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PKI Safety Net (PKISN): Addressing the Too-Big-to-Be-Revoked Problem of the TLS Ecosystem

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***Abstract*—In a public-key infrastructure (PKI), clients must have an efficient and secure way to determine whether a certificate was revoked (by an entity considered as legitimate to do so), while preserving user privacy. A few certification authorities (CAs) are currently responsible for the issuance of the large majority of TLS certificates. These certificates are considered valid only if the certificate of the issuing CA is also valid. The certificates of these important CAs are effectively *too big to be revoked*, as revoking them would result in massive collateral damage. To solve this problem, we redesign the current revocation system with a novel approach that we call PKI Safety Net (PKISN), which uses publicly accessible logs to store certificates (in the spirit of Certificate Transparency) and revocations. The proposed system extends existing mechanisms, which enables simple deployment. Moreover, we present a complete implementation and evaluation of our scheme.**

1. Introduction

The TLS public-key infrastructure (PKI) is an essential component of today's Internet, as it enables to use and verify certificates for secure communications. Certification authorities (CAs) are trusted third parties responsible for issuing and signing digital certificates, which contain authenticated public keys. To do so, CAs also own certificates. Naturally, the problem is that private keys can get compromised. As a consequence, the ability to revoke any certificate (including a CA certificate) and verify if a given certificate has been revoked is crucial. This process should be lightweight, secure, and preserve user privacy. To develop a new revocation scheme, one should also answer the question of who must be able to revoke a given certificate. The owner, the issuer, the root CA, intermediate CAs, or a combination of these?

The current revocation schemes simplify many aspects of the PKI ecosystem. The most striking example is the following. As any private key can be stolen, it should be possible to revoke any certificate; however, just like some corporations are said to be "too big to fail", the certificates of some certification authorities are, in practice, *too big to be revoked*. A study showed that around 75% of certificates had been issued by only three different companies, and one specific GoDaddy CA private key had signed 26% of all valid certificates in March 2013 [9], [17]. Revoking this particular certificate, if the corresponding private key were compromised, would mean that 26% of all websites that use HTTPS would be unavailable (or accessible only if the security warning displayed by browsers is ignored). Diginotar and Comodo are two infamous examples of attacked CAs. After the breach, while Diginotar had its certificate revoked and removed from most CA lists [2] (before eventually declaring bankruptcy), Comodo's incriminated CA certificate was not revoked and is still present in CA lists [6]. The Comodo Group is leading the certificate issuance business (with a market share of 33.9%, and some single private keys that have been used to sign the certificates of 5.5% of all the websites considered in a W3Techs survey from February 2015 [8]). Consequently, Comodo's root certificate could not be revoked without effectively preventing users from establishing TLS connections with a significant portion of the Internet. For this reason, we claim that the TLS revocation system needs to be redesigned to remove the collateral damage that would be induced by the revocation of some CA certificates.

We observe that time is a key element in this problem, as certificates issued before the certification authority was compromised should not become invalid when the CA certificate is revoked. Therefore, we suggest that introducing a timestamp server for certificates and revocations can prevent invalidating any legitimate certificate. Another problem of current revocation schemes is that a certificate cannot be directly revoked by its owner. Our approach, PKI Safety Net (PKISN), solves this issue. In PKISN, domain owners can use their private keys to revoke the corresponding certificates, while CAs can use a dedicated revocation key, which can be securely stored offline as it is not needed during normal operation.

The scheme we present is inspired by log-based solutions such as Certificate Transparency (CT), which was recently introduced and deployed [28]. CT aims to make the actions of CAs more transparent by introducing a log that makes certificates publicly visible. However, CT mainly covers the issuance aspect of the problem. We propose to improve the system in several ways, in particular, by using two distinct hash trees (the data structure on which CT relies) to store not only certificates, but also revocations. Moreover, PKISN gives CAs the ability to revoke their own certificates after a certain point in time to ensure that previously-signed certificates remain valid.

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Security breach notification laws require CAs to notify relevant authorities about a data breach. For example, in the E.U., this notification must occur within 24 hours. In other words, certification authorities are compelled by law to take rapid action to disclose a data breach when it is detected. This notification should be immediately followed (if not preceded) by a set of measures that can mitigate the attack, but it is currently not possible to simply revoke certain compromised CA certificates without incurring substantial collateral damage.

The major contributions of this paper are the following. Through PKISN, we redesign the revocation system to better express the hierarchical structure of certificates, rebalance the power of PKI actors, and address the too-big-to-be-revoked problem. In addition to the existing deployment plans of CT, we propose and discuss new models that maximize privacy and allow to monitor the log in a lightweight manner, and we show how the log can be designed to handle these deployment models. We present an evaluation and a full implementation of our system.

2. Background

2.1. The TLS Public-Key Infrastructure

In TLS, certificates form a chain of trust (*certificate chain*) that starts with the root CA's self-signed certificate and ends with the server's certificate. This chain can contain a number of intermediate CAs and each certificate in the chain (except the root) is signed by the private key corresponding to the public key of the parent certificate. TLS clients (e.g., browsers) need a list of root CA certificates considered trustworthy to initiate the verification of other certificates. The `basicConstraints` extension indicates whether a certificate is a CA certificate. For convenience, we will use a simple notation to represent the chain of trust formed by a series of certificates, as follows:

$$C_a \rightarrow C_b \rightarrow \cdots \rightarrow C_c, \quad (1)$$

where C_a is a root CA certificate, C_b and possibly other certificates are owned by intermediate CAs, and C_c is an end-entity (leaf) certificate.

Starting 1 April 2015, certificates must not be issued with a validity period greater than 39 months [5]. However, this concerns only leaf certificates, i.e., not CA certificates. In fact, certain root CA certificates are valid for up to 30 years (e.g., the certificate of *CA Disig Root R1*, present in the list provided by Mozilla [6], will be valid until July 2042).

2.2. Desired properties

Here are the properties that we expect of a satisfactory revocation system:

Efficiency: transmission, computation, and storage overheads are reasonable and the deployment of the system is cost-effective.

Timeliness: the *attack window*, i.e., the time between the detection of an attack and the moment when the corresponding certificate is considered invalid by all clients, is short (ideally, on the order of minutes/hours).

Privacy: clients can obtain certificate-validity information without sacrificing their privacy. In particular, users should not be forced to contact any other party than the server they connect to in order to obtain the certificate status.

Authenticity: only legitimate parties can create a revocation message for a certificate, but that message is verifiable by everyone. The set of legitimate parties depends on a revocation policy.

Independence: the revocation is independent from the circumstances in which the process takes place (e.g., server configuration or the availability of a special third party). Ideally, whenever an allowed entity has issued a revocation message, and a certain server is accessible, then clients of this server should be able to access the disseminated message. An adversary must not be able to suppress a revocation.

Complete status information: revocation messages must provide the status of all certificates in the chain of trust.

Transparency: revocations must be publicly accessible and persistent, to guarantee to the interested parties that, when a revocation is successfully issued, it is impossible to claim that the certificate is still valid.

Backward availability: the revocation system must solve the too-big-to-be-revoked problem of the current TLS PKI. In other words, it must be possible to revoke any CA, without causing collateral damage, i.e., without revoking certificates that were legitimately issued before the CA's private key got compromised.

(The efficiency of PKISN is evaluated in §7.2, §8.1, and §8.2, while security properties are discussed throughout §6.)

2.3. The Evolution of Revocation Schemes and their Drawbacks

The first attempt to address the revocation problem was realized with Certificate Revocation Lists (CRLs) [13], published by CAs at CRL distribution points. To verify the validity of a certificate, the browser downloads a CRL and checks whether the certificate is listed. Unfortunately, the CRL approach has many drawbacks: *a*) It is inefficient, since the entire CRL must be downloaded to verify a single certificate (a n-certificate chain requires n connections). *b*) CAs can violate the privacy of users by creating a dedicated distribution point for a target certificate. Whenever a user connects to this special distribution point, it means that this user is very likely to visit the website that corresponds to the target certificate. *c*) Gruschka et al. [19] reported that, during a 3-month period, only 86.1% of the CRL distribution points had been available. Mainly due to efficiency issues, the usefulness of CRLs was questioned several years ago [22], [32], [36].

There are many schemes that improve the format of standard CRLs. For instance, Kocher [24] proposed to use a Certificate Revocation Tree. This data structure, based on binary hash trees, allows to efficiently prove that a certificate is not revoked. Naor and Nissim [34] suggested a similar solution, and their Authenticated Dictionaries support certificate insertion and deletion more efficiently. Unfortunately, these methods have not been adopted.

