Formal analysis of privacy in Direct Anonymous Attestation schemes

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Abstract

This article introduces a definition of privacy for Direct Anonymous Attestation schemes. The definition is expressed as an equivalence property suited to automated reasoning using ProVerif and the practicality of the definition is demonstrated by analysing the RSA-based Direct Anonymous Attestation protocol by Brickell, Camenisch & Chen. The analysis discovers a vulnerability in the RSA-based scheme which can be exploited by a passive adversary and, under weaker assumptions, corrupt administrators. A security fix is identified and the revised protocol is shown to satisfy our definition of privacy.

Keywords. Accountability, anonymity, applied pi calculus, Direct Anonymous Attestation, privacy, ProVerif, trusted computing, TPM, traceability, unlinkability.

1 Introduction

Trusted computing allows commodity computers to provide cryptographic assurances about their behaviour. At the core of the architecture is a hardware device called the Trusted Platform Module (TPM), which is estimated to be embedded in over 500 million computers [Tru11] (although, some experts claim

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only 5% of these TPMs have been turned on [Mar08, §6] and we suspect significantly fewer are in active use). The TPM uses shielded memory to store cryptographic keys, and other sensitive data, which can be used to achieve security objectives, in particular, the chip can measure and report its state, and authenticate. These security objectives assume that a TPM's shielded memory protects keys and TPMs are said to be compromised if this assumption does not hold (see Tarnovsky [Tar10] for a hardware attack that successful extracts keys from shielded memory).

Cryptographic operations, by their nature, may reveal a platform's identity and as a consequence the TPM has been perceived as threat to privacy by some users, for example, see Stallman [Sta02, Sta10] and Anderson [And03, And04]. In an attempt to overcome these privacy concerns, Brickell, Camenisch & Chen [BCC04] have introduced Direct Anonymous Attestation (DAA). (A historical account of DAA's development as a privacy enhancing technology is presented by Brickell, Camenisch & Chen [BCC05].)

Direct Anonymous Attestation enables a platform to authenticate itself to a service in a way that provides privacy and accountability. The concept is based upon group signatures with stronger anonymity guarantees, in particular, the identity of a signer can never be revealed, but signatures may be linked with the signer's consent and signatures produced by compromised platforms can be identified. A DAA scheme considers a set of *hosts*, *issuers*, *TPMs*, and *verifiers*; the host and TPM together form a *trusted platform* or *signer*. DAA protocols proceed as follows. A host requests membership to a group of signers managed by an issuer. The issuer authenticates the host as a trusted platform and grants an *attestation identity credential* (occasionally abbreviated *credential*). The host in association with the TPM can now produce signatures using the credential, thereby permitting a verifier to authenticate the host as a group member and therefore a trusted platform.

Brickell, Chen & Li [BCL08b, BCL09] and Chen [Che10a, Che11] characterise the following security properties[1] for Direct Anonymous Attestation schemes:

- *Anonymity.* The identity of a signer cannot be revealed from a signature.
- *Linkability.* A signer's signatures can be detected as being from the same signer, if the signer consents.
- *Non-frameability.* An adversary cannot produce a signature associated with an honest TPM.
- *Unforgeability.* Signatures cannot be produced without a TPM.
- *Unlinkability.* A signer's signatures cannot be detected as being from the same signer without the signer's consent.

[1] The necessity for non-frameability was highlighted by Backes, Maffei & Unruh [BMU08] and formalised by Chen [Che10a, Che11], the remaining properties were formalised by Brickell, Chen & Li [BCL08b, BCL09].

These properties aim to balance the privacy (anonymity and unlinkability properties) demands of users with the accountability (linkability, non-frameability and unforgeability properties) needs of administrators. The distinction between privacy and accountability properties is reflected in our trust model: anonymity and unlinkability assume that two signers are honest, whereas, linkability, non-frameability and unforgeability assume that an issuer is honest. (The isser must be honest for linkability, since a dishonest issuer can provide an adversary with a new credential for every signature, thereby ensuring that two signatures are never linked.) In addition, DAA schemes must be *correct*: valid signatures can be verified and, where applicable, linked.

Brickell, Camenisch & Chen [BCC04] propose the first concrete instance of a Direct Anonymous Attestation scheme based upon RSA. Support for this RSA-based scheme is mandated by the TPM specification version 1.2 [TCG07] which has been defined as an ISO/IEC international standard [Int09], moreover, the scheme has been included in the ISO/IEC anonymous digital signature standard [Int11]. Appendix A presents a brief review of other Direct Anonymous Attestation schemes.

1.1 Contribution

We formalise Direct Anonymous Attestation protocols in the applied pi calculus (Section 3) and present a definition of privacy as an equivalence property (Section 4) which is suited to automated reasoning using ProVerif. Informally, the security definition asserts that an adversary cannot distinguish between signatures produced by two distinct signers, even when the adversary controls the issuer and has observed signatures produced by each signer. The application of the definition is demonstrated (Section 5) by analysing privacy in the RSA-based DAA protocol. The analysis discovers a vulnerability in the protocol which allows an adversary to violate privacy. A fix is identified, and the revised RSA-based DAA protocol is shown to be secure. We examine the balance between privacy and accountability offered by DAA and propose extensions to DAA (Section 6): we propose a stronger notion of privacy which is intuitively satisfied by the fixed RSA-based scheme, address an issue which can prevent linkability, and provide some practical guidelines for basenames to help resolve a flaw in unlinkability. Finally, directions for future work are identified and a brief conclusion is presented (Section 7).

1.2 Related work

In the computational model, Brickell, Camenisch & Chen [BCC04] introduce simulation-based models of security and Brickell, Chen & Li [BCL08b, BCL09] propose a game-based security definition; the relationship between the simulation-based models and the game-based definition is unknown [CMS08a, pp158]. Bernhard *et al.* [BFG+11] argue that the simulation-based definitions and the game-based definition are insufficient for accountability due to informal handling

of identities and propose an alternative game-based security definition, moreover, Bernhard *et al.* show that the simulation-based model by Chen, Morrissey & Smart [CMS09] is unsatisfiable (for all protocols there trivially exists a distinction between the ideal- and real-world). We consider a symbolic definition for privacy, based upon the game-based definition by Brickell, Chen & Li (we stress that the criticisms from Bernhard *et al.* relate to the accountability game and not the privacy game, hence, their concerns are not relevant to our work). By comparison, Backes, Maffei & Unruh [BMU08] formalise an earlier notion of privacy (informally described in [BCC04]) for the RSA-based DAA protocol. This formalisation is tightly coupled with their model of the RSA-based protocol and it is unclear whether other DAA schemes can be analysed or, indeed, how to analyse alternative models of the RSA-based protocol. In addition, the formalisation pre-dates the privacy definitions by Brickell, Chen & Li and considers a conceptually weaker adversary, for example, the following scenario is not considered: 1) signer $\mathcal{A}$ obtains a credential $\texttt{cre}_A$ and produces arbitrarily many signatures; 2) signer $\mathcal{B}$ obtains a credential $\texttt{cre}_B$ and produces arbitrarily many signatures; and 3) the adversary attempts to distinguish between two fresh signatures produced by the signers using credentials $\texttt{cre}_A$ and $\texttt{cre}_B$. Finally, our definition is intuitively simpler, which should aid analysis and, in particular, be better suited to automated reasoning.

Our earlier work also merits comparision. The attack and fix presented in this article originally appeared in Smyth, Ryan & Chen [SRC07]. The fixed scheme has been analysed by Delaune, Ryan & Smyth [DRS08] based upon an earlier notion of privacy, by comparision, our analysis considers a definition based upon the cryptographic game proposed by Brickell, Chen & Li. Smyth presented a version of this article in his thesis [Smy11, Chapter 4], in particular, Smyth's thesis contains a formalisation of Direct Anonymous Attestation schemes as processes in the applied pi calculus, a privacy definition (based upon the cryptographic game proposed by Brickell, Chen & Li), and an analysis of the RSA-based DAA protocol. The formalisaion of DAA schemes as processes and the privacy definition were developed by Smyth, Ryan & Chen [SRC11], in addition, Smyth, Ryan & Chen analysed the ECC-based DAA protocol by Brickell, Chen & Li [BCL08a, BCL09]. This article collates Smyth, Ryan & Chen [SRC07], Smyth [Smy11, Chapter 4] and, Smyth, Ryan & Chen [SRC11]; Smyth's thesis has not been previously published, hence the analysis of the fixed RSA-based DAA protocol and a special case of the attack which allows a passive adversary to violate privacy are new. In addition, this article provides a more detailed discussion of our results, highlights the limitations of our model, notes some ambiguities in the cryptographic game by Brickell, Chen & Li, and proposes a refinement to the RSA-based DAA protocol to help balance privacy and accountability.

2 Preliminaries: Calculus of ProVerif

We adopt a dialect [Bla04, BAF08] of the applied pi calculus [AF01, RS11] which is suited to automated reasoning using Blanchet's ProVerif [BS11].

2.1 Syntax and semantics

The calculus assumes an infinite set of names, an infinite set of variables, and a signature Σ consisting of a finite set of function symbols (constructors and destructors), each with an associated arity. A function symbol with arity 0 is a constant. We write f for a constructor, g for a destructor, and h for either a constructor or destructor. Terms are defined over names, variables, and constructors applied to other terms (Figure 1). A substitution, denoted $\{^M/_x\}$, replaces the variable x with the term M and we let the letters σ and τ range over substitutions. We write $N\sigma$ for the result of applying σ to the free variables of N.

The signature Σ is equipped with an equational theory E, that is, a finite set of equations of the form $M = N$. We define $=_E$ as the smallest equivalence relation on terms that contains E and is closed under application of constructors, substitution of terms for variables, and bijective renaming of names. The semantics of a destructor g of arity l is given by a finite set $\mathrm{def}_\Sigma(g)$ of rewrite rules $g(M'_1, \ldots, M'_l) \to M'$, where $M'_1, \ldots, M'_l, M'$ are terms containing only constructors and variables, the variables of M' are bound in $M'_1, \ldots, M'_l$, and variables are subject to renaming. The term $g(M_1, \ldots, M_l)$ is defined if and only if there exists a substitution σ and a rewrite rule $g(M'_1, \ldots, M'_l) \to M'$ in $\mathrm{def}_\Sigma(g)$ such that $M_i = M'_i\sigma$ for all $i \in \{1, \ldots, l\}$, and in this case $g(M_1, \ldots, M_l)$ is $M'\sigma$.

