PDFS: Practical Data Feed Service for Smart Contracts

Juan Guarnizo(✉) and Pawel Szalachowski(✉)

Singapore University of Technology and Design, Singapore, Singapore
`juan_guarnizo@mymail.sutd.edu.sg`, `pawel@sutd.edu.sg`

Abstract. Smart contracts allow untrusting parties to arrange agreements encoded as code deployed on a blockchain platform. To release their potential, it is necessary to connect the contracts with the outside world, such that they can understand and use information from other infrastructures. 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 Practical Data Feed Service (PDFS), a system 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 content which is easy to parse and efficient authenticity verification without breaking natural trust chains. PDFS keeps content providers auditable and mitigates their malicious activities (like data modification or censorship) and allows them to create a new business model. We show how PDFS is integrated with content providers, report on a PDFS implementation and present results from conducted experimental evaluations.

Keywords: Blockchain · Smart contract · Data feed

1 Introduction

The concept of smart contracts was introduced by Szabo [13,26,27]. They allow mutually untrusting parties to arrange and execute agreements without involving any third trusted party. These agreements are expressed in a programming language, hence can encode any processing logic possible to express in the used language in a precise and unambiguous way. The concept has been unexplored for decades; however, with the rise of Bitcoin [23], 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. This issue limits them from using external data provided by other infrastructures, like HTTP(S) data feeds. Ideally, smart contracts could process data provided by other infrastructures and

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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 [24] 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 [6,9,18,31]. This introduced 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). To relax it, a concept of oracles based on trust computing was proposed [31]. These oracles work similarly, however, the code run by them is executed with the Intel's Software Guard Extensions (SGX) [15] 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 [25] 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.

2 Background

2.1 Blockchain and Smart Contracts

Bitcoin [23] introduced the concept of open and decentralized consensus which, in combination with an append-only data structure, leaded to the existence of cryptocurrency without trusted parties. This combination and its variants are usually referred to as a blockchain. Bitcoin has inspired other systems (e.g., Litecoin [4] and Namecoin [5]). Interesting and promising platforms leverage blockchain to implement smart contracts. 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). Those platforms 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 [30]. It 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 deploy it on the blockchain (each smart contract gets a unique blockchain address). From this point, anyone can interact with the contract by sending transactions to its address and calling its method(s). Smart contracts can implement almost arbitrary logic, including monetary transfers, thus making this technology appealing to financial related services and other businesses.

2.2 Transport Layer Security

The Transport Layer Security (TLS) protocol [24] is one of the most widely deployed security protocols on the Internet. The protocol is designed for the client-server architecture. TLS aims to provide data confidentiality and integrity and authentication of protocol participants, but it was not designed to provide non-repudiation. Therefore, 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 is prominently deployed for securing web traffic (i.e., HTTPS).

Authentication in TLS is based on the X.509 public-key infrastructure (PKI) [14]. 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.

2.3 Tamper-Evident Data Structure

A Tamper-evident Data Structure (henceforth as 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: *(a)* every logged entry is still present in the log, and *(b)* 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 [11,19,20]. However, the semantics of TDS and multiple efficient constructions to achieve it were proposed by Crosby and Wallach [16]. In their system TDS is based on a Merkle tree [22] (also called a hash tree). A Merkle 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 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 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 Sect. 4.3):

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). Adding new data entries requires re-computing $O(log\ n)$ nodes, where n is the number of log entries.

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

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. It 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.

3 Architecture Overview

3.1 System Model

There are the following parties in a PDFS system:

Content Providers are entities that provide content. For a 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 to 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 (i.e., the one used to interact with the blockchain, also known as wallet private key) and cannot obtain a malicious certificate for a content provider (i.e., cannot compromise the TLS PKI). However, we discuss such strong adversaries in Sect. 5.

We also assume a content provider trying to misbehave by launching an equivocation attack [28] 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, censorship attempts should be at least visible.

3.2 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.

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 requiring new infrastructure 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.

Non-equivocation: Data feeds should be unable to modify or delete content retrospectively once data are committed and published. It enforces a content provider to verify and guarantees the correctness of data before performing publications. Preferably, providers should implement data structures that are append-only for their publications database.

3.3 High-Level Overview

Design decisions behind PDFS try to achieve all stated properties above. 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.

