DTKI: a new formalized PKI with no trusted parties

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Abstract—The security of public key validation protocols for web-based applications has recently attracted attention because of weaknesses in the certificate authority model, and consequent attacks. Recent proposals using public logs have succeeded in making certificate management more transparent and verifiable. However, those proposals involve a fixed set of authorities. This means an oligopoly is created. Another problem with current log-based system is their heavy reliance on trusted parties that monitor the logs.

We propose a distributed transparent key infrastructure (DTKI), which greatly reduces the oligopoly of service providers and removes the reliance on trusted parties. In addition, this paper formalises the public log data structure and provides a formal analysis of the security that DTKI guarantees.

Index Terms—PKI, SSL, TLS, key distribution, certificate, transparency, trust, formal verification.

1 Introduction

The security of web-based applications such as e-commerce and web-mail depends on the ability of a user’s browser to obtain authentic copies of the public keys for the application website. For example, suppose a user wishes to log in to her bank account through her web browser. The web session will be secured by the public key of the bank. If the user’s web browser accepts an inauthentic public key for the bank, then the traffic (including log-in credentials) can be intercepted and manipulated by an attacker.

Unfortunately, numerous problems with the current CA model have been identified. Firstly, CAs must be assumed to be trustworthy. If a CA is dishonest or compromised, it may issue certificates asserting the authenticity of fake keys; those keys could be created by an attacker or by the CA itself. Secondly, the assumption of honesty does not scale up very well. As already mentioned, a browser typically has hundreds of CAs registered in it, and the user cannot be expected to have evaluated the trustworthiness and security of all of them. This fact has been exploited by attackers [1], [2], [3], [4], [5], [6]. In 2011, two CAs were compromised: Comodo [7] and DigiNotar [8]. In both cases, certificates for high-profile sites were illegitimately obtained, and in the second case, reportedly used in a man in the middle (MITM) attack [9]. See [10] for a survey on CA compromises.

Proposed solutions

Several interesting solutions have been proposed to address these problems. For a comprehensive survey, see [11].

Key pinning mitigates the problem of untrustworthy CAs, by defining in the client browser the parameters concerning the set of CAs that are considered entitled to certify the key for a given domain [12], [13]. However, scalability is a challenge for key pinning.

Crowd-sourcing techniques have been proposed in order to detect untrustworthy CAs, by enabling a browser to obtain warnings if the received certificates are different from those that other people are being offered [14], [15], [16], [17], [18], [19], [20], [21]. Crowd-sourcing techniques have solved some CA-based problems. However, the technique cannot distinguish between attacks and authentic certificate updates, and may also suffer from an initial unavailability period.

Solutions for revocation management of certificates have also been proposed; they mostly involve periodically pushing revocation lists to browsers, in order to remove the need for on-the-fly revocation checking [22], [23]. However, these solutions create a window during which the browser’s revocation lists are out of date until the next push.

More recently, solutions involving public append-only logs have been proposed. We consider the leading proposals here.

Public log-based systems:

Sovereign Keys (SK) [24] aims to get rid of browser certificate warnings, by allowing domain owners to establish a long term (“sovereign”) key and by providing a mechanism by which a browser can hard-fail if it doesn’t succeed in establishing security via that key. The sovereign key is used to cross-sign operational TLS [25], [26] keys, and it is stored in an append-only log on a “time-line server”, which is
the security property of ARPKI is proved by using a protocol

Certificate transparency (CT) [27] is a technique proposed
by Google that aims to efficiently detect fake public key

certificates issued by corrupted certificate authorities, by

making certificate issuance transparent. They improved
the idea of SK by using append-only Merkle tree to organise
the append-only log. This enables the log maintainer to provide
two types of verifiable cryptographic proofs: (a) a proof that
the log contains a given certificate, and (b) a proof that a
snapshot of the log is an extension of another snapshot (i.e.,
only appends have taken place between the two snapshot).
The time and size for proof generation and verification are
logarithmic in the number of certificates recorded in the log.
Domain owners can obtain the proof that their certificates
are recorded in the log, and provide the proof together
with the certificate to their clients, so the clients can get a
guarantee that the received certificate is recorded in the log.

Accountable key infrastructure (AKI) [28] also uses public
logs to make certificate management more transparent. By
using a data structure that is based on lexicographic ordering
rather than chronological ordering, they solve the problem
of key revocations in the log. In addition, AKI uses the
“checks-and-balances” idea that allows parties to monitor
each other’s misbehaviour. So AKI limits the requirement to
trust any party. Moreover, AKI prevents attacks that use fake
certificates rather than merely detecting such attacks (as in
CT). However, as a result, AKI needs a strong assumption —
namely, CAs, public log maintainers, and validators do not
collude together — and heavily relies on third parties called
validators to ensure that the log is maintained without
improper modifications.

Extended certificate transparency (ECT) [29] is a proposal
for managing certificates for end-to-end encrypted email.
It proposes an idea to address the revocation problem left
open by CT, and the trusted party problem of AKI. It
collects ideas from both CT and AKI to provide transparent
key revocation, and reduces reliance on trusted parties by
designing the monitoring role so that it can be distributed
among user browsers. However, ECT can only detect attacks
that use fake certificates; it cannot prevent them. In addition,
since ECT was proposed for email applications, it does not
support the multiplicity of log maintainers that would be
required for web certificates.

Attack Resilient Public-Key Infrastructure (ARPKI) [30] is
an improvement on AKI. In ARPKI, a client can designate n
service providers (e.g. CAs and log maintainers), and only
needs to contact one CA to register her certificate. Each of
the designated service providers will monitor the behaviour
of other designated service providers. As a result, ARPKI
prevents attacks even when n – 1 service providers are
colluding together, whereas in AKI, an adversary who suc-
cessfully compromises two out of three designated service
providers can successfully launch attacks [30]. In addition,
the security property of ARPKI is proved by using a protocol
verification tool called Tamarin prover [31]. The weakness
of ARPKI is that all n designated service providers have to
be involved in all the processes (i.e. certificate registration,
confirmation, and update), which would cause considerable
extra latencies and the delay of client connections.

In public log-based systems, efforts have been made to
integrate revocation management with the certificate auditing.
CT introduced revocation transparency (RT) [32] to deal
with certificate revocation management; and in AKI and
ARPKI, the public log only stores currently valid certificates
(revoked certificates are purged from the log). However,
the revocation checking processes in both RT and A(RP)KI
are linear in the number of issued certificates making it
inefficient. ECT allows efficient proofs of non-revocation,
but it does not scale to multiple certificates which are required
for web certificates.

Remaining problems

A foundational issue is the problem of oligopoly. The
present-day certificate authority model requires that the set
of global certificate authorities is fixed and known to every
browser, which implies an oligopoly. Currently, the majority
of CAs in browsers are organisations based in the USA,
and it is hard to become a browser-accepted CA because
of the strong trust assumption that it implies. This means
that a Russian bank operating in Russia and serving Russian
citizens living in Russia has to use an American CA for
their public key. This cannot be considered satisfactory in
the presence of mutual distrust between nations regarding
cybersecurity and citizen surveillance, and also trade san-
cctions which may prevent the USA offering services (such as
CA services) to certain other countries.

None of the previously discussed public log-based sys-
tems address this issue. In each of those solutions, the set
of log maintainers (and where applicable, time-line servers,
validators, etc.) is assumed to be known by the browsers,
and this puts a high threshold on the requirements to
become a log maintainer (or validator, etc.). Moreover,
none of them solve the problem that a multiplicity of log
maintainers reduces the usefulness of transparency, since
a domain owner has to check each log maintainer to see
if it has mis-issued certificates. This can’t work if there is
a large number of log maintainers operating in different
geographical regions, each one of which has to be checked
by every domain owner.

A second issue is the requirement of trusted parties.
Currently, all existing proposals have to rely on some sort
of trusted parties or at least assume that not all parties
are colluding together. However, a strong adversary (e.g.
a government agency) might be able to control all service
providers (used by a given client) in a system.