To address the inefficiency of CRLs, the Online Certificate Status Protocol (OCSP) [38] was proposed. In OCSP, clients contact a CA to get the status of a certificate. However, this solution is still inefficient (the CA may be under heavy load, and an extra connection is required), and has a serious privacy issue (the CA learns about the server that the browser is contacting). OCSP Stapling [35] solves these problems. In OCSP Stapling, the server periodically obtains an OCSP response from its CA, and then sends the response along with the certificate in subsequent TLS connections. Unfortunately, the deployment and effectiveness of this technique depend on the server configuration (e.g., the age of a stapled response can be customized by a configuration parameter, which may introduce a long attack window). Liu et al. reported [29] that only 3% of certificates are served by servers supporting OCSP Stapling. Moreover, OCSP and OCSP Stapling only return the status of a single certificate (not the entire chain). To address this problem, an extension [35] was proposed.

Recently, browser vendors decided to disseminate special CRLs (called CRLSets) through software updates [3], [25]. Such an approach does not require any server reconfiguration, but CRLSets only support certain *Extended Validation* (EV) certificates [25]. Such a policy restricts the deployability and effectiveness of the method, as the fraction of EV certificates is relatively small [17], [21], and the revocation process is still conducted through a CA (a user cannot revoke his own certificate without contacting the CA). A study showed that Chrome's CRLSet contains only 0.35% of all revoked certificates [29].

Short-Lived Certificates (SLCs) [36], [42] solve problems associated with CRLs and OCSP, by periodically providing domains with fresh certificates with a limited validity period. SLCs are designed to be valid for a few days, and as they are irrevocable, a long attack window exists. SLCs are intended for leaf certificates, hence intermediate and especially root certificates cannot benefit from the properties of SLCs. In addition, their deployment depends on server configuration.

Another recent approach, called RevCast [39], improves revocation dissemination through unique properties of radio broadcast. RevCast proposes an architecture where CAs broadcast revocation messages and users with radio receivers can receive them immediately. RevCast employs a blacklist approach where the user must possess the entire CRL, and to satisfy this requirement an additional infrastructure must be provided or users have to continuously listen to broadcast transmission. RevCast also requires users to purchase and install radio receivers.

None of the schemes presented above provides the transparency property. Revocation Transparency [27], which was proposed as a supplement for Certificate Transparency (see §2.4), was the first attempt to provide that property. Unfortunately, due to the introduced data structure, checking whether a certificate is revoked might be inefficient in practice. Additionally, Revocation Transparency lacks a detailed description.

Log-based approaches such as AKI [23], ECT [37], ARPKI [10], PoliCert [40], and DTKI [43] take the transparency of revocations into consideration. However, AKI, ECT, and ARPKI do not allow domains to use multiple certificates (which is a common practice today [4]). In ECT, only the most recent certificate is considered valid for any given entity. Similarly, in AKI and ARPKI, a certificate expresses the domain's policy, which must be unique. Consequently, these systems are designed in such a way that, at a given point in time, there can exist only one active certificate per domain name. To solve this issue PoliCert decouples policies from certificates. Similarly, DTKI introduces a *master certificate* and a *mapping server*, which also allow a domain to possess multiple certificates. Unfortunately, all these schemes (including PoliCert and DTKI) simplify the certificate hierarchy by ignoring intermediate CAs, and consider that certificates are signed directly by root CAs. Such certificates are unusual in practice, and taking intermediate CAs into consideration would introduce a significant complexity to the log and protocol designs. For instance, to return complete status information, a log would need to efficiently look up all relevant information about a particular certificate chain (without performing a linear search). Furthermore, the previous proposals do not handle revocation of CA certificates.

Unfortunately, none of the methods proposed in the literature identifies and solves the too-big-to-be-revoked problem of the current TLS PKI and would thus create large collateral damage if a popular CA certificate were revoked.

2.4. Certificate Transparency

The Certificate Transparency (CT) [28] project was initiated by Google and aims at making the issuance of TLS certificates accountable and publicly visible. In order to achieve this goal, log servers are used to collect certificates that can be submitted by anyone (clients, servers, CAs).

The CT framework relies on the Merkle tree (also called hash tree) data structure. In the binary Merkle trees used in CT, leaves are essentially hashes of certificates and the other nodes are obtained by hashing the concatenation of their two children. We can distinguish between two types of Merkle trees. When new leaves are generated, they can either be appended to the tree (in chronological order) or the tree can be continuously sorted (in lexicographical order). In CT, logs use append-only trees sorted in chronological order, because it can be efficiently proven (with a number of node logarithmically proportional to the number of entries in the tree) that a certificate is part of the tree and that a given tree is the extension of another tree. Trees that are sorted in lexicographical order, on the other hand, allow to efficiently show that a certain entry is absent from the tree.

When a certificate is submitted to the log for inclusion, it returns a Signed Certificate Timestamp (SCT), which is a promise to incorporate the certificate to the tree within a fixed time period called the Maximum Merge Delay (MMD). The SCT must be provided by the TLS server to its clients at every connection, and the documentation [28] of CT describes three ways to do so: via OCSP Stapling, via a TLS extension, or via an X.509v3 extension. The last method is of particular interest as it is CA-driven (i.e., CAs directly embed the SCT into the certificate at issuance) and does not require servers to be updated, but it requires that CAs participate.

2.5. Assumptions

For our revocation system to be operational, we make the following assumptions:

- It is possible to determine when the private key of a CA is misued, in particular, by monitoring logs or with audits. (This is easier to achieve if certificate logging is mandatory, which is the case for PKISN.)
- CAs can store a special private key offline in a secure manner.
- Browser software is provided by a single vendor. (This assumption is introduced for the sake of simplicity and can be easily relaxed.)
- Browsers have a working software-update mechanism.
- The log server is highly available (for both read and update operations) to all parties.
- The different parties are loosely time-synchronized (up to few minutes), and time is expressed in Unix seconds.
- The cryptographic primitives used by PKISN are secure.
- Only one log server exists, but extending PKISN to multi-log settings is discussed in §9.

2.6. Adversary Model

We consider that an adversary can steal a domain's private key to perform a man-in-the-middle attack or a CA's private key to issue malicious certificates/revocations, but an attacker cannot access a CA's offline (revocation) key, and cannot access key(s) used for software update. The adversary can also contact the log (to fetch or submit data) as any other party. The adversary's goal can be to: *a*) cause collateral damage and make many websites unavailable, *b*) violate the revocation policy and convince a client that a revoked certificate is still valid, or *c*) revoke a valid certificate without legitimately owning the appropriate key.

2.7. Notation

Throughout the paper, we use the following notation:

C_x	certificate
R_{C_x}	revocation of certificate C_x
t_x	timestamp
sk_x	secret key associated with the public key authenticated by C_x
rk_x	revocation key (stored offline) associated with a CA certificate C_x
vk	key used by the software vendor
k_{log}	log key
$H(.)$	cryptographic hash function
$Sig_k(m)$	message m signed with key k
$\varnothing$	*null* value
$\|\|$	concatenation

3. PKISN Overview

This section gives a high-level picture of the overall system and introduces the entities involved and basic terminology. In PKISN, clients/browsers want to communicate securely with servers/domains. A server is authenticated through a certificate chain created by a number of CAs. All certificates and revocations must be logged by a log server. At every *update time*, each log updates its local database, and the time period between these updates is called the *scheduling period*. The log is verified by browsers and dedicated parties called *monitors*. CAs must also act as monitors to verify that no illegitimate certificate (issued on their behalf) is present in the log.

3.1. The Certificate Log as a Timestamping Service

The main goal of our work is to solve the too-big-to-be-revoked problem of the current TLS PKI. Namely, we want to enable revocation of CA certificates without causing collateral damage. The typical scenario in which a revocation is required is after a private key compromise. Currently, revocation of a compromised private key owned by an important CA, should invalidate all certificates signed by this key, as the certificates may have been fraudulently created.

Our main observation is that when a compromised CA can determine the time of the attack—more precisely, the time at which an illegitimate action (like certificate issuance or revocation) was first observed—then the certificates signed before the attack can still be considered valid. Only certificates issued after the attack are potentially malicious, and should not be trusted. It is possible for CAs to determine the time of that attack as, in the PKISN framework, all certificates and revocations must be logged before they are considered valid. Thus, the instant of the first maliciously registered certificate is the instant of compromise.

As we cannot rely on the creation-time field of a certificate (because it may be easily predated by the adversary), the main challenge in resolving the too-big-to-be-revoked issue is the lack of a trusted timestamping service [20]. PKISN leverages the concept of a certificate log to provide this service. Depending on the deployment scenario, a domain or a CA submits the certificate to a log. When the certificate is accepted, the log returns a *chain commitment* (CC) and appends the certificate to the tree in the next update. Additionally, all intermediate certificates are added as well (if they are not already in the log). The returned commitment includes a list of *registration timestamps* that specifies when the non-registered certificates in the chain will be present in the log (in this case, the timestamp denotes the next update time) and when the already registered certificates were appended to the log.

