Abstract—Smart contracts are a new paradigm that emerged with the rise of the blockchain technology. They allow untrusting parties to arrange agreements. These agreements are encoded as a programming language code and deployed on a blockchain platform, where all participants execute them and maintain their state. Smart contracts are promising since they are automated and decentralized, thus limiting the involvement of third trusted parties, and can contain monetary transfers. Due to these features, many people believe that smart contracts will revolutionize the way we think of distributed applications, information sharing, financial services, and infrastructures.

To release the potential of smart contracts, it is necessary to connect the contracts with the outside world, such that they can understand and use information from other infrastructures. For instance, smart contracts would greatly benefit when they have access to web content, such as financial information, sports results, or the weather. However, there are many challenges associated with realizing such a system, and despite the existence of many proposals, no solution is secure, provides easily-parsable data, introduces small overheads, and is easy to deploy.

In this paper we propose PDFS, a practical system for data feeds that combines the advantages of the previous schemes and introduces new functionalities. PDFS extends content providers by including new features for data transparency and consistency validations. This combination provides multiple benefits like security, efficiency, and possible new applications. In PDFS, data is authenticated over blockchain and validated by content providers, which allows smart contracts to use it in a precise and unambiguous way. If implemented successfully, the potential of smart contracts is tremendous as they promise to revolutionize many industries and business sectors (including finance, logistics, payments, and insurances) and create a new type of applications. The concept has been unexplored for decades; however, with the rise of Bitcoin, distributed consensus, and blockchain platforms in general, smart contracts can finally be implemented in a practical way.

Smart contracts deployed solely on a blockchain platform have some fundamental limitations. One problem is that a smart contract can only use resources available on the blockchain (like account addresses, other smart contracts, or a cryptocurrency native to the used blockchain platform). This issue limits smart contracts from using external data provided by other infrastructures, like HTTP(S) data feeds. Ideally, smart contracts could process data provided by other infrastructures, like websites, and use that to encode processing logic. Unfortunately, there are many challenges associated with that.

One such challenge is the authenticity of data feeds. Data provided to a smart contract should be authentic, so that the smart contract can verify its origin and execute accordingly. Unfortunately, the widely deployed Transport Layer Security (TLS) protocol [10] is inoperable in such a setting. Secure web servers that deploy it (i.e., running HTTP over TLS – HTTPS), cannot provide data authenticity to third parties like smart contracts. First approaches to make this data accessible to smart contracts, were centralized oracles [35], [1], [12], [23]. This introduced a new trusted third parties which fetch HTTPS websites, parse them, and provide the data to smart contracts (which finally process it). These solutions present strong trust assumptions (i.e., a new trusted party), and to relax it a concept of oracles based on trust computing was proposed [33]. These oracles work similarly, however, the code run by them is executed with the Intel’s Software Guard Extensions (SGX) framework, which allows proving attestation of the code executed by the oracles. A disadvantage of this approach is to position Intel as a centralized trusted entity, and SGX as a trusted technology. In contrast to these approaches, TLS-N [21] enhances the TLS protocol by providing non-repudiation. TLS-N authenticates TLS records sent to clients during client-server TLS sessions. TLS-N requires TLS stack modifications and provides hard-to-process data feeds, but it does not introduce any new trusted entities.

In this paper, we propose PDFS, a practical data feed service for smart contracts that aims to fill the gap between oracle solutions and transport-layer authentication. Our architecture allows content providers to link their web entities with their blockchain entities. This design provides many benefits like security, efficiency, and possible new features. In PDFS, data is authenticated over blockchain...
but without breaking TLS trust chains or modifying TLS stacks. Moreover, content providers can specify data formats they would like to use freely; thus data can be easily-parsable and tailored for smart contracts. Besides that, PDFS provides content providers with a payment framework, but it does not allow content providers to misbehave by equivocating or censoring queries.

II. Background

A. Blockchain and Smart Contracts

Bitcoin [21] introduced the concept of open and decentralized consensus which, in combination with an append-only data structure, let to the existence of cryptocurrency without trusted parties. This combination, and its variants, is usually referred to as a blockchain. Bitcoin has inspired other systems that either improve Bitcoin’s inefficiencies (e.g., Litecoin [17]) or provide completely different functionalities and applications (like Ethereum [34], Namecoin [22], Zcash [25], or Monero [20]). However, there are common properties and features that these systems share. For example, they are either completely open or aim to decentralize operations, such that everyone can actively participate in the system. They introduce native monetary transfers and cryptocurrencies that incentive participants to run the consensus protocol. Besides that, most of the blockchain platforms leverage an old idea of using (hashes of) public keys as participants’ identifiers [18].

A particularly interesting and promising class are platforms that leverage blockchain to implement smart contracts. Usually, these systems rely on the append-only property provided by blockchain platforms that allow realizing smart contracts by a replicated execution (i.e., all participants execute the same code for the same inputs, thus maintaining the same state). These platforms, besides standard monetary transfers, introduce high-level languages that allow to specify agreements by any parties and execute these agreements on top of the blockchain.

The most prominent smart contract platform is Ethereum [34]. Ethereum follows the replicated execution model and it provides smart-contract-oriented high-level languages. In Ethereum, anyone can specify a smart contract (i.e., an object with a set of methods and an associated state) and instantiate it by publishing it on the blockchain (by simply sending its code). After it is deployed, each smart contract gets a unique blockchain address and from this point anyone can interact with the contract using this address. Smart contracts can implement almost arbitrary logic, including monetary transfers, thus making this technology appealing to financial-related services and other businesses. Smart contract methods are triggered by sending transactions to its address (a transaction contains the smart contract’s address and the methods’ arguments). These transactions are ordered and processed by all miners (i.e., blockchain nodes that run the consensus protocol) in the system that execute the same code with the same input. Therefore, anyone can agree on a state change that a given execution has introduced. A smart contract can interact with other smart contracts, by simply calling its method(s). Every transaction that triggers a method has to be accompanied with a prepaid cost, called gas. Gas is the execution fee expressed in ether (the Ethereum’s native currency). Gas is consumed per operation and operations vary in gas cost depending on resources they need, thus more resource-consuming calls require more gas to be supplied with.

