Blockchain-based TLS Notary Service

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Abstract

The Transport Layer Security (TLS) protocol is a de facto standard of secure client-server communication on the Internet. Its security can be diminished by a variety of attacks that leverage on weaknesses in its design and implementations. An example of a major weakness is the public-key infrastructure (PKI) that TLS deploys, which is a weakest-link system and introduces hundreds of links (i.e., trusted entities). Consequently, an adversary compromising a single trusted entity can impersonate any website.

Notary systems, based on multi-path probing, were early and promising proposals to detect and prevent such attacks. Unfortunately, despite their benefits, they are not widely deployed, mainly due to their long-standing unresolved problems. In this paper, we present Persistent and Accountable Domain Validation (PADVA), which is a next-generation TLS notary service. PADVA combines the advantages of previous proposals, enhancing them, introducing novel mechanisms, and leveraging a blockchain platform which provides new features. PADVA keeps notaries auditable and accountable, introduces service-level agreements and mechanisms to enforce them, relaxes availability requirements for notaries, and works with the legacy TLS ecosystem. We implemented and evaluated PADVA, and our experiments indicate its efficiency and deployability.

1 Introduction

The security of TLS connections strongly depends on the authenticity of public keys. In the TLS PKI [12], a public key is authenticated by a trusted certification authority (CA), whose task is to verify a binding between an identity and a public key, and subsequently, issue a certificate asserting it. Unfortunately, this process does not provide a high-security level for various reasons. The identity verification is usually conducted over the Internet basing on the trust on first use model [6], moreover, it is a one-time operation (i.e., per certificate issuance). Therefore, an adversary able to impersonate a domain, even for just a moment, can obtain a valid certificate for this domain. Besides that, the TLS PKI is a weakest-link system, and compromising a single CA (out of hundreds of trusted CAs [35]) can result in a successful impersonation attack, as observed in the past [11].

One of the first approaches to mitigate such attacks were notary systems [26,45]. The main idea behind them is to introduce the new trusted party, known as a notary. The notary provides a TLS client with its view of the contacted server’s public key. Hence, the client gets better guarantees that the key is legitimate. Notary systems are based on multi-path probing and assume that attacks are usually short-lived or/and scoped to a network topology fragment. Although they inspired the research community, they did not receive enough traction to be widely deployed. Notary systems are often critiqued as they introduce privacy issues (i.e., TLS clients reveal servers they want to contact), increase latency of TLS connections (a response from a notary has to be delivered), and are required to provide high availability (otherwise client queries will timeout or introduce significant latency) [5,20,31]. Furthermore, notaries are trusted, not transparent, and difficult to audit.

In this paper, we present Persistent and Accountable Domain Validation (PADVA), a next-generation TLS notary service that solves multiple problems of the previously proposed notary systems. In PADVA, notaries persistently validate public keys of domains in an auditable and accountable manner. By leveraging properties of a blockchain platform, PADVA achieves transparency, provides a framework for service-level agreement (SLA) enforcement, and relaxes availability requirements. PADVA is compatible with legacy TLS infrastructure, and can be deployed today, even with TLS servers with desynchronized clocks. Our implementation and evaluation indicate efficiency and deployability.
of our system. With PADVA, the key validation becomes a service (instead of a one-time operation) with implementable SLAs, and with auditable and accountable notaries.

2 Background and Preliminaries

In this section, we introduce basic information on the TLS protocol, we define the problem, and introduce system and adversary models.

2.1 Transport Layer Security

The TLS protocol is designed to provide secure communication in the client-server model. It is widely deployed and its most prominent use is to secure the HTTP protocol (HTTPS). In such a setting, only a (web) server is authenticated and the authentication is based on X.509 certificates [12]. The current and the recommended version of the protocol is TLS 1.2 [13], however, older versions, like 1.0 and 1.1, are still widely supported.

2.1.1 Handshake

The first phase of the TLS connection establishment is the TLS handshake protocol. Its goal is to securely negotiate a shared symmetric key between communicating parties. There are many variants of the TLS handshake and we present the version based on the ephemeral Diffie-Hellman (DH) protocol [7]. This version is recommended due to its security benefits (i.e., it provides forward secrecy), and is used by default by modern TLS clients [41] and servers [2].

The handshake is presented in Figure 1. It starts with exchanging the ClientHello and ServerHello messages, where the client and server indicate their supported cryptographic primitives, their random nonces, and other connection parameters. Next, the server sends its certificate and the ServerKeyExchange message. This message contains DH parameters required to conduct an ephemeral DH key exchange and a signature that protects these parameters. This signature is computed using the private key corresponding to the public key of the server’s certificate. After the ServerHello phase is finished, the client verifies the signature and sends its DH contribution. Next, the client and server compute the shared secret and will then signal that the following communication will be encrypted.

2.1.2 Certificates

Certificates in the TLS protocol are used to verify end entities. In most cases, like HTTPS, only the server is authenticated (i.e., the client does not have a certificate), and usually, the server is identified by its domain name. Certificates are issued by a trusted CA that is obligated to validate the ownership of a public key prior to the certificate issuance. In the current TLS ecosystem, the dominant way of the validation is based on a domain name ownership. To get a domain-validated certificate, an entity has to prove to a CA that it controls the domain name for which a certificate is requested. CAs automate this process, and usually the validation is conducted via DNS, HTTP, or e-mail [6].

