230.12   | Tokyo, Japan        | 0.07    |
| 10.via0.com                  | 104.27.129.45   | San Francisco, U.S.A| 0.13    |
| ipfs.kavin.rocks             | 104.28.5.229    | Dallas, U.S.A       | 0.14    |
| ipfs.runfission.com          | 34.233.130.24   | Ashburn, U.S.A      | 0.25    |
| ipfs.klic.com                | 39.101.143.85   | Beijing, China      | 0.51    |
| ipfs.2read.net               | 195.201.149.81  | Gunzenhausen, DE    | 0.55    |
| ipfs.greyh.at                | 98.126.159.6    | Orange, U.S.A       | 0.56    |
| gateway.pinata.cloud         | 165.227.144.202 | Frankfurt, Germany  | 0.56    |
| ipfs.telos.miami             | 138.68.29.104   | Santa Clara, U.S.A  | 0.57    |
| hardbin.com                  | 174.138.8.194   | Amsterdam, NL       | 0.57    |
| ipfs.fleet.co                | 44.240.5.243    | Portland, U.S.A     | 0.57    |
| ipfs.greyh.at                | 35.208.63.54    | Council Bluffs, U.S.A| 0.69    |
| gateway.temporal.cloud       | 207.6.222.55    | Surrey, Canada      | 0.70    |
| ipfs.azurewebsites.net       | 13.66.138.105   | Redmond, U.S.A      | 0.72    |
| ipfs.best-practice.se        | 193.11.118.5    | Eskilstuna, Sweden  | 0.73    |
| ipfs.overpi.com              | 66.228.43.18     | Cedar Knolls, U.S.A | 0.74    |
| jorropo.net                  | 163.172.31.60   | Paris, France       | 0.76    |
| jorropo.ovh                  | 51.75.127.200   | Roubaix, France     | 0.76    |
| ipfs.stibarc.com             | 74.140.55.163   | Delaware, U.S.A     | 0.81    |
| ipfs.sloppytya.co            | 51.68.154.205   | Warsaw, Poland      | 0.83    |

6.4 Decentralization

During the 140 performance tests in different timings, we also identify IPFS gateways in over 20 different locations world-wide, which demonstrate the decentralization of AGChain. Table 4 lists the IPFS gateways we have identified. We can see that they are distributed in 21 different locations worldwide. Around a half, ten, gateways are located in US. This is probably because many IPFS nodes run in cloud servers, which are mainly provided by US companies. Other than US, Europe holds seven gateways out of the remaining 11. Compared with US and Europe, there are only three gateways in Asia (the remaining one gateway in Canada). However, we believe that with the recent popularity of FinTech in Asia [34], more and more IPFS nodes will be deployed locally in Asia for faster connections. Additionally, according to the RTT result in Table 4, nearby IPFS gateways usually have small RTTs, which suggests the value of identifying fast IPFS gateways in AGChain for app downloading (see §3.4).

7 DISCUSSION

In this section, we discuss several potential improvements AGChain could integrate with in the near future.
More user-friendly. In our current AGChain prototype, we require users to download apps according to their package names and version numbers. A more user-friendly way is to let them input or search app names. To do so, we can crawl the app page information from existing app markets and maintain a table of app names (in different languages) and their corresponding package names at the server side. Since app names are not the unique identifiers as package names, there is no need to store them in the smart contract. By providing a more user-friendly search of apps, we also reduce the possibility of a usability risk that an adversary uses a slightly different package name to cheat users for downloading a fake app.

Inviting developers. Although AGChain provides a real-time app delegation for users to download apps just in time, it would be beneficial if AGChain already stores a large number of apps. This also increases user-friendliness. To do so, we plan to invite developers on Google Play to submit their apps to AGChain, which helps their apps reach more users who desire decentralized access. Specifically, since each Google Play app page lists developers’ email, we can crawl that information and send automatic emails to them. To give developers more incentives, we can pay uploading gas fees for the first 10,000 developers who join our program and help them automatically upload their apps.

More secure. While we have performed repackaging checks to detect repackaged apps, AGChain currently cannot detect the more general Android malware. We plan to mitigate this issue by incorporating the malware scan of VirusTotal [19]. Specifically, we will use VirusTotal APIs to scan each uploaded app at the server side and save the URL of scanned reports as a part of app metadata into our smart contract. In this way, users can check those scan reports during app downloading, and we will also give explicit warnings for suspicious apps.