The grammar for processes appears in Figure 1. The process let $x = D$ in P else Q tries to evaluate D; if this succeeds, then x is bound to the result and P is executed, otherwise Q is executed. For convenience, the statement let $x = D$ in P else Q may be abbreviated as let $x = D$ in P when Q is the null process. The syntax does not include the conditional if $M = N$ then P else Q, but this can be defined as let $x = \mathsf{eq}(M, N)$ in P else Q, where x is a fresh variable and eq is a binary destructor with the rewrite rule $\mathsf{eq}(x, x) \to x$. We always include this destructor in Σ. The rest of the syntax is standard (see Blanchet [Bla04, BAF08] for details).

The sets of free and bound names, respectively variables, in process P are denoted by $\mathrm{fn}(P)$ and $\mathrm{bn}(P)$, respectively $\mathrm{fv}(P)$ and $\mathrm{bv}(P)$. We also write $\mathrm{fn}(M)$ and $\mathrm{fv}(M)$ for the sets of names and variables in term M. A process P is closed if it has no free variables. A context C is a process with a hole and we obtain $C[P]$ as the result of filling C's hole with P. An evaluation context is a context whose hole is not in the scope of a replication, an input, an output, or a term evaluation.

The operational semantics are defined by reduction ($\to_\Sigma$) in association with the auxiliary rules for term evaluation ($\Downarrow_\Sigma$) and structural equivalence ($\equiv$). Both $\equiv$ and $\to_\Sigma$ are defined only on closed processes. We write $\to^*_\Sigma$ for the reflexive

Figure 1 Syntax for terms and processes

$M, N ::=$	terms
$a, b, c, \ldots, k, \ldots, m, n, \ldots, s$	name
x, y, z	variable
$f(M_1, \ldots, M_l)$	constructor application
$D ::=$	term evaluations
M	term
eval $h(D_1, \ldots, D_l)$	function evaluation
$P, Q, R ::=$	processes
0	null process
$P \mid Q$	parallel composition
$!P$	replication
$\nu\, a.P$	name restriction
$M(x).P$	message input
$\overline{M}\langle N\rangle.P$	message output
let $x = D$ in P else Q	term evaluation

and transitive closure of $\rightarrow_\Sigma$, and we write $\rightarrow_\Sigma^*\equiv$ for the union of $\rightarrow_\Sigma^*$ with $\equiv$. We occasionally abbreviate $\rightarrow_\Sigma$ as $\rightarrow$ and $\Downarrow_\Sigma$ as $\Downarrow$.

2.2 Biprocesses

The calculus provides a notation for modelling pairs of processes that have the same structure and differ only by the terms and term evaluations that they contain. We call such a pair of processes a *biprocess*. The grammar for the calculus with biprocesses is a simple extension of Figure 1, with additional cases so that $\mathrm{diff}[M, M']$ is a term and $\mathrm{diff}[D, D']$ is a term evaluation. The semantics for biprocesses include the rules in Figure 2, except for (Red I/O), (Red Fun 1), and (Red Fun 2), which are revised in Figure 3. We also extend the definition of contexts to permit the use of diff.

Given a biprocess P, we define processes $\mathrm{fst}(P)$ and $\mathrm{snd}(P)$, as follows: $\mathrm{fst}(P)$ is obtained by replacing all occurrences of $\mathrm{diff}[M, M']$ with M and $\mathrm{diff}[D, D']$ with D in P; and, similarly, $\mathrm{snd}(P)$ is obtained by replacing $\mathrm{diff}[M, M']$ with M' and $\mathrm{diff}[D, D']$ with D' in P. We define $\mathrm{fst}(D)$, $\mathrm{fst}(M)$, $\mathrm{snd}(D)$, and $\mathrm{snd}(M)$ similarly.

2.3 Observational equivalence

Intuitively, processes P and Q are said to be observationally equivalent if they can output on the same channels, no matter what context they are placed inside. Formally, we write $P \downarrow_M$ when P can send a message on M, that is, when $P \equiv C[\overline{M'}\langle N\rangle.R]$ for some evaluation context $C[\_]$ such that $\mathrm{fn}(C) \cap \mathrm{fn}(M) = \emptyset$

Figure 2 Semantics for terms and processes

$M \Downarrow M$

eval $h(D_1, \ldots, D_n) \Downarrow N\sigma$
  if $h(N_1, \ldots, N_n) \to N \in \mathrm{def}_\Sigma(h)$,
  and σ is such that for all i, $D_i \Downarrow M_i$ and $\Sigma \vdash M_i = N_i\sigma$

$P \mid 0 \equiv P$	$P \equiv P$
$P \mid Q \equiv Q \mid P$	$Q \equiv P \Rightarrow P \equiv Q$
$(P \mid Q) \mid R \equiv P \mid (Q \mid R)$	$P \equiv Q, Q \equiv R \Rightarrow P \equiv R$
$\nu\, a.\nu\, b.P \equiv \nu\, b.\nu\, a.P$	$P \equiv Q \Rightarrow P \mid R \equiv Q \mid R$
$\nu\, a.(P \mid Q) \equiv P \mid \nu\, a.Q$ if $a \notin \mathrm{fn}(P)$	$P \equiv Q \Rightarrow \nu\, a.P \equiv \nu\, a.Q$

$\overline{N}\langle M\rangle.Q \mid N'(x).P \to Q \mid P\{^M/_x\}$ if $\Sigma \vdash N = N'$ (Red I/O)

let $x = D$ in P else $Q \to P\{^M/_x\}$ if $D \Downarrow M$ (Red Fun 1)

let $x = D$ in P else $Q \to Q$ if there is no M such that $D \Downarrow M$ (Red Fun 2)

$!P \to P \mid !P$ (Red Repl)

$P \to Q \Rightarrow P \mid R \to Q \mid R$ (Red Par)

$P \to Q \Rightarrow \nu\, a.P \to \nu\, a.Q$ (Red Res)

$P' \equiv P, P \to Q, Q \equiv Q' \Rightarrow P' \to Q'$ (Red $\equiv$)

Figure 3 Generalised semantics for biprocesses

$\overline{N}\langle M\rangle.Q \mid N'(x).P \to Q \mid P\{^M/_x\}$ if $\Sigma \vdash \mathrm{fst}(N) = \mathrm{fst}(N')$ and $\Sigma \vdash \mathrm{snd}(N) = \mathrm{snd}(N')$ (Red I/O)

let $x = D$ in P else $Q \to P\{^{\mathrm{diff}[M_1, M_2]}/_x\}$ if $\mathrm{fst}(D) \Downarrow M_1$ and $\mathrm{snd}(D) \Downarrow M_2$ (Red Fun 1)

let $x = D$ in P else $Q \to Q$ if there is no M_1 such that $\mathrm{fst}(D) \Downarrow M_1$ and there is no M_2 such that $\mathrm{snd}(D) \Downarrow M_2$ (Red Fun 2)

and $\Sigma \vdash M = M'$. The definition of observational equivalence [Bla04, BAF08] follows.

Definition 1 (Observational equivalence)**.** Observational equivalence $\sim$ *is the largest symmetric relation $\mathcal{R}$ between closed processes such that $P\ \mathcal{R}\ Q$ implies:*

1. *if $P \downarrow_M$, then $Q \downarrow_M$;*
2. *if $P \to P'$, then $Q \to Q'$ and $P'\ \mathcal{R}\ Q'$ for some Q';*
3. *$C[P]\ \mathcal{R}\ C[Q]$ for all evaluation contexts $C[\_]$.*

We define observational equivalence as a property of biprocesses.

Definition 2. *The closed biprocess* P satisfies observational equivalence *if* $\mathrm{fst}(P) \sim \mathrm{snd}(P)$.

2.3.1 Assumptions and notation

In this article, all signatures are tacitly assumed to include the constant $\varnothing$, unary destructors fst and snd, and the binary constructor pair. Furthermore, for all variables x and y we assume the rewrite rules

$$\mathsf{fst}(\mathsf{pair}(x, y)) \to x \qquad \mathsf{snd}(\mathsf{pair}(x, y)) \to y$$

For convenience, $\mathsf{pair}(M_1, \mathsf{pair}(\ldots, \mathsf{pair}(M_n, \varnothing)))$ is occasionally abbreviated as $(\!|M_1, \ldots, M_n|\!)$ and $\mathsf{fst}(\mathsf{snd}^{i-1}(M))$ is denoted $\pi_i(M)$.

3 Direct Anonymous Attestation schemes

A Direct Anonymous Attestation scheme comprises of five algorithms, each of which will now be discussed.

Setup. The setup algorithm is used by the issuer to construct a DAA key pair sk_I and $\mathsf{pk}(sk_I)$, the public part $\mathsf{pk}(sk_I)$ is published. In addition, the setup algorithm may define implementation-specific parameters.

Join. The join algorithm is run between a trusted platform and an issuer for the purpose of obtaining group membership. The algorithm assumes that the trusted platform and issuer have established a one-way authenticated channel, that is, the issuer is assured to be communicating with a host and TPM. The definition of DAA does not mandate a particular authentication mechanism (the Trusted Computing Group recommend encrypting every message sent by the issuer under the TPM's endorsement key [TCG07]). On successful completion of the join algorithm, the issuer grants the trusted platform with an attestation identity credential `cre` based upon a secret `tsk` known only by the TPM.

Sign. The sign algorithm is executed by a trusted platform to produce a signature σ, based upon an attestation identity credential `cre` and secret `tsk`, which asserts group membership and therefore trusted platform status. In addition to `cre` and `tsk`, the algorithm takes as input a message m and a basename `bsn`. The basename is used to control linkability between signatures: if $\texttt{bsn} = \perp$, then signatures should be unlinkable; otherwise, signatures produced by the same signer and based upon the same basename can be linked (see Section 6 for further discussion on linkability).

Verify. The verification algorithm is used by a verifier to check the validity of a signature. The algorithm takes as input a set of secret keys $\texttt{ROGUE}_{\texttt{tsk}}$, which are known to have been successfully extracted from compromised

TPMs, allowing the identification of rogue platforms. The methodology used to build $\texttt{ROGUE}_{\texttt{tsk}}$ is not defined by DAA.

Link. The link algorithm is used by a verifier to check if two valid signatures are linked, that is, signed using the same basename `bsn` and secret `tsk`.

The inputs and outputs of these algorithms are explicitly summarised in Table 1.

3.1 Direct Anonymous Attestation schemes as processes

In the applied pi calculus, it is sufficient to model the parts of the protocol that must be honestly executed for the purposes of the desired security property. This article considers privacy, which is dependent on the honest behaviour of trusted platforms, that is, the join and sign algorithms. Accordingly, we model these algorithms as a pair of processes $\langle \mathsf{Join}, \mathsf{Sign} \rangle$.