2.2 Problem Definition

Notary systems were motivated by the weak authentication of public keys that the standard TLS PKI model provides. As described above, in most cases, CAs rely only on a domain validation conducted over an insecure channel, moreover, they validate the given domain only once per certificate’s lifetime (i.e., just before the certificate is issued). Consequently, an adversary with the ability to temporarily launch a man-in-the-middle (MitM) attack between any CA and a domain, or temporarily control the domain’s DNS zone, e-mail, or a web server, can get a valid certificate for this domain. Such a certificate can be then used to impersonate the domain to any client.

Notary systems try to improve the security of the TLS connections, providing their views of domains’ public keys. Notaries can periodically check domains’ public
keys and the key continuity [15] of the observed keys can be measured, such that notaries can inform clients about historical views to give them better guarantees about public keys they currently see. The effectiveness of notary systems is based on the following assumptions:

- impersonation attacks are usually short-lived, thus key continuity, that says for how long a public key is being used by an entity, can be a practical measure for estimating how a given public key is suspicious,
- multipath probing can detect various MitM attacks, as usually attacks are limited to a fragment of the network topology.

Unfortunately, notary systems never received mainstream deployment, mainly due to availability, privacy, and security issues. Below, we list the desired properties that a successful notary system should hold. This list is motivated by lessons learned from deployments of notary (and other security) infrastructures.

**Persistence:** in contrast to today CAs, notaries should validate public keys persistently. The validation conducted persistently can increase security level, as then an adversary has to have a permanent ability to impersonate a targeted domain. With such validation, it is possible to reliably implement security metrics like key continuity. Interestingly, similar benefits can be provided by short-lived certificates [37], however, due to the CA ecosystem ossification the attempts of introducing short-lived certificates failed [3].

**Auditability:** in the previous proposals notaries are trusted. Such a setting is circular as trust problems of the CA ecosystem are addressed by another trusted parties (notaries). Some level of trust seems to be unavoidable as clients that contact a notary have to rely on the notary’s view. However, where possible notaries should be auditable, such that they can be kept accountable for their actions. Ideally, operations of notaries are authentic and transparent, such that anyone can audit them.

**Privacy:** notary systems are designed in the interactive client-server model, where clients wishing to check notary’s view have to contact notary server(s). That design gives a notary infrastructure ability to learn which websites are visited by which clients. This is unacceptable and a successful notary system should be privacy-preserving.

**Availability:** another consequence of the interactive model is an increased latency of TLS connection establishments and strong availability requirements, as information from a notary has to be reliably sent to clients. Unfortunately, maintaining high availability level for front-end servers is a challenging task, and currently, existing security infrastructures (like PKI revocation infrastructures [12] or certificates logs [22]) have major problems with achieving it [17, 18, 23, 38].

**Backward compatibility:** a notary should be compatible with the legacy TLS ecosystem (or at least a large its portion), such that it can provide benefits immediately when deployed. The TLS PKI ecosystem has many stakeholders like CAs, browser vendors, and influential websites. As we witnessed in the past, it is challenging to deploy a new security enhancement without reaching a broad consensus [29]. Ideally, a notary system should be orthogonal to the deployed TLS protocol and the TLS PKI, such that it can be deployed almost immediately without requiring flag days, servers’ upgrades, and protocol changes.

### 2.3 Assumptions

#### 2.3.1 System Model

PADVA introduces the following parties:

- **Server:** provides a service via the TLS protocol (e.g., HTTPS). We assume that services (and servers consequently) are identified by domain names.
- **Notary:** is an entity that offers a PADVA service. Notaries are obligated to monitor servers by validating their public keys.
- **Requester:** is an entity interested in monitoring server’s public key(s). It can be a server’s operator or any other entity. A requester orders the PADVA service from a notary.

We assume that notaries and requesters have an access to a blockchain platform with smart contracts enabled. For simple description, we also assume that the platform has its cryptocurrency that is used by notaries and requesters, however money transfers in PADVA can be realized with a fiat currency if desired (e.g., due to cryptocurrency volatility). For instance, our scheme can be combined with systems like Ethereum [4] or Hyperledger [5]. We describe PADVA using an open blockchain platform, however, PADVA can be adjusted to a private platform if needed. We do not require that clocks of servers are synchronized. However, we assume that the requester and notary can agree on at least one reference time source (in particular this can be the monitored server).

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[1] https://cabforum.org/2015/11/11/ballot-153-short-lived-certificates/
[2] https://www.ethereum.org/
[3] https://hyperledger.org/
2.3.2 Adversary Model

With regards to MitM attacks, we use the adversary model introduced by previous notary systems [26,45]. Namely, we assume that impersonation attacks have limited duration, or are limited to only a fragment of the network topology. Otherwise, a long-lived attack that encompasses the entire topology would be difficult to detect by any notary system (as the detection bases on finding views’ inconsistency).

We assume that a notary can misbehave by reporting an invalid view or censoring requester audit queries. However, in such a case the misbehavior should be detected and the notary should be punished.

We assume that the adversary cannot undermine security properties of the underlying blockchain platform, and we assume that the adversary cannot compromise the security of the used cryptographic primitives.

3 PADVA Overview

The main observation behind the PADVA’s design is that although benefits of notary systems are attractive, their deployment is marginal due to deployment, operational, and design issues. Hence, first we introduce the core design decisions that enable to build a more powerful notary system, and then we outline an overview of PADVA.

3.1 Design Choices

Our first design choice is to position a persistent and auditable key validation as the main task of notaries. Notaries in our system are not authorized to issue certificates. In PADVA, notaries constantly validate public keys of domains and measure key continuity. That allows implementing effective protection and detection mechanisms in an ecosystem with predominant domain-validated certificates. In such a setting, there are some similarities between notaries and CAs conducting domain validation except:

- notaries validate public key of domains permanently (in short intervals), and
- notaries are not authorized to issue certificates.