Every new certificate is appended along with its registration timestamp. Thereafter, anyone with the obtained commitment can query the log for the presence proof of the certificate. As a presence proof includes a registration timestamp, it is the confirmation that the log contained a given certificate at a given point in time. Hence, a requester can assert that the certificate was created before this timestamp.

3.2. Transparent and Persistent Revocation

PKISN also employs a public log for storing revocations. In order to enhance the transparency of the current PKI ecosystem, revocations need to be logged. For instance, whenever a key is compromised or lost, the owner should have a guarantee that a revocation will be visible for others at least until the revoked certificate expires. The obligation of logging certificates also makes CAs more transparent, as they cannot misbehave by distributing two different CRLs or two different OCSP responses.

PKISN introduces special types of revocation messages (see §4.1), and due to the hierarchical nature of the certificate chain, a given certificate can be revoked by a set of entities (see PKISN's revocation policy below).

An authorized entity (usually the owner of a certificate) who wishes to revoke a certificate can create a special revocation message. This message is submitted to the log, which, after verification, returns a *revocation commitment* stating that the revocation will be appended to the log in the next update. When the revocation message is in the log, the presence proof for the corresponding certificate must contain this revocation message. To minimize the attack window, whenever a revocation is pending for addition, the log can accompany the presence proof of a certificate with its revocation, without waiting for the end of a scheduling period.

3.3. Revocation Policy

In the current PKI ecosystem, a certificate can be revoked only by two parties, namely the issuer and a software vendor (e.g., a browser or an OS vendor). Whenever a domain wishes to revoke its own certificate, the domain must contact the appropriate CA that will eventually issue the revocation. Obviously, such a procedure results in a prolonged attack window and depends completely on the issuing CA. Alternatively, the software vendor can simply blacklist certain certificates and propagate the changes through software updates. In this case, a domain has to contact the software vendor. This option can be also used for revoking misbehaving CAs. However, software vendors are reluctant to use this option, as it renders all servers with a certificate issued by that particular CA unavailable.

PKISN introduces a revocation policy that reflects the interactions of the current PKI and the hierarchical structure of the certificate chain. Specifically, we introduce the following revocation rules:

The owner of a leaf certificate can revoke this certificate using the associated private key.[1] This option gives domains the opportunity to revoke, without the need to contact CAs or a software vendor.

The issuer (or an upper-level issuer, i.e., a CA in the certificate chain) of a leaf certificate can revoke that certificate. The revocation message is created by the issuer's (i.e., a CA's) private key and can be performed, for example, when a domain lost its private key. Note that a certificate can be revoked directly by a root CA, without involving intermediate CAs.

CAs can revoke their own certificates and the certificates of their child CAs from a given point in time called *revocation timestamp*. This revocation states that certificates and revocations issued after a revocation timestamp should be considered invalid and should be ignored during the certificate-chain validation. The CA's own certificates are revoked with a dedicated *revocation key*, while child certificates are revoked with a regular private key. With the revocation key, a CA can prevent all potentially malicious actions starting from a certain point in time. A CA can use its revocation key only once, and as it invalidates the CA's certificate there is no need to revoke or update a revocation key. A new revocation key is generated every time a CA's certificate is created.

A software vendor can revoke any certificate, and for CA certificates, they have to specify a revocation timestamp as above. Only child certificates and revocations issued with the revoked certificate before that timestamp are considered valid. Currently, software vendors effectively have the ability to revoke any certificate, so this option explicitly reflects their power in the current TLS PKI ecosystem. Moreover, PKISN holds their actions accountable and transparent. For the sake of simplicity, we assume that there is a single software vendor that issues revocations with a private *vendor key*. The corresponding public key is provided to the clients within the software (like today), and can be updated with a software update (but cannot be revoked through PKISN).

Note that we do not allow a revoked (i.e., compromised, usually) CA to revoke its child certificates, even if the revocation had been legitimate (otherwise an adversary could cause collateral damage by invalidating certificates with the already revoked key). In such a case, any non-revoked CA in the certificate chain can still issue a valid revocation for the

1. By *associated private key* we mean the one corresponding to the public key that the certificate authenticates.

leaf certificate. However, after a CA is revoked, its clients should be informed that, although their legitimately-issued certificates are still valid and can be used, the CA lost its revocation ability, and the certificates should be reissued in the near future (e.g., few days or weeks).

Possible revocation actions for an example certificate chain are presented in Fig. 1. A single certificate can have many associated revocations. All these revocations can be fetched from the log with a presence proof.

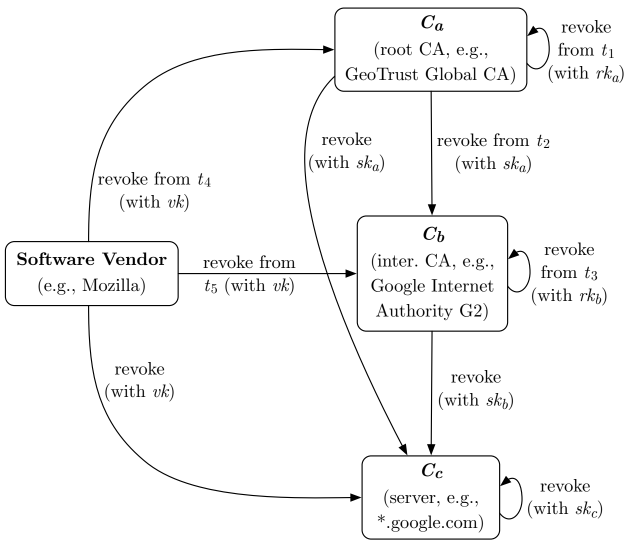


Figure 1. All possible revocations for a certificate chain $C_a \rightarrow C_b \rightarrow C_c$, where C_a and C_b have associated keys sk_a, rk_a and sk_b, rk_b, respectively (standard and revocation private keys), while the leaf certificate is associated only with a standard private key sk_c, and vk denotes the software vendor key.

3.4. Validation

For a successful validation, a client must be provided with a certificate chain, a corresponding chain commitment (CC), and a proof from the log. First, the input data is pre-validated (for details see §4.4), and verified. This includes a standard chain validation as executed in modern browsers. However, the PKISN validation process goes further, as it determines time periods for which CAs were behaving legitimately.

As shown in Fig. 1, a single certificate can be revoked by different entities and through different revocation messages. Hence, to achieve an unambiguous validation of revocation messages, priorities must be established. PKISN introduces the following priorities for revocation messages, from the highest priority to the lowest:

1) revocations issued by the software vendor,
2) revocations created with a dedicated revocation key (only applies to non-leaf certificates),
3) revocations issued by parent CAs,
4) revocations created with the standard private key associated with the certificate (only applies to leaf certificates).

To conduct a validation, PKISN introduces the notion of a *legitimacy period*, which denotes a time period during which actions performed by CAs are considered valid. The legitimacy period is defined between the moment when a certificate is received by the log for the first time (registration timestamp) and the moment when it expires or is legitimately revoked (revocation timestamp). A certificate is considered valid when it passes the *pre-validation* and when all certificates in the chain were issued (and never revoked) during corresponding legitimacy periods.

An example that illustrates the concept of legitimacy periods is presented in Fig. 2. In this example, the root CA certificate C_a gets compromised, but the attack is then detected and the CA is able to determine the time at which the attack was performed. In the meantime, the adversary used the private key to maliciously revoke the certificate C_b of an intermediate CA.[2] In this particular case, the leaf certificate C_c is valid even though its parent CA certificate was revoked, as PKISN allows to express the fact that C_b was maliciously revoked (the revocation was done during the *illegitimacy period* of C_a).

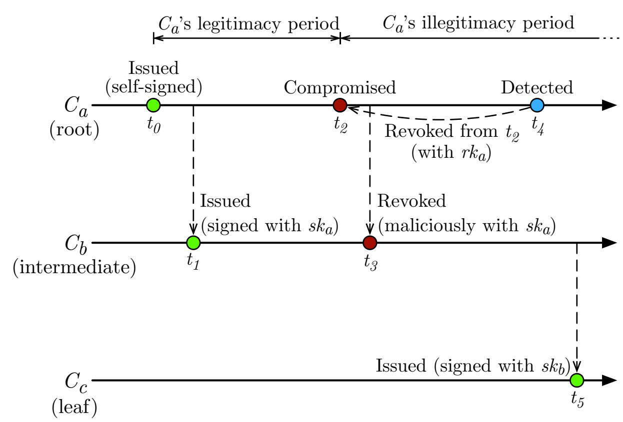


Figure 2. Timelines for a chain of three certificates, with an attack (against the root CA) and a detection thereof.

3.5. Log Consistency

Periodically, a browser contacts a random monitor to ensure that they share the same view of the log. As monitors have a copy of the log, they can inform about historic versions. To prevent equivocation, browsers can compare log information obtained during the TLS connections with corresponding monitor statements. Even if such a procedure does not completely protect against malicious logs, it enables to detect log misbehavior.