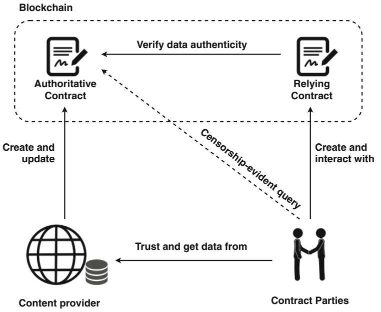

Fig. 1. High-level overview of PDFS.

In our design, content providers link their TLS identities with their blockchain identities and the 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 Fig. 1, and in this section, we describe its steps and the main components.

The first step in our protocol is to create a *authoritative contract* by a content provider who wishes to participate in PDFS. The main aim of authoritative contracts is to enable other contracts to verify the authenticity of the content produced by content providers. Authoritative 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 authoritative contract provides an API that allows: *(a)* its owner (i.e., the content provider) to update it, *(b)* other contracts to verify that the content provider indeed produced given data, *(c)* 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 is censoring some queries).

In the second step, the content providers create a signed *manifest* that contains the following elements: *(a)* a location (i.e., a blockchain address) and interface structure of its authoritative contract, *(b)* 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. Although PDFS data may be published using HTTPS services, those services focus on data privacy and integrity. We define that the manifest must be signed and added into the TDS to extend security properties including non-repudiation and non-equivocation to it.

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 authoritative contract (they do not store any actual content, but only TDS roots — the short authentication information about the content.) The authoritative 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 membership proofs are published at a pre-defined URL location, 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). When contract parties find the content provider they would like to use, they locate and verify its manifest and authoritative contract, and associate the location of the authoritative 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 authoritative contract's membership verification method. When the data entry is verified, the relying contract's method can continue with its processing logic.

4 Details

In this section, we describe components of the PDFS architecture and explain its different steps from 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 Fig. 2, a PDFS service consists of an authoritative 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.

4.1 Service Initialization

In the first step, the content provider initializes a PDFS service by deploying an authoritative 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 authoritative 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 authoritative contracts are discussed in Sect. 4.2. Once it is deployed, the content provider gets an address of the authoritative contract instance.

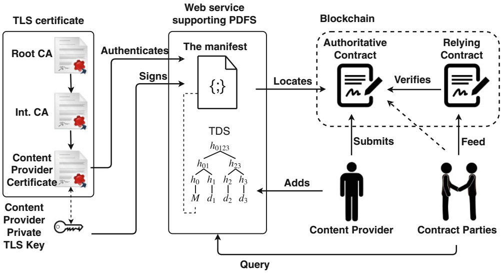

Fig. 2. Details of the PDFS architecture and parties interactions.

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 CA are widely trusted parties on the Internet, the content provider can sign the manifest using the private key corresponding to its TLS certificate for supporting 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 an already existing trust chain. When the manifest is signed, it is added as the first element to the content provider's TDS. 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.

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

Authoritative Contract Interface is an abstract structural descriptor of the authoritative contract. It includes definitions of functions, access method, and parameters. Likewise the authoritative contract address, data contained in this field has to be embedded in the relying contracts as an object interface. This field is platform dependent (e.g., the ABI in Ethereum).

Data Structure describes the encoding or 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. Thus, 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.

If the TLS certificate expires, the PDFS service is not affected for relying contracts already deployed. It is because contract parties use the certificate to verify the manifest signature before they create relying contracts. Furthermore, neither the authoritative contract nor relying contracts perform any signature verification later. Also, 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.

4.2 Authoritative Contract

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

- The content provider to store root hashes once the consistency is verified. This procedure is executed by calling the UPDATE function (details about the consistency verification in Sect. 4.3). The UPDATE function can be executed only by the content provider. For efficient storage management and time delays or race conditions avoidance, the authoritative contract only stores an array of the last K root hash values committed (K is defined by the content provider).
- 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 is valid comparing to stored roots.
- Contract parties to make censorship-evident queries using the QUERY function and get responses 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 payments for providing data over a PDFS service.[1]

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[1] Fees for executing PDFS functions are different from fees for executing transactions on the blockchain (e.g., Ethereum gas cost).

Algorithm 1. Authoritative Contract Pseudo-Code.