Besides that, PADVA aims to provide auditable and accountable key validation. Notaries in our system are not trusted parties, as they have to get a proof that given domain used given key at given time. These proofs, called validation results, and other actions of notaries are auditable what enables requesters to verify them.

PADVA notaries offer key validation as a service. In short, we argue that notaries should serve a demand-driven service, ideally with payment and SLA frameworks available. There are many challenges associated with designing and implementing key validation as a service. However, offering key validation as a service would incentivize notaries to maintain a robust infrastructure. On the other hands, implementable SLAs would secure requesters from notaries violating mutual agreements.

To be deployed, a notary system must be compatible with the legacy ecosystem. It means that we should not propose any modifications to the TLS protocol nor need any server-side changes (including even small changes like time synchronization). The system should be deployable within the current environment.

This choice is motivated by the history of TLS security enhancements deployment. Many security proposals failed due to server-side changes required or due to low adoption rate (as to work effectively they require large-scale adoption) [10,29]. For instance, even such a critical functionality like certificate revocation cannot be successfully deployed [24].

We use a blockchain as a publishing and contract enforcement platform [6]. Although the blockchain technology is still in its infancy, its inherent properties, like transparency, consistency, and censorship resistance, make it a promising underlying technology for a notary system.

Firstly, PADVA notaries use the blockchain as a publishing platform to increase transparency (auditability), availability, and to preserve users’ privacy. In contrast to interactive client-server architectures, where clients have to contact a notary to get its view, in PADVA notaries publish they validation outcomes in the blockchain, thus anyone can read it passively.

Secondly, smart contracts built upon the blockchain allow us to automate the notary system by:

- introducing automated payments, that would incentivize notaries to keep a robust infrastructure, and
- implementing an SLA enforcement mechanism, to provide guarantees to the requesters (in the case of a misbehaving or unavailable notary).

We decouple interface between notaries and requesters into a direct and indirect interface. Requesters and notaries follow the client-server model for the direct interface, which is used mainly for auditing notaries (i.e., querying audit proofs). However, for critical operations, this model is enriched by the blockchain-based indirect interface, where smart contracts act as a proxy to pass queries and as an oracle to resolve potential disputes. Operations over the indirect interface are implemented as blockchain transactions thus are transparent, accountable, and cannot be censored. This interface is intended only for critical operations like an agreement creation or an SLA execution (e.g., when a notary is unresponsive.

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6 Although our system does not necessarily require the blockchain data structure and can be instantiated with most distributed ledgers, we use the blockchain term as the most of the existing distributed ledgers deploy the blockchain data structure or similar.
or censors queries sent via the direct interface), so interactions with blockchain are involved only when it is necessary.

### 3.2 High-level Overview

A high-level overview of PADVA is presented in Figure 2. The central point of our design is a blockchain platform that implements two main functionalities (the indirect interface between notaries and requesters, and publishing of validation results). The indirect interface is used to initialize a PADVA service and to enforce an SLA between the notary and requester, while the direct interface is used mainly for auditing the notary.

We assume that a requester knows (e.g., through a website) a notary, location (address) of its smart contracts, the service fee, and the guaranteed SLA. Then, the protocol is executed as follows.

1. In the first step, a requester requests the notary service by sending a transaction (to the notary’s contract) that contains a fee for the service and specifies request details like a domain name to be validated and its legitimate public keys.

2. The notary notices the request and configures the service to serve the request. Additionally, the notary deposits money that will be used to ensure its SLA. Alternatively, the notary can refuse the request for any reason, like a misconfigured or inaccessible target server.

3. Every validation period $T$, the notary contacts the server and obtains an authenticated and fresh information about the server’s public key. Depending on an outcome of this validation the notary is obligated to publish in the blockchain any change of the validation state. Hence, the validation state can be read by any blockchain user.

4. If there is no state change, the notary does not publish anything, which implies that the previous state is still valid. Therefore, we optimize for the common case (i.e., no state change per $T$).

5. In order to ensure that the validation state in the blockchain is correct, at any time the requester can query the notary through the indirect interface to provide validation result(s). If the notary cannot provide the requested result(s) (e.g., the notary is unavailable or refusing the query), then the requester can use the indirect interface to send the same query over the blockchain. If within a predefined time period the notary does not respond using the indirect interface, then the SLA is executed (i.e., the deposit is sent to the requester and the service contract terminates).

The service in PADVA can be ordered by anyone, although we predict that usually server operators have incentives to order it. We do not mandate how validation results are used and interpreted, but some potential deployment models can be: a) a public service accessible to all TLS clients, b) a monitoring tool used only by domain operators, c) results can be aggregated and delivered to TLS clients [21], or d) or can be part of a more powerful system [16].

### 4 PADVA Details

In this section, we present details of PADVA. We start with service setup, then we present how notaries validate public keys and report outcomes of these validations. Next, we show how to monitor TLS servers that do not have clocks synchronized, and finally, we present auditing and SLA mechanisms provided.

#### 4.1 Service Setup

To order a notary service, a requester sends a transaction to the notary’s contract specifying the following parameters (see request() in Figure 3).