8 RELATED WORK
AGChain is mostly related to several recent works [36–38, 43] that also leveraged the blockchain and IPFS technology to build decentralized systems in different domains. For example, PubChain [43] is a decentralized publication platform, which saved paper metadata in the blockchain layer and stored raw paper files in IPFS. In particular, it designed an incentive mechanism called PubCoin to reward the participants through a process we summarized as “publishing or reviewing as mining.” Another paper on arXiv, DClaims [37], presented a censorship-resistant service that uses decentralized web notations to disseminate information on the Internet. Similar to AGChain, it used Ethereum as the blockchain platform and integrated IPFS as the backend data storage. Since web notating could be very frequent among a large number of users, DClaims built a small network of nodes to assemble multiple blockchain transactions and broadcast them together so that it could reduce the average cost of each transaction. Besides these works, Shafagh et al. [38] published a pioneer study on integrating blockchain and IPFS, which was inspired by the Blockstack [23] system’s four-layer design, namely blockchain, virtualchain, routing, and storage layers. Compared with these related studies, AGChain is unique in the following four aspects:

Firstly, unlike other blockchain systems that asked users to choose between the existing IT infrastructure and theirs, we did not aim to replace existing app markets with AGChain. Instead, we designed AGChain to be a gateway that not only brings permanent app delegation to end users but also makes use of massive apps in existing markets. We believe that such a design opens a new direction on combining the advantages of traditional IT infrastructure and decentralized blockchain.

Secondly, we significantly reduced gas costs in AGChain by proposing a set of design-level mechanisms. In contrast, no aforementioned related works [36–38, 43] tried to do that. There were some other works on gas optimization but they focused only on the language-level optimizations. Specifically, GASP [29] identified gas-costly smart contract coding patterns and summarized them into two categories, loop-related and useless codes. MadMax [31] leveraged control- and data-flow analysis of smart contracts’ bytecode to detect the gas-related vulnerabilities, including unbounded mass operations, non-isolated external calls, and integer overflows. Besides these two detection works, GASOL [22] introduced a gas optimization approach by replacing one multiple accesses to the global storage data with several single accesses to the data in local memory. An access to the local memory (3 Gas per access) costs much fewer than an access to the storage data (each write access costs 20 Gas in the worst case and 5 Gas in the best case). However, such an optimization is still at the code level and designed only for the specific gas-costly pattern.

Thirdly, no aforementioned related works [36–38, 43] mentioned the undistributed problem of IPFS, where IPFS files are cached in other nodes only when the node requests that file. Besides our attempt to this problem in §3.4, IPFS designers themselves also tried to address this issue. Recently, they have launched Filecoin [10], an incentive token mechanism for encouraging peers in the IPFS network to stay online and take the responsibility to store files. However, Filecoin requires users to pay for file storage, and the entire progress of storing 1MB file takes five to ten minutes in the current Filecoin network [10]. Due to these limitations, we built our own IPFS consortium network that leveraged IPFS gateways and crowdsourced server nodes to periodically backup files.

Lastly, we encountered three context-specific challenges that are unique to AGChain, as already explained in §4.
9 CONCLUSION

In this paper, we proposed a novel gateway design for app markets called AGChain. By nature, it is a blockchain-based gateway for permanent, distributed, and secure app delegation for massive apps stored in existing markets (and custom apps via GitHub URLs). We designed a smart contract and IPFS-based architecture to make AGChain permanent and distributed, for which we overcame two previously underestimated design challenges to significantly reduce gas costs in our smart contract and make IPFS-based file storage really distributed. We further addressed three AGChain-specific system challenges to make it secure and sustainable. We have implemented a publicly available AGChain prototype (https://www.agchain.ltd/) on Ethereum with 2,485 LOC. We then experimentally evaluated its performance and gas costs, and empirically demonstrated security effectiveness and decentralization. The evaluation shows that on average, AGChain introduced 12% performance overhead in 140 app tests from seven app markets and costed 0.00008466 Ether per app uploading. We will continue to improve AGChain for it to be more user-friendly, secure, and gas-efficient.