The signer (or trusted platform) is able to execute arbitrarily many instances of the join and sign algorithms to become a member of a group of signers and, subsequently, produce signatures as a group member. This behaviour is captured by the Signer process modelled below. The join and sign algorithms are modelled by the processes Join and Sign, which are expected to behave like services, that is, they can be called by, and return results to, the Signer process. The communication between the Signer and Join/Sign processes is achieved using private communication over channels a_j, a'_j, a_s, and a'_s. In essence, the private channel communication models the internal bus used by computer systems for communication between the host and TPM.

$$
\begin{aligned}
\mathsf{Signer} \;=\; & \nu\, a_j \,.\, \nu\, a'_j \,.\, \nu\, a_s \,.\, \nu\, a'_s \,.\, (\,(!\mathsf{Join}) \mid (!\mathsf{Sign}) \mid (\\
& \quad \nu\, \mathtt{cnt} \,.\, \nu\, \mathtt{DAASeed} \,.\, \nu\, sk_M \,.\, \overline{c}\langle \mathsf{pk}(sk_M) \rangle \,.\\
& \quad c(w_{\mathsf{params}}) \,.\, !\overline{a_j}\langle (\!| w_{\mathsf{params}}, \mathtt{DAASeed}, \mathtt{cnt}, sk_M |\!) \rangle \,.\, a'_j(x) \,.\\
& \quad \text{let } x_{\mathsf{cre}} = \pi_1(x) \text{ in let } x_{\mathtt{tsk}} = \pi_2(x) \text{ in } (\\
& \qquad !c(y) \,.\, \text{let } y_{\mathsf{bsn}} = \pi_1(y) \text{ in let } y_{\mathsf{msg}} = \pi_2(y) \text{ in}\\
& \qquad \overline{a_s}\langle (\!| w_{\mathsf{params}}, y_{\mathsf{bsn}}, y_{\mathsf{msg}}, x_{\mathsf{cre}}, x_{\mathtt{tsk}} |\!) \rangle \,.\, a'_s(z) \,.\, \overline{c}\langle z \rangle\\
& \quad)\\
&))
\end{aligned}
$$

The process Signer instantiates arbitrarily many instances of the Join and Sign processes. The restricted channel names a_j and a'_j are introduced to ensure private communication between the Signer and Join processes; similarly, names a_s and a'_s ensure private communication between the Signer and Sign processes. The bound name `cnt` is a counter value selected by the host (in this article we consider a static counter value). The bound name `DAASeed` represents the TPM's internal secret and sk_M represents the TPM's endorsement key (these values are defined during manufacture [TCG07]). The public part of the endorsement key is published by the Signer process. The remainder of the Signer process models a signer's ability to execute arbitrarily many instances of the join and sign algorithms. The Signer process must first input system parameters w_{params}, provided by the issuer. The Join process is assumed to act like

Algorithm	Input	Output
Setup	Security parameters.	A DAA key pair sk_I and $\mathsf{pk}(sk_I)$, and any implementation-specific parameters.
Join	Trusted platform's input: the system parameters (namely, the DAA public key and any implementation-specific parameters defined by the setup algorithm), the TPM's internal secret `DAASeed` (this value is defined during manufacture [TCG07]), a counter value `cnt` selected by the host, and the TPM's endorsement key. Issuer's input: the system parameters.	Trusted platform's output: a pair consisting of the attestation identity credential `cre` and secret `tsk`. Issuer's output: the public part of the TPM's endorsement key.
Sign	The system parameters, a verifier's basename `bsn`, a message m, an attestation identity credential `cre`, and a secret `tsk`.	A signature σ.
Verify	The system parameters, a verifier's basename `bsn`, a message m, a candidate signature σ for m, and a set of secret keys $\mathtt{ROGUE}_{\mathtt{tsk}}$.	1 (accept) or 0 (reject).
Link	The system parameters, and two candidate signatures σ and σ' for messages m and m'.	-1 (invalid signature) if the verify algorithm outputs 0 for signature σ (or σ') using the system parameters, basename $\perp$, the message m (respectively m'), and the empty set of secret keys. Otherwise, the algorithm returns 1 if the signatures can be linked and 0 if the signatures cannot be linked.

Table 1: Summary of inputs and outputs for Direct Anonymous Attestation algorithms

a service and listens for input on channel a_j. It follows that the Signer process can invoke the service by message output $\overline{a_j}\langle(\!|w_{\mathsf{params}}, \mathtt{DAASeed}, \mathtt{cnt}, w_{\mathsf{ek}}|\!)\rangle$, where $(\!|w_{\mathsf{params}}, \mathtt{DAASeed}, \mathtt{cnt}, w_{\mathsf{ek}}|\!)$ models the join algorithm's parameters. The Join process is assumed to output results on channel a'_j, and this response can be received by the Signer process using message input $a'_j(x)$; the result is bound to the variable x, and is expected to consist of a pair $(\!|x_{\mathsf{cre}}, x_{\mathtt{tsk}}|\!)$ representing the attestation identity credential and TPM's secret. The interaction between the Sign and Signer processes is similar. The Signer process first inputs a variable y which is expected to be a pair representing the verifier's basename y_{bsn} and a message y_{msg}. The invocation of the sign algorithm by the signer is modelled by the message output $\overline{a_s}\langle(\!|w_{\mathsf{params}}, y_{\mathsf{bsn}}, y_{\mathsf{msg}}, x_{\mathsf{cre}}, x_{\mathtt{tsk}}|\!)\rangle$, where $(\!|w_{\mathsf{params}}, y_{\mathsf{bsn}}, y_{\mathsf{msg}}, x_{\mathsf{cre}}, x_{\mathtt{tsk}}|\!)$ represents the algorithm's parameters. The sign algorithm is expected to output a signature which can be sent to a verifier, in the Signer process this signature is received from the Sign process by message input $a'_s(z)$ and the variable z, representing the signature, is immediately output.

Limitations. This article focuses on privacy and we assume that the processes Join and Sign are initiated by input on channels a_j and a_s and, similarly, output results on channels a'_j and a'_s. Intuitively, it follows that some processes not satisfying these conditions will satisfy our definition of privacy, in fact, the DAA process specification $\langle 0, 0\rangle$ will satisfy our definition, as can be observed from the next section. We tolerate this limitations here, and future work could consider a complete definition of the DAA properties, including: correctness, linkability, non-frameability, and unforgeability. The correctness property will exclude degenerate process specifications such as $\langle 0, 0\rangle$. Similar considerations are made in the literature, for example, degenerate processes can satisfy the definition of ballot secrey for electronic voting by Delaune, Kremer & Ryan [DKR09, DKR10] and the definition of privacy for vehicular ad-hoc networks by Dahl, Delaune & Steel [DDS10].

4 Security definition: privacy

Informally, the notion of privacy asserts that given two honest signers $\mathcal{A}$ and $\mathcal{B}$, an adversary cannot distinguish between a situation in which $\mathcal{A}$ signs a message, from another one in which $\mathcal{B}$ signs a message. Based upon the game-based definition by Brickell, Chen & Li [BCL08b, BCL09] we present the following description of our privacy property.

Initial: The adversary constructs the DAA key pair sk_I and $\mathsf{pk}(sk_I)$, and publishes the public part $\mathsf{pk}(sk_I)$ along with any additional parameters. Moreover, the adversary may request the public keys of honest TPMs during this phase.

Phase 1: The adversary makes the following requests to signers $\mathcal{A}$ and $\mathcal{B}$:

- Join. The signer executes the join algorithm with the adversary to create `cre` and `tsk`. (The adversary, behaving as the issuer, will typically construct `cre` but not learn `tsk`.)
- Sign. The adversary submits a basename `bsn` and a message m. The signer runs the sign algorithm and returns the signature to the adversary.

We insist that sign requests to $\mathcal{A}$ (or $\mathcal{B}$) must be proceeded by at least one join request to $\mathcal{A}$ (respectively $\mathcal{B}$). Moreover, at the end of Phase 1, both signers are required to have run the join algorithm at least once.

Challenge: The adversary submits a message m' and a basename $\texttt{bsn}'$ to the signers, with the restriction that the basename has not been previously used if $\texttt{bsn}' \neq \perp$. Each signer produces a signature on the message and returns the signature to the adversary.

Phase 2: The adversary continues to probe the signers with join and sign requests, but is explicitly forbidden to use the basename $\texttt{bsn}'$ used in the Challenge phase if $\texttt{bsn}' \neq \perp$.

Result: The protocol satisfies privacy if the adversary cannot distinguish between the two signatures output during the challenge.

Intuitively, our description captures anonymity because the adversary cannot distinguish between the two signatures output during the challenge; formally, this can be witnessed as follows: suppose a protocol satisfies the above description of privacy but the identity of a signer can be revealed from a signature, it follows immediately that the adversary can test which challenge signature belongs to $\mathcal{A}$, therefore, allowing the signatures to be distinguished and hence deriving a contradiction. Moreover, our description also captures unlinkability. This can be witnessed as follows. Suppose a protocol satisfies our description of privacy but signatures can be linked without the signer's consent. It follows from our description that no adversary can distinguish between two signatures output during the challenge. Let us consider an adversary that requests a signature σ_A from $\mathcal{A}$ during Phase 1 using basename $\texttt{bsn} = \perp$ (that is, the signer does not consent to linkability) and an arbitrary message m. The adversary submits an arbitrary message m' and basename $\texttt{bsn}' = \perp$ during the challenge, and the signers return signatures σ_1 and σ_2. Since signatures can be linked without the signer's consent, the adversary is able to test if σ_A and σ_1 are linked or if σ_A and σ_2 are linked, exactly one test will succeed, thereby allowing the adversary to distinguish between signatures σ_1 and σ_2. We have derived a contradiction and, therefore, a protocol satisfying our description of privacy provides unlinkability.

Comparison with Brickell, Chen & Li. Our description of privacy clarifies some ambiguities in the cryptographic game proposed by Brickell, Chen & Li:

- The side condition that both signers must execute the join algorithm at least once during Phase 1 is only implicitly included in the cryptographic game by Brickell, Chen & Li with the requirement that "[the adversary] *chooses two signers' identities* [...]" [BCL09, §2.2.2]. We stress that their cryptographic game is unsatisfiable without this condition, in particular, privacy can never be achieved in a setting with one signer. Accordingly, we make the side condition explicit in our description.

- Sign queries with $\mathcal{A}$ or $\mathcal{B}$ are restricted to the basename $\perp$ in Phase 2 of the cryptographic game, more precisely, Brickell, Chen & Li state "[the adversary is] *not allowed to make Sign* [queries] *with* `bsn` *if* `bsn` $\neq \perp$ [...]" [BCL09, §2.2.2]. However, we believe their universal quantification over basenames was unintentional and we only forbid sign requests with $\mathcal{A}$ or $\mathcal{B}$ from using the challenge basename.