- **Domain name** whose public key(s) will be validated.
- **Whitelist of public key(s)** that allows the requester to specify which public keys are legitimate. If the notary will observe a listed key, then it is treated as a normal event and no warning notification is issued. Keys in the list are identified by their hashes. If the whitelist is empty, then any new public key observed will be reported.
- **Fee** that is paid to the notary for the service. Fees are predefined by notaries and determine the service duration and the SLA provided.
- **Reference time source** specifies a time source server that will be used as a reference. This parameter is optional and used if the monitored server does not return the correct time. If the time source is not provided, then the monitored server act as the reference time source.
Beside parameters given by requesters, each service has associated conditions of the SLA it offers. These conditions specify:

- how frequent the notary validates the public key of the server (the validation interval $T$), and
- the availability level provided and a penalty when the level is not met.

The notary observes all transactions sent to its contract and processes incoming requests (calling `handle_request()` from Figure 3). The notary checks whether the requester’s input is correct (checking the domain name, the whitelist, the fee, and the time source if specified) and accepts the request (`accept()` from Figure 3) by creating a new service and transferring deposit that will be used for ensuring the SLA.

The notary may refuse the request if the given parameters are incorrect, the server is unresponsive or misconfigured, or for any other reason. In such a case, the requester gets the fee back by calling the `timeout()` function that triggers the `timeout()` method (see Figure 3).

### 4.2 Public-Key Validation and Reporting

PADVA is designed to be compatible with the current TLS infrastructure. However, there are a few challenges associated with that. Since we want to keep notaries auditable and accountable, a notary to prove that it is validating a domain’s public key has to periodically obtain an authentic and fresh information that the corresponding private key is being used by the domain. But the TLS protocol was not designed to provide such information.

To overcome this issue, we exploit a message of the TLS handshake protocol (see subsubsection 2.1.1). Namely, the `ServerKeyExchange` message is signed with a server’s private key, and is sent by a server when the key exchange protocol negotiated is a variant of the `DHE_DSS` or `DHE_RSA` methods. These methods are widely deployed and used [3].

The `ServerKeyExchange` message is introduced to provide authentication for client-server negotiated parameters. It contains a server’s signature over the `signed_params` structure, which consists of client and server random values and server DH parameters (see Figure 4).

This is the only message signed by a server during the TLS handshake, hence only that can be obtained by notaries as a non-repudiable proof that a given key was used. However, the authenticity of the message is not enough, as it only proves that the key was used, but does not specify when it happened.

A message has to be fresh, as otherwise, a misbehaving notary could conduct multiple handshakes at once, and then use them to claim a fake event timeline. There is no explicit timestamp in the structure, but fortunately, the client and server random inputs are defined as presented in Figure 5, where the `gmt_unix_time` field is the current...
struct {
    uint32 gmt_unix_time;
    opaque random_bytes[28];
} Random;

Figure 5: The Random structure, that specifies server’s and client’s random inputs.

GMT Unix 32-bit timestamp, and the random_bytes is 28-byte long random value, generated by a secure random number generator.

Using these messages, the notary can periodically obtain a signed statement from the server which implies that a given key was used at given point in time. To do so, the notary at least every \( T \) conducts a new TLS handshake with the server and saves as a validation result the server’s certificate, signed values (including server’s timestamp), and the signature. These messages are sent during a TLS handshake in plaintext, and they allow to prove to anyone that the corresponding private key was used at the time specified in the gmt_unix_time field of the Random structure sent by the server. For each such a public-key validation a notary assigns a unique number (counter) called a validation id (vid). Validation results, accompanied by their corresponding vids, are stored by notaries for audits.

A notary has to inform about results of the validation process. A naive approach would be to just to publish a validation result every \( T \) in the blockchain. However, that would cause a significant overhead incurred by publishing the result of every validation. To minimize the interactions between notaries and the blockchain (i.e., to not flood the blockchain with the protocol messages), notaries keep all validation results but report in the blockchain only changes of the validation state. More specifically, the validation state is encoded using the following messages:

**OK:** successful validation, i.e., the observed public key is whitelisted.

**Error:** unsuccessful validation that can be caused by various reasons. The following error types are specified:

* NewKey: a new public key, outside the whitelist, was observed. This event can denote a misconfiguration or an impersonation attack. The notary that changes the state to NewKey publishes also the hash of the newly observed key.

* Time: timestamp signed by the monitored server (or the time source, if specified — see the next section) in the ServerKeyExchange message is incorrect (i.e., deviating from the notary time).

* Connect: denotes availability issues, when the notary cannot conduct a successful TLS connection with the server. It can be caused by a network outage, a server-side error, or an adversary blocking the connection.

* Other: other error, not specified above.

The notary submits each state update by calling change_state() that triggers the state() method of the notary’s contract (see Figure 6). A state update is associated with the corresponding vid, i.e., the id of the validation when the state change happened. If there is no state change, then no message is sent. Using this simple approach, PADVA optimizes for the common case (i.e., a public key of a server changes infrequently).

Reported state changes allow drawing an event timeline. An example of such a timeline is presented in Figure 7. In the first validation, the notary obtains a whitelisted public key, thus it reports the OK message with vid equals 0. Then, the subsequent 30 validations are also successful, thus no state change is published in the blockchain. With the validation 31, the notary detects
a public key outside the whitelist, therefore a NewKey error specifying the hash of the newly observed key is reported. The last validation presented is again successful, hence the notary changes the state back to OK.

4.3 Handshake Timestamping

So far, we present PADVA in the setting where a timestamp returned by the monitored server acts as the reference time. However, the TLS protocol does not require clocks to be set correctly [13], and moreover, some implementations violate the specification and do not set correct timestamps [27]. As presented in subsection 6.2 about 63% of tested TLS servers do not put correct timestamps into their ServerHello messages.