A third foundational issue of a different nature is that of
analysis and correctness. SK, CT, AKI and ECT are large and
complex protocols involving sophisticated data structures,
but none of them have been subjected to rigorous analysis.
It is well-known that security protocols are notoriously
difficult to get right, and the only way to avoid this is with
systematic verification. For example, attacks on AKI and ECT have been identified in [30] and in the appendix of our supplementary file [33], respectively. The flaws may be easily fixed, but only once they have been identified. It is therefore imperative to verify this kind of complex protocol. ARPKI is the first formally verified log-based PKI system. However, they used several abstractions during modelling in Tamarin prover. For example, they represent the underlying log structure (a Merkle tree) as a list. However, in systems like ECT and this paper with more complex data structures, it is important to have a formalised data structure and its properties to prove the security claim. The formalisation of complex data structures and their properties in the log-based PKI systems is a remaining problem.

The last problem is the management of certificate revocation. As explained previously, existing solutions for managing certificate revocation (e.g. CRL, OCSP, RT) are still unsatisfactory.

This paper

We propose a new public log-based architecture for managing web certificates, called Distributed Transparent Key Infrastructure (DTKI), with the following contributions.

- We identify anti-oligopoly as an important property for web certificate management which has hitherto not received attention.
- Compared to its predecessors, DTKI is the first system to have all desired features — it minimises the presence of oligopoly, prevents attacks that use fake certificates, provides a way to manage certificate revocation, does not rely on any trusted party, and is secure even if all service providers (e.g. CAs and log maintainers) collude together (see Section 5 for our security statement). A comparison of the properties of different log-based systems can be found in Section 6.
- We provide a formal analysis of DTKI. We formalise the data structures needed for transparent public logs, and provide rigorous proofs of their properties.

2 Overview of DTKI

Distributed Transparent Key Infrastructure (DTKI) is an infrastructure for managing keys and certificates on the web in a way which is transparent, minimises oligopoly, and eliminates the need for trusted parties. In DTKI, we mainly have the following agents:

Certificate log maintainers (CLM): A CLM maintains a database of all valid and invalid (e.g. expired or revoked) certificates for a particular set of domains for which it is responsible. It commits to digests of its log, and provides efficient proofs of presence and absence of certificates in the log with respect to the digest. CLMs behave transparently: their actions can be verified and therefore they do not require to be trusted.

A mapping log maintainer (MLM): To minimise oligopoly, DTKI does not fix the set of certificate logs. The MLM maintains association between certificate logs and the domains they are responsible for. It also commits to digests of the log, and provides efficient proof of current association, and behaves transparently. Clients of MLM are not required to trust the MLM, because they can efficiently verify the obtained associations.

Mirrors: Mirrors are servers that maintain a full copy of the mapping log downloaded from the MLM, and the corresponding digest of the log signed by the MLM. In other words, mirrors are distributed copies of the mapping log. Anyone (e.g. ISPs, CLMs, CAs, domain owners) can be a mirror. Unlike in SK, mirrors are not required to be trusted in DTKI, because they give a proof for every association that they send to their clients. The proof is associated to the digest of the MLM.

Certificate authorities (CA): They check the identity of domain owners, and create certificates for the domain owners’ keys. However, in contrast with today’s CAs, the ability of CAs in DTKI is limited since the issuance of a certificate from a CA is not enough to convince web browsers to accept the certificate (proof of presence in the relevant CLM is also needed).

In DTKI, each domain owner has two types of certificate, namely TLS certificate and master certificate. Domain owners can have different TLS certificates but can only have one master certificate. A TLS certificate contains the public key of a domain server for a TLS connection, whereas the master certificate contains a public key, called “master verification key”. The corresponding secret key of the master certificate is called “master signing key”. Similar to the “sovereign key” in SK [24], the master signing key is only used to validate a TLS certificate (of the same subject) by issuing a signature on it. This limits the ability of certificate authorities since without having a valid signature (issued by using the master signing key), the TLS certificate will not be accepted. Hence, the TLS secret key is the one for daily use; and the master signing key is rarely used. It will only be used for validating a new certificate, or revoke an existing certificate. We assume that domain owners can take care of their master signing key.

After a domain owner obtains a master certificate or a TLS certificate from a CA, he needs to make a registration request to the corresponding CLM to publish the certificate into the log. To do so, the domain owner signs the certificate using the master signing key, and submits the signed certificate to a CLM determined (typically based on the top-level domain) by the MLM. The CLM checks the signature, and accepts the certificate by adding it to the certificate log if the signature is valid. The process of revoking a certificate is handled similarly to the process of registering a certificate in the log.

When establishing a secure connection with a domain server, the browser receives a corresponding certificate and proofs from a mirror of the MLM and a CLM, and verifies the certificate, the proof that the certificate is valid and recorded in the certificate log, and proof that this certificate log is authorised to manage certificates for the domain. Users and their browsers only accept a certificate if the certificate is issued by a CA, and validated by the domain
Fake master certificates or TLS certificates can be easily detected by the domain owner, because the CA will have had to insert such fake certificates into the log (in order to be accepted by browsers), and is thus visible to the domain owner.

Rather than relying on trusted parties (e.g. monitors in CT and validators in AKI) to verify the healthiness of logs and the relations between logs, DTKI uses a crowdsourcing-like way to ensure the integrity of the log and the relations between mapping log and a certificate log, and between certificate logs. In particular, the monitoring work in DTKI can be broken into independent little pieces, and thus can be done by distributing the pieces to users’ browsers. In this way, users’ browsers can perform randomly-chosen pieces of the monitoring role in the background (e.g. once a day). Thus, web users can collectively monitor the integrity of the logs.

To avoid the case that attackers create a “bubble” (i.e. an isolated environment) around a victim, we share the same assumption as other existing protocols (e.g. CT and ECT) – we assume that gossip protocols [34] are used to disseminate digests of the log. So, users of logs can detect if a log maintainer shows different versions of the log to different sets of users. Since log maintainers sign and timestamp their digests, a log maintainer that issues inconsistent digests can be held accountable.

3 The public log

DTKI uses append-only logs to record all requests processed by the log maintainer, and allows log maintainers to efficiently generate some proofs that can be efficiently verified. These proofs mainly include that some data (e.g. a certificate or a revocation request) has or has not been added to the log; and that a log is extended from a previous version.

So, the log maintainer’s behaviour is transparent to the public, and the public is not required to blindly trust log maintainers. Public log data structures have been widely studied [35], [36], [37], [38], [24], [27], [29]. To the best of our knowledge, no single data structure can provide all proofs required by DTKI. We adopt and extend the idea of ECT (see Table 1); and for all sequence of data stored in a chronological data structure, i.e. only the operation of adding some data is allowed. With a chronological data structure, for a given sequence \( S \) of data of size \( N \), such that \( p \) can be efficiently verified by using VerifPoEx (see Table 1); and for all sequence \( S' \) with digest \( d' \) and size \( N' < N \), we have that \( S' \) is a prefix of \( S \), if and only if there exists a proof \( p' \) of size \( O(\log(N)) \), called the proof of extension of \( S' \) from \( S \), such that \( p' \) can be efficiently verified by using VerifPoEx (see Table 1).

In this way, to verify that some data is included in a sequence of data stored in a chronological data structure (of size \( N \)), the verifier only needs to download the corresponding digest, and the corresponding proof of presence (with size \( O(\log(N)) \)). The verification of proof of extension is similarly efficient. Possible implementations are append-only Merkle tree [35] and append-only skip list, as proposed.

3.1 Data structures

Our log makes use of two data structures, namely chronological data structure and ordered data structure, to provide all proofs required by DTKI. We use the notion of
in [27] and [37], respectively.

With the append-only property, the chronological data structure enables one to prove that a version of the data structure is an extension of a previous version. This is useful for our public log since it enables users to verify the history of a log maintainer’s behaviours.

Unfortunately, the chronological data structure does not provide all desired features. For example, it is very inefficient to verify that some data (e.g. a revocation request) is not in the chronological data structure (the cost is $O(N)$, where $N$ is the size of the data structure). To provide missing features, we need to use the ordered data structure.