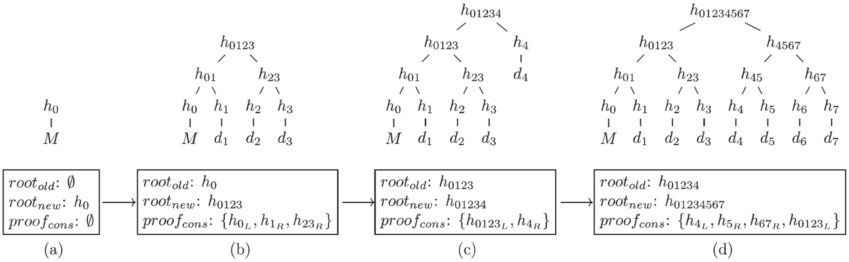
```
$FEE_{mem}$: the cost for membership verification,
$FEE_{query}$: the cost for making a censorship-evident query,
locked: boolean value that indicates whether the authoritative contract can be updated,
roots: a map of roots hashes; it uses a timestamp as the key,
time: a value that indicates the last updating time,
queries: a map of censorship-evidence query made; it uses a number as the key,
responses: a map of responses for queries made; the key is associated to existing identifiers in the queries map,
counter: an incremental number used as the identifier for the queries made,
NOW(): the current block timestamp,
HASH(): a cryptographic hash function.

procedure INIT
    $roots \leftarrow \emptyset$
    $time \leftarrow 0$
    $locked \leftarrow False$
end procedure
procedure UPDATE($root, proof_{cons}$)
    assert($sender = owner$)
    assert($locked = False$)
    if CONSISTENCY($root, proof_{cons}$) then
        $time \leftarrow$ NOW()
        $roots[time] \leftarrow root$
    end if
end procedure
procedure LOCK
    assert($sender = owner$)
    $locked \leftarrow True$
end procedure
procedure CONSISTENCY($root, proof_{cons}$)
    if $time = 0$ then
        return true
    end if
    $(root_{new}, root_{old}) \leftarrow$ MTH($proof_{cons}, \emptyset$)
    return ($root_{new} = root$ & $root_{old} = roots[time]$)
end procedure
procedure MEMBERSHIP($data, proof_{mem}, fee$)
    assert($fee = FEE_{mem}$)
    $leaf \leftarrow$ HASH($data$)
    $(root_{mem}, \text{-}) \leftarrow$ MTH($proof_{mem}, leaf$)
    return $root_{mem} \in roots$
end procedure
procedure MTH($proof, leaf$)
    $i \leftarrow 0$
    $hash_x \leftarrow hash_y \leftarrow leaf$
    if $leaf = \emptyset$ then
        $i \leftarrow 1$
        $hash_x \leftarrow hash_y \leftarrow proof_{(0)}.hash$
    end if
    for $i <$ LEN($proof$) do
        if $proof_{(i)}.side = RIGHT$ then
            $hash_x \leftarrow$ HASH($hash_x || proof_{(i)}.hash$)
        else
            $hash_x \leftarrow$ HASH($proof_{(i)}.hash || hash_x$)
            $hash_y \leftarrow$ HASH($proof_{(i)}.hash || hash_y$)
        end if
        $i \leftarrow i + 1$
    end for
    return ($hash_x, hash_y$)
end procedure

// Censorship Evidence functions
procedure QUERY($filter, fee$)
    assert($fee = FEE_{query}$)
    $counter \leftarrow counter + 1$
    $queries[counter] \leftarrow filter$
    return $counter$
end procedure
procedure STORE_RESPONSE($id, data$)
    assert($sender = owner$)
    assert($id \leq counter$)
    $responses[id] \leftarrow data$
end procedure
procedure GET_RESPONSE($id$)
    assert($id \leq counter$)
    return $responses[id]$
end procedure
```

4.3 Data Update

Adding new data entries to the TDS requires re-computing the root. To run PDFS service properly, it also requires synchronization of changes between the content provider back-end (maintaining the TDS) and the authoritative contract which has to be updated to enable the membership verification of any newly added entry. To synchronize, the content provider submits the new root hash value along with a corresponding proof for the consistency verification. This verification uses the provided proof to re-calculate two hash values. and then, it compares those calculated hashes checking whether they are equal to the new root value to store and the last one stored in the authoritative contract accordingly. This guarantees that the new TDS is an extension of the last one committed confirming that no previous data entry has been altered or removed. If there is an error, the authoritative contract ignores the submitted data and



(a) (b) (c) (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 authoritative contract. Each element of the $proof_{cons}$ indicates the hash value and the corresponding side (h_{x_L} refers left position and h_{x_R} refers right position).

remains in the current state. Once the new root is accepted by the authoritative contract, the content provider can make the updated TDS accessible over HTTPS.