In addition, there are some high level distinctions between our description of the privacy property and the cryptographic game proposed by Brickell, Chen & Li:

1. *No key verification.* In the cryptographic game a key constructed by the adversary in the Initial phase is verified[2], whereas, no verification of the key is performed in our model.

2. *Static corruption of honest TPMs.* In the cryptographic game the adversary can dynamically corrupt honest TPMs, whereas, all TPMs except two are assumed to be corrupt in our model.

3. *Indistinguishability definition.* In the game-based definition either $\mathcal{A}$ or $\mathcal{B}$ signs the message during the Challenge and privacy is satisfied if the adversary has a negligible advantage over guessing the correct signer. By comparison, in our definition, both $\mathcal{A}$ and $\mathcal{B}$ sign the message during the Challenge and privacy is satisfied if these signatures are indistinguishable.

The first abstraction is trivially sound, but not complete (nonetheless, the level of abstraction in the symbolic model typically precludes attacks of this type). The second simplifying abstraction appears to be reasonable since TPMs can be simulated by the adversarial context. Indeed, this is a typical simplification in symbolic models, for example, definitions of ballot secrecy for electronic voting [KR05, DKR06, BHM08] and privacy for vehicular ad hoc networks [DDS10] also fix the set of honest participants. However, it is unknown if these simplifications are sound. The third abstraction is intuitively sound, since an adversary strategy that can detect whether a signature belongs to $\mathcal{A}$ or $\mathcal{B}$ can be transformed into a strategy that distinguishes the signatures of $\mathcal{A}$ and $\mathcal{B}$. More precisely, let $\mathcal{M}$ be an adversary that, given a signature σ, returns the identity

[2] We remark that the cryptographic game by Brickell, Chen & Li implicitly suggests the existence of validation algorithms to verify keys, but these algorithms are not explicitly specified in the definition of a Direct Anonymous Attestation scheme.

$id = \mathcal{M}(\sigma)$ of the signer. Then a strategy $\mathcal{M}'$ for distinguishing σ_1 and σ_2 simply tests whether $\mathcal{M}(\sigma_1) = \mathcal{M}(\sigma_2)$.

Finally, our model will overcome the following shortcoming in the privacy game: the cryptographic game does not permit the adversary to interact with TPMs during the Initial phase. As a consequence, any Direct Anonymous Attestation scheme satisfying the game-based definition may exhibit the following undesirable property, namely, if a malicious issuer interacts with TPMs before constructing a key, then no security assurances are offered. We avoid this limitation by modelling dishonest TPMs as part of the adversarial context and allow the adversary to receive the public keys of honest TPMs during the Initial phase. In future work, the cryptographic game could be revised to allow the adversary to probe the challenger during the Initial phase (the accountability game exhibits the same weakness and could be similarly revised).

4.1 Privacy as an equivalence

Informally, privacy asserts that an adversary cannot distinguish between signatures produced by two distinct signers. Formally, our definition of privacy can be modelled as an observational equivalence property (Definition 3) using the *DAA game biprocess* DAA-G presented in Figure 4.

Definition 3 (Privacy)**.** *Given a pair of processes* $\langle \mathsf{Join}, \mathsf{Sign} \rangle$*,* privacy *is satisfied if the DAA game biprocess* DAA-G *satisfies observational equivalence.*

This definition will be used to analyse privacy in the RSA-based DAA protocol (Section 5). First we evaluate the suitability of our definition.

4.2 Critique of our symbolic security definition

Let us critique the suitability of Definition 3 by relating the operations performed in DAA-G to those performed in our description of privacy. The first operation that can be performed in the process DAA-G is either outputting public keys of honest TPMs or inputting w_{params}, where w_{params} models the public key $\mathsf{pk}(sk_I)$ and any additional parameters from the adversary, which corresponds immediately to the *Initial* step of our description. (As observed by Rudolph [Rud07], and specified in our description and enforced by our biprocess DAA-G, the privacy property can only be expected if both signers use w_{params}, that is, the signers do not accept two distinct tuples of system parameters from the issuer.) The processes $\mathsf{Signer}^+\{^{b_A}/_{w_b}, ^{sk_A}/_{w_{\mathsf{ek}}}\}$ and $\mathsf{Signer}^+\{^{b_B}/_{w_b}, ^{sk_B}/_{w_{\mathsf{ek}}}\}$, which form part of the process DAA-G, allow the adversary to initiate two signers and perform arbitrarily many join and sign requests, capturing *Phases 1 & 2* of our description. Moreover, the side condition that a sign request to $\mathcal{A}$ (or $\mathcal{B}$) must be proceeded by at least one join request to $\mathcal{A}$ (respectively $\mathcal{B}$) is captured by the sequential description of the process Signer^+ and the condition that both signers are required to have run the join algorithm at least once during Phase 1 is similarly captured. The Challenge process, which forms part of the process DAA-G, is designed to capture the behaviour of the signers in the Challenge

Figure 4 Biprocess modelling privacy in DAA

Given a pair of processes $\langle \mathsf{Join}, \mathsf{Sign} \rangle$, the *DAA game biprocess* DAA-G is defined as

$$\nu\, sk_A \,.\, \nu\, sk_B \,.\, \big(\overline{c}\langle \mathsf{pk}(sk_A)\rangle \mid \overline{c}\langle \mathsf{pk}(sk_B)\rangle \mid c(w_{\mathsf{params}}) \,.\, \nu\, b_A \,.\, \nu\, b_B \,.\, (\mathsf{Challenge} \mid \mathsf{Signer}^+\{^{b_A}/_{w_b}, ^{sk_A}/_{w_{\mathsf{ek}}}\} \mid \mathsf{Signer}^+\{^{b_B}/_{w_b}, ^{sk_B}/_{w_{\mathsf{ek}}}\})\big)$$

such that $b_A, b_B, sk_A, sk_B, w_b, w_{\mathsf{ek}} \notin (\mathrm{fn}(\mathsf{Sign}) \cup \mathrm{fv}(\mathsf{Sign}) \cup \mathrm{fn}(\mathsf{Join}) \cup \mathrm{fv}(\mathsf{Join}))$ and where

$$\begin{aligned}
\mathsf{Signer}^+ \;=\;& \nu\, a_j \,.\, \nu\, a'_j \,.\, \nu\, a_s \,.\, \nu\, a'_s \,.\, (\,(!\mathsf{Join}) \mid (!\mathsf{Sign}) \mid (\\
& \quad \nu\, \mathtt{cnt} \,.\, \nu\, \mathtt{DAASeed} \,.\\
& \quad !\overline{a_j}\langle (\!| w_{\mathsf{params}}, \mathtt{DAASeed}, \mathtt{cnt}, w_{\mathsf{ek}} |\!) \rangle \,.\, a'_j(x) \,.\\
& \quad \text{let } x_{\mathsf{cre}} = \pi_1(x) \text{ in let } x_{\mathtt{tsk}} = \pi_2(x) \text{ in } (\\
& \qquad !c(y) \,.\, \text{let } y_{\mathsf{bsn}} = \pi_1(y) \text{ in let } y_{\mathsf{msg}} = \pi_2(y) \text{ in}\\
& \qquad \text{if } y_{\mathsf{bsn}} = \bot \text{ then}\\
& \qquad\quad \overline{a_s}\langle (\!| w_{\mathsf{params}}, y_{\mathsf{bsn}}, y_{\mathsf{msg}}, x_{\mathsf{cre}}, x_{\mathtt{tsk}} |\!) \rangle \,.\, a'_s(z) \,.\, \overline{c}\langle z \rangle\\
& \qquad \text{else}\\
& \qquad\quad \overline{a_s}\langle (\!| w_{\mathsf{params}}, (\!| chl^+, y_{\mathsf{bsn}} |\!), y_{\mathsf{msg}}, x_{\mathsf{cre}}, x_{\mathtt{tsk}} |\!) \rangle \,.\, a'_s(z) \,.\, \overline{c}\langle z \rangle\\
& \quad) \mid (\\
& \qquad \overline{w_b}\langle (\!| x_{\mathsf{cre}}, x_{\mathtt{tsk}} |\!) \rangle\\
& \quad)\\
&))\\
\mathsf{Challenge} \;=\;& \nu\, a_s \,.\, \nu\, a'_s \,.\, (\,(\mathsf{Sign}) \mid (\\
& \quad b_A(x) \,.\, \text{let } x_{\mathsf{cre}} = \pi_1(x) \text{ in let } x_{\mathtt{tsk}} = \pi_2(x) \text{ in}\\
& \quad b_B(y) \,.\, \text{let } y_{\mathsf{cre}} = \pi_1(y) \text{ in let } y_{\mathsf{tsk}} = \pi_2(y) \text{ in}\\
& \quad c(z) \,.\, \text{let } z_{\mathsf{bsn}} = \pi_1(z) \text{ in let } z_{\mathsf{msg}} = \pi_2(z) \text{ in}\\
& \quad \text{if } z_{\mathsf{bsn}} = \bot \text{ then}\\
& \qquad \overline{a_s}\langle (\!| w_{\mathsf{params}}, z_{\mathsf{bsn}}, z_{\mathsf{msg}}, \mathrm{diff}[x_{\mathsf{cre}}, y_{\mathsf{cre}}], \mathrm{diff}[x_{\mathtt{tsk}}, y_{\mathsf{tsk}}] |\!) \rangle \,.\\
& \qquad a'_s(z) \,.\, \overline{c}\langle z \rangle\\
& \quad \text{else}\\
& \qquad \overline{a_s}\langle (\!| w_{\mathsf{params}}, (\!| chl^-, z_{\mathsf{bsn}} |\!), z_{\mathsf{msg}}, \mathrm{diff}[x_{\mathsf{cre}}, y_{\mathsf{cre}}], \mathrm{diff}[x_{\mathtt{tsk}}, y_{\mathsf{tsk}}] |\!) \rangle \,.\\
& \qquad a'_s(z) \,.\, \overline{c}\langle z \rangle\\
&))
\end{aligned}$$

for some constants chl^+, chl^-.

phase of our description. This is achieved by communicating the attestation identity credential x_{cre} and TPM's secret $x_{\mathtt{tsk}}$, produced by the signers in Phase 1, from the processes $\mathsf{Signer}^+\{^{b_A}/_{w_b}, ^{sk_A}/_{w_{\mathsf{ek}}}\}$ and $\mathsf{Signer}^+\{^{b_B}/_{w_b}, ^{sk_B}/_{w_{\mathsf{ek}}}\}$ to the Challenge process using private channels b_A and b_B. The Challenge process also inputs a basename and a message from the environment. The inputs (namely, x, y, and z) to the Challenge process are used to construct a signature and the process uses $\mathrm{diff}[x_{\mathsf{cre}}, y_{\mathsf{cre}}]$ and $\mathrm{diff}[x_{\mathtt{tsk}}, y_{\mathsf{tsk}}]$ to ensure that the signature is produced by $\mathcal{A}$ in fst(DAA-G) and $\mathcal{B}$ in snd(DAA-G). The necessity for a

distinct basename bsn' in the Challenge phase (when $bsn' \neq \perp$) is enforced by prefixing the basename z_{bsn} used by $\mathsf{Challenge}$ with chl^- and, similarly, prefixing the basenames y_{bsn} used by Signer^+ with chl^+; capturing distinct basenames in this manner introduces an abstraction. Finally, the *Result* step of our description is captured using observational equivalence.