An ordered data structure is a data structure allowing one to insert, delete, and modify stored data. In addition, with an ordered data structure, for a given sequence $S$ of data of size $N$ and with digest $dg$, we have $d \in S$ (resp. $d \notin S$) for some data $d$; if and only if there exists a proof $p$ of size $O(\log(N))$, called the proof of presence (resp. absence) of $d$ in (resp. not in) $S$, such that $p$ can be efficiently verified by using VerifPoP$_O$ (resp. VerifPoP$_{Abs}$) (see Table 1).

Possible implementations of ordered data structure are Merkle tree which is organised as a binary search tree (as proposed in [29]), and authenticated dictionaries [36].

With ordered data structure, however, the size of proof that the current version of the data is extended from a previous version is $O(N)$. As the chronological data structure and the ordered data structure have complementary properties, we use the combination of them to organise our log.

3.2 Mapping log

To minimise oligopoly, DTKI uses multiple certificate logs, and does not fix the set of certificate logs and the mapping between domains and certificate logs. A mapping log is used to record associations between domain names and certificate log maintainers, and can provide efficient proofs regarding the current association. It would be rather inefficient to explicitly associate each domain name to a certificate log, due to the large number of domains. To efficiently manage the association, we use a class of simple regular expressions to present a group of domain names, and record the associations between regular expressions and certificate logs in the mapping log. For example, the mapping might include (.\org, Clog$_1$) and ([a-h]\.*.com, Clog$_2$) to mean that certificate log maintainer Clog$_1$ deals with domains ending .org and domains starting with letters from $a$ to $h$ ending .com. In our supplementary file [33], we have formally defined some constraints on the regular expressions we use, the relations between them, and how to use random verification to verify that no overlap between regular expressions exists.

Let $mlog$ be a mapping log and $clog$ be a certificate log. A mapping log is organised by using chronological data structure, stores received requests with digests of different ordered data structures representing the status of the log.

In more detail, as presented in Figure 1, each entry of the mapping log is of the form $h(\text{req}, N, dg^\text{irx})$ (as shown in 2), where $dg^\text{irx}$ are digests after processing the request req (received by the mapping log maintainer at time t) on the digest stored in the previous record. Each of the notations is explained as follows:

- req can be $\text{add}(\text{rgx}, \text{id})$, $\text{del}(\text{rgx}, \text{id})$, $\text{new}(\text{cert})$, $\text{mod}(\text{cert}, \text{sign}_{sk}(\text{cert}), \text{sign}_{sk}(n, dg, t))$, $\text{bl}(\text{id})$, and $\text{end}$, respectively corresponding to a request to add a mapping $(\text{rgx}, \text{id})$ of regular expression $\text{rgx}$ and identity $\text{id}$ of a $\text{clog}$, to delete a mapping $(\text{rgx}, \text{id})$, to add a certificate $\text{cert}$ of a new $\text{clog}$, to change the certificate of a $\text{clog}$ from $\text{cert}$ to $\text{cert}'$, to blacklist $\text{id}$ of an existing $\text{clog}$, and to close the update request; where $sk$ and $sk'$ are signing keys associated to the certificate $\text{cert}$ and $\text{cert}'$, respectively; $\text{cert}$ and $\text{cert}'$ share the same subject, and $n$ and $dg$ are the size and the digest of the corresponding $\text{clog}$ at time $t$, respectively;
- $dg^s$ is the digest of an ordered data structure storing the identity information of the form $(\text{cert}, \text{sign}_{sk}(n, dg, t))$ for the currently active certificate logs, where $\text{cert}$ is the certificate for the signing key $sk$ of the certificate log, and $n$ and $dg$ are respectively the size and digest of the certificate log at time $t$. Data are ordered by the domain name in $\text{cert}$.
- $dg^{bl}$ is the digest of an ordered data structure storing the domain names of blacklisted certificate logs. Data are ordered by the stored domain names.
- $dg'$ is the digest of an ordered data structure storing elements of the form $(\text{id}, \text{ri}x)$, which represents the mapping from regular expression $\text{rgx}$ to the identity $\text{id}$ of a $\text{clog}$, data are ordered by $\text{rgx}$;
- $dg^i$ is the digest of an ordered data structure storing elements of the form $(\text{id}, \text{ri}x)$, which represents the mapping from identity $\text{id}$ of a $\text{clog}$ to a digest $\text{dg}^\text{irx}$ of ordered data structure storing a set of regular expressions, data are ordered by $\text{id}$.

The requests are used for modifying mappings or the existing set of certificate log maintainers. When a request $\text{del}(\text{rgx}, \text{id})$ has been processed, the maintainer of certificate log with identity $\text{id}$ needs to remove all certificates whose subject is an instance of regular expression $\text{rgx}$: when a request $\text{add}(\text{rgx}, \text{id})$ has been processed, the maintainer of certificate log with identity $\text{id}$ needs to download all certificates whose subject is an instance of $\text{rgx}$ from the previous authorised log maintainer, and adds them into his log. These requests require certificate logs to synchronise with the mapping log; see Section 3.4.

3.3 Certificate logs

The mapping log determines which certificate log is used for a domain. The certificates for the domain are stored in that certificate log.

A certificate log is also organised by using chronological data structure, such that each entry of the log is of the form $h(\text{req}, N, dg^\text{reg})$ (as shown in 2), where

- req can be $\text{reg}(\text{sign}_{sk}(\text{cert}, t, '\text{reg}'))$, $\text{rev}(\text{sign}_{sk}(\text{cert}, t, '\text{rev}'))$, $\text{upadd}(h(\text{id}), h)$, and
Figure 1: A figure representation of the format of each record in the mapping log.

...upadd(h(id), h), corresponding to a request to register and revoke a certificate cert at an agreed time t, where reg includes add(rgx, id), del(rgx, id), new(cert), mod(cert), sign_trusted(cert), and end.

Figure 2: A figure representation of the format of each record in the certificate log.

3.4 Synchronising the mapping log and certificate logs

The mapping log periodically (e.g. every day) publishes a signature \( \text{sign}_{sk}(t, dg, N) \), called signed Mlog timestamp, on time t indicating the publishing time, and the digest \( dg \) and size \( N \) of the mapping log. Mirrors of the mapping log need to download this signed data, and update their copy of the mapping log when it is updated. A signed Mlog timestamp is only valid during the issue period (e.g. the day of issue). Note that mirrors can provide the same set of proofs as the mapping log maintainer, because the mirror has the copy of the entire mapping log; but mirrors are not required to be trusted, they do not need to sign anything, and a mirror which changed the log by itself will not be able to convince other users to accept it since the mirror cannot forge the signed Mlog timestamp.

When a mapping log maintainer needs to update the mapping log, he requests all certificate log maintainers to perform the required update, and expects to receive the digest and size of all certificate logs once they are updated. After the mapping log maintainer receives these confirmations from all certificate log maintainers, he publishes the series of update requests in the mapping log, and appends an extra constant request end after them in the log to indicate that the update is done.

Log maintainers only answer requests according to their new updated log if the mapping log maintainer has published the update requests in the mapping log. If in the log update period, some user sends requests to the mapping log maintainer or certificate log maintainers, then they give answers to the user according to their log before the update started.

We say that the mapping log and certificate logs are synchronised, if certificate logs have completed the log update according to the request in the mapping log. Note that a misbehaving certificate log maintainer (e.g. one recorded...
fake certificates in his log, or did not correctly update his log according to the request of the mapping log) can be terminated by the mapping log maintainer by putting the certificate log maintainer’s identity into the blacklist, which is organised as an ordered data structure represented by $dg^{bl}$ (as presented in 3.2).

4 Distributed transparent key infrastructure

Distributed transparent key infrastructure (DTKI) contains three main phases, namely certificate publication, certificate verification, and log verification. In the certificate publication phase, domain owners can upload new certificates and revoke existing certificates in the certificate log they are assigned to; in the certificate verification phase, one can verify the validity of a certificate; and in the log verification phase, one can verify whether a log behaves correctly.

We present DTKI using the scenario that a TLS user Alice wants to securely communicate with a domain owner Bob who maintains the domain \textit{example.com}.