Therefore, the protocol can be also easily combined PADVA with other protocols and infrastructures (as discussed in subsection 7.1).

By executing the protocol, the notary gets the evidence that the message SKE signed by the monitored server is older than \( (r, t_1, \sigma_1) \) and newer than \( (h_2, t_2, \sigma_2) \). The notary keeps all the messages of the protocol as a validation result, that can prove that the server’s public key was validated between \( t_1 \) and \( t_2 \).

Interestingly, any TLS server that can be monitored by PADVA, can also act as a time source. In such a case, the notary simply uses the random field of the ClientHello message to submit data to be timestamped and receives a ServerKeyExchange message that signs this data. As presented in subsection 6.2 in such a setting an average time difference between receiving \( t_2 \) and \( t_1 \) was measured as 0.34s, thus such estimation is precise. Moreover, the protocol can be also easily combined PADVA with other protocols and infrastructures (as discussed in subsection 7.1).

4.4 Auditing and SLAs

The main task of a notary is to periodically check a monitored server’s public key(s). PADVA keeps notaries audit-able and accountable for their actions, and to facilitate the audit process, a notary is obligated to:

1. the notary initiates the protocol by sending a random value \( r \) to the time source server.
2. The time source, responds with a signed message \( (r, t_1, \sigma_1) \) which contains the random input, a timestamp \( t_1 \) (set by the time source), and the signature computed by the time source.
3. Next, the notary prepares the ClientHello message \( CH \) to be sent to the monitored server. The notary sets the random field of this message to the hash of \( (r, t_1, \sigma_1) \), and subsequently initiates a TLS handshake with the monitored server by sending \( CH \).
4. The server responds with the signed ServerKeyExchange message \( SKE \). Timestamp included in this message is incorrect (as we assumed that the server timestamps are unreliable), however, the ClientHello random field is the hash over the \( (r, t_1, \sigma_1) \) message, which in turn contains the trusted timestamp \( t_1 \). Thus, it implies that \( SKE \) was created after \( t_1 \).
5. Then, the notary sends \( h_2 = H(SKE) \) to be timestamped by the time server.
6. Finally, the time source returns a signed \( (h_2, t_2, \sigma_2) \) message, which contains the (trusted) timestamp \( t_2 \) and \( H(SKE) \) in the ClientHello random field. This implies, that \( SKE \) is older than \( (h_2, t_2, \sigma_2) \), thus is older than its timestamp \( t_2 \).

Figure 8: The extended public-key validation protocol, with the time source server involved. \( H() \) stands for a cryptographic hash function.
• publish all changes of the validation state in the blockchain (as described in subsection 4.2),
• store validation results for all monitored domains throughout their service lifetimes.

At any time the requester can ask a notary about any validation results. This is realized with the direct interface, implemented as a standard client-server communication (e.g., an HTTP API), where the requester sends a query specifying the validation id for which he would like to obtain the result. The notary has to return the relevant validation result, such that the requester can compare it with the state encoded in the blockchain.

In the case of an inconsistency detected, the requester can publicly announce the validation id that contradicts the state encoded in the blockchain, as it is evidence that the notary misbehaved. For instance, it can be a validation result where the validated key is not whitelisted, while at the same time the state in the blockchain was not updated (e.g., when any validation between vid 1 and 30 was for a non-whitelisted key — see Figure 7).

One challenge with the direct interface (and any client-server service) is that the notary can be unavailable or censor queries while the requester cannot prevent or prove that fact. In our context, a notary can have some reasons to not return some validation results. For instance, the notary is unavailable, or was unavailable at some validation period(s), misbehaved, or made a mistake and tries to hide that. PADVA provides a framework to keep notaries accountable and responsible for such cases. Namely, besides the standard client-server direct interface, the blockchain-based indirect interface is introduced.

If the requester notices that the notary is unavailable (or was unavailable at a given time interval) or censors queries, the requester can query the notary over the blockchain. In order to do so, the requester calls the query() function that triggers the sla_query() function of the notary’s contract (see Figure 9). When the transaction with the query is added to the blockchain it is managed by a smart contract and the notary is obligated to submit a response to the blockchain.

If the notary does not return any result until the deadline specified in the SLA then the smart contract will execute the SLA, sending the deposit to the requester. To trigger it, the requester calls the contract’s sla_claim() method with the unresponded query specified. It is also visible to anyone that the notary did not respond to the query. Alternatively, when the notary returns a response (calling the response() function that triggers the contract’s sla_response()), the SLA is not executed, as the notary proved its availability, and the response can be processed by the requester (see details in section 5). Also, in that case, the response is visible to everyone.

Thanks to dividing interactions into the two interfaces (the standard client-server and the blockchain-based one) the regular audit operations are conducted efficiently without involving blockchain, while the blockchain interface is used only when necessary.

5 Security Analysis

MitM attacks The main goal of notary systems is to detect and prevent MitM attacks through multipath probing. PADVA follows this strategy, except the public key
validation is positioned as a service, where notaries constantly validate public keys and draw event timelines in the blockchain. These timelines are essential for measuring key continuity and detecting anomalies.

We do not mandate PADVA to be deployed in a specific way. Service can be requested by domain owners and used only by themselves. Alternatively, it can be run as a public service accessible for everyone or can be used as a data feed for other systems [16][21]. We also emphasize that PADVA is orthogonal to the TLS PKI. A requester can whitelist any public keys believed or known to be legitimate.