5 Case study: RSA-based DAA

The first concrete Direct Anonymous Attestation scheme was introduced by Brickell, Camenisch & Chen [BCC04] and is based on RSA. The TPM specification version 1.2 [TCG07], which has been defined as an ISO/IEC international standard [Int09], mandates support for the RSA-based scheme, and the scheme has also been included in the ISO/IEC anonymous digital signature standard [Int11]. Moreover, TPM version 1.2 is estimated to have been embedded in over 500 million computers [Tru11]. In this section, we analyse privacy in the RSA-based protocol using our definition.

5.1 Primitives and building blocks

We first recall the details of Camenisch-Lysyanskaya (CL) signatures [CL03, Lys02], which form the foundations of RSA-based DAA, and introduce some notational conventions.

Signature scheme. A CL signature is denoted $\mathsf{clsign}(x_{\mathsf{sk}}, x_{\mathsf{prime}}, x_{\mathsf{rand}}, x_{\mathsf{msg}})$, where x_{sk} is the secret key, x_{prime} is a random prime, x_{rand} is a nonce, and x_{msg} is a message. The prime and nonce components can be derived from a signature. Verification is standard given a signature, message and public key, namely, $\mathsf{checkclsign}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{msg}}, \mathsf{clsign}(x_{\mathsf{sk}}, x_{\mathsf{prime}}, x_{\mathsf{rand}}, x_{\mathsf{msg}})) = \mathsf{accept}$.

Signature scheme for committed values. The scheme supports signatures on committed values. Given the public part of a signing key $\mathsf{pk}(x_{\mathsf{sk}})$, a message x_{csk}, and commitment factor x_{cf}, the corresponding commitment is $U = \mathsf{clcommit}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{cf}}, x_{\mathsf{csk}})$ and the associated signature is $\mathsf{clsign}(x_{\mathsf{sk}}, y_{\mathsf{prime}}, y_{\mathsf{rand}}, U)$, where y_{prime} is a randomly chosen prime and y_{rand} is a nonce. This signature can be opened to recover $\sigma = \mathsf{clopen}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{cf}}, \mathsf{clsign}(x_{\mathsf{sk}}, y_{\mathsf{prime}}, y_{\mathsf{rand}}, U)) = \mathsf{clsign}(x_{\mathsf{sk}}, y_{\mathsf{prime}}, y_{\mathsf{rand}} \circ x_{\mathsf{cf}}, x_{\mathsf{csk}})$ – that is, the signature on x_{csk} – where $\circ$ is commutative and associative. (A proof should also be provided to demonstrate that σ does not contain a covert channel – such details will be omitted from the model presented here – see Brickell, Camenisch & Chen [BCC04] or Smyth [Smy11, pp159] for further details.)

Notation for primitives that prove knowledge. Various primitives which prove knowledge of, and relations among, discrete logarithms are used by CL

signatures and RSA-based DAA. These primitives will be described using the notation introduced by Camenisch & Stadler [CS97]. For instance,

$$PK\{(\alpha, \beta) : N = \mathsf{commit}(\alpha, Z) \wedge U = \mathsf{clcommit}(\mathsf{pk}(sk_I), \alpha, \beta)\}$$

denotes a *"zero-knowledge* P*roof of* K*nowledge of* α, β *such that* $N = \mathsf{commit}(\alpha, Z)$ *and* $U = \mathsf{clcommit}(\mathsf{pk}(sk_I), \alpha, \beta)$ *holds."* In the example, the Greek letters are used for values about which knowledge is being proved and these values are kept secret by the prover. All other values, that is, those from the Latin alphabet, are known to the verifier. The Fiat-Shamir heuristic [FS87, PS96] allows an interactive zero-knowledge scheme to be converted into a signature scheme. A signature acquired in this way is termed a S*ignature* P*roof of* K*nowledge* and is denoted, for example, as $SPK\{(\alpha) : N = \mathsf{commit}(\alpha, Z)\}(m)$, where m is a message.

Proving knowledge of a signature. The signature scheme for committed values can be used to build an anonymous credential system. Given a signature $\sigma = \mathsf{clsign}(x_{\mathsf{sk}}, x_{\mathsf{prime}}, x_{\mathsf{rand}}, x_{\mathsf{csk}})$ and commitment factor x_{cf}, an anonymous credential $\hat{\sigma} = \mathsf{clcommit}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{cf}}, \sigma)$. The zero-knowledge proof of knowledge

$$PK\{(x_{\mathsf{csk}}, x_{\mathsf{cf}}) : \mathsf{checkclsign}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{csk}}, \mathsf{clopen}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{cf}}, \hat{\sigma})) = \mathsf{accept}\}$$

can then be used to demonstrate that the anonymous credential $\hat{\sigma}$ is indeed a commitment to a signature on the message x_{csk} using commitment factor x_{cf}.

The application of these primitives to construct the RSA-based DAA protocol will be considered in the next section.

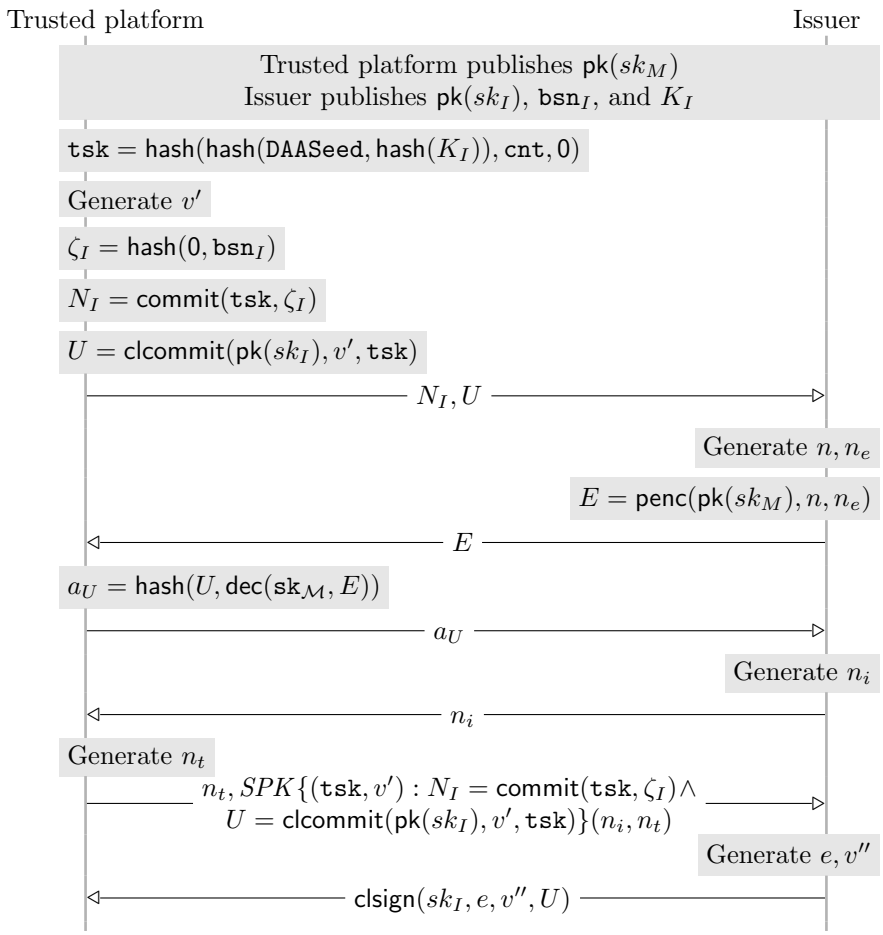
5.2 Protocol description

For the purpose of studying privacy, it is sufficient to consider the join and sign algorithms. The join algorithm (Figure 5) is defined below, given the algorithm's input: system parameters $\mathsf{pk}(sk_I)$, $\mathtt{bsn}_I$, and K_I (that is, the DAA public key, basename, and the long-term key); the TPM's secret `DAASeed`; a counter value `cnt`; and the TPM's endorsement key $\mathsf{pk}(sk_M)$.

1. The host computes $\zeta_I = \mathsf{hash}(0, \mathtt{bsn}_I)$ and sends ζ_I to the TPM. The TPM computes secret $\mathtt{tsk} = \mathsf{hash}(\mathsf{hash}(\mathtt{DAASeed}, \mathsf{hash}(K_I)), \mathtt{cnt}, 0)$ and derives the commitment $N_I = \mathsf{commit}(\mathtt{tsk}, \zeta_I)$. The TPM also generates a blinding factor v', which is used to compute the commitment $U = \mathsf{clcommit}(\mathsf{pk}(sk_I), v', \mathtt{tsk})$. The trusted platform sends U and N_I to the issuer.

2. The issuer generates a nonce n_e, encrypts the nonce with the TPM's endorsement key $\mathsf{pk}(sk_M)$, and sends the encrypted nonce to the TPM. The TPM decrypts the ciphertext to recover n_e, computes $a_U = \mathsf{hash}(U, n_e)$ and sends a_U to the issuer, therefore authenticating as a trusted platform. (Note that the RSA-based DAA protocol does not rely on the authentication technique recommended by the Trusted Computing Group.)

Figure 5 RSA-based DAA join algorithm



3. The trusted platform generates a signature proof of knowledge that the messages U and N_I are correctly formed and sends it to the issuer.

4. The issuer verifies the proof and evaluates a policy to decide if a new credential should be granted (the policy dictates how many distinct credentials may be issued to a particular trusted platform). To proceed, the issuer generates a signature $\mathsf{clsign}(sk_I, e, v'', U)$ and sends it to the trusted platform.