4.1 Certificate insertion and revocation

To publish or revoke certificates in the certificate log, the domain owner Bob needs to know which certificate log is currently authorised to record certificates for his domain. This can be done by communicating with a mirror of the mapping log. We detail the protocol for requesting the mapping for Bob’s domain.

4.1.1 Request mappings: Bob starts by sending a request with his domain name to a mirror of the mapping log. Upon receiving the request, the mirror locates the certificate $cert$ of the authorised certificate log maintainer and generates the proofs that will be verified by Bob. To do so, the mirror obtains the data of the latest element of the copy of the mapping log, denoted $h = h(rgx, t, dg^s, dg^{bl}, dg^f, dg^i)$, and generates the proof of its presence in the digest (denoted $dg_{mlog}$) of its log of size $N$. Then, it generates the proof of presence of the element $(cert, sign_{sk}(n, dg, t))$ in the digest $dg^s$ for some $sign_{sk}(n, dg, t)$, proving that the certificate log maintainer whose $cert$ belongs to is still active. Moreover, it generates the proof of presence of some element $(rgx, id)$ in the digest $dg^f$ where $id$ is the subject of $cert$ and \textit{example.com} is an instance of the regular expression $rgx$, proving that $id$ is authorised to stores the certificates of \textit{example.com}. The mirror then sends to Bob the hash $h$, the signature $sign_{sk}(n, dg, t)$, the regular expression $rgx$, the three generated proofs of presence, and the latest signed Mlog time-stamp containing the time $t_{mlog}$ and digest $dg_{mlog}$ and size $N_{mlog}$ of the mapping log.

Bob first verifies the received signed Mlog time-stamp with the public key of the mapping log maintainer embedded in the browser, and verifies whether $t_{mlog}$ is valid. Then Bob checks that \textit{example.com} is an instance of $rgx$, and verifies the three different proofs of presence. If all checks hold, then Bob sends the signed Mlog time-stamp containing $(t_{mlog}', dg_{mlog}', N_{mlog}')$ that he stored during a previous connection, and expects to receive a proof of extension of $(dg_{mlog}', N_{mlog}')$ into $(dg_{mlog}, N_{mlog})$. If the received proof of extension is valid, then Bob stores the current signed Mlog time-stamp, and believes that the certificate log with identity $id$, certificate $cert$, and size that should be no smaller than $n$, is currently authorised for managing certificates for his domain.

4.1.2 Insert and revoke certificates: The first time Bob wants to publish a certificate for his domain, he needs to generate a pair of master signing key, denoted $sk_{mr}$, and verification key. The latter is sent to a certificate authority, which verifies Bob’s identity and issues a master certificate $cert_{m}$ for Bob. After Bob receives his master certificate, he checks the correctness of the information in the certificate. The TLS certificate can be obtained in the same way.

Figure 3 presents the process to publish the master certificate $cert_{m}$. Bob signs the certificate together with the current time $t$ by using the master signing key $sk_{mr}$, and sends it together with the request \textit{AddReq} to the authorised certificate log maintainer whose signing key is denoted $sk_{clog}$. The certificate log maintainer checks whether there exists a valid master certificate for \textit{example.com}; if there is one, then the log maintainer aborts the conversation. Otherwise, the log maintainer verifies the validity of time $t$ and the signature.

If they are all valid, the log maintainer updates the log, generates the proof of presence of $(b(id), h(cert_{m}, dg^s, dg^{reg}))$ in $dg^i$, $(rgx, dg^{id})$ in $dg^{rgx}$, and $h(reg(sign_{sk}(cert_{m}, t, 'reg'))$, $N_{mlog}$, $dg^{regx}$) is the last element in the data structure represented by $dg_{clog}$, where $id$ is the subject of $cert_{m}$ and an instance of $rgx$; $reg(sign_{sk}(cert_{m}, t, 'reg'))$ is the register request to adding $cert_{m}$ into the certificate log with digest $dg_{clog}$ at time $t$. The log maintainer then issues a signature on $(dg_{clog}, N, h)$, where $N$ is the size of the certificate log, and $h = (rgx, dg^{id}, dg^{regx}, P)$, where $P$ is the sequence of the generated proofs, and sends the signature $\sigma_{2}$ together with $(dg_{clog}, N, rgx, dg^{id}, dg^{regx}, dg^{n}, dg^{r}, P)$ to Bob. If the signature and the proof are valid, and $N$ is no smaller than the size $n$ contained in the signed Mlog time-stamp that Bob received from the mirror, then Bob stores the signed $(dg_{clog}, N, h)$, sends the previous stored $(dg_{clog}, N')$ to the certificate log maintainer, and expects to receive a proof of extension of $(dg_{clog}, N')$ into $(dg_{clog}, N)$. If the received proof of extension is valid, then Bob believes that he has successfully published the new certificate.

Note that it is important to send $(dg_{clog}, N')$ after receiving $(dg_{clog}, N)$, because otherwise the log maintainer could learn the digest that Bob has, then give a pair $(dg^{n'}, N'')$ of digest and size of the log such that $N' < N'' < N$. This may open a window to attackers who wants to convince Bob to use a certificate which was valid in $dg^{n'}$ but revoked in $dg_{clog}$.

In addition, if Bob has run the request mapping protocol more than once, and has obtained a digest that is different from his local copy of the corresponding certificate log, then he should ask the CLM to prove that one of the digests is an extension of the other.

The process of adding a TLS certificate is similar to the process of adding a master certificate, but the log maintainer
needs to verify that the TLS certificate is signed by the valid master signing key corresponding to the master certificate in the log.

To revoke a (master or TLS) certificate, the domain owner can perform a process similar to the process of adding a new certificate. For a revocation request with $\text{sign}_{sk_m}(cert, t)$, the log maintainer needs to check that $\text{sign}_{sk_m}(cert, t')$ is already in the log and $t > t'$. This ensures that the same master key is used for the revocation.

### 4.2 Certificate verification

![Certificate verification diagram]

The protocol presenting how domain owner Bob communicates with certificate log (clog) maintainer to publish a master certificate $cert_m$.

When Alice wants to securely communicate with example.com, she sends the connection request to Bob, and expects to receive a master certificate $cert_m$ and a signed TLS certificate $\text{sign}_{sk_m}(cert, t)$ from him. To verify the received certificates, Alice checks whether the certificates are expired. If both of them are still in the validity time period, Alice requests as described in 4.1.1 the corresponding mapping from a mirror to find out the authorised certificate log for example.com, and communicates with the authorised certificate log maintainer to verify the received certificate.

The Fig. 4 presents the process of verifying a certificate. After Alice learns the identity of the authorised certificate log, she sends the verification request $\text{VerifyReq}$ with her local time $t_A$ and the received certificate to the certificate log maintainer. The time $t_A$ is used to prevent replay attacks, and will later be used for accountability. The certificate log maintainer checks whether $t_A$ is in an acceptable time range (e.g. $t_A$ is in the same day as his local time). If it is, then he locates the corresponding $(rgx, dg^{id})$ in $dg^{9x}$ in the latest record of his log such that $example.com$ is an instance of regular expression $rgx$, locates $(h(id), h(cert_m, dg^{a}, dg^{rv}))$ in $dg^{id}$ and $cert$ in $dg^{t}$, then generates the proof of presence of $cert$ in $dg^{t}$, $(h(id), h(cert_m, dg^{a}, dg^{rv}))$ in $dg^{id}$, $(rgx, dg^{id})$ in $dg^{9x}$, and $h(req, N_{mlog}, dg^{9x})$ is the latest record in the digest $dg_{clog}$ of the log with size $N$. Then, the certificate log maintainer signs $(dg_{clog}, N, t_A, h)$, where $h = h(m)$ such that $m = (dg^{a}, dg^{rv}, rgx, dg^{id}, req, N_{mlog}, dg^{9x}, P)$, and $P$ is the set of proofs, and sends $(dg_{clog}, N, \sigma)$ to Alice.