In all these cases, PADVA can provide an effective protection against MiTM attacks as long as an attack is short-lived or is limited only to a fragment of the network topology. In the former case, the attack is seen as an anomaly (i.e., a new observed public key outside the whitelisted set), thus it is suspicious. In the latter case, the attack is identified as an inconsistency between the notary and the TLS client views. In this context, the previous systems provide similar properties, however, the advantage of PADVA is that it provides more reliable and auditable event timelines.

Misbehaving Notary PADVA keeps notaries accountable, and if an adversary impersonates the domain throughout the validation interval, then the notary cannot make a false statement undetected that it has not happened. More specifically, if the notary contacts the monitored server and notices a public key that is not whitelisted by the requester, then either a) the notary announces the state change making it visible, or b) it does not report the state change, hiding this fact.

In the latter case, the notary takes a risk, as the requester conducting an audit will notice that either the state is incorrect (as one or more validation results are contradicting it), or the validation result(s) are missing. (We emphasize that the notary cannot produce a validation result on behalf of the monitored server, as the private key corresponding to a whitelisted key is required.) If some validation results are contradicting the published state, the requester has evidence of the notary misbehaving. However, if validation results are missing/censored, the requester can query the notary via the indirect interface. The notary is obligated to respond, so either it responds with an incorrect data, or it refuses to respond, losing the SLA deposit and showing its unavailability to everyone.

(D)DoS Resilience Availability is one of the major issues of the previous notary systems. They were designed in the client-server architecture, where a client wishing to learn a validation state has to contact a notary server and wait for its response. Client queries are expected to be handled immediately 24/7, and due to that availability of notary servers is crucial. Unfortunately, such a setup can be easily attacked with a botnet targeting notary front-end servers, practically stopping their operations.

PADVA provides a more flexible architecture, by placing a blockchain as a publishing medium, while still exposing a client-server interface for heavyweight operations. An adversary with a botnet can still attack notary front-end servers blocking their direct interfaces, however, it is much more difficult to stop the notary’s operation. The notary can still use any back-end server (unknown to the adversary) to conduct public-key validations, and report the corresponding state changes (if any) in the blockchain, such that it is available to everyone who reads the blockchain. Namely, PADVA changes availability requirements from “a notary needs to be up all the time” to “a notary has to have at least one back-end up once per the validation period T”. Moreover, to avoid enumeration back-ends can be in different locations, with dynamic IPs, using network tunnels or anonymity infrastructures. To completely block notary operations, the adversary has to either block the underlying peer-to-peer blockchain network or censor blockchain transactions.

Privacy PADVA provides privacy benefits over the previous schemes, as the validation state history can be read from the blockchain, without contacting any third party. In particular, no notary infrastructure is contacted by clients.

6 Implementation and Evaluation

To prove deployability and efficiency of PADVA we implemented it and then evaluated in a real-world scenario. In this section, we report our implementation and the obtained evaluation results.

6.1 Implementation

The notary’s internal architecture is presented in [Fig. 10] and it consists of the following elements:

Monitoring module periodically conducts TLS handshakes with monitored domains. This module collects cryptographic proofs and supports the timestamping protocol (as described in subsection 4.3). Results gathered by the monitoring module are reported to the database module.

Database module stores all necessary state and data to run a notary service (i.e., active and inactive services, results of all validations, pending requests, ...).
**Reporting module** observes state of validations and reports validation state changes into the blockchain (using the blockchain API).

**Direct interface** is an HTTP API used to serve validation results to requesters. The direct interface can be publicly accessible to provide this data to any party that would like to audit the notary.

**Indirect interface** uses the blockchain API to handle service initialization and SLA requests.

![Diagram of the internal architecture of a PADVA notary.](image)

**Monitoring Module**

**Direct Interface**

**Indirect Interface**

**Database Module**

**Reporting Module**

**Blockchain API**

**Read/Write Blockchain Transactions**

**TLS Comm.**

**HTTP API**

**Figure 10:** The internal architecture of a PADVA notary.

We implemented most of the modules in Python. The monitoring module was implemented with the Scapy and Scapy-SSL-TLS libraries. In our implementation TLS handshakes are not finished, instead, a notary sends a TCP RST packet whenever a ServerHelloDone message is received (see [Figure 1]). With this modification, our implementation saves one round-trip time and is server-friendly (as after receiving a TCP RST the server removes the associated connection state).

We chose Ethereum as the blockchain platform, and the smart contract part of PADVA was implemented using the Viper [10] language. The blockchain API was implemented with Go’s [9] and Python’s [10] Ethereum implementations.

### 6.2 Evaluation

First, we investigated what is the fraction of TLS servers can be monitored by PADVA. To this end, we scanned 15,000 domains from the Alexa top list [11] and checked how many of them deploy TLS on the HTTPS port (i.e., 443). If a domain does not deploy TLS we also try to prepend it with the “www,” prefix. Then, for the deploying domains, we checked how many of them return correct timestamps in the ClientHello message (prior to this test we synchronized our clock with time.google.com). The results are presented in [Table 1]. As presented, about 37% of the TLS servers investigated return precise timestamps (i.e., deviating from the correct time up to one second). These servers can be monitored by PADVA notaries directly (without involving a time source) or can act as time sources for servers that return incorrect timestamps.

Next, we conducted a series of experiments to evaluate our implementation of PADVA in a realistic scenario. We deployed a notary server using Linux Ubuntu 16.04 (64 bit) equipped with Intel i7-6600U CPU @ 2.60GHz and 8GB of RAM. From an academic network in Asia, we conducted 100 public-key validations selecting a random supported TLS server (the single-server case) each time, and another 100 public-key validations where for each validation we selected a random supported TLS server and another supported TLS server acting as a time source (the timestamp case). We reported the obtained results in [Table 2] specifying minimum, maximum, average, and median value for every measurement.