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REFERENCES

[1] 2016. logs - How does Ethereum make use of bloom filters? https://ethereum.stackexchange.com/questions/3418/how-does-ethereum-make-use-of-bloom-filters/.
[2] 2017. Change Your App Store Country to Download Region-Locked Apps & Games on Your iPhone. https://ios.gadgethacks.com/how-to/change-your-app-store-country-download-region-locked-apps-games-your-iphone-0176591/.
[3] 2018. Bloom Filters in Ethereum. https://medium.com/@naterush1997/eth-goes-bloom-filling-up-ethereums-bloom-filters-6844ec237009.
[4] 2018. Diving into Ethereum’s world state. https://medium.com/cybermiles/diving-into-ethereums-world-state-c893102030ed.
[5] 2018. Easily Change Your Play Store Country to Download Region-Locked Apps & Games. https://android.gadgethacks.com/how-to-easily-change-your-play-store-country-download-region-locked-apps-games-0186542/.
[6] 2018. Top 5 most dangerous Public WiFi attacks. https://e-channelnews.com/top-5-most-dangerous-public-wifi-attacks/.
[7] 2019. 5 Best VPNs to watch TVB from anywhere. https://www.comparitech.com/blog/vpn-privacy/bvpn-tvb/.
[8] 2020. Androguard. https://androguard.readthedocs.io/en/latest/.
[9] 2020. Changing permissions for an IAM user. https://docs.aws.amazon.com/IAM/latest/UserGuide/id_users_change-permissions.html.
[10] 2020. Filecoin Network Performance. https://docs.filecoin.io/about-filecoin/network-performance/.
[11] 2020. How to access Google Play Store in China. https://www.bestvpn.co/how-to-unblock-websites-access-google-play-store-china/.
[12] 2020. How to Unblock Hulu from Anywhere in 2020. https://www.vpmentor.com/blog/how-to-unblock-hulu-from-anywhere/.
[13] 2020. The Huawei ban explained: A complete timeline and everything you need to know. https://www.androidauthority.com/huawei-google-android-ban-988382/.
[14] 2020. JS IPFS. https://js.ipfs.io/.
[15] 2020. Mitmproxy. https://mitmproxy.org/.
[16] 2020. React – A JavaScript library for building user interfaces. https://reactjs.org/.
[17] 2020. Summary of Changes of the Google Play Developer Distribution Agreement. https://play.google.com/about/developer-distribution-agreement/summary.html.
[18] 2020. The Power of Content-addressing. https://flyingzumwalt.gitbooks.io/decentralized-web-primer/content/avenues-for-lessons/power-of-content-addressing.html.
[19] 2020. VirusTotal. https://www.virustotal.com/.
[20] 2020. web3.js for Ethereum. https://web3js.readthedocs.io/en/v1.3.0/.
[21] 2020. web3.py for Python. https://web3py.readthedocs.io/en/stable/.
[22] Elvira Albert, Jesús Correas, Pablo Gordillo, Guillermo Román-Diez, and Albert Rubio. 2020. GASOL: Gas Analysis and Optimization for Ethereum Smart Contracts. In Proc. Springer TACAS.
[23] Muneeb Ali, Jude Nelson, Ryan Shea, and Michael J. Freedman. 2016. Blockstack: A Global Naming and Storage System Secured by Blockchains. In Proc. USENIX ATC.
[24] Kevin Allix, Tegawende F. Bissyande, Jacques Klein, and Yves Le Traon. 2016. AndroZoo: Collecting Millions of Android Apps for the Research Community. In Proc. ACM MSR.
[25] Elli Androulaki, Artem Barger, Vita Bortnikov, Christian Cachin, Konstantinos Christidis, Angelo De Caro, David Eneyart, Christopher Ferris, Gennady Laventman, Yacov Manevich, Srinivasan Murailharan, Chet Murthy, Binh Nguyen, Manish Sethi, Gari Singh, Keith Smith, Alessandro Sorniotti, Chrysoula Statathkopoulou, Marko Vukolic, Sharon Weed Coco, and Jason Yellick. 2018. Hyperledger fabric: a distributed operating system for permissioned blockchains. In Proc. ACM EuroSys.
[26] Juan Benet. 2014. IPFS - Content Addressed, Versioned, P2P File System. CoRR arXiv abs/1407.3561 (2014).
[27] block.one. 2018. EOS.IO Technical White Paper v2. https://github.com/EOSSO/Documentation/blob/master/TechnicalWhitePaper.md.
[28] Vitalik Buterin et al. 2014. A next-generation smart contract and decentralized application platform. white paper (2014).
[29] Ting Chen, Xiaoqi Li, Xiapu Luo, and Xiaosong Zhang. 2017. Under-optimized smart contracts devour your money. In Proc. IEEE SANER.
[30] Brian Curran. 2018. What is Interplanetary File System IPFS? Complete Beginner’s Guide.
[31] Neville Grech, Michael Kong, Anton Jurisevic, Lexi Brent, Bernhard Scholz, and Yannis Smaragdakis. 2018. MadMax: surviving out-of-gas conditions in Ethereum smart contracts. In Proc. ACM OOPSLA.
[32] Rahul Hiran, Niklas Carlsson, and Philippa Gill. 2013. Characterizing Large-scale Routing Anomalies: A Case Study of the China Telecom Incident. In Proc. Springer PAM.
[33] Li Li, Tegawende F. Bissyande, and Jacques Klein. 2019. Rebooting next-for-asia-in-fintech-adoption.
[34] James Lloyd. 2020. What is next for Asia in FinTech adoption. https://www.evm.com/en/gl/banking-capital-markets/what-is-next-for-asia-in-fintech-adoption.
[35] Jude Nelson, Muneeb Ali, Ryan Shea, and Michael J. Freedman. 2016. Extending Existing Blockchains with Virtualchain. In Workshop of Distributed Cryptocurrencies and Consensus Ledgers.
[36] Van-Duy Pham, Canh-Tuan Tran, Thang Nguyen, Tien-Thao Nguyen, Ba-Lam Do, Thanh-Chung Dao, and Binh Minh Nguyen. 2020. B-Box - A Decentralized Storage System Using IPFS, Attributed-based Encryption, and Blockchain. In Proc. IEEE RIVF.
[37] João Santos, Nuno Santos, and David Dias. 2019. DClaims: A Censorship Resistant Web Annotations System using IPFS and Ethereum. CoRR arXiv abs/1912.03388 (2019).