2. Although such an attack was never observed in the real world (to the best of our knowledge), nothing currently prevents an adversary who compromised a private key from performing revocations. Therefore, our new scheme should take this case into account.

4. PKISN Details

4.1. Revocation Messages

PKISN introduces a new dedicated revocation key pair for CAs. The revocation private key is only used when a given CA notices that its standard private key (used in production) has been compromised or lost. As the revocation key is not used in production, it should be securely stored offline.

PKISN supports two formats of revocation messages. The first one is used for invalidating leaf certificates:

$$R_{C_x} = \mathit{Sig}_k(H(C_x), \texttt{revoke}), \tag{2}$$

where k can be: *a*) a private key associated with the authenticated public key in a leaf certificate, *b*) the private key of one of the CAs in the certification chain, or *c*) a software vendor key. Note that in contrast with the current revocation system, domains can revoke their own certificates without any interaction with the issuing CAs. Leaf certificates do not contain a special revocation key and can be revoked without a revocation timestamp, as they cannot cause collateral damage.

Because CA certificates introduce collateral damage, they are always revoked by the following revocation message:

$$R_{C_x} = \mathit{Sig}_k(H(C_x), \texttt{revoke from } \mathit{rev\_timestamp}), \tag{3}$$

where k can be *a*) the CA's revocation key, *b*) the standard private key of a parent CA, or *c*) a software vendor key. This revocation message contains a revocation timestamp, that indicates a time from which all actions (certificates and revocations issuances) of the revoked CA must be considered invalid. This timestamp must be earlier than the expiration time specified within the revoked certificate.

4.2. Structure of the Log

In PKISN, a log stores all the issued certificates and revocations, and additionally processes them like a timestamping service. On demand, the log can produce efficient proofs about the stored content. The log is designed to support the following operations:

1) prove that a given certificate or revocation is in the log and was appended to the log at a given point in time,
2) prove that a given certificate or revocation was not appended to the log at a given point in time,
3) with a given chain commitment (CC), prove that all certificates from the chain were appended correctly (according to the timestamps of the CC) and show all revocations associated with these certificates,
4) prove that one snapshot of the log is an append-only extension of any previous one.

Additionally, relevant information about a particular certificate chain must be processed efficiently. To provide these features, the log maintains two hash-tree-based data structures: a *TimeTree* and a *RevTree* (Revocation Tree). Fig. 3 depicts an example of these trees.

The TimeTree contains all objects added to the log in chronological order. It stores certificates (C_x), revocations (R_{C_x}), and roots of the RevTree. All objects are accompanied with a registration timestamp that denotes when the object was actually appended to the tree. With the TimeTree, it is possible to prove that a given object is indeed an element of the log and was inserted at a given registration timestamp. Additionally, it is possible to prove that one version of the TimeTree is an extension of the previous TimeTree.

The RevTree consists of sub-trees (it is, in fact, a forest) that reflect the hierarchical structure of certificate chains. The RevTree is built after every scheduling period, and the root of this tree is the last element appended to the TimeTree in every update of the log. The leaves of every sub-tree consist of:

- A hash $H_x = H(C_x \| t_x)$ that identifies a certificate C_x and a registration timestamp t_x. The leaves of every sub-tree are sorted in lexicographical order of these hashes.
- The possible revocation messages of C_x. This may be $\varnothing$ when a certificate has no associated revocation message. Every revocation R_{C_x} is accompanied with a registration timestamp, which indicates when the revocation was appended to the log (this is not a revocation timestamp as in Eq. (3)).
- The root (r_x) of the sub-tree (the sub-tree contains certificates signed with the private key associated to C_x), that may be $\varnothing$ when the certificate does not have any children (e.g., leaf certificates). For efficiency reasons, leaves can also store pointers to their sub-trees.

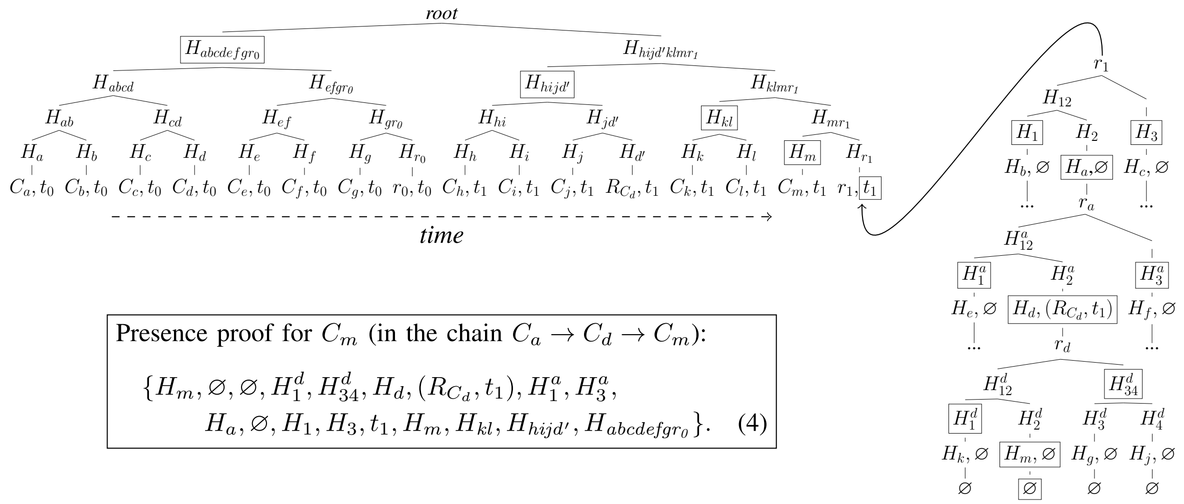
The RevTree's top sub-tree identifies root certificates, and every leaf is associated with a sub-tree of its child certificates. This design allows the log to efficiently: *a*) prove that all certificates from a chain were appended to the log at a given time, and *b*) show all the revocations associated with these certificates. As all the leaves of a RevTree's sub-trees are sorted in lexicographical order, it is also possible to prove that a given certificate was not appended to the tree at a given time. In combination with a TimeTree, a complete proof contains the information that the RevTree's proof comes from the current version of the RevTree, as its root is the very last element of the TimeTree.

4.3. Interactions with the Log

Certificate Registration. Before a certificate is used it must be submitted to the log. For instance, a domain with leaf certificate C_m sends the following certificate chain to the log:

$$C_a \rightarrow C_d \rightarrow C_m. \tag{5}$$

To automate this operation, certificates can also be submitted to the log by CAs, in a similar way as *pre-certificates* can be submitted in CT [28]. The log verifies the chain, and schedules the inclusion of non-appended certificates from



Presence proof for C_m (in the chain $C_a \to C_d \to C_m$):

$$\{H_m, \varnothing, \varnothing, H_1^d, H_{34}^d, H_d, (R_{C_d}, t_1), H_1^a, H_3^a, H_a, \varnothing, H_1, H_3, t_1, H_m, H_{kl}, H_{hijd'}, H_{abcdefgr_0}\}. \quad (4)$$

Figure 3. Example of log trees. The TimeTree stores all objects in chronological order, while the leaves of the RevTree's subtrees are sorted lexicographically. The log contains one revocation message R_{C_d} associated with the certificate C_d. Nodes in boxes are needed for the presence proof of certificate chain $C_a \to C_d \to C_m$.

the chain to the TimeTree and the RevTree. Any new certificate will be appended along with a registration timestamp. The log returns a *Chain Commitment* (CC) signed with k_{log} immediately after verification. The CC consists of:

$$Sig_{k_{log}}(H(C_m), t_m, t_d, t_a). \quad (6)$$

It constitutes a promise that C_m will be appended at t_m, and that C_d, C_a are or will be visible after t_d and t_a, respectively. As each certificate is unique within a log, the registration timestamps for CA certificates will often be from the past (as it is likely that these certificates have been submitted before). The following must always be satisfied: $t_m \geq t_d \geq t_a$.

Proof Querying. In the first update time after a successful submission, the certificate is added to the trees. Thereafter, anyone can query the log for the presence proof of the certificate. The internal design of PKISN optimizes the log for serving presence/absence proofs to a requester with a certificate chain and a corresponding CC, as this is the most common interaction with the log.