Alice should verify that $N_{mlog}$ is the same as her local copy of the size of mapping log. If the received $N_{mlog}$ is greater than the copy, then it means that the mapping log is changed (it rarely happens) and Alice should run the request mapping protocol again. If $N_{mlog}$ is smaller, then it means the CLM is misbehaved. Alice then verifies the signature and proofs, and sends the previously stored $dg_{clog}$ with the size $N'$ to the log maintainer, and expects to receive the proof of extension of $(dg'_{clog}, N')$ into $(dg_{clog}, N)$. If they all valid, then Alice replaces the corresponding cache by the signed $(dg_{clog}, N, t_A, h)$ and believes that the certificate is an authentic one.

In order to preserve privacy of Alice’s browsing history, instead of asking Alice to query all proofs from the log maintainer, Alice can send the request to Bob who will redirect the request to the log maintainer, and redirect the received proofs from the log maintainer to Alice.

With DTKI, Alice is able to verify whether Bob’s domain has a certificate by querying the proof of absence of certificates for example.com in the corresponding certificate log. This is useful to prevent TLS stripping attacks, where an attacker can maliciously convert a HTTPS connection into a HTTP connection.

### 4.3 Log verification

Every time a certificate log maintainer is blacklisted by the mapping log maintainer, Bob checks the authenticity of the master certificate for his domain stored in the corresponding certificate log.

In addition, we need to ensure that the mapping log maintainer and certificate log maintainers behaved honestly. In particular, we need to ensure that the mapping log maintainer and certificate log maintainers did update their log correctly according to the request, and certificate log maintainers did follow the latest mappings specified in the mapping log.

These checks can be easily done if there are trusted third parties (TTPs) who can monitor the log. However, since we aim to provide a TTP-free system, DTKI uses a crowdsourcing-like method, based on random checking, to monitor the correctness of the public log. The basic idea of random checking is that each user randomly selects a record in the log, and verifies whether the request and data in this record have been correctly managed. If all records are verified, the entire log is verified. Users only need to
run the random checking periodically (e.g. once a day). The full version (with formalisation) of random checking can be found in our supplementary file. We give a flavour here by providing some examples. Example 1 presents the random checking process to verify the correct behaviour of the mapping log.

**Example 1.** If the verifier has randomly selected the \( k \)-th record labelled by \( h(\text{add}(r gx, i d, t k, d g_k^a, d g_k^b, d g_k^c, d g_k^d)) \) in the mapping log, then it means that all digests in this record are updated from the \((k-1)\)-th record by adding a new mapping \((r gx, i d)\) in the mapping log at time \( t k \).

Let the label of the \((k-1)\)-th record be \( h(\text{rc}g_{k-1}, t k_{k-1}, d g_{k-1}^a, d g_{k-1}^b, d g_{k-1}^c, d g_{k-1}^d) \), then to verify the correctness of this record, the verifier should run the following process:

- verify that \( d g_k^a = d g_{k-1}^a \) and \( d g_k^b = d g_{k-1}^b \); and
- verify that \( d g_k^c \) is the result of adding \((r gx, i d)\) into \( d g_{k-1}^c \) by using VerifPoAdd\(O\), and \( i d \) is an instance of \( r gx \); and
- verify that \((i d, d g_{k-1}^r g x)\) is the result of replacing \((i d, d g_k^r g x)\) in \( d g_{k-1}^r g x \) by \((i d, d g_k^r g x)\) by using VerifPoM\(O\); and
- verify that \( d g_k^r g x \) is the result of adding \( r gx \) into \( d g_{k-1}^r g x \) by using VerifPoAdd\(O\).

Note the all proofs required in the above are given by the log maintainer. If the above tests succeed, then the mapping log maintainer has behaved correctly for this record.

The verification on the certificate log is similar to the mapping log. However, there is one more thing needed to be verified – the synchronisation between the mapping log and certificate logs. This verification includes that the certificate log only manage the certificates for domains they are authorised to (according to the mapping log); and if there are modifications on the mapping, then the corresponding certificate log maintainer should add or remove all certificates according to the modified mapping. We present an example to show what a verifier should do to verify that the certificate log was authorised to add or remove a certificate.

**Example 2.** If the verifier has randomly selected the \( k \)-th record labelled by \( h(\text{reg}(\text{sn}_{sk}(c e r t_{T L S}, t, \text{reg}'))), N_k, d g_k^{r g x} ) \) in the certificate log, where \( d g_k^{r g x} \) is the digest of ordered sequence of format \((r gx, d g_k^c)\), \( d g_k^c \) is the digest of ordered sequence of format \((h(i d), h(\text{cert}_{m}, d g_k^a, d g_k^c))\), \( c e r t_{m} \) is a master certificate, and \( c e r t_{T L S} \) is a TLS certificate. Let \( d g_k^{r g x} \) be the digest \( d g_{k-1}^{r g x} \) in the \( k-1 \)-th record, and similarly for \( d g_{k-1}^a, d g_{k-1}^b, d g_{k-1}^c, d g_{k-1}^d \). Let the subject of \( c e r t_{T L S} \) be \( i d' \). The verifier should verify the following tests:

- Verify that \( \text{sn}_{sk}(c e r t_{T L S}, t) \) is correctly signed according to \( c e r t_{m} \) and \( c e r t_{T L S} \); and
- Verify that \( c e r t_{m} \) is not expired, and shares the same subject \( i d' \) with \( c e r t_{T L S} \), and \( i d' = i d \); and
- Verify that \( d g_k^c \) is the result of adding \( c e r t_{T L S} \) into \( d g_{k-1}^c \); and
- Verify that \( d g_k^c \) is the result of replacing \((h(i d), h(\text{cert}_{m}, d g_{k-1}^a, d g_{k-1}^b, d g_{k-1}^c, d g_{k-1}^d)) \) by \((h(i d), h(\text{cert}_{m}, d g_k^a, d g_k^b, d g_k^c)) \) in \( d g_{k-1}^c \); and
- Verify that \( d g_{k-1}^c = d g_{k-1}^c \); and
- Verify that \( d g_{k-1}^{r g x} \) is the result of replacing \((r gx, d g_{k-1}^c) \) by \((r gx, d g_k^c) \) in \( d g_{k-1}^{r g x} \); and
- Verify that \((r gx, i d')\) is in the \( N_k \) element of the mapping log, such that \( r gx' = r gx \), and \( i d' \) is the identity of the certificate log.

If the above tests succeed, then the certificate log maintainer behaves correctly on this record.

**4.4 Performance Evaluation**

In this section, we measure the cost of different protocols in DTKI.

**Assumptions:** We assume that the size of a certificate log is \( 10^6 \) (the total number of registered domain names currently is \( 2.71 \times 10^6 \) [39], though only a fraction of them have certificates). In addition, we assume that the number of stored regular expressions, the number of certificate logs, and the size of the mapping log are 1000 each. (In fact, if we assume a different number or size (e.g. 100 or 10000) for them, it makes almost no difference to the conclusion). Moreover, in the certificate log, we assume that the size of the set of data represented by \( d g^{r g x} \) is 10, by \( d g^a \) is \( 10^5 \), by \( d g^b \) is 10, and by \( d g^c \) is 100. These assumptions are based on the fact that \( d g^{r g x} \) represents the set of regular expressions maintained by a certificate log; the \( d g^a \) represents the set of domains.
which is an instance of a regular expression; and \( dq^a \) and \( dq^r \) represent the set of currently valid certificates and the revoked certificates, respectively. Furthermore, we assume that the size of a certificate is 1.5 KB, the size of a signature is 256 bytes, the length of a regular expression and an identity is 20 bytes each, and the size of a digest is 32 bytes.

**Space:** Based on these assumptions, the approximate size of the transmitted data in the protocol for publishing a certificate is 4 KB, for requesting a mapping is 3 KB, and for verifying a certificate is 5 KB. Since the protocols for publishing a certificate and requesting a mapping are run occasionally, we mainly focus on the cost of the protocol for verifying a certificate, which is required to be run between a log server and a web browser in each secure connection.