B. Transport Security Layer

The Transport Security Layer (TLS) protocol [10] is one of the most widely deployed security protocols on the Internet. The protocol is designed for the client-server architecture. It aims to provide data confidentiality and integrity, as well as authentication of protocol participants. TLS was not designed to provide non-repudiation. Therefore, even a communicating party (i.e., a client or a server) cannot prove to any third party that a given content was produced during the TLS connection. The TLS protocol is not specific to any application, however most prominently, it is deployed for securing web traffic (i.e., HTTPS). In such a setting it is common that only the server’s identity is authenticated.

Identity authentication in TLS is based on the X.509 public-key infrastructure (PKI) [7]. Every entity that wishes to get its identity authenticated has to obtain a digital certificate asserting the identity and its public key. Certificates are issued by trusted entities called certification authorities, which are obligated to verify the identity of a requester and issue a certificate correspondingly. During a TLS connection establishment, a server presents its certificate to the client which verifies the certificate and the server’s identity and then uses the corresponding public key to continue an agreement of a shared secret key. This key is used for protecting the subsequent communication.

C. Tamper-evident Data Structure

A Tamper-evident Data Structure (TDS) is a data structure that allows building log systems where an untrusted logger records clients’ entries in an append-only log. The logger must be able to prove to auditors that

• every logged entry is still present in the log, and
• one snapshot of the log is consistent with any its previous version.

Many early proposals aimed to achieve similar properties, mainly in the context of building a digital notary [14], [4]. However, the semantics of TDS and the first efficient construction to achieve it were proposed by Crosby and Wallach [9]. In their system TDS is based on a Merkle hash tree also called a hash tree. A Merkle hash tree is a binary tree where leaf nodes are labeled with the hash of entries and non-leaf nodes are labeled with the hash of the

1Although Bitcoin has a script language that allows to express smart contracts it is neither easy nor efficient [2].

2In fact, the server sends a certificate chain that includes the server’s certificate, the certificate of the issuing intermediate CA (there can be multiple intermediate CA certificates), and a self-signed root CA’s certificate that TLS clients have preloaded in their software.

3By hash we mean an output of a cryptographic hash function.
concatenated labels of its child nodes. Therefore, the root of the tree is an aggregated integrity information about all its leaves.

In the Crosby-Wallach construction, the log’s primary structure is a Merkle hash tree with submitted entries as the leaves. The log is append-only, i.e., the entries are sorted in chronological order of their submission, and no leaf can be retrospectively removed or modified. The log supports the following history-related operations (we give examples of these operations in subsection IV-C):

**Addition** of an entry. Whenever a new entry is added to a log, a new leaf is added to the tree, and the tree is re-computed (entries can be added in batches, so that the tree need not re-compute for every single entry).

**Membership Proof Generation** for an entry produces a membership proof that proves that the entry is part of the log. The membership proof of an entry is the minimal set of the tree nodes (i.e., hashes) required to reconstruct the root. In the described construction, a membership proof requires $O(\log n)$ nodes, where $n$ is the number of log entries.

**Membership Verification** for a given entry verifies whether the entry is part of the given log snapshot. It takes an entry, a membership proof, and a root value as input and verifies whether the entry matches the proof and whether the proof terminates at the given root (i.e., the computed path has the root at the end). The operation returns True if the verification is successful and False otherwise. Membership verification is efficient since it only requires $O(\log n)$ hash operations.

**Consistency Proof Generation** for two different snapshots of the log, a newer and an older, provides a short proof (i.e., $O(\log n)$ nodes) that the newer snapshot is an extension of the older one, i.e., the newer snapshot was produced by only appending entries to the older snapshot.

**Consistency Verification** takes as an input a consistency proof between two snapshots and verifies whether the consistency proof is correct, i.e., whether indeed the new version of the log was obtained by appending new entries. The verification procedure is also efficient (i.e., logarithmic in time and space) with respect to the log’s size.

### III. Architecture Overview

**A. System Model**

There are the following parties in a PDFS system:

**Content Providers** are entities that provide content. For simple and intuitive description, we assume that the content is provided through the secure web (HTTPS); however, such a setting is not mandatory, and content providers do not have to run web services. Domain names identify content providers, and their content is accessed through URL addresses. Each content provider has a valid TLS certificate. In essence, content providers are not different from today’s websites.

**Contract Parties** are mutually untrusting parties that would like to arrange a smart-contract-based agreement which requires data from a content provider. Contract parties have to agree on who can act as the content provider for their relying contract. Therefore, content providers are trusted only locally by parties that want trust them. We assume that the protocol parties have access to a blockchain platform with smart contracts enabled (e.g., Ethereum).

We assume an adversary whose goal is to produce fake data on behalf of a content provider. The adversary can eavesdrop, modify, and inject any protocol messages. She can also interact freely with protocol parties and the blockchain platform. We assume that the adversary cannot compromise underlying cryptographic primitives and protocols (i.e., TLS), and cannot violate properties of the deployed blockchain platform. Moreover, we assume that the adversary cannot compromise content providers’ secret keys and cannot obtain a malicious certificate for a content provider (i.e., cannot compromise the TLS PKI). However, we discuss such strong adversaries in section V.

We also assume a content provider trying to misbehave by launching an equivocation attack [31] or by censoring queries for its content. In the former case, the content provider should not be able to modify or delete any published content retrospectively. For the latter case, censorship is especially important in the context of the smart contract, as a content provider could influence a contract execution by censoring some required content. Thus for this attack, such censorship attempts should be at least visible.

**B. Desired Properties and Design Space**

Below we list the desired properties of a data feeds service for smart contracts.

**Easily parsable data feeds:** data feeds should be easily parsable by smart contracts which use them. Besides practical implications like a more straightforward code base, this property improves the cost-effectiveness of smart contracts deployment, as smart contract platforms usually charge contract executions per number of operations (see subsection II-A).

**Authenticity of data feeds:** the high evidence that data feeds are authentic (i.e., were produced by a content provider trusted by contract parties) should be provided. Ideally, authenticity verification should follow a direct and natural trust chain (i.e., contract parties trusting example.com can specify in their contract that the contract can rely only on data provided by example.com).