For instance, with a certificate chain $C_a \to C_d \to C_m$ and the corresponding CC from Eq. (6), the following request is prepared and sent to the log:

$$H(C_m \| t_m), H(C_d \| t_d), H(C_a \| t_a). \quad (7)$$

Due to the structure of the request, the log can efficiently locate the requested leaves in the RevTree, and generate a presence proof, by showing all intermediate nodes necessary to build the tree root. For instance, for the content presented in Fig. 3 and the previous request, the log can produce the presence proof from Eq. (4) (see Fig. 3). Note that whenever a certificate from the chain has some associated revocation messages, these messages must be contained within the proof. It guarantees that a revocation status for every certificate from the chain is known. The proof is returned to the requester accompanied with the current signed root:

$$Sig_{k_{log}}(root, t_x). \quad (8)$$

The signed root can also be requested separately. In our setting, the combination of a presence proof and the signed root is the most important piece of information from a client's perspective; it contains almost everything to perform a certificate validation. However, in PKISN, a log is also obligated to provide extension proofs between two versions of the TimeTree (to prove the consistency of two snapshots of the log).

Certificate Revocation. An entity allowed to revoke a certificate C_x can create a revocation message from Eq. (2) or Eq. (3). The revocation message R_{C_x} is sent along with a certificate chain whose last certificate is intended to be revoked. The log, after verifying whether the revocation is legitimate and matches the certificate, schedules the revocation and returns a message:

$$Sig_{k_{log}}(H(R_{C_x}), t_x), \quad (9)$$

which states that the revocation will be appended to the log after time t_x. However, during the scheduling period (when the revocation is not yet appended) the log can attach a revocation message to every relevant presence proof. This would reduce the attack window. During the update of the log, the revocation message is appended to the TimeTree and is appended to the RevTree's leaf which corresponds to the revoked certificate. From that time forward, every presence proof requested for a chain that contains the revoked certificate must contain the revocation message.

Monitoring. The role of a *monitor* is to verify the correct behavior of a log. Each monitor periodically (after every log update) contacts the log and downloads the newly appended objects and the current signed root. Then, the monitor updates its own copy of the log, by appending new certificates and revocations to the TimeTree, and by introducing all changes to the RevTree. After that, the monitor puts the current root of its RevTree as the last leaf into the TimeTree. Finally, the monitor computes the root of its own copy of the TimeTree and compares it with the root received from the log. During this update, the monitor also verifies whether the certificates and revocations accepted by the log were legitimate.

Through this periodic update, the monitors can detect any inconsistency/misbehavior of the log. Anyone can request signed roots from a monitor, and report a proof of misbehavior such as:

- an incorrect CC (with incorrect registration timestamps or absence proof of a certificate that was not appended),
- a revocation that is not appended (showing a message from Eq. (9), and a proof that the revocation is not in the log),
- two different roots from the same time period,
- the presence proof of an invalid certificate or revocation.

The monitor, in such a setting, must replicate the log's content. In §5.4, we propose a novel deployment model that allows to implement a monitor in a lightweight manner.

Algorithm 1: Complete certificate validation.

```
root : signed root (TimeTree), e.g., Eq. (8)
proof : presence proof, e.g., Eq. (4)
chain : certificate chain, e.g., Eq. (5)
CC : signed chain commitment, e.g., Eq. (6)
name : name of the contacted domain
t_x : registration timestamp of C_x
LP : dictionary that maps certificates to their legitimacy periods
currTime() : returns current time in Unix seconds
preValidate() : returns true ⇔ pre-validation passes
verifyProofs() : returns true ⇔ proof is correct
determineLP() : returns legitimacy period of a certificate
function isValid(root, proof, chain, CC, name)
    if not preValidate(chain, name) then
        return FAIL;
    if not verifyProofs(root, proof, chain, CC) then
        return FAIL;
    for C_x ∈ chain /*start from root CA*/ do
        LP[C_x] ← determineLP(LP, C_x, t_x, R_{C_x}, ...);
        if C_x is not a root certificate then
            if t_x ∉ LP[C_x.parent] then
                return FAIL;
        if C_x is a leaf certificate /*last certificate*/ then
            if currTime() ∈ LP[C_x] then
                return SUCCESS;
            else
                return FAIL;
```

4.4. Validation

To conduct a certificate validation, a client needs: *a*) a certificate chain, *b*) a chain commitment, *c*) a proof of presence, *d*) and the corresponding signed root. The full validation is presented in Algorithm 1. This section presents the different steps. We assume that before validation, the structure and format of all messages is checked.

Pre-Validation. The first step is to pre-validate the certificate chain against a given domain name. This is similar to the standard validation procedure executed by modern browsers. It encompasses checking whether the leaf certificate is issued for the given domain, checking whether the certificate chain is correct and terminates with a trusted root certificate. Usually, such a pre-validation also includes expiration checks, but this functionality is enhanced by PKISN.

Proof Verification. During the next step, the browser verifies the authenticity and correctness of the obtained log proofs. First, the match between a proof, a certificate chain, and a chain commitment is verified. The browser checks whether the proof contains (in correct locations) the hashes of all the chain's certificates concatenated with the corresponding timestamps (from the CC). Then, by hashing the elements of the proof, a root is computed and compared with the signed root provided as input. When the roots are the same, the verification passes, and the signed root can be kept for further consistency checks and monitoring (§4.3).

Legitimacy-Period Determination. The next step in the validation procedure is to determine the legitimacy periods of all certificates in the chain. This procedure slightly differs depending on the type of certificate (leaf certificates do not introduce any collateral damage and thus are revoked without specifying a revocation timestamp). Legitimacy periods are determined as presented in Fig. 4 (for CA certificates) and as in Fig. 5 (for leaf certificates).

The procedure starts with the first (the root) certificate in the chain, and is executed for every subsequent certificate. First, the legitimacy period is set as a time range from t_x (the registration timestamp) to C_x.`NotAfter` (which denotes the expiration time specified within the certificate). If a revocation issued by the software vendor is present, the legitimacy period of the current certificate is limited by the time from which the vendor revoked this certificate (i.e., up to the revocation timestamp). If a certificate is revoked with a private key associated with the certificate (rk_x for a CA certificate and sk_x for a leaf certificate), the legitimacy period is similarly limited by the revocation timestamp from the revocation message. The last option is a revocation realized by parent CAs. Similarly, the legitimacy period can be restricted, but this revocation message must be issued during the legitimacy period of the issuer.

The legitimacy period of a leaf certificate can express two states (revoked or non-revoked), but the processing logic is similar to the previous case.

During the complete validation procedure (see Algorithm 1), it is also ensured that every certificate from the chain (except the root) has a registration timestamp within the legitimacy period of its parent. In the final step of the validation, it is ensured that the leaf certificate is neither revoked nor expired.

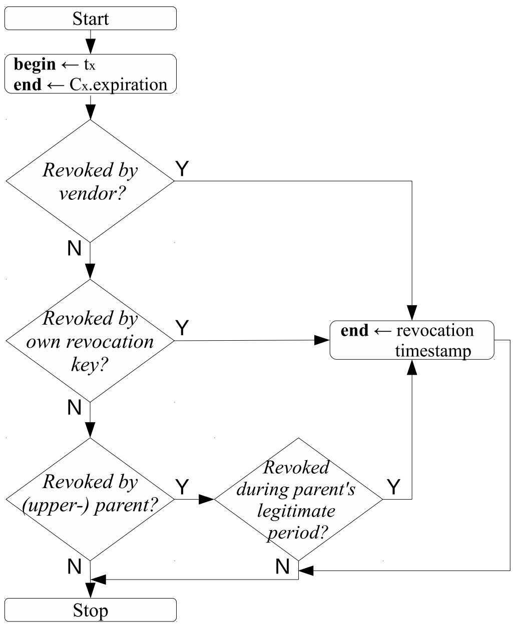


Figure 4. Legitimacy period determination for CA certificates, where t_x denotes C_x's registration timestamp. After the algorithm's execution, the legitimacy period is expressed as a time range (from **begin** to **end**).

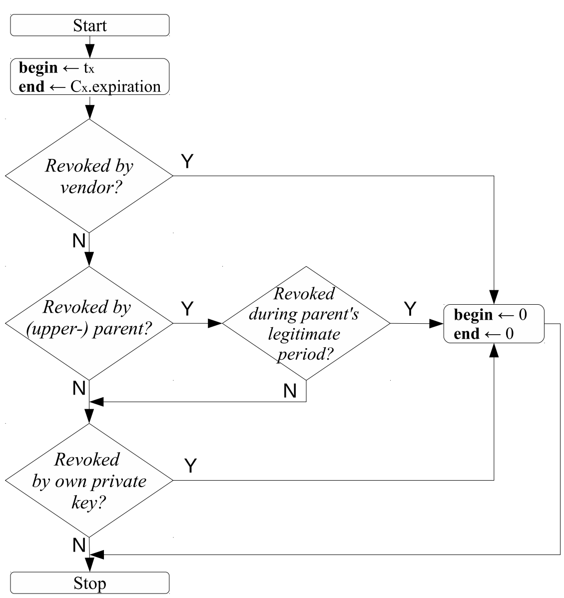


Figure 5. Legitimacy period determination for leaf certificates, where t_x denotes C_x's registration timestamp. After the algorithm's execution, the legitimacy period is expressed as a time range (from **begin** to **end**).