For both, the single-server and timestamp case, we report time required to conduct a validation ($t_{sing}$ and $t_{ts}$ respectively), as well as transmission overhead incurred in the validation ($s_{sing}$ and $s_{ts}$ respectively). The validation time is mainly determined by network latency. (We emphasize, that in our implementation only half TLS handshakes are conducted, minimizing this latency.) For the single-server case, it ranges between 0.04-0.31s with an average value of 0.16s. For the same case, the number of bytes transmitted is between 1.3-6.9KB, with an average

| $\Delta$ (s) | 0-1 | 2-5 | 6-60 | 61-300 | >300 |
|------------|-----|-----|------|--------|------|
| # of servers | 3061 | 420 | 130 | 82 | 5823 |
| 32.17% | 4.41% | 1.37% | 0.86% | 61.19% |

![Table 1: The distribution of timestamps returned by the TLS servers.](image)

$\Delta$ is defined as $abs(t_l - t_s)$, where $t_l$ is the current local time, and $t_s$ is a server’s timestamp.

For both, the single-server and timestamp case, we report time required to conduct a validation ($t_{sing}$ and $t_{ts}$ respectively), as well as transmission overhead incurred in the validation ($s_{sing}$ and $s_{ts}$ respectively). The validation time is mainly determined by network latency. (We emphasize, that in our implementation only half TLS handshakes are conducted, minimizing this latency.) For the single-server case, it ranges between 0.04-0.31s with an average value of 0.16s. For the same case, the number of bytes transmitted is between 1.3-6.9KB, with an average

| $t_{sing}$ (s) | Min | Max | Avg | Med. |
|------|-----|-----|-----|-----|
| $t_{ts}$ (s) | 0.04 | 0.31 | 0.16 | 0.15 |
| $s_{sing}$ (B) | 1313 | 6865 | 4369 | 4483 |
| $s_{ts}$ (B) | 6031 | 17973 | 13190 | 13445 |
| $t_2 - t_1$ (s) | 0.16 | 0.48 | 0.34 | 0.34 |
| $s_{cert}$ (B) | 806 | 6071 | 3815 | 3976 |

![Table 2: The obtained performance results.](image)
around 4.5KB. The timestamp case, which requires three TLS handshakes, needs between 0.19s to 0.73s with an average value of half a second, and to transmit between 6-17KB with an average of about 13.5KB.

Next, we investigated how precise is the variant of the public-key validation with time source involved. To this end, we measured the time difference between receiving the timestamps $t_1$ and $t_2$ from a time server (see Figure 8). This measurement illustrates how much time it takes to timestamp a TLS handshake (i.e., what overhead is introduced by running the protocol from Figure 8). The results obtained by our measurements are presented in the table. As we can see, the overhead introduced by deploying the timestamping protocol is around 0.20s on average, what should be marginal when compared with a realistic validation period $T$ (see subsection 7.3).

PADVA notaries have to store exchanged TLS messages as validation results. However, when stored naively this storage overhead may be significant. On average, a single validation takes 4483B, thus a storage required for yearly validations of one server, with $T$ equals one hour, would be around 39.27MB. However, validation results are usually highly redundant, as their size is dominated by certificates sent from servers to notaries (see Figure 1). Since certificates are usually the same, there is no need to store them all. As an average certificate chain’s size $s_{cer}$ was measured as 3976B, the same yearly validation results without storing redundant certificates would require 4.44MB (almost 9 times less).

7 Discussion

7.1 Time Sources

We presented PADVA such that it deploys TLS servers as external time sources (see subsection 4.3). However, our scheme can be easily combined with other protocols and infrastructure that provide authentic and reliable timestamps.

One, such an infrastructure is the time-stamp protocol (TSP) [2], a document timestamping protocol that relies on the X.509 PKI. In TSP, a client submits a hash of data to a timestamp authority which in turn timestamps and signs this data. The signed message is returned to the client, so the client can prove to everyone when the data was timestamped by the authority. This model is almost the same as the model presented in subsection 4.3 (see Figure 8). Thus, a TSP server can be used as an external time source in PADVA.

Another example is time synchronization infrastructures. Usually, secure time synchronization protocols use random client inputs to prevent replay attacks. Such an input is timestamped and signed by a time synchronization server, thus it can be used analogically as presented in Figure 8. One instantiation of this approach could be a novel time synchronization protocol Roughtime proposed by Google[12].

7.2 TLS 1.3

As for February 2018, the next version (1.3) of the TLS protocol is being standardized. The standardization process is not finished and as we have learned from other server-side protocol upgrades [34], we should not expect a quick upgrade to TLS 1.3 (especially, as the TLS 1.3 failure rate is high right now [40][41]). However, with the current draft [36] the TLS 1.3 protocol introduces the following changes which might affect PADVA:

1. removed the ServerKeyExchange message type,
2. removed the GMT timestamp fields from the client and server random structures.

The first change is not disruptive, as the new CertificateVerify message with similar semantics was introduced instead. The CertificateVerify message contains a signature that is computed over the client’s and server’s random inputs, thus it can be used to prove that a given key was used for signing (exactly as with the ServerKeyExchange message).