By using Wireshark, we\(^1\) measure that the size of data for establishing an HTTPS protocol to log-in to the internet bank of HSBC, Bank of America, and Citibank are 647.1 KB, 419.9 KB, and 697.5 KB, respectively. If we consider the average size (≈588 KB) of data for these three HTTPS connections, and the average size (≈6 KB) of data for their corresponding TLS establishment connections, we have that in each connection, DTKI incurs 83% overhead on the cost of the TLS protocol. However, since the total overhead of a HTTPS connection is around 588 KB, so the cost of DTKI only adds 0.9% overhead to each HTTPS connection, which we consider acceptable.

**Time:** Our implementation uses a SHA-256 hash value as the digest of a log and a 2048 bit RSA signature scheme. The main purpose of DTKI is to enable Alice to verify that the certificate she received in the TLS session is indeed a valid certificate of Bob. In DTKI, a valid certificate means that the certificate is active. A certificate is active if the certificate is authentic and not revoked; and a certificate is authentic if the certificate’s subject has run the registration protocol to register it.

To formally define an authentic certificate and an active certificate, we define a function keys_B to model the status of all public keys of B. We present time by integers e.g. seconds, consider that all protocols are run within one unit of time, and denote the infinite set of all public keys by \( \mathcal{PK} \).

**Definition 1.** Let \( B \) be a domain. A key function keys_B for \( B \) is a function from \( \mathbb{N} \) to a set of finite sets of elements in \( \mathcal{PK} \times \{0,1\} \) such that for all \( pk \in \mathcal{PK} \), for all \( t \in \mathbb{N} \), \( pk \) occurs at most once in \( \text{keys}_B(t) \). Moreover, for all \( pk \in \mathcal{PK} \), if there exists \( t \) such that \( pk \) occurs in \( \text{keys}_B(t) \) then:

- either there exists \( t_{\text{reg}}, t_{rev} \in \mathbb{N} \) such that \( t < t_{\text{reg}} \), \( pk \) does not occur in \( \text{keys}_B(t) \); and for all \( t < t_{\text{reg}} \), \( (pk, 1) \in \text{keys}_B(t) \); and for all \( t \geq t_{\text{reg}} \), \( (pk, 0) \in \text{keys}_B(t) \);
- or there exists \( t_{\text{reg}} \in \mathbb{N} \) such that for all \( t < t_{\text{reg}} \), \( pk \) does not occur in \( \text{keys}_B(t) \); and for all \( t \geq t_{\text{reg}} \), \( (pk, 1) \in \text{keys}_B(t) \).

We say that a public key \( pk \in \mathcal{PK} \) is authentic (w.r.t domain \( B \)) at time \( t \) if \((pk, b) \in \text{keys}_B(t) \) for some \( b \in \{0,1\} \); and \( pk \) is active at the time \( t \) if \((pk, 1) \in \text{keys}_B(t) \).

In addition, given user A and log maintainer L, we consider a function \( d_{A,L} \) such that given a time \( t \) as input, \( d_{A,L}(t) \) outputs the pair of values (expected to be the digest and size, respectively, of L’s log) given by L, and stored in the cache of A’s browser at time \( t \). Note that we have \( d_{A,L}(0) = (null, 0) \) for participants A and L, where null is the null bitstring.

We assume that both Alice and Bob are honest, meaning that they run the protocols of DTKI correctly. We say that \((dq, N)\) represents a chronological log \( S \) if \( \text{digest}(S) = dq \) and \( |\text{content}(S)| = N \), where \( \text{content}(S) \) is the sequence of data stored in chronological log \( S \). We have the following lemma to show that if a participant stores a pair of values after successfully running a protocol with a log maintainer L at time \( t \), and the pair of values are indeed the digest and size of a log, then all previously stored values associated to L are also pairs of digest and size of a historic version of the log.

**Lemma 1.** Let \( A \) be an honest participant, and \( L \) a log maintainer. If there exists a time \( t \in \mathbb{N} \) and a log \( S \) such that \( d_{A,L}(t) \) represents \( S \) at time \( t \), then for all \( t' < t \), then an adversary can launch attacks, but the attacks will be detected afterwards.

The detailed analysis is presented in our supplementary file [33], and we only give a reduced analysis here due to the space limitation.

Consider a scenario where an internet user Alice wants to share some secret data with a domain owner Bob by running the TLS protocol. The main purpose of DTKI is to enable Alice to verify that the certificate she received in the TLS session is indeed a valid certificate of Bob. In DTKI, a valid certificate means that the certificate is active. A certificate is active if the certificate is authentic and not revoked; and a certificate is authentic if the certificate’s subject has run the registration protocol to register it.

To formally define an authentic certificate and an active certificate, we define a function keys_B to model the status of all public keys of B. We present time by integers e.g. seconds, consider that all protocols are run within one unit of time, and denote the infinite set of all public keys by \( \mathcal{PK} \).

**Definition 1.** Let \( B \) be a domain. A key function keys_B for \( B \) is a function from \( \mathbb{N} \) to a set of finite sets of elements in \( \mathcal{PK} \times \{0,1\} \) such that for all \( pk \in \mathcal{PK} \), for all \( t \in \mathbb{N} \), \( pk \) occurs at most once in \( \text{keys}_B(t) \). Moreover, for all \( pk \in \mathcal{PK} \), if there exists \( t \) such that \( pk \) occurs in \( \text{keys}_B(t) \) then:

- either there exists \( t_{\text{reg}}, t_{rev} \in \mathbb{N} \) such that \( t < t_{\text{reg}} \), \( pk \) does not occur in \( \text{keys}_B(t) \); and for all \( t < t_{\text{reg}} \), \( (pk, 1) \in \text{keys}_B(t) \); and for all \( t \geq t_{\text{reg}} \), \( (pk, 0) \in \text{keys}_B(t) \);
- or there exists \( t_{\text{reg}} \in \mathbb{N} \) such that for all \( t < t_{\text{reg}} \), \( pk \) does not occur in \( \text{keys}_B(t) \); and for all \( t \geq t_{\text{reg}} \), \( (pk, 1) \in \text{keys}_B(t) \).

We say that a public key \( pk \in \mathcal{PK} \) is authentic (w.r.t domain \( B \)) at time \( t \) if \((pk, b) \in \text{keys}_B(t) \) for some \( b \in \{0,1\} \); and \( pk \) is active at the time \( t \) if \((pk, 1) \in \text{keys}_B(t) \).

In addition, given user A and log maintainer L, we consider a function \( d_{A,L} \) such that given a time \( t \) as input, \( d_{A,L}(t) \) outputs the pair of values (expected to be the digest and size, respectively, of L’s log) given by L, and stored in the cache of A’s browser at time \( t \). Note that we have \( d_{A,L}(0) = (null, 0) \) for participants A and L, where null is the null bitstring.

We assume that both Alice and Bob are honest, meaning that they run the protocols of DTKI correctly. We say that \((dq, N)\) represents a chronological log \( S \) if \( \text{digest}(S) = dq \) and \( |\text{content}(S)| = N \), where \( \text{content}(S) \) is the sequence of data stored in chronological log \( S \). We have the following lemma to show that if a participant stores a pair of values after successfully running a protocol with a log maintainer L at time \( t \), and the pair of values are indeed the digest and size of a log, then all previously stored values associated to L are also pairs of digest and size of a historic version of the log.

**Lemma 1.** Let \( A \) be an honest participant, and \( L \) a log maintainer. If there exists a time \( t \in \mathbb{N} \) and a log \( S \) such that \( d_{A,L}(t) \) represents \( S \) at time \( t \), then for all \( t' < t \),
there exists a log \( S' \) such that \( \text{dg}_{A,L}(t') \) represents \( S' \) and \( \text{content}(S') \subseteq \text{content}(S) \).

Informally, the above lemma holds because \( A \), being honest, will run the verification of proof of extension, and will accept and store the digest at time \( t \) only if it was successful; and a valid proof of extension ensures that a chronological data structure represented by the newly received digest is an extension of a chronological data structure represented by a previously stored digest. In addition, the condition that \( \text{dg}_{A,L}(t) \) represents \( S \) at the time \( t \) will be verified by the random checking procedure \( \text{Rand}\exists_C \).