Log Consistency. After validation succeeded, the client saves the signed root for future consistency checks. Then periodically, the client contacts a monitor to compare the obtained root with the monitor's version. If two roots with the same timestamps are different, it means that the log misbehaved, which can be proved and reported (e.g., to a software vendor). To strengthen consistency checking, PKISN can be enhanced by a system such as ARPKI [10], or by gossip protocols as proposed by Chuat et al. [14].

5. Deployment

The deployability of a system like PKISN depends on many factors, such as the incentives of the different parties to adopt the technology and the number of required parties. CT introduced two ways of providing proofs that a certificate is logged to clients while preserving privacy [26], [28]. We describe these models in the context of PKISN in the following two subsections. We also show that the deployment of PKISN is challenging with one of the models introduced by CT, and the main reason for this is that the ultimate goals of the two systems are different (CT tries to detect misbehaving CAs, while a revocation system tries to avoid using invalid certificates). However, we present new models including a browser-driven deployment that brings many advantages, and a new lightweight realization of a log monitor. The presented deployment models can also be used in conjunction.

5.1. Server-Driven Deployment

In the first deployment scenario, depicted in Fig. 6, servers are driving the process of proving to their clients that their certificate is not revoked:

1) The server contacts the log at regular intervals (at least every scheduling period) to obtain a fresh signed tree root and a fresh presence proof.
2) The log returns the requested data.
3) Every time a client connects to the server, this data, together with the certificate chain and the CC, is transmitted to the client (e.g., via an OCSP-stapling mechanism).
4) Clients can communicate with monitors to verify that they share a consistent and compatible vision of the log.

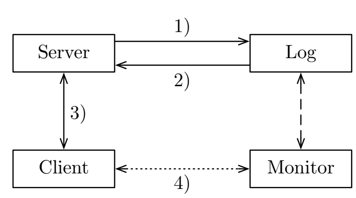


Figure 6. Server-driven deployment model. Dotted and dashed lines represent optional and periodic communications, respectively.

This deployment model is ideal in terms of efficiency (because only the server needs to periodically perform a few extra connections and the storage requirements are low) and privacy (because the client does not need to contact a third party to verify the validity of a server certificate). However, this model requires that servers are updated and this is not likely to happen rapidly for all TLS servers on the Internet.

5.2. ISP-Driven Deployment

As many servers are not updated regularly, the burden of contacting the log to retrieve the revocation information could be put on clients, but there is a privacy issue if clients do so directly. The documentation of CT [26] mentions that clients could use a modified DNS resolver (provided by their ISPs) as an intermediary to contact the log. However, this model is problematic when it comes to revocation, since the goal is no longer to simply detect attacks in an unspecified future, but to instantly determine if a certificate can be considered valid. Moreover, in a revocation system, such a connection would be required after the certificate chain is received and before it is accepted (otherwise the client does not know for which certificate chain a validity message should be returned), which would increase latency and be prone to blocking attacks. For these reasons, it would be challenging to adapt this model in PKISN.

5.3. Browser-Driven Deployment

Since the ISP-driven deployment does not fit the requirements of PKISN, and since we cannot assume that all servers would quickly be configured to provide fresh proofs to TLS connections (server-driven model), we seek an alternative solution. We present a variant of browser-driven deployment with the goal of providing users with the minimal information required to ensure that no certificate (from the chain) is revoked. To achieve this goal, we propose to extend a browser update mechanism (mentioned in §2.3) that is already deployed, namely CRLSets.

As in a browser-driven deployment clients are periodically provided with revocation messages, it is crucial to minimize bandwidth and storage overheads. In our deployment model, vendors employ the log as a source of new revocations, and they push CRLSets that consist of identifiers (in our case hashes) of all revoked and non-expired certificates with their corresponding legitimacy periods (for CA certificates). Additionally, vendors are obliged to log every CRLSet before it is propagated to the browsers, and are obliged to propagate the CRLSet with a commitment (or presence proof) from the log, indicating that the CRLSet is accepted by the log and will be visible in the near future. We call this concept a *Transparent CRL* (TCRL). On the log-side, the TCRL is simply appended to the TimeTree. This deployment model does not provide properties as strong as the server-driven deployment, but it allows to verify certificate validity and it enables the audit of TCRLs.

The connection establishment and certificate validation of this deployment model are presented in Fig. 7 and proceed as follows:

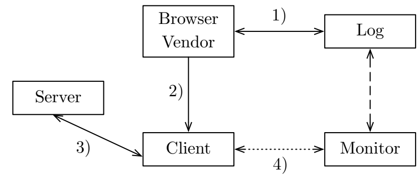


Figure 7. Browser-driven deployment model. Dotted and dashed lines represent optional and periodic communications, respectively.

1) Periodically, the browser vendor contacts a log to obtain the new revocations (note that a vendor can also act here as a monitor).
2) The vendor prepares a software update creating a list of new revocations (TCRL). Then this TCRL is submitted to the log, which returns a commitment indicating that the TCRL will be appended to the TimeTree. Finally, with this commitment (or a presence proof), the vendor pushes the TCRL to the browsers. Browsers verify whether log proofs matched the TCRL and accept the update.
3) During the TLS handshake, the client obtains a certificate chain along with the corresponding CC.[3] Then, with a locally-stored TCRL, the browser verifies whether all certificates from the chain have not been revoked. (As TCRLs provide complete revocation messages, clients can determine the legitimacy periods.) The browser continues with a verification similar to Algorithm 1.
4) The browser can (optionally) contact a monitor, to verify that the local version of the TCRL (vendor's view) is consistent with the monitor's view. Note that this communication does not reveal any information on the domains that the browser has contacted.

5.4. Lightweight Monitoring

Monitors are an integral part of many log-based schemes. They have the responsibility to constantly monitor the logs to verify whether they behave correctly. In previous proposals [10], [23], [26] monitors were implemented as replicas of the logs that perform some extra checks on demand (e.g., confirm that their view of the log is consistent with the root provided by the client). Because of that design, the bandwidth and storage required to operate a monitor are significant. In this section, we propose a novel deployment model that allows to run a lightweight monitoring service. This model could be used by network devices with security features or by power-users, for example. Such a service can assist the clients in additional verification of a connection, and the required features are:

- confirm the root of the log,
- prove that the log is consistent (i.e., a version of the log is the extension of a previous one),

3. If a server deploys PKISN, then a proof is sent during the handshake, and the client validates the certificate chain as in §5.1.

- prove that a given object is in the log.

Our first observation is that the large storage requirement of the log is induced by the necessity of storing entire certificates (a single certificate takes about 2 kB in PEM format). However, as PKISN clients are provided with certificate chains and the corresponding information during TLS connections, monitors need not store actual certificates but only the corresponding hashes. This is sufficient to ensure that a certificate is indeed in the log and that the log is consistent. In our proposal, a lightweight monitor is not directly equipped with the TimeTree's leaves, but with their parent nodes (i.e., hashes) and with revocation messages. Another observation is that certificates have a standardized maximum lifetime. Therefore, after some time, the TimeTree will contain a continuous list of expired certificates and there is no need to store the hashes of these certificates, unless they are parts of non-expired chains.

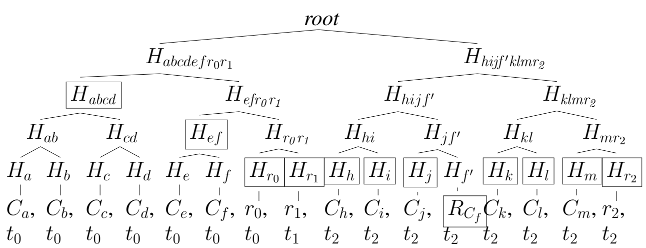


Figure 8. An example of a TimeTree, where all certificates before t_1 are expired. Only nodes in boxes are stored by the lightweight monitor.

An example of our optimization is depicted in Fig. 8. It shows the original TimeTree and the values that a monitor must provide. In this case, a monitor must initially obtain from the log only the following:

$$\begin{aligned} &t_0 : \{H_{abcd}, H_{ef}, H_{r_0}\}, \\ &t_1 : \{H_{r_1}\}, \\ &t_2 : \{H_h, H_i, H_j, R_{C_f}, H_k, H_l, H_m, H_{r_2}\}, \\ &\quad \{root, t_2\}_{k_{log}}. \end{aligned} \tag{10}$$

Then, periodically, a *delta update* between the current TimeTree and the monitor's local list is transferred. Every update is also accompanied with the corresponding signed root (Eq. (8)). Such a design allows a monitor to store a *minimized* version of TimeTree and to:

- check if every non-expired certificate of the chain is indeed present in the tree (e.g., on a client's query),
- check the revocations of certificates and determine legitimacy periods (e.g., on a client's query),
- build the TimeTree's root, and optionally compare it with other monitors to verify that the view is consistent,
- extend the tree with new hashes,
- verify the proofs received from the clients.