In Fig. 3, we show an example of how a TDS evolves when data entries are added, and what values are sent for submitting roots to the authoritative contract. In case (a), the new root is directly stored 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 ($proof_{cons}$). The authoritative contract uses the provided data to evaluate the TDS consistency. In this case, the consistency verification is easy to deduce since the previous root (h_0) is contained in the provided proof. Similarly in the case (c), the previous root (h_{123}) is contained in the $proof_{cons}$ array.

However, the case (c) shows a particular situation due to the TDS is unbalanced. It changes how the consistency verification works for the next root submission, the case (d). For it, the consistency proof provided is: $proof_{cons} = \{h_{4_L}, h_{5_R}, h_{67_R}, h_{123_L}\}$. Because of the unbalanced TDS, the consistency verification re-calculates both roots, the previous one (h_{1234}) and the new one ($h_{1234567}$) by using the same provided proof. To calculate the previous root, the consistency verification only needs the contained elements $\{h_{4_L}, h_{123_L}\}$. Furthermore, the complete array is used to re-calculate the new root. Therefore, the procedure can confirm the consistency of the new TDS.

4.4 Relying Contracts

A relying contract is a smart contract which is created by contract parties and needs content providers data to validate conditions and perform transactions. Before it is created, contracts parties agree on a content provider they trust which provides a PDFS service. After validating its manifest signature, contract parties extract the information contained in the manifest and use it to prepare and deploy a relying contract. In that way, the relying contract will interact with the correct authoritative contract and be able to: *(a)* execute the membership verification procedure, *(b)* get the response for a censorship-evident query, and *(c)* parse data entries and execute a processing logic depending on data entry fields. We provide a pseudo-code example of a relying contract in Algorithm 2.

When needed, contract parties request a specific data entry to the content provider, which responses a data entry along with its respective membership proof. Considering case (c) in Fig. 3, let us assume the content provider is queried for the data entry d_2, so its response will contain the asked data entry d_2 along with a membership proof $proof_{mem} = \{h_{3_R}, h_{01_L}, h_{4_R}\}$. Once that data is submitted to the relying contract, it will execute the membership verification intreating with the authoritative contract. As we see in this example, the provided proof and the data entry's hash value lead to re-calculate the root h_{1234} which is stored in the authoritative contract and it confirms data authenticity. If any value is modified, either the data or the proof, the membership verification re-calculates a different hash value which does not correspond to any stored root, so the verification fails.

Algorithm 2. Relying Contract Template.

```
    $cc$: authoritative contract object interface.

procedure INIT($addr$)
    $cc \leftarrow$ AUTHORITATIVE_CONTRACT($addr$)
end procedure
procedure SUBMIT_DATA($data, proof_{mem}, fee_{mem}$)
    $v \leftarrow False$
    $v \leftarrow cc$.MEMBERSHIP($data, proof_{mem}, fee_{mem}$)
    if $v = True$ then
        ... Decode data input
        ... Decide and make transaction
    end if
end procedure
procedure IF_CENSORSHIP($id$)
    $data \leftarrow cc$.GET_RESPONSE($id$)
    if $data \neq \emptyset$ then
        ... Decode data input
        ... Decide and make transaction
    end if
end procedure

interface AUTHORITATIVE_CONTRACT:
    procedure MEMBERSHIP($data, proof, fee$)
    procedure GET_RESPONSE($id$)
    ... Any additional procedure defined
```

4.5 Censorship Evidence

Censorship is an especially challenging threat since a content provider censoring queries can influence executions of agreements based on smart contracts, and censorship is difficult to prove. However, PDFS extends the authoritative and the relying contract with functions to allow *censorship-evident queries*. So contract parties can query a content provider over the blockchain whenever they cannot obtain data directly through conventional channels (e.g., like HTTPS). All interactions, contract parties' query and content provider's response, are recorded as transactions in the blockchain. Therefore, they are visible for anyone, and any censorship attempt is publicly observable. We discuss censorship attacks further in Sect. 5.2.