[38] Hossein Shafagh, Lukas Burkhalter, Anwar Hithnawi, and Simon Duquennoy. 2017. Towards Blockchain-based Auditable Storage and Sharing of IoT Data. In Proc. ACM Cloud Computing Security Workshop (CCSW).

[39] Petar Tsankov, Andrei Marian Dan, Dana Drachsler-Cohen, Arthur Gervais, Florian Bünzli, and Martin T. Vechev. 2018. Securify: Practical Security Analysis of Smart Contracts. In Proc. ACM CCS.

[40] Sarah Underwood. 2016. Blockchain Beyond Bitcoin. Commun. ACM 59 (2016).

[41] Haoyu Wang, Zhe Liu, Jingyue Liang, Narseo Vallina-Rodriguez, Yao Guo, Li Li, Juan Tapiador, Jingcun Cao, and Guoai Xu. 2018. Beyond Google Play: A Large-Scale Comparative Study of Chinese Android App Markets. In Proc. ACM IMC.

[42] Huibo Wang, Pei Wang, Yu Ding, Mingshen Sun, Yiming Jing, Ran Duan, Long Li, Yulong Zhang, Tao Wei, and Zhiqiang Lin. 2019. Towards Memory Safe Enclave Programming with Rust-SGX. In Proc. ACM CCS.

[43] Taotao Wang, Soung Chang Liew, and Shengli Zhang. 2019. PubChain: A Decentralized Open-Access Publication Platform with Participants Incentivized by Blockchain Technology. CoRR arXiv abs/1910.00580 (2019).

[44] Gavin Wood et al. 2014. Ethereum: A secure decentralised generalised transaction ledger. Ethereum project yellow paper (2014), 1–32.

[45] Haoqian Zhang, Yancheng Zhao, Abhishek Paryani, and Ke Yi. 2020. Infnote: A Decentralized Information Sharing Platform Based on Blockchain. CoRR arXiv abs/2002.04533 (2020).

[46] Wu Zhou, Yajin Zhou, Xuxian Jiang, and Peng Ning. 2012. Detecting Repackaged Smartphone Applications in Third-Party Android Marketplaces. In Proc. ACM CODASPY.