5. The trusted platform verifies the signature and opens it to reveal the credential $\mathtt{cre} = \mathsf{clsign}(sk_I, e, v' \circ v'', \mathtt{tsk})$, that is, the TPM's secret $\mathtt{tsk}$ signed by the issuer.

The join algorithm outputs `cre` and `tsk`, which can be provided as input to the sign algorithm, along with the system parameters, a basename `bsn` and message m. The sign algorithm proceeds as follows.

6. If $\texttt{bsn} = \perp$, the host generates a nonce ζ; otherwise, the host computes $\zeta = \mathsf{hash}(0, bsn)$. The host provides the TPM with ζ. The TPM generates a nonce w, and computes the commitment $N_V = \mathsf{commit}(\texttt{tsk}, \zeta)$ and anonymous credential $\widehat{\texttt{cre}} = \mathsf{clcommit}(\mathsf{pk}(sk_I), w, \texttt{cre})$. The trusted platform then produces a signature proof of knowledge that $\widehat{\texttt{cre}}$ is a commitment to a valid credential and that N_V is correctly formed.

The sign algorithm outputs the signature proof of knowledge which is sent to the verifier. Intuitively, if a verifier is presented with such a proof, then the verifier is convinced that it is communicating with a trusted platform.

5.3 Signature and equational theory

Before modelling the RSA-based DAA scheme as a process, we construct a suitable signature Σ (defined below) to capture the cryptographic primitives used and define an equational theory E to capture the relationships between these primitives.

$$\Sigma = \{\mathsf{accept}, \perp, 0, 1, \mathsf{F}_{\mathsf{join}}, \mathsf{F}_{\mathsf{sign}}, \mathsf{clgetnonce}, \mathsf{clgetprime}, \mathsf{hash}, \mathsf{pk}, \mathsf{commit}, \circ, \\ \mathsf{dec}, \mathsf{checkclsign}, \mathsf{checkspk}, \mathsf{clcommit}, \mathsf{clopen}, \mathsf{penc}, \mathsf{spk}, \mathsf{clsign}\}$$

Functions accept, $\perp$, 0, 1, $\mathsf{F}_{\mathsf{join}}$, $\mathsf{F}_{\mathsf{sign}}$ are constant symbols; $\mathsf{clgetnonce}$, $\mathsf{clgetprime}$, hash, pk are unary functions; commit, $\circ$, dec are binary functions; $\mathsf{checkclsign}$, $\mathsf{checkspk}$, $\mathsf{clcommit}$, clopen, penc, spk are ternary functions; and clsign is a function of arity four. We occasionally write $\mathsf{hash}(x_{\mathsf{plain},1}, \ldots, x_{\mathsf{plain},n})$ to denote $\mathsf{hash}(\langle\!| x_{\mathsf{plain},1}, \ldots, x_{\mathsf{plain},n} |\!\rangle)$. The equations associated with these functions are defined below:

$$\mathsf{dec}(x_{\mathsf{sk}}, \mathsf{penc}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{rand}}, x_{\mathsf{plain}})) = x_{\mathsf{plain}}$$

$$\mathsf{clgetprime}(\mathsf{clsign}(x_{\mathsf{sk}}, x_{\mathsf{prime}}, x_{\mathsf{rand}}, x_{\mathsf{msg}})) = x_{\mathsf{prime}}$$

$$\mathsf{clgetnonce}(\mathsf{clsign}(x_{\mathsf{sk}}, x_{\mathsf{prime}}, x_{\mathsf{rand}}, x_{\mathsf{msg}})) = x_{\mathsf{rand}}$$

$$\mathsf{checkclsign}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{msg}}, \mathsf{clsign}(x_{\mathsf{sk}}, x_{\mathsf{prime}}, x_{\mathsf{rand}}, x_{\mathsf{msg}})) = \mathsf{accept}$$

$$\mathsf{clopen}(x, x_{\mathsf{rand}}, \mathsf{clcommit}(x, x_{\mathsf{rand}}, x_{\mathsf{plain}})) = x_{\mathsf{plain}}$$

$$\mathsf{clopen}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{rand}}, \mathsf{clsign}(x_{\mathsf{sk}}, y_{\mathsf{prime}}, y_{\mathsf{rand}}, \mathsf{clcommit}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{rand}}, x_{\mathsf{msg}}))) \\ = \mathsf{clsign}(x_{\mathsf{sk}}, y_{\mathsf{prime}}, y_{\mathsf{rand}} \circ x_{\mathsf{rand}}, x_{\mathsf{msg}})$$

A signature proof of knowledge is encoded in the form $\mathsf{spk}(F, U, V)$, where F is a constant declaring the particular proof in use, U denotes the witness (or private component) of a signature proof of knowledge, and V defines the public

parameters and message being signed. The function $\mathsf{checkspk}$ is used to verify a signature and we define the following equations.

$$\mathsf{checkspk}(\mathsf{F}_{\mathsf{join}}, V, \mathsf{spk}(\mathsf{F}_{\mathsf{join}}, (x_{\mathtt{tsk}}, x_{\mathsf{cf}}), V)) = \mathsf{accept}$$
$$\text{where } V = (x_{\zeta_{\mathsf{I}}}, x_{\mathsf{pk}}, \mathsf{commit}(x_{\mathtt{tsk}}, x_{\zeta_{\mathsf{I}}}), \mathsf{clcommit}(x_{\mathsf{pk}}, x_{\mathsf{cf}}, x_{\mathtt{tsk}}), x_{\mathsf{msg}})$$

$$\mathsf{checkspk}(\mathsf{F}_{\mathsf{sign}}, V, \mathsf{spk}(\mathsf{F}_{\mathsf{sign}}, (x_{\mathtt{tsk}}, x_{\mathsf{cf}}), V)) = \mathsf{accept}$$
$$\text{where } V = (x_{\zeta}, \mathsf{pk}(x_{\mathsf{sk}}), \mathsf{commit}(x_{\mathtt{tsk}}, x_{\zeta}),$$
$$\mathsf{clcommit}(\mathsf{pk}(x_{\mathsf{sk}}), x_{\mathsf{cf}}, \mathsf{clsign}(x_{\mathsf{sk}}, x_{\mathsf{prime}}, x_{\mathsf{rand}}, x_{\mathtt{tsk}})), x_{\mathsf{msg}})$$

The first equation is used to verify the signature proof of knowledge produced by the trusted platform during the join algorithm and the second is used by a trusted platform during the sign algorithm to assert group membership.

5.4 Model in applied pi

The RSA-based join and sign algorithms are modelled by the pair of processes $\langle \mathsf{Join}_{\mathsf{RSA}}, \mathsf{Sign}_{\mathsf{RSA}} \rangle$ presented in Figure 6, where $c(x).\text{let } x_1 = \pi_1(x) \text{ in } \ldots \text{ let } x_n = \pi_n(x) \text{ in } P$ denotes $c(x_1, \ldots, x_n).P$. The join process $\mathsf{Join}_{\mathsf{RSA}}$ is instantiated by inputting the join algorithm's parameters: the RSA-based DAA system parameters w_{params}, the TPM's internal secret w_{DAASeed}, the counter value w_{cnt} chosen by the host, and the TPM's endorsement key w_{ek}. The system parameters w_{params} are expected to be a triple containing the DAA public key w_{pk}, basename $w_{\mathsf{bsn_I}}$, and long-term key K_I. The process constructs the terms N_I and U in accordance with the protocol's description (Section 5.2) and outputs the values to the issuer. The process then receives a ciphertext x, which it decrypts, and outputs the hash of the plaintext paired with U. A nonce y is then input and a signature proof of knowledge is produced. Finally, the process inputs a signature z on the commitment U and concludes by outputting the attestation identity credential $\mathtt{cre}$ and TPM's secret $\mathtt{tsk}$ on the private channel a'_j, that is, the $\mathsf{Join}_{\mathsf{RSA}}$ process returns the values $\mathtt{cre}$ and $\mathtt{tsk}$ to the Signer^+ process. The sign process $\mathsf{Sign}_{\mathsf{RSA}}$ is instantiated by inputting the sign algorithm's parameters: the RSA-based DAA system parameters w_{params}, the verifier's basename w_{bsn}, the message w_{msg} to be signed, the attestation identity credential w_{cre}, and the TPM's secret w_{tsk}. The process recovers the DAA public key w_{pk} from the system parameters, and inputs a nonce x from the verifier. The if-then-else branch models the signer's ability to produce either linkable or unlinkable signatures, based upon the parameter w_{bsn}; in particular, the if-branch produces an unlinkable signature, whereas the else-branch produces a linkable signature. The process concludes by outputting a signature on the private channel a'_s, that is, the $\mathsf{Sign}_{\mathsf{RSA}}$ process returns the signature to the Signer^+ process.

5.5 Analysis: Violating privacy

The DAA game biprocess $\mathsf{DAA\text{-}G}_{\mathsf{RSA}}$ derived from $\langle \mathsf{Join}_{\mathsf{RSA}}, \mathsf{Sign}_{\mathsf{RSA}} \rangle$ does not satisfy privacy. Informally, this can be observed by consideration of the following adversaries.