4.6 PDFS Service Termination

Content providers might need to terminate a PDFS service due to operational management or security reasons. To do so, they can execute the LOCK function which disallows any future update attempt of the authoritative contract. Locking authoritative contracts does not introduce collateral damage to already-deployed relying contracts. A locked authoritative contract can be used for membership verifications as long as the corresponding root value is 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 Sect. 5.1).

5 Security Discussion

In this section, we discuss different attacks and their implications over PDFS. However, this discussion is extended in Sect. A in the appendix which also addresses issues and disagreements that one might argue against our proposed solution.

5.1 PKI and Key Compromise

An adversary able to compromise the TLS PKI can create a malicious manifest and an authoritative contract, and can 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* authoritative contract instance for data verification. Moreover, by deploying a new (malicious) authoritative 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 authoritative 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 authoritative contract is updated publicly, on the blockchain. Thus, the content provider will notice it and terminate its service (see Sect. 4.6).

5.2 Malicious Content Provider

PDFS prevents and mitigates some attacks conducted by a malicious content provider. The design of authoritative 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 authoritative contract enforces the consistency of the TDS for every update (see Fig. 3). This property is also crucial for thwarting equivocation attacks [28]. A manifest file identifies the authoritative contract that guarantees that the content provider cannot equivocate as long as the blockchain platform is secure (see Sect. A.2 in the appendix).

The content provider can create multiple manifest files and authoritative 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.

PDFS provides non-equivocation by ensuring that content providers' database is append-only. However, it does not prevent a content provider from adding two semantically conflicting entries to their databases (e.g., two different results for a same football game). Conflicting entries can be harmful to relying contracts as they may lead to completely different execution paths. Since PDFS does not allow content providers to "overwrite" their entries, we suggest that such conflicts should be handled by relying contracts themselves. More precisely, using agreement protocols like implementing *grace periods* or submitting data from *multiple content providers* before making final decisions, such that any conflicting entry submitted can reverse contracts agreements.

A subtler attack is a content provider censoring queries. That risk is especially important, when a malicious content provider ignores contract parties' queries, pretending unavailability or displaying incorrect data that cannot be successfully verified by relying contracts. In such a case, PDFS allows contract parties to query the content provider over the blockchain for a required query (see Sect. 4.5). The content provider is obligated to response due to the query and content provider's response are publicly visible.

6 Realization in Practice

In this section, we demonstrate that PDFS fulfills the desired properties explained in Sect. 3.2. We fully implemented a proof of concept which involved both parties of a PDFS architecture (the content provider and contract parties). Although we tested PDFS under a generic scenario (see Sect. B.1 in the appendix), 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 content and data type, to become a trustworthy data feed for smart contracts.

6.1 Implementation

To approach our implementation of PDFS, we developed a web service for the content provider using Go v1.10.1 as the programming language. It is a RESTFul API which offers data entries encoded in JSON format. This application is configured to support HTTPS, and we deployed a private PKI infrastructure and TLS certificates using OpenSSL v1.1. For contract parties, we implemented a client in Python v3.6.5 which is able to request data entries to the created web service. Smart contracts, the authoritative and the relying contract are coded in Solidity v0.4.21 and deployed in an Ethereum blockchain. To allow reproducibility of our experiments and evaluations, we publish our implementation at https://gitlab.com/juan794/pdfs.

6.2 Evaluation

In this section, we discuss results obtained from a series of experiments we performed. To evaluate PDFS, we used a computer which has 16 GB of RAM and a CPU Intel Core i7 7700H. 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 Fig. 4, we observe that the cost for the consistency and membership verification grows on a logarithmic scale as expected since we deployed a TDS using binary Merkle trees. In the case of the JSON parsing, the cost is constant and does not change with the TDS size. We also disaggregate total costs to investigate the details for executing PDFS procedures (see details in Table 1). 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. On the other hand, the *gas* consumptions are 813,111 and 4,355,638 respectively for the authoritative contract and the relying contract deployment.