When a participant wants to register (or revoke, or verify) a certificate, she requests the corresponding certificate log information (e.g., the certificate of the log maintainer, the digest and size of the log) from the mapping log maintainer, then runs the corresponding protocol for registering (or revoking, or verifying) a certificate with the certificate log maintainer. In the protocol, she obtains a digest and size of the certificate log. She should verify that the pair of digest and size is a latter (or the same) version of the pair received from the mapping log maintainer. This is formally described as follows.

**Lemma 2.** Let \( A \) be an honest participant running the protocol for verifying (resp. registering, revoking) a certificate \( \text{cert} \) at time \( t \). Let \( M \) be the mapping log maintainer. If the protocol ran successfully, then there exists a certificate log maintainer \( C \), such that if there exists a mapping log \( S_M \) represented by \( \text{dg}_{A,M}(t) \) and a certificate log \( S_C \) represented by \( \text{dg}_{A,C}(t) \), then the following properties hold:

- there exists \( \text{req}, N, \text{dg} \) such that \( \text{h}(\text{req}, N, \text{dg}) \) is the last element of \( \text{content}(S_C) \) and \( N = |\text{content}(S_M)| \); and
- there exists \( t', \text{dg}^*, \text{dg}^t, \text{dg}^r \) and \( \text{dg}^t \) such that \( \text{h}(\text{end}, t', \text{dg}^*, \text{dg}^t, \text{dg}^r, \text{dg}^t) \) is the last element of \( \text{content}(S_M) \); and
- \( t' \leq t \); and
- \( \text{dg}^* \) is the digest of an ordered data structure \( S_s \) such that there exists \( \text{cert}_s, \text{sk}, n' \) and \( \text{dg}' \) such that \( \langle \text{cert}_s, \text{sk}, (n', \text{dg}', t') \rangle \in \text{content}_s(S_s) \), where \( \text{content}_s(S) \) is the sequence of data stored in ordered data structure \( S_s \), \( C \) is the subject of \( \text{cert}_s, n' \leq |\text{content}(S_C)| \) and \( \langle \text{digest}(S_C), |\text{content}(S_C)| \rangle \) is an extension of \( (\text{dg}', n') \); and
- \( \text{dg}^t \) is the digest of an ordered data structure \( S_r \) such that there exists \( \langle \text{rgx}, \text{id} \rangle \in \text{content}_r(S_r) \), where \( \text{id} \) is the identity of \( C \) and \( \text{id} \) is an instance of regular expression \( \text{rgx} \).

Lemma 2 enables one to associate a given identity Alice and digest \( \text{dg}_{A,C}(t) \) with a certificate log maintainer \( C \) (in the statement of the lemma) that satisfies the properties in the lemma. We call such a certificate log maintainer \( \text{designated certificate log maintainer} \).

We have the following theorem.

**Theorem 1.** Let \( \text{Alice} \) and \( \text{Bob} \) be two honest participants. Assume that \( \text{Alice} \) is successfully running at time \( t_A \) the protocol for verifying a certificate \( \text{cert} \) whose identity is \( \text{Bob} \). Let \( t_B \leq t_A \) and let \( C_A \) (resp. \( C_B \)) be the designated certificate log maintainer of Bob in \( \text{dg}_{A,M}(t_A) \) (resp. \( \text{dg}_{B,M}(t_B) \)). If there exists a mapping log \( S_M \) and certificate logs \( S_{C_A}, S_{C_B}, S_{C_1}, \ldots, S_{C_n} \) such that:

1) \( S_M \) and \( S_{C_A}, S_{C_B}, S_{C_1}, \ldots, S_{C_n} \) are synchronised; and
2) \( \langle \text{digest}(S_M), |\text{content}(S_M)| \rangle = \text{dg}_{A,M}(t_A) \) and is an extension of \( \text{dg}_{B,M}(t_B) \); and
3) \( \langle \text{digest}(S_{C_A}), |\text{content}(S_{C_A})| \rangle = \text{dg}_{A,C}(t_A) \); and
4) \( \langle \text{digest}(S_{C_B}), |\text{content}(S_{C_B})| \rangle \) is an extension of \( \text{dg}_{B,C}(t_B) \); and
5) for all \( i > N \), the \( i \)-th element of \( S_M \) is not a blacklist request where \( \langle \text{dg}, N \rangle = \text{dg}_{B,M}(t_B) \) then the public key contained in \( \text{cert} \) is authentic at time \( t_A \). If moreover between \( t_B \) and \( t_A \), \( \text{Bob} \) does not run the revocation protocol then the public key contained in \( \text{cert} \) is active at time \( t_A \).

Loosely speaking, to convince Alice to accept a TLS certificate, an attacker needs to make some fake proofs (detailed in the section 4.2) and to forge a signature corresponding to the master certificate. However, if the master certificate that Alice received is the same as the master certificate Bob published, then the attacker cannot forge such a signature on TLS certificates, though an attacker who colluded with the corresponding certificate log maintainer could forge the proofs (but it would be detected later).

Consider the scenario that an internet user Alice wants to securely communicate with a domain owner Bob who has successfully registered a master certificate and some TLS certificates. Let \( t_B \) be the time when Bob has successfully verified his certificates by communicating the mapping log maintainer \( M \) and a certificate maintainer \( C_B \). We show how to achieve the conditions listed in the theorem 1 to guarantee the certificate Alice received in the TLS session is active w.r.t. Bob’s domain. After Alice receives a certificate \( \text{cert} \) from Bob, Alice contacts the mapping log maintainer \( M \) and obtains the identity information of the authorised certificate log maintainer \( C_A \) for Bob’s domain, then runs the certificate verification protocol with \( C_A \). Let \( t_A > t_B \) be the time when Alice has successfully verified \( \text{cert} \) with \( C_A \).

Condition 1 is a property that expresses the existence and synchronisation of logs. In practice, it is ensured by using the distributed random checking. As discussed in the section of log verification (Section 4.3), the full coverage of the random verification can be expected to be achieved because of the large number of internet users.

Conditions 2 and 3 ensure that the mapping log and certificate log maintained by the designated log maintainers are represented by the pairs of digit and size that they sent to Alice, and together with condition 4, they indicate that Bob (or Alice) was not in a “bubble” created by the attacker. These conditions can be guaranteed by using the gossip protocol.

The last condition requires that no new certificate log maintainer is blacklisted since time \( t_B \) that Bob verified his certificates with \( C_B \). Since we assume that Bob is an honest participant, then as required by the protocol, he will verify
his certificates at least when a certificate log maintainer is blacklisted by the mapping log maintainer.

Thus, thanks to Theorem 1, by the end of the protocol, Alice can be sure that the certificate she received from the TLS session is active.

6 Comparison

As mentioned previously, DTKI builds upon a wealth of ideas from SK [24], CT [27], ECT [29], and AKI [28]. Figure 5 shows the dimensions along which DTKI aims to improve on those systems.

Compared with CT, DTKI supports revocation by enabling log providers to offer proofs of absence and currency of certificates. In CT, there is no mechanism for revocation. CT has proposed additional data structures to hold revoked certificates, and those data structures support proofs of their contents [40]. However, there is no mechanism to ensure that the data structures are maintained correctly in time.

Compared to ECT, DTKI extends the log structure of ECT to make it suitable for multiple log maintainers, and provides a stronger security guarantee as it prevents attacks rather than merely detecting them. In addition, the presence of the mapping log maintainer and multiple certificate log maintainers create some extra monitoring work. DTKI solves it by using a detailed crowd-sourcing verification system to distribute the monitoring work to all users’ browsers.

Compared to AKI and ARPKI, in DTKI the log providers can give proof that the log is maintained append-only from one step to the next. The data structure in A(RP)KI does not allow this, and therefore they cannot give a verifiable guarantee to the clients that no data is removed from the log.

DTKI improves the support that CT and A(RP)KI have for multiple log providers. In CT and AKI, domain owners wishing to check if there exists a log provider that has registered a certificate for him has to check all the log providers, and therefore the full set of log providers has to be fixed and well-known. This prevents new log providers being flexibly created, creating an oligopoly. In contrast, DTKI requires the browsers only to have the MLM public key built-in, minimising the oligopoly element.