Figure 6 Applied pi process specification for the RSA-based DAA protocol

$$
\begin{array}{lcl}
\mathsf{Join}_{\mathsf{RSA}} & \hat{=} & a_j(w_{\mathsf{params}}, w_{\mathsf{DAASeed}}, w_{\mathsf{cnt}}, w_{\mathsf{ek}}) \,.\, \nu\, v' \,. \\
& & \text{let } w_{\mathsf{pk}} = \pi_1(w_{\mathsf{params}}) \text{ in} \\
& & \text{let } w_{\mathsf{bsn_I}} = \pi_2(w_{\mathsf{params}}) \text{ in} \\
& & \text{let } w_{\mathsf{K}} = \pi_3(w_{\mathsf{params}}) \text{ in} \\
& & \text{let } \zeta_I = \mathsf{hash}(0, w_{\mathsf{bsn_I}}) \text{ in} \\
& & \text{let } \mathtt{tsk} = \mathsf{hash}(\mathsf{hash}(w_{\mathsf{DAASeed}}, \mathsf{hash}(w_{\mathsf{K}})), w_{\mathsf{cnt}}, 0) \text{ in} \\
& & \text{let } N_I = \mathsf{commit}(\mathtt{tsk}, \zeta_I) \text{ in} \\
& & \text{let } U = \mathsf{clcommit}(w_{\mathsf{pk}}, v', \mathtt{tsk}) \text{ in} \\
& & \overline{c}\langle(\!|N_I, U|\!)\rangle \,.\, c(x) \,.\, \overline{c}\langle\mathsf{hash}(U, \mathsf{dec}(w_{\mathsf{ek}}, x))\rangle \,.\, c(y) \,.\, \nu\, n_t \,. \\
& & \overline{c}\langle(\!|n_t, \mathsf{spk}(\mathsf{F}_{\mathsf{join}}, (\!|\mathtt{tsk}, v'|\!), (\!|\zeta_I, w_{\mathsf{pk}}, N_I, U, (\!|n_t, y|\!)|\!))|\!)\rangle \,.\, c(z) \\
& & \text{let } \mathtt{cre} = \mathsf{clopen}(w_{\mathsf{pk}}, v', z) \text{ in} \\
& & \text{if } \mathsf{checkclsign}(w_{\mathsf{pk}}, \mathtt{tsk}, \mathtt{cre}) = \mathsf{accept} \text{ then} \\
& & \overline{a'_j}\langle(\!|\mathtt{cre}, \mathtt{tsk}|\!)\rangle \\
\\
\mathsf{Sign}_{\mathsf{RSA}} & \hat{=} & a_s(w_{\mathsf{params}}, w_{\mathsf{bsn}}, w_{\mathsf{msg}}, w_{\mathsf{cre}}, w_{\mathsf{tsk}}) \,.\, \text{let } w_{\mathsf{pk}} = \pi_1(w_{\mathsf{params}}) \text{ in} \\
& & c(x) \,.\, \nu\, n_t \,.\, \nu\, w \,. \\
& & \text{if } w_{\mathsf{bsn}} = \perp \text{ then} \\
& & \quad \nu\, \zeta \,. \\
& & \quad \text{let } \widehat{\mathtt{cre}} = \mathsf{clcommit}(w_{\mathsf{pk}}, w, w_{\mathsf{cre}}) \text{ in} \\
& & \quad \text{let } N_V = \mathsf{commit}(w_{\mathsf{tsk}}, \zeta) \text{ in} \\
& & \quad \text{let } spk = \mathsf{spk}(\mathsf{F}_{\mathsf{sign}}, (\!|w_{\mathsf{tsk}}, w|\!), (\!|\zeta, w_{\mathsf{pk}}, N_V, \widehat{\mathtt{cre}}, (\!|n_t, x, w_{\mathsf{msg}}|\!)|\!)) \text{ in} \\
& & \quad \overline{a'_s}\langle(\!|\zeta, w_{\mathsf{pk}}, N_V, \widehat{\mathtt{cre}}, n_t, spk|\!)\rangle \\
& & \text{else} \\
& & \quad \text{let } \zeta = \mathsf{hash}(0, w_{\mathsf{bsn}}) \text{ in} \\
& & \quad \text{let } \widehat{\mathtt{cre}} = \mathsf{clcommit}(w_{\mathsf{pk}}, w, w_{\mathsf{cre}}) \text{ in} \\
& & \quad \text{let } N_V = \mathsf{commit}(w_{\mathsf{tsk}}, \zeta) \text{ in} \\
& & \quad \text{let } spk = \mathsf{spk}(\mathsf{F}_{\mathsf{sign}}, (\!|w_{\mathsf{tsk}}, w|\!), (\!|\zeta, w_{\mathsf{pk}}, N_V, \widehat{\mathtt{cre}}, (\!|n_t, x, w_{\mathsf{msg}}|\!)|\!)) \text{ in} \\
& & \quad \overline{a'_s}\langle(\!|\zeta, w_{\mathsf{pk}}, N_V, \widehat{\mathtt{cre}}, n_t, spk|\!)\rangle
\end{array}
$$

Passive adversary. A passive adversary can violate privacy under the following assumptions: first, the identity of a trusted platform can be observed during the join algorithm[3]; secondly, there exists a basename which is shared between an issuer and a verifier; and, thirdly, a signer is willing to accept the same basename from an issuer and verifier. By our second assumption, there exists an issuer's basename $\mathtt{bsn}_I$ and a verifier's basename $\mathtt{bsn}$ such that $\mathtt{bsn}_I = \mathtt{bsn}$. The attack proceeds as follows. Let us suppose that

[3]The RSA-based DAA protocol [BCC04] does not explicitly specify how the issuer learns a trusted platform's public endorsement key during an execution of the join algorithm. However, it seems reasonable to assume that the public key would be sent as plaintext. By contrast, Cesena *et al.* [CLR+10, Ces10] define an extension of RSA-based DAA which uses TLS to hide the affiliation between groups and trusted platforms, this variant would thwart a passive adversary, but not corrupt administrators.

the trusted platform executes the join protocol with the issuer and subsequently runs the sign protocol with the verifier. Since the signer is willing to accept the same basename as both algorithms, it follows that $\zeta_I = \zeta$ and $N_I = N_V$. The commitments N_I and N_V are unique for a particular signer and the adversary knows the identity of the trusted platform that produced N_I during the join algorithm, it follows that the signer's identity can be revealed.

Corrupt administrators. Corrupt administrators can violate privacy under the assumption that a signer is willing to accept the same basename from an issuer and verifier. This is a special case of our passive attack: an issuer and verifier conspire to use the same basename (that is, $\mathtt{bsn}_I = \mathtt{bsn}$) and since the issuer knows the identity of the trusted platform that produced N_I, the identity of the signer can be revealed.

The linchpin of these attacks is the willingness of a signer to accept the same basename from an issuer and verifier. This can be justified as follows. Firstly, this mode of operation is not explicitly forbidden by the protocol definition [BCC04]. Secondly, this behaviour is expected when the issuer and verifier are the same entity, as demonstrated by Camenisch *et al.* [CL01, CH02] in the *idemix* system, for example. Finally, the signer has insufficient resources to handle such a duty.

Formally, Theorem 1 demonstrates that $\mathsf{DAA\text{-}G_{RSA}}$ does not satisfy privacy. This result is witnessed using a context $C[\_]$ such that $\mathrm{fst}(C[\mathsf{DAA\text{-}G_{RSA}}]) \rightarrow^* Q$ and Q can output on channel b, but there is no reduction $\mathrm{snd}(C[\mathsf{DAA\text{-}G_{RSA}}]) \rightarrow^* Q'$ such that Q' can output on b, where both reductions are of the same length. Intuitively, the context behaves as follows. First, the context outputs system parameters $(\!|\mathsf{pk}(sk_I), \mathtt{bsn}, K_I|\!)$. Secondly, the context executes the join algorithm with both signers and binds $(\!|\mathsf{commit}(\mathtt{tsk}, \mathsf{hash}(0, \mathtt{bsn})), \mathsf{clcommit}(\mathsf{pk}(sk_I), v', \mathtt{tsk})|\!)$ to x, where $\mathtt{tsk} = \mathsf{hash}(\mathsf{hash}(\mathtt{DAASeed}, \mathsf{hash}(K_I)), \mathtt{cnt}, 0)$ and $\mathtt{cnt}$, $\mathtt{DAASeed}$ and v' are restricted names. Thirdly, the context issues a challenge using the basename $\mathtt{bsn}$ and message msg, and binds T to y, where $\pi_3(T) = \mathsf{commit}(\mathrm{diff}[\mathtt{tsk}, \mathtt{tsk}'], \mathsf{hash}(0, \mathtt{bsn}))$, $\mathtt{tsk}' = \mathsf{hash}(\mathsf{hash}(\mathtt{DAASeed}', \mathsf{hash}(K_I)), \mathtt{cnt}', 0)$, and $\mathtt{cnt}'$ and $\mathtt{DAASeed}'$ are restricted names. Finally, the context compares $\pi_1(x)$ and $\pi_3(y)$ to derive a distinction between $\mathrm{fst}(C[\mathsf{DAA\text{-}G_{RSA}}])$ and $\mathrm{snd}(C[\mathsf{DAA\text{-}G_{RSA}}])$.

Theorem 1. *The RSA-based DAA process specification* $\langle \mathsf{Join_{RSA}}, \mathsf{Sign_{RSA}} \rangle$ *does not satisfy privacy.*

Proof. Let $\mathsf{DAA\text{-}G_{RSA}}$ be the Direct Anonymous Attestation game biprocess derived from the specification $\langle \mathsf{Join_{RSA}}, \mathsf{Sign_{RSA}} \rangle$ and consider the evaluation

context $C[\_]$ defined below:

$$\begin{array}{rcl} C[\_] & = & \overline{c}\langle(\!|\mathsf{pk}(sk_I), \mathtt{bsn}, K_I|\!)\rangle. \\ & & c(w).c(x).\overline{c}\langle\mathsf{penc}(w, n, n_e)\rangle.c(z_a).\text{if } z_a = \mathsf{hash}(n_e, \pi_2(x)) \text{ then} \\ & & \overline{c}\langle n_i\rangle.c(z_s).\overline{c}\langle\mathsf{clsign}(sk_I, e, v'', \pi_2(x))\rangle. \\ & & c(w').c(x').\overline{c}\langle\mathsf{penc}(w', n, n_e)\rangle.c(z'_a).\text{if } z'_a = \mathsf{hash}(n_e, \pi_2(x')) \text{ then} \\ & & \overline{c}\langle n_i\rangle.c(z'_s).\overline{c}\langle\mathsf{clsign}(sk_I, e, v'', \pi_2(x'))\rangle. \\ & & \overline{c}\langle(\!|\mathtt{bsn}, \mathsf{msg}|\!)\rangle.\overline{c}\langle n_v\rangle.c(y).\text{if } \pi_1(x) = \pi_3(y) \text{ then } \overline{b}\langle\mathsf{fail}\rangle \text{ else } 0 \mid \_ \end{array}$$

We have the following reductions:

$$\begin{array}{rcl} \text{fst}(C[\mathsf{DAA\text{-}G_{RSA}}]) & \rightarrow^* & C'[\text{if } M = M \text{ then } \overline{b}\langle\mathsf{fail}\rangle \text{ else } 0] \\ \text{snd}(C[\mathsf{DAA\text{-}G_{RSA}}]) & \rightarrow^* & C'[\text{if } M = N \text{ then } \overline{b}\langle\mathsf{fail}\rangle \text{ else } 0] \end{array}$$

where

$$\begin{array}{rcl} M & = & \mathsf{commit}(\mathsf{hash}(\mathsf{hash}(\mathtt{DAASeed}, \mathsf{hash}(K_I)), \mathtt{cnt}, 0), \mathsf{hash}(0, \mathtt{bsn})) \\ N & = & \mathsf{commit}(\mathsf{hash}(\mathsf{hash}(\mathtt{DAASeed}', \mathsf{hash}(K_I)), \mathtt{cnt}', 0), \mathsf{hash}(0, \mathtt{bsn})) \end{array}$$

It follows that $\text{fst}(C[\mathsf{DAA\text{-}G_{RSA}}]) \not\approx \text{snd}(C[\mathsf{DAA\text{-}G_{RSA}}])$ because $\text{fst}(C[\mathsf{DAA\text{-}G_{RSA}}])$ can output on channel b but $\text{snd}(C[\mathsf{DAA\text{-}G_{RSA}}])$ cannot and, therefore, $\mathsf{DAA\text{-}G_{RSA}}$ does not satisfy privacy. □

An attack in the computational model follows immediately from our formal result (Theorem 1), see Smyth [Smy11, Appendix B] for details.