Next, we show in Fig. 4 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$105.05 per ether; those are maximum conversion rates presented at the writing time. As a result, the consistency verification costs around US $0.048 in a PDFS service that contains more than 1 million data entries. This means a cost of US $1.7x10^{-7}$ per data entry. On the other hand, the membership verification of one data entry in a TDS of that size (2^{20}) costs around US $0.11. 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.

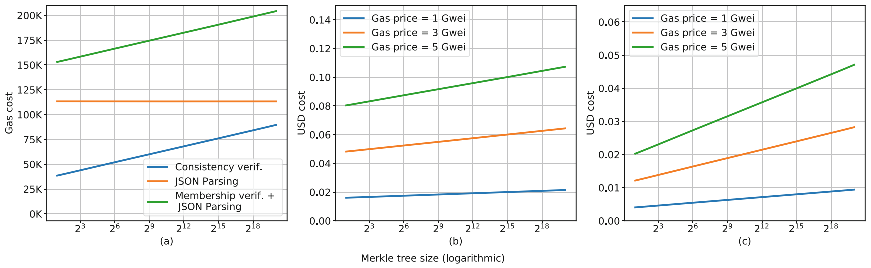


Fig. 4. Ethereum gas consumption and price variation analysis converted to US dollars. (a) Gas cost of PDFS operations (b) membership verification cost (c) consistency verification cost.

Table 1. Cost analysis for membership and consistency verification considering multiple sizes of the TDS.

TDS size	2^1	2^5	2^{10}	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

Table 2. Ethereum gas consumption of PDFS compared to signature verifications.

PDFS	secp256r1	RSA	ECRecover
87,361	1,854,634	596,287	38,887

In Table 2, we show the *gas* consumption comparing PDFS against signature verification algorithms, such as ECRecover [2] (native in Ethereum), TLS-N implementation of secp256r1 [10] and RSA [7]. We observe that the Ethereum native function for signature verification is cheaper than PDFS. On the other hand, PDFS is significantly cheaper that implementations coded on Solidity programming language. Although those alternatives allow contract parties to verify integrity and provenance, they do not provide accountability or non-equivocation properties from content providers.

Table 3. The gas cost of the query and response operations.

Oper.	50 B	150 B	500 B	1 KB	2 KB	5 KB
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

Lastly, we investigated the cost of censorship-evident queries and responses (see Sect. 4.5). As storing data in Ethereum smart contracts is expensive [30], 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 authoritative 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 3. As presented, the cost grows linearly with query/response's size, but queries and responses of the same size have roughly the same cost.

7 Related Work

TLSNotary [9] 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 [8]. TLSNotary is specified with obsolete cryptography algorithms, and it 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 other solutions, like Oraclize [6], 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, such as [1] and [3]. In such systems, 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) [31] takes a different approach to instantiate data feeds for smart contracts. TC deploys trusted computing (i.e., the Intel SGX technology [15]) 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 then can 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 [29]) 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 [18], 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 [25] 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. Because of the TLS-N's layer of authentication, TLS records are being authenticated which is 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 4. Comparison to most related works.

	No third trusted party	Easy content parsing	Required changes on
TLSNotary [9]	—	—	TLS Protocol
TLS-N [25]	✓	—	TLS Protocol
Town Crier [31]	—	✓	—
PDFS	✓	✓	App

In Table 4 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 does not require an additional trusted party besides the content provider itself.

Moreover, we believe that the adoption of PDFS is much more likely than the adoption of competing schemes. In contrast to transport-layer authentication systems, PDFS requires changes only on the application layer. It also does not require trusted hardware or relies on ubiquitous TLS certificates following natural for HTTPS trust relationships. Last but not least, content providers are motivated by economic incentives as PDFS allows them to be paid for authenticating content which usually they publish for free.

8 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 [28], where clients have to collect and validate all related transactions by themselves. We believe PDFS could achieve the same property with much shorter proofs.

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A Extended Security Discussion

A.1 Data Authentication

Our first claim is that *an adversary cannot create a content on behalf of a content provider*. To achieve that, the adversary need to either: *(a)* tamper authenticated proofs generated by the content providers, or *(b)* update the authoritative contract on behalf of the content provider, or *(c)* forge the manifest binding the authoritative contract and identity of the content provider. 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 [16]. 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 authoritative contract by a new root. However, in this attack, the adversary cannot update the authoritative contract as it enforces the update procedure (see Sect. 4.3). The update procedure allows only the contract's owner to update it. Therefore, without the content provider's blockchain key, the adversary cannot update the legitimate authoritative 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.