**Easy to adopt and deploy:** all protocol parties (including content providers) should be able to start using the data feed system without major changes like a new infrastructure required or non-backward compatible changes to lower-layer protocols. Ideally, the system should be implementable and deployable in today’s setting with existing protocols and infrastructures.
One of the main challenges of designing a practical data feed service is to achieve both easily parsable and authentic data feeds at the same time. Many of the existing proposals (see section VII) are introducing new third trusted parties that break natural trust relationships. For instance, contract parties trusting bbc.co.uk to use its data feeds have to trust another party (unauthorized by bbc.co.uk).

A conceptually different design is to authenticate data feeds directly by content providers. To achieve that, the currently existing proposals (see section VII) enhance the TLS protocol by providing non-repudiation at the TLS layer. Therefore, TLS records are signed, so can be directly verified by relying smart contracts. On the other hand, systems following that design produce content that may be difficult to parse (without significant and low-level application changes) and require major TLS modifications and TLS stack updates on TLS servers.

C. High-level Overview

Design decisions behind PDFS try to balance the designs presented above and try to achieve all stated properties. First of all, in our system non-repudiation is provided directly by content providers. This is similar to the approaches that modify the TLS protocol; however, the authentication is not conducted at the TLS layer. Instead, we introduce a layer of indirection that allows authenticating content on the blockchain.

In our design, content providers link their TLS identities with their blockchain identities and locations of special smart contracts used for authenticating and verifying their content. Such a design provides multiple benefits. Firstly, it enables verifying blockchain identities, directly through the existing TLS PKI. Secondly, it allows relying contracts to validate the authenticity of data as simple as calling another smart contract’s method (without involving any in-contract expensive public-key operations). Lastly, integrating content providers with blockchain enables new features like keeping the providers accountable, proving their unavailability, or providing a payment framework that can incentivize them to initiate the service.

A high-level overview of our system is shown in Figure 1, and in this section, we describe its steps and the main components.

The first step in our protocol is to create a content contract by a content provider who wishes to participate in PDFS. The main aim of content contracts is to enable other contracts to verify the authenticity of the content produced by content providers. Content contracts provide additional functionalities by ensuring that content providers do not misbehave: a) by retrospectively tampering with their data, or b) by censoring queries sent to them.

Every content contract provides an API that allows:

- its owner (i.e., the content provider) to update it,
- other contracts to verify that the content provider indeed produced given data,
- contract parties to make censorship-evident queries to the content provider for the specific content (this option is used when the content provider seems unavailable or censoring some queries).

Newly created content contracts do not store any data.

In the second step, the content providers create a signed manifest that contains the following elements:

- a location (i.e., a blockchain address) and interface structure of its content contract,
- metadata specifying details of provided content.

The manifest is signed, and the manifest’s signature is computed using the private key corresponding to the public key from the content provider’s TLS certificate. Such a setting follows the natural trust chain; therefore, it allows contract parties to verify the authenticity of manifests directly, using the TLS PKI, and without breaking existing trust chains.

The content provider creates a TDS that will store data entries that the content provider wants to serve. The first entry of this data structure is the manifest. For every update, the content provider adds new data entries to its TDS, re-computes the data structure, and sends the new root and its corresponding consistency proof to the content contract. (Content contracts do not store any actual content, but only TDS roots — the short authentication information about the content.) The content contract first ensures that the update is called by the content provider (i.e., the contract’s owner). Then, the content contract validates the sent information enforcing the append-only property (i.e., it makes sure that the content provider is appending data only – not modifying nor removing any entries). The data entries with their corresponding

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4 Application data in TLS is transported within data units called records.
membership proofs are published at a pre-defined URL location (e.g., https://example.com/pdfs/data/), so that everyone can locate and access it.

Contract parties that would like to deploy a relying contract (i.e., a smart contract which depends on a data feed from an external website) have to find and agree on a content provider. This process is realized out of band, e.g., by checking pre-defined URLs of high-profile websites (like https://yahoo.com/pdfs/ or https://skysports.com/pdfs/) or searching a catalog of known content providers. When the contract parties find the content provider they would like to use, they locate and verify its manifest and content contract, and hardcode the location of the content contract as an oracle in their relying contract.

Whenever one contract party would like to call a method that uses content provider’s data, it accesses the required data entry and its membership proof from the content provider and then calls this method with this pair (and a fee for content provider) as the arguments. Now, the method needs to verify whether the content provider indeed produced the data entry and to do so, the relying contract only requires to call the content contract’s membership verification method. When the data entry is verified, the relying contract’s method can continue with its processing logic.

IV. Details

In this section, we describe components of the PDFS architecture and explain its different steps since a content provider establishing its PDFS service until contract parties using the provider’s data to make a transaction within their smart contract. We also discuss how the content provider maintains the service. As shown in Figure 2, a PDFS service consists of a content contract, a web service whose entries are kept within a TDS, and a manifest. We provide details of these components and their functionality in this section.

A. Service Initialization

In the first step, the content provider initializes a PDFS service by deploying a content contract in the blockchain. This contract is designed to interact with the content provider’s back-end service, relying contracts, and contract parties. Initially, the content contract has empty storage; however, it will store root hashes of the deployed TDS. These root hashes will enable the contract to check on demand the consistency between two TDS snapshots (i.e., ensuring that the content provider updates its TDS correctly) and to conduct a membership verification (i.e., verifying for relying parties that an entry is part of the content provider’s TDS). (Further details of content contracts are discussed in subsection IV-B.) Once it is deployed, the content provider gets an address of the content contract instance.

Then, the content provider creates a manifest. The manifest is a file that describes details of the PDFS service. It is necessary for contract parties, since based on the manifest, they can create a workable relying contract.

The manifest has to be authentic. Therefore, the content provider signs it. As TLS certificates issued by certification authorities are widely trusted parties on the Internet, the content provider signs the manifest using the same private key (corresponding to its TLS certificate) that is used for serving its HTTPS web traffic. Such a design choice has multiple benefits. Firstly, it simplifies the signature creation and verification process since contract parties can obtain the required certificate by visiting the content provider’s website. Secondly, the manifest is authenticated following the already existing trust chain, so no new third party is trusted (see Figure 2). When the manifest is signed, it is added as the first element to the content provider’s TDS (all other elements of the TDS are data entries). We define and describe the fields that a manifest contains:

- **URL** corresponds to the URL address used by the content provider to publish data, and it indicates where contract parties can access data entries. For example, a weather forecast provider offers a PDFS service under the URL https://www.weather.com/pdfs/ and so that, contract parties would use that URL to get the desired data (e.g., https://www.weather.com/pdfs/?city=london&date=01-01-2018).