In this setting, a monitor is able to verify millions of certificates and needs to store only tens of megabytes, instead of several gigabytes for a complete TimeTree. A detailed analysis of the required resources is presented in §8.1. Moreover, such an optimization can be easily applied to other log-based approaches that employ hash trees.

6. Security Analysis

Our first claim is that PKISN provides authenticity, i.e., *a non-capturing adversary cannot create any legitimate revocation message*, as long as he cannot forge a digital signature. An adversary with the private key of the domain can revoke only the domain's certificate. However, by this action, an attacker would reveal that the key is compromised, as the revocation must be logged.

A more powerful adversary, able to capture a CA's private key, can revoke that CA's certificate, and all its child certificates. We claim that PKISN provides backward availability and timeliness, i.e., *such an adversary can misbehave only for a short time period* (e.g., by temporarily introducing collateral damage or malicious certificates). Specifically, that time period is less than or equal to $T_d + T_a + T_s + T_p$, where T_d is a detection time, i.e., the duration between the moment when a misbehavior (illegitimate revocation or certificate issuance) is logged and the moment when the CA notices that misbehavior. T_a denotes the audit delay, i.e., the time during which the CA determines when the first misbehavior was logged, T_s is the scheduling period of the log (see §3). For existing CT logs a scheduling period (called in CT MMD) is set between 1-24 hours. T_p stands for the propagation time, i.e., the time it takes for a new change to be propagated to clients. This time depends on a deployment model, however in all presented models (see §5) we may expect this time to be bounded by a few hours. Overall, we estimate that it is feasible to conduct the entire process within several hours.

Let's consider the extreme case in which such an adversary compromises the root CA's private key and revokes all child certificates with a revocation timestamp close to the creation time of the CA. This would invalidate all the actions of this CA. With PKISN, these revocation messages must be submitted to the log. The log accepts them if they are signed with an authentic key. These revocation messages will be visible, at the latest, when the log is updated. After the update, the malicious revocations are noticed by the CA, which, after an audit procedure, can estimate when the breach happened, and can revoke its own certificate with a revocation timestamp set to the breach time, using the offline revocation key. Thereafter, in the next update of the log, all malicious revocations will be invalidated, and this change will eventually be propagated among clients (see §5). In general $T_a > T_d$, but when a CA is revoked, or many revocations are submitted with a single key, the log could inform the CA about these actions before the update. Such an information would give a CA some time to take actions in order to completely eliminate the collateral damage.

As explained above, PKISN enables to remove collateral damage from the TLS PKI, but with the assumption that the log is not malicious. We stress that the log itself is only trusted to a certain extent, as it is constantly monitored and is only supposed to: 1) be append-only, 2) accept object registrations, 3) return cryptographic evidence about the content/consistency of the trees. Hence, the log cannot revoke certificates by itself, as it requires a private key to sign appropriate revocation messages. However, a misbehaving log can block requests (by simply ignoring them), which is a more generic problem of all log-based schemes.

The combination of a capturing adversary and a malicious log is especially dangerous. Consider the case (similar to the previous one) in which an important CA is compromised and malicious revocation messages for child certificates are issued and logged. Then, when the CA wants to revoke its own certificate, the malicious log can just ignore the requests. As a consequence, the malicious revocations will not be invalidated. This attack is simple and severe, but to succeed, an adversary must compromise the CA and the log at the same time.

PKISN requires that all actions are signed and logged, *making the parties accountable*. Revocations as well as certificates are *transparent and visible*, which makes *split-world attacks* [31] detectable. Consider the case where an adversary controls the log and captures a server's old revoked key. Now, the adversary can produce a single fake presence proof, which states that a given certificate is not revoked for example, and can launch a man-in-the-middle attack on clients. Then, with such a proof, the adversary must provide the corresponding signed root to the attacked client. The attack can succeed, as the client trusts the log, but the attack is detectable if the client contacts a monitor (or any other party) which has a different (legitimate) view of the log. Such an attack is more difficult to conduct with the deployment scenario sketched in §5.3, as revocations are stored in the browsers.

PKISN *preserves user privacy*. In all the presented deployment models (§5), clients receive complete revocation status either through browser update or directly from the contacted server. Clients do not contact any third parties to ensure that a given certificate is valid. Clients obtain signed roots and extension proofs from the monitors, but this action also does not reveal any information about websites visited.

7. Realization in Practice

7.1. Implementation

In order to prove the feasibility of PKISN, we implemented the system in Python (2.7.6) and C++ (gcc-4.8.2), using the M2Crypto, libpki, and OpenSSL (1.0.1f) cryptographic libraries. We modified libpki to add a dedicated revocation key into the extension field of every CA X509v3 certificate [15]. To minimize overheads we decided to use the Ed25519 signature scheme, except for the standard keys of X509v3 certificates where RSA-4096 was used instead. We used the SHA-256 hash function for both certificates and the implementation of hash trees.

We wrote a complete log and TLS client that implements the validation logic from §4.4. For the server side, we used Nginx, which periodically requests a fresh presence proof and signed root from the log. For every subsequent TLS Handshake, the server sends these values (and the chain commitment) using `TLS Certificate Status Request` [38], while the server's certificate is sent within a standard `ServerHello` message. Such a configuration enables deployment of PKISN without any changes to the TLS protocol. This setting is specific to the deployment scenario presented in §5.1.

7.2. Performance

With the setting presented above, we measured the efficiency of our system by conducting a series of experiments. Every presence proof in our test contained two revocation messages (pessimistic setting) and every certificate chain contained three certificates. All results were obtained by executing a given operation one thousand times on one Intel i5-3380M core @ 2.90 GHz, on Ubuntu 14.04 with 16 GB of RAM. During one second, the log was able to register 1907 certificate chains on average. For these registrations, the log verified the chains and returned signed chain commitments. To add 10000 new certificate chains to the trees, and to update the trees, the log needed on average 3.154 seconds. Our client's implementation conducted a complete validation within 1.266 ms on average, where the pre-validation and proofs validations take 0.405 ms and 0.370 ms, respectively. This computational overhead should be unnoticed by users [41].

8. Evaluation

We evaluate PKISN in terms of storage and bandwidth overheads and focus on the server-driven deployment model, the browser-driven model, and the lightweight-monitor proposal. For the server-driven deployment, the information required to verify a certificate chain is obtained directly from the TLS Handshake. For the lightweight monitor deployment, the monitor is provided with a delta update, as in Eq. (10), which allows the browser to reconstruct minimized trees. In the browser-driven deployment (TCRL), the browser receives a delta update from the vendor as hashes of revoked certificates. Note that these two variants provide different properties (see §5.3). In our simulations, we assume that the Ed25519 [12] scheme is used as the signature scheme and that the hash function produces an output of 20 bytes (this is a parameter, and second preimage resistance is the main property we rely on).

8.1. Storage

The Server-driven deployment does not require any storage on the client-side, and only a small amount of storage on the server-side: a signed root (88 bytes), a chain commitment (96 bytes for a chain of three certificates), and a presence proof (each node takes 20 bytes). In the standard case, this overhead should be around 1 kB.

To estimate the storage overhead required for the presented deployment variants, we used data available from one of CT's public logs.[4] First, we conservatively qualified certificates as valid considering their `NotBefore`

4. http://ct.googleapis.com/pilot

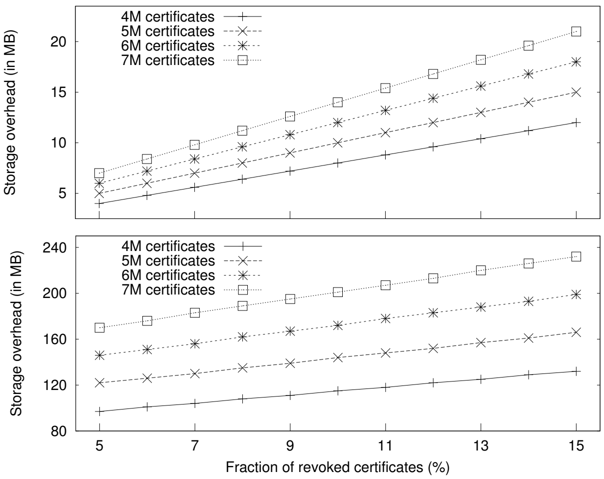


Figure 9. Storage overhead required by TCRL-enabled browser (top chart), and by a monitor with the minimized-trees variant (bottom chart).