In DTKI, no trusted party is required, as it uses crowd-sourcing verification to eliminate the need of trusted parties, i.e. a trusted party’s verification work can be done probabilistically in small pieces, meaning that users’ browsers can collectively perform the monitoring role.

Unlike the mentioned previous work, DTKI allows the possibility that all service providers (i.e. the MLM, CLMs, and mirrors) to collude together, and can still prevent attacks. In contrast, SK and CT can only detect attacks, and to prevent attacks, A(RP)KI requires that not all service providers collude together. Similar to A(RP)KI, DTKI also assumes that the domain is initially registered by an honest party to prevent attacks, otherwise A(RP)KI and DTKI can only detect attacks.

7 Discussion

Coverage of random checking: As mentioned, several aspects of the logs are verified by user’s browsers performing randomly-chosen checks. The number of things to be checked depends on the size of the mapping log and certificate logs. The size of the mapping log mainly depends on the number of certificate logs and the mapping from regular expressions to certificate logs; and the size of certificate logs mainly depends on the number of domain servers that have a TLS certificate. Currently, there are $2.71 \times 10^8$ domains [39] (though not every domain has a certificate), and $3 \times 10^9$ internet users [41]. Thus, if every user makes one random check per day, then everything will on average, be checked 10 times per day.

Gossip protocol: As mentioned in the overview, to avoid victims being trapped in a “bubble” created by very powerful attackers who controls the network and all service infrastructures such as ISPs and log maintainers, DTKI assumes the existence of a gossip protocol [34] that can be used for users to detect if a log maintainer shows different versions (i.e. different pairs of digest and size) of the log to different sets of users. The gossip protocol allows client browsers to exchange with other users the digest and size of the log that they have received in the DTKI protocols. The gossip protocol provides a means for a browser to identify peers with whom to exchange digests. The mobility of phones and laptops help ensure maximum gossip performance. At any time, a user can request a proof that the pair of digest and size currently offered by the log is an extension of a previous pair of digest and size of the log received from other users via the gossip protocol.

Master certificate concerns: One concern is that a CA might publish fake master certificates for domains that the CA doesn’t own and are not yet registered. However, this problem is not likely to occur: CAs are businesses, they cannot afford the bad press from negative public opinion and they cannot afford the loss of reputation. Hence, they will only want to launch attacks that would not be caught. (Such an adversary model has been described by Franklin and Yung [42], Canetti and Ostrovsky [43], Hazay and Lindell [44], and Ryan [29]). In DTKI, if a CA attempts to publish a fake master certificate for some domain, it will have to leave evidence of its misbehaviour in the log, and the misbehaviour will eventually be detected by the genuine domain owner.

Avoidance of oligopoly: As we mentioned in the introduction, the predecessors (SK, CT, ECT, AKI, ARPKI) of DTKI do not solve a foundational issue, namely oligopoly. These proposals require that all browser vendors agree on a fixed list of log maintainers and/or validators, and build it into their browsers. This means there will be a large barrier to create a new log maintainer.

CT has some support for multiple logs, but it doesn’t have any method to allocate different domains to different logs. In CT, when a domain owner wants to check whether mis-issued certificates are recorded in logs, he needs to contact all existing logs, and download all certificates in each of the logs, because there is no way to prove to the domain owner that no certificates for his domain is in the log, or to prove that the log maintainer has showed all certificates in the log for his domain to him. Thus, to be able to detect fake certificates, CT has to keep a very small number of log maintainers. This prevents new log providers being flexibly created, creating an oligopoly.
### Terminology

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Log provider</td>
<td>Time-line server</td>
<td>Log</td>
<td>Integrity log server (ILS)</td>
<td>Integrity log server (ILS)</td>
</tr>
<tr>
<td>Log extension</td>
<td>-</td>
<td>Log consistency</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Trusted party</td>
<td>Mirror</td>
<td>Auditor &amp; monitor</td>
<td>Validator</td>
<td>Validator (optional)</td>
</tr>
</tbody>
</table>

### Whether answers to queries rely on trusted parties or are accompanied by a proof

| Subject-absent-from-log query: | Rely | Rely | Rely | Proof | Proof |

### Non-necessity of trusted party

| Trusted party role can be distributed randomly to browsers | No | No | No* | No* | Yes |

### Trust assumptions

| Not all service providers collude together | Yes | Yes | Yes | Yes | No |
| Domain is initially registered by an honest party | No | No | Yes* | Yes* | Yes* |

### Security guarantee

| Attacks detection or prevention | Detection | Detection | Prevention | Prevention | Prevention |

### Oligopoly issues

| Log providers required to be built into browser (oligopoly) | Yes | Yes | Yes | Yes | Only MLM |
| Monitors required to be built into browser (oligopoly and trust non-agility) | Yes | No | Yes | Yes† | No |

† The system limits the trust in each server by letting them to monitor each other’s behaviour.
* Without the assumption, the security guarantee is detection rather than prevention.
† The trusted party is optional, if there is a trusted party, then the trusted party is required to be built into browser.

Figure 5: Comparison of log-based approaches to certificate management. Terminology helps compare the terminology used in the papers. How queries rely on trusted parties shows whether responses to browser queries come with proof of correctness or rely on the honesty of trusted parties. Necessity of trusted parties shows whether the TP role can be performed by browsers. Trust assumptions shows the assumption for the claimed security guarantee. Oligopoly issues shows the entities that browsers need to know about.

In contrast to its predecessors, DTKI does not have a fixed set of certificate log maintainers (CLMs) to manage certificates for domain owners, and it is easy to add or remove a certificate log maintainer by updating the mapping log. In DTKI, the public log of the MLM is the only thing that browsers need to know.

MLM may be thought to represent a monopoly; to the extent that it does, it is a much weaker monopoly than the oligopoly of CAs or log maintainers. CAs and log maintainers offer commercial services and compete with each other, by offering different levels of service at different price points in different markets. MLM does not offer any commercial services; it performs a purely administrative role, and is not required to be trusted because it behaves fully transparently and does not manage any certificate for web domains.

Synchronisation concerns: The synchronisation among a large number (e.g. thousands) of participants is normally a difficult task. However, in DTKI, the synchronisation among the MLM and CLMs is not expected to be a problem. First, the mapping log is rarely changed – it will be changed only if a new CLM has been added or terminated. In the steady state, this is likely to be no more than a few times per year. Second, the MLM can send the corresponding update request to CLMs in advance, and the synchronisation process is allowed to take an acceptable time period. During this time period, users will use the current logs until all logs are synchronised. Third, the MLM can terminate a CLM that has failed to update on time (e.g. have not finished the update process in a certain time period). So, in a long run, all parties will be able to do their work properly.

8 Conclusions and future work

Sovereign keys (SK), certificate transparency (CT), accountable key infrastructure (AKI), enhanced certificate transparency (ECT), and attack resilient PKI (ARPKI) are
recent proposals to make public key certificate authorities more transparent and verifiable, by using public logs. CT is currently being implemented in servers and browsers. Google is building a certificate transparency log containing all the current known certificates, and is integrating verification of proofs from the log into the Chrome web browser.

Unfortunately, as it currently stands, CT risks creating an oligopoly of log maintainers (as discussed in section 7), of which Google itself will be a principal one. Therefore, adoption of CT risks investing more power about the way the internet is run in a company that arguably already has too much power.

In this paper we proposed DTKI – a TTP-free public key validation system using an improved construction of public logs. DTKI can prevent attacks based on mis-issued certificates, and minimises undesirable oligopoly situations by using the mapping log. In addition, we formalised the public log structure and its implementation; such formalisation work was missing in the previous systems (i.e. SK, CT, A(RP)KI, and ECT). Since devising new security protocols is notoriously error-prone, we provide a formalisation of DTKI, and correctness proofs.

References


[9] C. Arthur, “Rogue web certificate could have been used to attack Iran dissidents,” The Guardian, 2011.