- **Content Contract Address** is the address in the blockchain associated with the deployed content contract. Contract parties preload their relying contract with the value of this field (to allow them calling procedures or functions on the content contract instance).

- **Content Contract Interface** is an abstract structural descriptor of the content contract. It includes definitions of functions, their access method or visibility, and parameters. Likewise the contract address, the content contract interface has to be embedded as an object interface in the relying contracts. This field is platform dependendent.

- **Data Structure** describes the encoding and the structure of data entries that the content provider stores in its TDS. Typically, content providers use widely adopted data encodings, such as JSON or XML. In that way, the content provider presents here which values and data types are expected to be found within every data entry. This field is necessary for contract parties to understand the semantics of data entries and to create their relying contracts able to parse data entries and implement their processing logic correctly.

- **Signature** is a field that authenticates all values contained in the manifest. As described above, the signature is computed using the private key associated with the content provider’s TLS certificate (used to serve HTTPS traffic). This allows anyone (especially, contract parties) to validate the integrity and authenticity of the manifest, and ensure that it corresponds to the specific content provider by using the publicly available TLS certificate.

If the TLS certificate used to verify the manifest

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5 For instance, Ethereum provides the Application Binary Interface (ABI) which is JSON-encoded data that establishes a standard way for contract-to-contract interactions.
expires, the PDFS service is not affected for relying contracts already deployed. It is because signatures and certificates are used by the contract parties to verify the authenticity of the manifest before they create relying contracts. Furthermore, neither the content contract nor relying contracts perform any signature verification later. On the other hand, the content provider does not require to terminate the PDFS service if the TLS certificate is reissued using the same private-public key pair that was used in the manifest creation.

**B. Content Contract**

The content contract is a central point in the PDFS architecture. It interacts with the content provider back-end (maintaining its TDS), relying contracts, and contract parties. Its primary goal is to ensure that the content provider indeed published a specific data entry. The pseudo-code of a content contract is shown in Algorithm 1, and it consists of the functions that allow:

- The content provider to store a new root hash of the TDS once its consistency is verified against the previous (already stored) root value. This procedure is executed by calling the `update` function (we discuss details about how the consistency verification is realized in subsection IV-C). The `update` function can be executed only by the content provider, as otherwise, an adversary would be able to violate the consistency of the PDFS service.
- Relying contracts to make trustworthy transactions based on data entries whose origin and integrity are verified by calling the `membership` function. This function checks whether a data entry (and its membership proof) validate against a root stored by the contract. In order to prevent time delays and race conditions, content contracts store a history of all committed roots.
- Contract parties to make censorship-evident queries to the content provider using the `query` function, and get responses to them by calling the `get_response` function. These queries and responses are sent over the blockchain, therefore they are publicly visible.

Functionalities offered to contract parties are designed to require payments for their executions. It allows content providers to adopt a new business model receiving micro-payments for providing a PDFS service.

**C. Data Update**

When new data entries are added to the TDS, it is re-computed producing a new root. Then, to run the service properly, PDFS requires synchronization of changes between the content provider back-end (maintaining the TDS) and the content contract which has to be updated to enable relying contracts to execute the membership verification of any newly added entry. To synchronize, the content provider submits the new root hash value along with the corresponding proof for the consistency verification (by calling the `update` function). The proof is a set of tuples where each one contains a hash value and a side indicator (either left or right). The consistency verification uses the set of provided hashes and their corresponding side to re-calculate two hash values. Then, it compares the calculated hashes checking whether they are equal to the new root value which is submitted and the last one stored in the content contract accordingly (see the `consistency` function in Algorithm 1). This guarantees that the new TDS is an extension of the last one committed confirming

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6 Fees for executing PDFS functions are different from fees for executing transactions on the blockchain (e.g., Ethereum gas cost).
Algorithm 1 Content Contract Pseudo-Code.

```
procedure INIT
1. roots ← ∅
2. time ← 0
3. locked ← False
4. procedure UPDATE(root, proof_cons)
5.  assert(sender = owner)
6.  assert(locked = False)
7.  if CONSISTENCY(root, proof_cons) then
8.      time ← NOW()
9.      roots[time] ← root
10. procedure CONSISTENCY(root, proof_cons)
11.  if time = 0 then
12.     return true
13.  (root_new, root_old) ← MTH(proof_cons, ∅)
14.  return (root_new = root & root_old = roots[time])
15. procedure LOCK
16.  assert(sender = owner)
17.  locked ← True
18. procedure MEMBERSHIP(data, proof_mem, fee)
19.  assert(fee = FEE_mem)
20.  leaf ← HASH(data)
21.  (root_mem, _ ) ← MTH(proof_mem, leaf)
22.  return root_mem ∈ roots
23. procedure MTH(proof, leaf)
24.  i ← 0
25.  hash_x ← leaf
26.  hash_y ← leaf
27.  if leaf = ∅ then
28.     i ← 1
29.     hash_x ← proof(0).hash
30.     hash_y ← proof(0).hash
31.     for i < len(proof) do
32.        if proof (i).side = RIGHT then
33.           hash_x ← HASH(hash_x || proof(i).hash)
34.        else
35.           hash_x ← HASH(proof(i).hash || hash_x)
36.        hash_y ← HASH(proof(i).hash || hash_y)
37.        i ← i + 1
38.     return (hash_x, hash_y)
39. procedure QUERY(filter, fee)
40.  assert(fee = FEE_query)
41.  counter ← counter + 1
42.  queries[counter] ← filter
43.  return counter
44. procedure STORE_RESPONSE(id, data)
45.  assert(sender = owner)
46.  assert(id ≤ counter)
47.  responses[id] ← data
48. procedure GET_RESPONSE(id)
49.  assert(id ≤ counter)
50.  return responses[id]
```

that none previous data entry has been altered or removed. When the new root is accepted by the content contract, the content provider can make the updated TDS accessible over HTTPS.