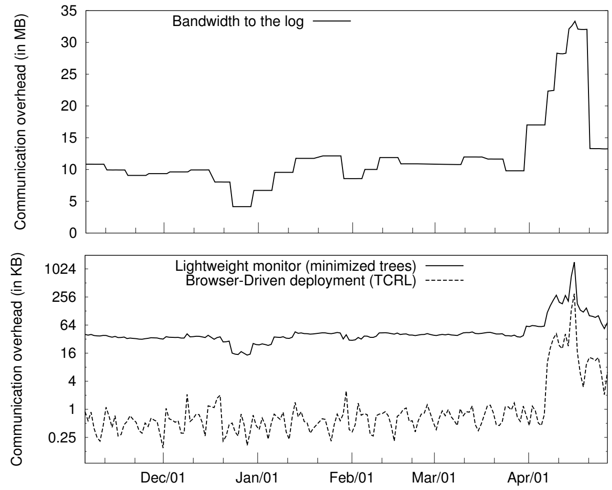


Figure 10. Bandwidth required by the log to receive certificate registrations and revocations (top chart), and by the browser to receive daily updates (bottom chart, note that the y-axis in logarithmic scale).

and `NotAfter` validity fields, and found that out of the 7,427,474 certificates in the log, 3,938,656 were valid on 15 May 2015, 12:00:00 UTC (note that certificate chains can be added to the log only if the root certificate is contained in a set of acceptable roots that the log maintains). Then, we simulated storage overheads for the two deployment variants, depending on the number of certificates and the fraction of revoked certificates (this fraction in HTTPS was recently reported as 8% [29]).

As shown in Fig. 9, the results differ significantly depending on the deployment variant. With today's number of valid certificates and a 10% revocation rate (which is considered as high), a browser employing the TCRL mechanism needs 8 MB of storage, while, for the same scenario, a lightweight monitor needs 115 MB, whereas the log in such a setting stores about 8 GB.

8.2. Bandwidth

We also evaluated PKISN in terms of bandwidth required, using real-world traces. Zhang et al. [44], using data gathered by Rapid7,[5] collected information about certificates and the corresponding revocations. The certificates were filtered to consider only valid ones from the Alexa Top 1 Million global sites.[6] For these 628,692 certificates, the 1,386 corresponding CRLs were downloaded and processed.

The dataset we used[7] covers a period from 30 October 2013 to 28 April 2014. This period is especially interesting from our point of view as *Heartbleed*—a critical vulnerability in an OpenSSL extension—was publicly announced in April 2014. Heartbleed allowed attackers to remotely read a server's protected memory including sensitive information like private keys. As a consequence, in mid-April 2014 we observed the highest frequency of certificate re-issuance and revocation ever. This unique event and its impact on the TLS ecosystem has been thoroughly analyzed [16], [44].

We evaluated the bandwidth required by PKISN during normal operations (i.e., a few months before Heartbleed) and during what we will refer to as the *peak time* (i.e., right after Heartbleed was announced). For this test, we used the abovementioned dataset to extract all new certificate issuances and revocations observed over the time period. We assumed that certificate chains consist of three certificates, as this is, reportedly, the length of the vast majority (about 98%) of certificate chains [17], [21]. By fetching all entries from one of CT's public logs (as in §8.1), we determined that the average size of a single certificate is about 1966 bytes. The setting of cryptographic primitives used here is the same as in the previous test.

First, we estimated the total bandwidth required by the log to register all issued certificates and revocations. The results are presented in Fig. 10. During the normal period (between November 2013 and March 2014), the log receives 5–13 MB per day. At peak time, the number of certificate issuances and revocations increases, causing higher demands on bandwidth. However, even then, the maximum bandwidth required is less than 35 MB per day.

Second, we estimated the bandwidth required for the daily update of a browser (TCRL) and a lightweight monitor (minimized trees). Fig. 10 depicts the results for these two variants.

In a standard scenario, the daily update for the minimized trees variant is 15–40 kB, but with the increasing number of revocations caused by Heartbleed, the required bandwidth increases as well. On 17 April 2014, it reaches around 1.4 MB, which is the highest number observed. After this date, the bandwidth required decreases rapidly. In a similar manner, for the deployment variant using TCRL, the normal update is below 1 kB, while the update during the

5. https://scans.io/study/sonar.ssl
6. http://s3.amazonaws.com/alexa-static/top-1m.csv.zip
7. https://ssl-research.ccs.neu.edu/dataset.html

peak reaches 300 kB at most. We believe that such overhead is acceptable, but we expect that with a higher revocation rate (which may occur in practice) browser vendors would reduce the transfer cost through a more efficient encoding of TCRLs or by limiting the scope of TCRLs (e.g., to EV certificates only—see CRLSets in §2.3).

In the server-driven deployment, for every TLS connection, a client is provided with about 1 kB (see §8.1) of additional data.

8.3. Comparison

We now summarize the above results and compare the different deployment models of PKISN with competing revocation schemes. The comparison encompasses storage and bandwidth overhead on the client-side, as well as the potential latency introduced by the revocation scheme to the TLS connection. The results are presented in Table 1. Depending on the scheme, the revocation information can be passed through an update (e.g., daily) or during every TLS Handshake (per connection), which is described in the Bandwidth column. For PKISN and other log-based approaches we show the storage required for a revocation rate of 8% and four million active certificates (see §8.1). The bandwidth required by PKISN is given as the median value observed in §8.2, while for CRLSets we used the dataset provided by Liu et al., and for CRLs we used a dataset provided by ISC [7].

Besides efficiency, the schemes compared here differ significantly in the properties they offer (see §2.3 and §5).

8.4. Case Study

GoDaddy is currently one of the largest issuers of TLS certificates [9]. We take the "Go Daddy Secure Certification Authority" certificate (serial number `07969287`) as an example in a case study on how effective PKISN could be in practice. By analyzing the content of Google's pilot CT log, we found 139,086 valid certificates (on 19 November 2015) signed by the aforementioned intermediate CA. The oldest of these certificates (as indicated by the `NotBefore` field) was issued on 29 January 2007, which means that a single private key was used to sign about 43.25 certificates per day on average, during more than 8 years. If that key was compromised and the corresponding certificate revoked with current methods, thousands of websites would be affected. With PKISN, only a small number of certificates would be revoked (provided that the detection process is reasonably fast). For instance, if a misbehavior was detected after one week, only about 300 certificates would have to be revoked and re-issued, which constitutes only about 0.2% of all certificates issued with this key.

TABLE 1. COMPARISON OF REVOCATION SCHEMES.

Scheme	Storage	Bandwidth	Latency
CRL	34 MB	24 kB/conn.	increased
OCSP	None	0.5 kB/conn.	increased
OCSP Stapling	None	0.5 kB/conn.	unaltered
CRLSet	0.2 MB	0.12 kB/day	unaltered
ECT/DTKI	None	1 kB/conn.	increased
AKI/ARPKI	None	0.5 kB/conn.	unaltered
PKISN (srv-driven, §5.1)/PoliCert	None	1 kB/conn.	unaltered
PKISN (browser-driven, §5.3)	6.4 MB	0.7 kB/day	unaltered
PKISN (light. monitor, §5.4)	108 MB	39 kB/day	unaltered

9. Discussion

The effectiveness and security of our system depend on the length of update periods, which introduces an obvious trade-off between the log's performance and the size of the attack window. We believe that a delay of a few hours between log updates is a good compromise.

One remaining challenge, and a potential subject for future work, is the multi-log scenario, which is challenging as synchronization between the logs would be necessary. One interesting approach to make the multi-log scenario scalable, is to introduce domain-driven security policies [40] that would allow domains to specify which logs they trust. Then, all certificate registrations and revocations could be submitted only to these logs. Another interesting aspect that could be investigated relates to the question of how PKISN can be extended to other trust models, log systems, and their applications [18], [33]. In particular, PKISN could be combined with ARPKI [10], for example, to provide additional security properties (such as "connection integrity"). We also plan to conduct a formal analysis of PKISN.

An open problem, that all new log-based approaches face, is to find an optimal deployment model and an incremental deployment plan. PKISN can benefit from the previous works [11], [30], but we plan to investigate and analyze the proposed deployment models in depth. An advantage of PKISN is that it can be easily built on the top of CT, which currently is being deployed.

We believe that the revocation policy employed by PKISN fits the current TLS ecosystem and reflects the power of PKI actors and the connections between them. However, we envision that this policy could be optimized and standardized by organizations and consortia such as the CAB Forum [1].

10. Conclusion

The current certificate revocation systems suffer from many drawbacks such as large attack windows, privacy issues, and configuration dependencies. In this paper, we redesigned the current TLS revocation system and presented PKISN, which resolves several problems that we identified. The most important advantage of PKISN is that it is the first system (to the best of our knowledge) to solve the too-big-to-be-revoked problem of the current PKI. It also enhances transparency and introduces a novel revocation policy that reflects the actual interactions within the TLS ecosystem. Only a few changes are required to deploy PKISN with the current infrastructure. Moreover, the evaluation and performance results of our implementation indicate that PKISN is viable for use in practice.

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