A.2 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 [23] 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 authoritative contract 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 [21].

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.

A.3 General Discussion

By analyzing the implications and costs of adopting it, we present PDFS as a viable alternative for smart contracts to receive authenticated data from content providers. In this paper, we focus on design a system with desired properties explained in Sect. 3.2. However, we are aware of issues and disagreements that one might argue against our proposed solution.

Firstly, one might claim that signature verification solutions would requires less effort for contract providers, and further, it provides properties of authenticity and provenance of data. Nevetherless, as observed in Sect. 6.2, PDFS is cheaper regarding *gas* cost and extends security properties to include accountability and non-equivocation for content providers. On the other hand, a naive solution would be to publish data hashes itself in a smart contract, however, that would be prohibitively expensive due to smart contract storage fees.

Secondly, we aimed a design for smart contracts data feed that avoids the complexity of alternative solutions and related works. We consider that modifying a protocol extensively used or including special hardware and network specifications makes a solution highly difficult to deploy; such as modifying the TLS protocol or including oracles using SGX. By contrast, PDFS offers as a simplier alternative that only requires changes on the application layer for content providers and contract-to-contract communication for contract parties. We consider it makes PDFS more practical and easy to adopt, even without taking the new business model that a content providers might get by providing data in a PDFS service.

Lastly, our current approach keeps the common trust chain with only includes contract parties who want to stablish an agreements and a content provider who is an autoritative entity who defines trustworthy data, also known as *the truth.*

Although the content provider may be able to misbahave, PDFS is not able to detect such actions due to data content is not analyzed, but that issue also affects the related works. However, it can be solved by including agreement protocols. For instance, the relying contract might revoke any agreement if two conflicting data are submitted within a time gap.

B Case Study and Implementation Details

B.1 Case Study

In our proof of concept, we considered a scenario where contract parties decide to settle gambling agreement creating and deploying a smart contract which uses trusted data from a content provider who adopts PDFS in its service.

Content Provider. Following specifications in Sect. 4 and templates provided in Sect. B.2, our implementation of the content provider is a web service which offers data of football matches in JSON format. We configured it to support HTTPS, and we obtained a free dataset from https://www.football-data.org/. We implemented the TDS using Keccak-256 [12] as a cryptographic hash function. We chose Keccak as it is a state-of-the-art hash function (the current standard SHA-3 [17] 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. It is capable to get and validate the authenticity of the manifest, and it is able to submit data obtained from the content provider to the relying contract which executes the membership verification, interacting with the authoritative contract, and proceeds to parse the JSON data. In this case, we use a JSON parser coded in Solidity since it is not supported natively in Ethereum platform.

B.2 Implementations

In this section, we show examples of how JSON data look like in our implementation and experiments. The JSON examples are related to the case study explained in Sect. B.1.

```
{
”signed”:{
  ”url”:”https://example.com/
   soccer”,
  ”sc_address”:”0x539c94cb89E127
   ...”,
  ”sc_interface”:
    ”[{”constant”:true,
        ”inputs”:[{”name”:”json”,
                   ”type”:”string
   ”}],
        ”name”:”parseJSONdata”,
        ”outputs”:[{”name”:””,
                     ”type”:”bool
   ”}],
        ...}]”,
  ”data_structure”:
    ”{id:string, local:string,
      visitor:string, localGoals:
   int,
      visitorGoals:int}”
},
”signature”:”63
   cc6a76fd07252ff4af4c...”
}
```

Listing 1.1. A manifest example.

```
{
”content”:{
  ”id”:”341576”,
  ”date”:”2018-07-15T18:00:00Z”
  ”local”:”France”,
  ”visitor”:”Croatia”,
  ”localGoals”:4,
  ”visitorGoals”:2
},
”proofs”:[
  {”side”:0, ”hash”:”5e41f...”},
  {”side”:1, ”hash”:”01950...”},
  ... more items]
}
```

Listing 1.2. A PDFS data entry example. It consist of the data content itself and its membership proof which is an array of elements containing a hash value and a side (0 indicates left side and 1 indicates right one).

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