The first time the updating procedure is executed, it stores the root value directly with no verification. However, that happens only on the initialization phase, when the manifest is the only data entry in the TDS (for instance, case (a) in Figure 3). If any tampering or misbehavior is detected, the content contract ignores the submitted data and remains in the current state.

In Figure 3, we show an example of how the TDS evolves when data entries are added, and what values are sent for the submitting roots to the content contract. In case (a), the new root is stored into the content contract with no previous validation as it is the first one, and there is no consistency to evaluate. In case (b), the new root is submitted along with the following consistency proof:

\[ \text{proof}_{cons} = \{ h_{0L}, h_{1R}, h_{23R} \}. \]

The content contract uses the provided proof (i.e., the hashes and their sides encoded), to calculate a temporal hash value and evaluate whether it equals the root value that the provider is submitting. In this case, the consistency verification is easy to deduce since the previous root \((h_0)\) is contained in the provided proof. Intuitively, the new hashes in the proof \(h_{1R}, h_{23R}\) have “right” sides. Therefore it implies that the tree is growing.) Similarly when submitting the case (c), the consistency verifies the previous root \((h_{123})\) is contained in the \(proof_{cons}\) array.

However, case (c) in Figure 3 shows a particular situation due to the Merkle tree being unbalanced. It changes how the consistency verification works on next root submission. For case (d), the following consistency proof is provided:

\[ \text{proof}_{cons} = \{ h_{4L}, h_{5R}, h_{67R}, h_{1234L} \}. \]

Because of the unbalanced tree, the consistency verification re-calculates both roots, the previous \((h_{1234})\) and the new one \((h_{1234567})\), using the same provided proof. To
calculate the hash of the previous root, the consistency verification uses only the elements \( \{h_{4L}, h_{123L}\} \). Furthermore, the complete array is used to re-calculate the new root. Therefore, the procedure can confirm the consistency of the new TDS.

### D. Relying Contracts

A relying contract is created by contract parties who want to establish an agreement using a smart contract and data provided by a content provider. Firstly, once the contract parties agree on a content provider they trust, they access and verify the provider’s manifest (available at a pre-defined location, e.g., [https://a.com/pdfs/manifest.json](https://a.com/pdfs/manifest.json)). Once they ensure that the information contained in the manifest is authentic, contract parties use the manifest’s content contract’s address, the content contract’s interface, and the data structure description fields to prepare a relying contract. As shown in Algorithm 2, this information is necessary to be encoded in the relying contract code as it allows the relying contract to connect with the correct content contract instance and process data entries according to their semantics. At this point, the relying contract will be able to execute the membership verification procedure or get the response for a censorship-evident query made. Both these functionalities require contract parties to pay fees for their executions (although, the content provider can offer a free service by setting the fees to zero). Also, the relying contract will be able to parse a data entry and execute a processing logic depending on the data entry fields. Contract parties can encode an arbitrary processing logic, e.g., including monetary transfers.

When needed, a contract party requests the content provider for a specific data entry, which is returned along with the respective membership proof from the content provider. For instance, considering case (c) in Figure 3, if the content provider is queried for the data entry \( d_2 \), it responds to contract parties the data entry with the corresponding membership proof:

\[
\text{proof}_{mem} = \{h_{5L}, h_{91}, h_{4R}\}.
\]

As we see in this example, the provided proof and the hash value of the data entry lead to re-calculate the hash value \( h_{1234} \) which confirms the root. If any of the values are modified, either the data or the proof, the membership verification re-calculates a hash value which does not correspond to any stored root in the content contract, i.e., the verification fails.

The content provider may update its TDS and the content contract right after a contract party accessed a data entry with its corresponding proof. Thanks to the order of the update procedure (see subsection IV-C) and the design for the content contract, this situation does not lead to membership verification failures. The contract party can still submit the data entry with its “stale” membership proof, and because the content contract stores previously submitted roots, the membership verification will succeed.

### E. Censorship Evidence

In the context of content providers and smart contracts, censorship is an especially challenging threat. A content provider censoring queries can influence executions of smart-contract-based agreements. Additionally, censorship is difficult to prove. PDFS extends content contracts by censorship-evident queries. Whenever a data entry and its membership proof cannot be obtained directly from the content provider, it can be queried over the blockchain. A contract party can send a query to the content contract by calling the QUERY function, which for a query (following a SQL-like syntax) returns an ID number of the query made. When the content provider notices the query, the

\[\text{root}_{old}: \emptyset \quad \text{root}_{new}: h_0 \quad \text{proof}_{cons}: \emptyset \quad (a) \]

\[\text{root}_{old}: h_0 \quad \text{root}_{new}: h_{123} \quad \text{proof}_{cons}: \{h_{0L}, h_{1R}, h_{23R}\} \quad (b) \]

\[\text{root}_{old}: h_{123} \quad \text{root}_{new}: h_{1234} \quad \text{proof}_{cons}: \{h_{123L}, h_{4R}\} \quad (c) \]

\[\text{root}_{old}: h_{1234} \quad \text{root}_{new}: h_{1234567} \quad \text{proof}_{cons}: \{h_{4L}, h_{5R}, h_{67R}, h_{123L}\} \quad (d) \]

Fig. 3. An example of maintaining a TDS. It is a representation of information provided for the consistency verification when a new snapshot of the TDS is updated to the content contract. Each element of the proofcons indicates the hash value and the corresponding side (\( h_{xR} \) refers left position and \( h_{xR} \) refers right position).
response is prepared and published on the blockchain. Contract parties use the obtained ID number to get the respective response (by calling the GET_RESPONSE function). All these interactions are recorded as transactions in the blockchain; thus, any query and response become visible for anyone. Therefore, any censorship attempts are publicly visible. We discuss censorship-evident queries further in subsection V-C.

F. PDFS Service Termination

The content provider might need to terminate a PDFS service due to operational, management, or security reasons. To do so, the content contract can execute the LOCK function which disallows any future update attempt of the content contract (see Algorithm 1). Locking content contracts does not introduce collateral damage to already-deployed relying contracts. A locked content contract can be still used by relying contracts for a membership verification as long as the corresponding root value is already stored. In particular, the locking function might be useful in the case of a security breach (like a stolen blockchain private key), to prevent an adversary from submitting malicious root values (we discuss details in subsection V-B).