The latter change was introduced to prevent fingerprinting, as a GMT timestamp could be used to track clients and servers (note, that the most of the handshake messages are exchanged in the plaintext, thus an eavesdropping adversary can read them) [27]. Due to this change, it is impossible to prove when a given key was used (as there is no timestamp). If this change reminds stable in the specification, it will break relying upon protocols (like TLSDate[13] and will partially affect PADVA as well. Namely, the simple version (the version without external timestamping presented in subsection 4.2) of the protocol will become unusable as due to this change notaries would not be able to prove when a given key was used. Fortunately, PADVA can still be deployed in the scenario with an external time source (see subsection 4.3). Moreover, if the monitored server deploys TLS 1.3, then any server with a lower TLS version (e.g., TLS 1.2) can act as a time source. Furthermore, as described in subsection 7.1 other services can be used for providing reference timestamps.

7.3 Blockchain Time

A public blockchain is an open distributed infrastructure, and nodes do not have precisely synchronized clocks [43]. However, by definition, the blockchain structure preserves the order of blocks, and this is why time in the presented smart contracts (i.e., time() calls)
can be expressed in numbers of blocks and not in seconds (usually, blockchain platforms are configured such that new blocks arrive in equal intervals). Consequently, timeouts specified in SLAs can be measured in block numbers.

The validation interval \( T \) is specified by a notary in seconds. It is a trade-off between security and efficiency, and although we do not require any minimum/maximum values for \( T \), there are some underlying constraints and implications that notaries should take into consideration. In particular, PADVA has to combine the two notions of time: \( a \) time maintained by TLS servers or external time sources, used for conducting validations, and \( b \) time of the underlying blockchain platform.

In blockchain systems new blocks arrive at intervals (e.g., approximately 10 minutes in Bitcoin \([32]\), and 15 seconds in Ethereum). Let us denote this interval as \( T_B \). If \( T < T_B \), then reporting multiple state changes within \( T_B \) has some implications as it can occur that many state changes happen within \( T_B \), such the corresponding transactions announcing it will be added in the same block. Each state change has the associated validation id, thus as the results, the timeline can be created, however, users that observe the blockchain get results in batches. With \( T \geq T_B \) this problem is relaxed as usually state changes will be propagated in separate blocks.

8 Related work

Perspectives \([45]\) was the first comprehensive notary system presented. In Perspectives, notaries continuously observe domain certificates. Clients can contact a notary server and compare their view of the domain’s key with the view of the notary. Convergence \([26]\) is a similar system where the main improvements over Perspectives are related to privacy and performance. Deployment of Convergence was analyzed by Bates et al. \([5]\), where the increased latency of TLS connection establishment (about 108 ms) is reported. Besides that, these systems are critiqued as they need to have highly available front ends, they require a significant trust in notaries, and introduce privacy violations \([20][31]\).

Certificate Transparency (CT) \([22]\) is a log-based detection scheme. CT aims to introduce transparency to the CA ecosystem, by making each certificate visible. To this end, CT introduces publicly verifiable certificate logs that maintain append-only databases of certificates. To accept a TLS connection, the client has to obtain a certificate accompanied by a signed promise from a log (the promise asserts that certificate was seen by the log). CT is designed to detect attacks, rather than prevent them. Logs are required for certificate issuance, thus their front-end servers have to be highly available, what in practice is challenging \([17][18][38]\). Although log servers are auditable, to assure that they do not equivocate (by creating an alternative log’s version) they need to be monitored by external protocols \([9][33]\). PADVA aims to improve CT ensuring that a given key is actually being used, moreover, the availability requirement is significantly relaxed, and notaries cannot equivocate as long as the underlying blockchain platform is secure.

CT has inspired other log-based approaches, that improve its efficiency \([19][39]\), enhance security \([4][19]\), and add new features \([39][44]\). Unfortunately, some of these system increase latency of TLS connection establishment, and other require major changes to the TLS PKI. As for today, no other log-based system than CT is widely deployed.

CoSi \([42]\) is a witness framework proposed to keep CA accountable. In CoSi, a large number of witnesses co-signs assertions about certificates they have seen. As a witness scheme, CoSi is focused on detection rather than prevention, and its design objective (similarly to CT) is to make attacks visible. It is assumed that an adversary would not conduct an attack if it would be eventually visible. In order to achieve efficient co-signatures, CoSi requires coordination among witnesses.

Researchers already tried to reuse properties of blockchain to problems existing in PKI. For instance, Namecoin \([25]\) (the first fork of Bitcoin) provides a namespace where names can be associated with public keys. Certcoin \([14]\) improves Namecoin’s inefficiency and supplements the original scheme by features like key revocation and recovery. Bonneau proposed EthIKS \([8]\) to improve auditability of the CONIKS system \([30]\), while Matsumoto and Reischuk \([28]\) introduce a blockchain-based system that provides financial incentives for detecting fraudulent certificates.

9 Conclusions

In this paper, we presented PADVA, the next generation TLS notary system. PADVA provides many features and properties that the previous notary system could not provide. By leveraging the TLS specification and redesigning the validation process, notaries in PADVA do not have to be trusted as much as they were in the past. Notaries become auditable and accountable, able to monitor desynchronized servers, and ready for TLS 1.3. By placing a blockchain platform as one of its central elements, PADVA provides a flexible payment framework and mechanisms for defining and enforcing service-level agreements, and relaxes availability requirements making the overall system more resilient. The public-key validation is persistent and implemented as a service.

With the increasing capabilities of blockchain platforms, PADVA could be improved by more sophisticated smart contracts. For instance, with the current design, a
notary can respond via blockchain with any (even incorrect) response. Although doing so the notary would ruin its reputation (as everyone can see it), in the future the SLA contract could validate the response and act accordingly.

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