V. SECURITY DISCUSSION

A. Data Authentication

Our first claim is that an adversary cannot create a content on behalf of a content provider. To achieve that the adversary would need to either

1) tamper authenticated proofs generated by the content providers, or
2) update the content contract on behalf of the content provider, or
3) forge the manifest binding the content contract and identity of the content provider, or

All these attacks are out of scope our adversary model.

The first attack is infeasible due to the security of the tamper-evident data structured used [9]. More specifically, generating a membership proof for a non-element of the data structure is equivalent to breaking a deployed hash function. Therefore, the adversary to create such a proof for a malicious element has to extend the data structure by adding the element and updating the content contract by a new root. However, in this attack, the adversary cannot update the content contract as the content contract itself enforces the update procedure (see subsection IV-C). The update procedure allows only the contract’s owner (i.e., the owner of the associated private key) to update it. Therefore, without the content provider’s blockchain key, the adversary cannot update the legitimate content contract and prove on the malicious content.

For the last attack, the manifest’s digital signature is verified using the TLS PKI. Thus, without the ability to a) use a TLS private key of the content provider, or b) obtain a digital certificate of the content provider, the adversary cannot create a malicious manifest on behalf of the content provider. These attacks are out of the scope of our adversary model, but we discuss them and their implications in the next section.

B. PKI and Key Compromise

An adversary able to compromise the TLS PKI can create a malicious manifest and a content contract, and impersonate the content provider by creating arbitrary content. Interestingly, even if successful, such an adversary cannot undermine the security of the relying contracts already deployed since these contracts use the correct content contract instance for data verification. Moreover, by deploying a new (malicious) content contract, the adversary needs to deploy it over the blockchain, which makes the attack visible and detectable.

A more severe attack is a compromise of the private key used for the interactions between the content provider and the blockchain platform. In such a case, the adversary can add to the existing TDS malicious entries, re-compute the structure, and update the content contract with a new root. Then, these malicious entries can be used by relying smart contracts for processing. However, even in that case the attack is visible since the content contract is updated publicly, on the blockchain. Thus, the content provider will notice it and terminate its service (see subsection IV-F).

C. Malicious Content Provider

PDFS prevents and mitigates some attacks conducted by a malicious content provider.

The design of content contracts in PDFS does not allow the content provider (or an adversary with the content provider’s blockchain key) to retrospectively modify or remove content. The content contract enforces the consistency of the TDS for every update (see Figure 3). This property is also crucial for thwarting equivocation attacks [51]. A manifest file identifies the content contract that guarantees that the content provider cannot...
equivocate as long as the blockchain platform is secure (see
subsection V-D). The content provider can create multiple manifest files and content contract, however, a) it does not influence already deployed contracts, b) is not necessarily a malicious activity, and c) is visible over the blockchain. Thus, it can be monitored.

A subtler attack is a content provider censoring queries. That risk is especially important, when a contract party Bob tries to collude with the content provider to censor queries of another contract party Alice. Usually, a relying contract should specify a timeout after which contributions of the corresponding contract parties are sent back to them. Therefore, a party that would lose its money due to some event reported by a content provider has incentive to collude with the content provider to cause a timeout. The colluding content provider can ignore Alice queries, pretend unavailability, or display her incorrect data that cannot be successfully verified by the relying contract. Censorship is a generic attack, and the content provider does not risk its reputation as no malicious entry is created; however, such behavior can lead to attack Alice.

In such a case, PDFS allows Alice to query the content provider over the blockchain for a required query (see subsection IV-E). The content provider is obligated to respond to such a query. Moreover, Alice’s query and the content provider’s response are publicly visible. The content provider has three options a) respond with a valid response, and in that case Alice can just use the response to process the contract, b) respond with an invalid response, that would be publicly visible thus would ruin the reputation of the content provider, or c) can ignore the query, proving this fact to everyone.

D. 51%-Blockchain Attack

In this section we discuss how adversaries able to undermine the blockchain properties (although they are outside our adversary model) can impact PDFS. In particular, we focus on the 51%-attack [21] where an adversary possesses more than 50% of the total mining power of the blockchain network, which would allow her to rewrite the blockchain history. Such an adversary, could attack availability of PDFS (and any other blockchain application) by reverting or denying arbitrary transactions (or even content contracts creations).

An interesting scenario is an adversary colluding with a content provider. Besides availability attacks, the adversary could allow the content provider to equivocate by creating two conflicting TDS versions. One version would be maintained on the “main” blockchain, while the second one would exist only on the “malicious” blockchain mined by the adversary. Such an attack violates the desired property of keeping content providers consistent, and enables attacks similar as double-spending attacks [15].

Another interesting scenario is an adversary colluding with one of the contract parties to attack another contract party. Such an adversary cannot forge data entries or an outcome of the membership verification. However, it is a common practice that smart contracts define a timeout for inaction, after which deposits of the contract parties are sent back to them. In that case, the adversary could reverse a genuine transaction of the victim, causing the timeout from which the colluding party would benefit.

VI. Realization in Practice

In this section we demonstrate how PDFS fulfills the desired properties explained in subsection III-B. We fully implemented a proof of concept system by taking a real-world example which involved both parties of a PDFS architecture (the content provider and contract parties). Although we tested PDFS under a specific scenario (see subsection VI-B), PDFS can be integrated into any context where smart contracts need to make decisions based on external data. Our solution allows content providers, regardless of the format and data type, to become a trustworthy data feed for smart contracts.

A. Implementation

To approach our implementation of PDFS, we developed a web service for the content provider. It is a RESTful API which offers data entries encoded in JSON. In this case, we used Go v1.10.1 as the programming language. This application is configured to support HTTPS, and we created a private PKI infrastructure and TLS certificates using OpenSSL v1.1. The web service interacts with a smart contract, performing as the content contract. All data entries added in the TDS of PDFS are stored in RAM, so none database is required for data persistence.

Moreover, we created a web client able to request data entries to the web service explained above. This application is implemented in Python v3.6.5, and likewise the web service application, it interacts with a smart contract which performs as the relying contract. Smart contracts are coded in Solidity v0.4.21 and deployed in an Ethereum blockchain. We discuss details about the functionalities of each component in subsection VI-B. To allow reproduction of our experiments and evaluations, we publish our implementation at [https://gitlab.com/juan794/pdfs].

B. Case of study

In our proof of concept, we considered a scenario where two parties want to bet a certain amount of money, expressed in Eth, on the final score of a soccer game. For that, they decide to settle the agreement creating and deploying a smart contract which uses trusted data from a content provider who adopts PDFS in its service. Below we describe details of our application and how it can be integrated with PDFS.

Content Provider Following specifications and templates provided in section IV, our implementation of the content provider is a web service which offers scores of soccer games (i.e., The World Cup results) in the JSON format. We configured it to support HTTPS. The back-end of this application proceeds to execute the following tasks in order.

1) Knowing the content contract’s address and its interface, it creates and signs the manifest using the same private key associated with TLS certificates
(used for serving HTTPS connections). We show an example of how the manifest looks like in [Figure 4].

2) It appends the manifest as the first element of the TDS, and then submits the root to the content contract (this time, the proof of consistency is empty).

3) It periodically adds new entries to the TDS.
   a) The data entries are copied from a free football data provider [https://www.football-data.org/]. Data entries are slightly modified by reducing the number of fields, and in the end, each data entry contains a unique identifier, the date when the match happened, the name of the local team, the name of the visitor team, goals scored by the local team, and the goals scored by the visitor team (see an example in [Figure 5]). Data entries might be duplicated when our experiments required a bigger TDS for measurement purposes (only the id value is changed).
   b) It submits the final root value along with the consistency proof to the content contract, and then, it keeps idle waiting for queries.

We implemented the TDS using Keccak-256 [5] as a cryptographic hash function. We chose Keccak as it is a state-of-the-art hash function (the current standard SHA-3 [11] is an instance of Keccak) and it allows us to reduce the cost of membership and consistency verifications due to its native support in the Ethereum platform.

**Contract parties** It is an HTTP client application able to interact with the content provider and a relying contract. Firstly, it tries to get the manifest and validates the authenticity of the signature contained. Then, it requests a data entry and sends the response to the relying contract. In that way, the relying contract receives the data as the content provider delivers it, and then, executes the membership verification through interactions with the content contract. Once the origin and the integrity of the provided data are guaranteed, the relying contract proceeds to parse the JSON data and make transactions based on the extracted data; in our case study, the winner of the match.

As shown in [Figure 6], content provider responses consist of the content which is the data entry itself and the proofs field which is an array of elements indicating a hash value and a side (0 indicates left side and 1 indicates right one).

C. Evaluation

In this section, we discuss results obtained from a series of experiments we performed. To evaluate PDFS, we used a computer which has 16GB of RAM and a CPU Intel® Core i7 7700H. We deployed the content contract and the relying contract on a private Ethereum blockchain. We ran the applications for the content provider and contract parties in the same specification. We performed measurements regarding the execution cost which is expressed in Ethereum gas units, and then, converted to US dollars.

We analyzed the cost growth according to the number of data entries in the TDS. As shown in [Figure 7], we can see that the cost for the consistency and membership
TABLE I.  Cost analysis for membership and consistency verification considering multiple sizes of the TDS.

| TDS size | $2^1$ | $2^2$ | $2^{16}$ | $2^{15}$ | $2^{20}$ |
|----------|-------|-------|--------|--------|--------|
| Membership verification cost | | | | | |
| JSON Parsing | 113,349 (74%) | 113,325 (69%) | 113,293 (63%) | 113,273 (59%) | 113,298 (55%) |
| Hash calculation | 447 (1%) | 1,107 (1%) | 1,933 (2%) | 2,757 (2%) | 3,583 (3%) |
| Miscellaneous | 39,253 (25%) | 49,369 (30%) | 61,905 (35%) | 74,633 (39%) | 87,361 (42%) |
| **Total** | 153,049 | 163,801 | 177,131 | 190,663 | 204,242 |
| Consistency verification cost | | | | | |
| Hash calculation | 149 (1%) | 809 (2%) | 1,634 (3%) | 2,294 (3%) | 3,284 (4%) |
| Miscellaneous | 38,419 (99%) | 48,551 (98%) | 60,961 (97%) | 71,158 (97%) | 86,358 (96%) |
| **Total** | 38,568 | 49,360 | 62,595 | 73,452 | 89,642 |

Fig. 7. PDFS algorithms cost in an Ethereum blockchain (gas cost).

verification grows on a logarithmic scale as expected since we used TDS deploys binary Merkle trees. In the case of the JSON parsing, the cost is constant and does not change with the TDS size. Furthermore in Table I, we also disaggregate total costs to investigate the details for executing PDFS procedures. In the case of having a data feed with more than 1 million ($2^{20}$) data entries, we observe that the consistency verification has a gas cost of 86,642 on average, where only 4% of this cost is related to the hash calculations. The remaining percentage corresponds to miscellaneous code, including storage and control statements, such as asserts. Moreover, we also measured the cost of executing a membership verification, and we observe that it has an average gas cost of 204,242. However, as JSON parsing is not natively supported in Ethereum, 55% of the total cost is spent on performing this task.

Next, we show in Figure 8 what would be the maximum cost considering the two prices involved. For our measures, we assumed a price of 5 Gwei per gas unit and a price of US$414.01 per ether; those are maximum conversion rates presented at the writing time. As a result, the consistency verification costs around US$0.42. We recall that it is including the JSON parsing which is a costly task on smart contracts. Therefore, we show that PDFS is costly viable to create and deploy a trustworthy data feed for a smart contract. The cost can decrease if Ethereum starts supporting JSON parsing natively or if content providers use a more efficient data entry encoding.

Lastly, we investigated the cost of censorship-evident queries and responses (see subsection IV-E). As storing data in Ethereum smart contracts is expensive [34], we implemented this functionality without involving smart contract storage. Instead, queries and responses are published as blockchain transactions (as calls to the corresponding functions), but without storing them in content contracts. That improves the cost efficiency greatly while providing the same functionality i.e., queries and responses can be read (as they are part of the blockchain) and responses are authentic (as they are sent within blockchain transactions signed by content providers). The gas cost of these operations depending on a size of a query and response are shown in Table II. As presented, the cost grows linearly with query/response’s size, but queries and responses of the same size have roughly the same cost.

TABLE II.  The gas cost of the query and response operations.

| Oper. | 50B | 150B | 500B | 1KB | 2KB | 5KB |
|-------|-----|------|------|-----|-----|-----|
| Query | 25,597 | 32,399 | 56,337 | 90,483 | 158,644 | 363,282 |
| Resp.  | 25,804 | 32,606 | 56,544 | 90,690 | 158,851 | 363,489 |

VII. Related Work

TLSNotary [11] is a service that introduces a third-party auditor which attests TLS session data exchanged between a client and a server. To provide this functionality, the protocol requires changes to the TLS protocol like an introduction of a dedicated client-auditor protocol. TLSNotary has many drawbacks. For instance, it is only compatible with TLS 1.0 and 1.1, while TLS 1.2 is widely deployed and recommended as default [10]. TLSNotary is specified with weak hash functions, such as MD5 and SHA-1 [26], [27], and supports only cipher suites with the RSA algorithm for a secret key establishment. As TLS records are being authenticated, the output obtained from TLSNotary is hard to parse and process by smart contracts. Although, the protocol has many disadvantages, it got adopted by

9Gwei, also known as Shannon, is a smaller fraction of the Ether unit. 1 Gwei is 1x10^-9 ETH. According to https://ethgasstation.info/ 75% of all transactions is added with the gas price ≤ 4 Gwei.
other solutions, like Oraclize [23], which integrates multiple data feed systems. However, as combined with TLSNotary, it introduced a trusted third-party that holds secret keys used for auditing TLS sessions.

An alternative approach proposed is to use prediction markets for providing data feeds. In such systems [13], [34, 6] users try to predict real-world events by betting or voting for them. Usually, these systems are implemented on top of blockchain platforms, hence they could be easily integrated with smart contracts. Unfortunately, they have many drawbacks as in the case of disputes there is no responsible party (i.e., responsibility is distributed). Moreover, data feeds depend on human inputs which can be biased, slow, or incomplete.

Town Crier (TC) [35] takes a different approach to instantiate data feeds for smart contracts. TC deploys trusted computing (i.e., the Intel SGX technology [8]) to allow special applications to interact with HTTPS-enabled websites. In order to provide authentic data feeds, such an application, is executed within an SGX enclave. Thus, it is possible to conduct a remote attestation that the correct code was executed. The application establishes a secure TLS connection with a website and parses its content, which can then be used as an input to smart contracts. In contrast to TLSNotary, TC can provide easy-to-parse data and is flexible since there can be many applications. With the assumption that the contract parties have verified an attestation of the used enclave, TC allows relying contracts to avoid expensive public-key verifications by making assertions between enclaves and their blockchain identities (this is a similar concept as in PDFS). However, TC has some significant limitations. First of all, it positions Intel as a trusted party required to execute a remote attestation. Secondly, its security relies on the security of the SGX framework (undermined by recent severe attacks [32, 33]) and the security of its attestation infrastructure, which is especially undesired as the SGX attestation infrastructure is a weakest-link-security system (i.e., one leaked attestation private key allows an adversary to attest any application). TC has inspired other systems, like ChainLink [12], which aims to decentralize TC applications by forming a network of them (to detect and deal with possible inconsistencies). Unfortunately, this design does not solve the main drawbacks of TC.

TLS-N [24] is a more generic approach to provide non-repudiation to the TLS protocol. In order to realize it, TLS-N modifies the TLS stack such that TLS records sent by a server are authenticated (in batches). Therefore, TLS-N clients can present received TLS-N records to third parties which can verify it, just trusting the server (without any other third trusted parties). The main drawbacks of TLS-N are in its deployability. It requires significant changes to the TLS protocol and as learnt from the previous deployments the TLS standardization and adoption processes are very slow. Moreover, due to the popularity of cloud hosting, many content providers (i.e., website operators) do not control servers or TLS stacks they use. Because of the TLS-N’s layer of authentication, TLS records are being authenticated, which are inconvenient and expensive to process by smart contracts. Furthermore, the TLS layer is uncontrollable by web developers, and thus, most of their applications would need to be rewritten for TLS-N. Besides that, TLS-N relying contracts have to conduct an authentication verification, which is a costly operation.

| TABLE III. COMPARISON TO MOST RELATED WORKS |
|---------------------------------------------|
| No third trusted party | Easy content parsing | Required changes on |
| TLSNotary [1] | ✓ | — | TLS Protocol |
| TLS-N [24] | ✓ | ✓ | App |
| Town Crier [35] | ✓ | — | — |
| PDFS | ✓ | — | — |

In Table III we compare PDFS with the competing schemes. As shown, PDFS makes data feeds authentic and easy to parse without major changes. It is easy to implement, and it does not require modifications beyond adding new functionalities in the content provider web service. It is an advantages compared to the solutions
which require changes on the TLS protocol for operating. Additionally, PDFS operational schema does not include an additional trusted party besides the content provider itself.

VIII. Conclusions

In this paper, we proposed PDFS, a practical system that provides authenticated data feeds for smart contracts. In contrast to the previous work, PDFS seamlessly integrates content providers with the blockchain platform. This combination provides multiple benefits like efficient and easy data verification without any new trusted parties, and new interesting features that the previous platforms do not provide. Thanks to the deployed tamper-evident data structure (TDS) that is monitored by a smart contract, content providers cannot equivocate. To mitigate censorship, our scheme provides a blockchain based API for querying content providers. Besides that, native to blockchain platforms monetary transfers allow content providers to explore new business models, where relying contracts would pay a fee for the content verification. Last but not least, PDFS can be easily deployed today in the application layer without any modifications to underlying protocols.

We plan to investigate PDFS and its components in other applications. One particularly interesting example is a non-equivocation scheme for lightweight clients. Due to placing validation logic in smart contracts, it should be more efficient than, for instance, Catena [31], where clients have to collect and validate all related transactions by themselves. We believe that PDFS could achieve the same property with much shorter proofs.

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