Violating security properties in other schemes. The RSA-based DAA protocol has been used as a building block in other applications – for example, the peer-to-peer networking scheme by Balfe, Lakhani & Paterson [BLP05a, BLP05b] and the authentication scheme by Leung & Mitchell [LM07] – and as an immediate consequence of our results, these schemes are also flawed.

5.6 Solution: Fixing RSA-based DAA

The protocol can be fixed by refining the definition of ζ, namely, the revised RSA-based Direct Anonymous Attestation process specification $\langle\mathsf{Join_{RSA'}}, \mathsf{Sign_{RSA'}}\rangle$ is the same as the original, except ζ is redefined as $\zeta = \mathsf{hash}(1, \mathtt{bsn})$. The attacks presented are no longer possible, regardless of whether $\mathtt{bsn}_I = \mathtt{bsn}$. Furthermore, the revised RSA-based Direct Anonymous Attestation process specification $\langle\mathsf{Join_{RSA'}}, \mathsf{Sign_{RSA'}}\rangle$ satisfies privacy; this can be automatically verified using ProVerif (see Appendix B). A solution in the computational model follows immediately, see Smyth [Smy11, Appendix B.4] for details.

6 Balancing privacy and accountability

Balancing the privacy demands of users and the accountability needs of administrators is a fundamental objective of Direct Anonymous Attestation schemes,

in particular, DAA schemes permit signatures to be linked, without revealing the identity of the signer. The degrees of linkability are identified below, with reference to an application domain in which an honest issuer offers membership to a single group of signers and several verifiers offer multiple services.

- *Single-service linkability.* A verifier offering a single service is able to link transactions made by a given signer.
- *Cross-service linkability.* A verifier offering multiple services is able to link transactions made by a given signer over multiple services, when the services share the same basename.
- *Cross-verifier linkability.* Multiple verifiers offering services are able to link transactions made by a given signer across all the verifiers, when the services share the same basename.

In this section, we reflect upon the notions of linkability for Direct Anonymous Attestation schemes and extend the degree of privacy available in such schemes.

6.1 Linkability between an issuer's groups

Let us identify an issuer by its long-term key K_I, and recall that the game-based security definition by Brickell, Chen & Li [BCL08b, BCL09] assumes that an issuer controls a single group of signers, where the group of signers is identified by a public key $\mathsf{pk}(sk_I)$. In this section, we generalise to the situation in which an issuer may issue credentials to several groups of signers, where each group of signers is associated with a different key $\mathsf{pk}(sk_I)$. In this situation, one can ask the following question:

- Can a verifier link two signatures constructed using distinct DAA public keys $\mathsf{pk}(sk_I)$ and $\mathsf{pk}(sk'_I)$, each belonging to the same issuer? We call this *linkability between an issuer's groups.*

The RSA-based scheme permits linkability between an issuer's groups, when the signatures share the same basename. This can be observed as follows: given the issuer's long-term key K_I and the basename $\mathtt{bsn}$ such that $\mathtt{bsn} \neq \perp$, the TPM's secret $\mathtt{tsk} = \mathsf{hash}(\mathsf{hash}(\mathtt{DAASeed}, \mathsf{hash}(K_I)), \mathtt{cnt}, 0)$ and signatures produced using $\mathtt{tsk}$ will include $N_V = \mathsf{commit}(\mathtt{tsk}, \zeta)$, where $\zeta = \mathsf{hash}(1, \mathtt{bsn})$. (In the computational setting, linkability between an issuer's groups assumes that the groups' public keys share the same modulus Γ and order ρ, see [BCC04, §4.3] for definitions of Γ and ρ.) We can modify the RSA-based scheme to prevent linkability between an issuer's groups by defining $\zeta = \mathsf{hash}(1, \mathtt{bsn}, \mathsf{pk}(sk_I))$, rather than $\zeta = \mathsf{hash}(1, \mathtt{bsn})$. Intuitively, linkability between an issuer's groups strengthens accountability and weakens privacy, hence, the original RSA-based scheme provides stronger accountability, whereas our modification provides stronger privacy.

6.2 Practical guidelines for basenames

Basenames are particularly sensitive for DAA because they enable linkability, in particular, the ability to uniquely identify a set of services for which a basename can be used is a prerequisite of linkability. However, no methodology for basename construction has been defined and this may lead to a security vulnerability, for example, a signer may inadvertently consent for signatures to be linked by using the same basename for multiple signatures, we argue that this scenario is likely because signers have insufficient resources to maintain a history of all basenames. We overcome this problem with the presentation of guidelines for the construction of basenames. First, basenames should be constructed from service-specific data such as the following:

- Service information, for example, issuer's public key, verifier's public key, service URL, and terms and conditions of service.
- Basename validity date, for example, start and expiry dates.
- DAA signing mode, for example, Attestation Identity Key (AIK) signing, Platform Configuration Register (PCR) signing, and external input signing.

Secondly, given a basename constructed in this manner, a signer can evaluate whether the basename is suitable for use with a particular service. This construction allows a signer to give *informed consent* for signatures to be linked.

7 Further work and conclusion

Direct Anonymous Attestation is a relatively new concept and its properties merit further study, in particular, correctness, linkability, non-frameability and unforgeability have received limited attention. Extending this work to include a complete definition of DAA properties would be an interesting direction for the future. Moreover, establishing a unified definition which includes all properties (that is, anonymity, correctness, linkability, non-frameability, unforgeability, and unlinkability) would be of interest to reduce the verification workload. As a starting point, this could be achieved by developing the formalisation of join and sign algorithms, modelled by $\langle \mathsf{Join}, \mathsf{Sign} \rangle$, to distinguish between operations performed by the host and those performed by the TPM. This distinction is not necessary for our definition of privacy because this property can only be achieved if both the host and TPM are trusted. By contrast, a corrupt host – even in collaboration with a corrupt TPM (where the TPM is known to be rogue) – should not be able to violate accountability properties and therefore an alternative model of $\langle \mathsf{Join}, \mathsf{Sign} \rangle$ would be required such that the actions performed by the host and TPM are distinguished.

For privacy it is necessary to ensure a distinct basename is used during the Challenge. Since the applied pi calculus does not record state, this is achieved by an abstraction. Accordingly, we believe the definition is necessary, but may

not be sufficient. This limitation could be overcome by introducing a stateful variant of the applied pi calculus, indeed, Arapinis, Ritter & Ryan [ARR11] make some progress in this direction. A further limitation of our privacy definition is the restriction to settings with one issuer, indeed, this corresponds to the cryptographic game. Extending the definition to multiple issuers remains as future work.

Conclusion. This article presents a definition of privacy for Direct Anonymous Attestation protocols. The definition is expressed as an equivalence property suitable for automated reasoning and the practicality of the approach is demonstrated by evaluating the RSA-based Direct Anonymous Attestation protocol. The RSA-based scheme is particularly significant because support is mandated by the TPM specification version 1.2, which has been implemented and deployed in over 500 million computers (although the number of TPMs in active use is estimated to be significantly smaller). The analysis discovers a vulnerability which can be exploited by a passive adversary and, under weaker assumptions, by corrupt administrators. A security fix is identified and the revised protocol is shown to satisfy our definition of privacy. The fix only affects the host's part of the protocol and therefore no hardware changes to the TPM are required. Furthermore, the fix has influenced the design of subsequent Direct Anonymous Attestation schemes, for example, [BCL08a, BCL09].

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A A brief review of DAA schemes

The first concrete Direct Anonymous Attestation scheme was introduced by Brickell, Camenisch & Chen [BCC04] and is based upon RSA. However, RSA-based cryptography requires larger keys than equivalent ECC-based schemes. Moreover, the RSA-based DAA protocol is reliant on the strong RSA and decisional Diffie-Hellman assumptions, and some users are uncomfortable with the strong RSA assumption. This motivated the work of Brickell, Chen & Li [BCL08a, BCL09] who provide the first ECC-based DAA protocol using symmetric pairing. This scheme is more efficient and therefore better suited to devices with limited resources, such as the TPM. Furthermore, the ECC-based protocol is reliant on the LRSW [LRSW00] and decisional Bilinear Diffie-Hellman assumptions, which some users may prefer. Chen, Morrissey & Smart [CMS08a, CMS08b] extended the scheme based upon symmetric pairing to an asymmetric setting to improve efficiency. However, Li discovered a vulnerability in

the asymmetric scheme which violates basename linkability and Chen & Li propose a fix [CL10]; a further attack has been identified by Chen, Morrissey & Smart [CMS09] which, in theory, violates unforgeability. In addition, Chen, Morrissey & Smart [CMS11] have found theoretical accountability attacks against the symmetric pairing based scheme [BCL08a, BCL09] and the original RSA-based scheme [BCC04]. The Chen, Morrissey & Smart [CMS09, CMS11] attacks allow a malicious host to extract the TPM's secret `tsk`, if the protocol is implemented in hardware without *stage control mechanisms*; the host can then forge signatures. However, since the TPM provides stage control protection, there is no practical threat in the current setting; but, these attacks are of practical interest because they identify settings in which DAA protocols cannot be deployed (for example, in other trusted computing settings which do not use the TPM). We remark that the analysis of unforgeability in the RSA-based scheme by Backes, Maffei & Unruh [BMU08] could not identify the Chen, Morrissey & Smart attack because they consider a setting where the host and TPM are both honest. Chen, Morrissey & Smart [CMS09, CMS11] also propose a new asymmetric scheme and Chen, Page & Smart [CPS10] propose an optimisation, moreover, Chen [Che10b] provides a further optimisation to the Chen, Page & Smart scheme. Brickell, Chen & Li [BCL11] have shown that an adversary can forge signatures in the variant by Chen and propose a fix. We are aware of six further ECC-based DAA protocols: Chen & Feng [CF08], Brickell & Li [BL09a, BL09b], Chen [Che10a, Che11], Brickell & Li [BL10], Bernhard *et al.* [BFG+11], and Bernhard, Fuchsbauer & Ghadafi [BFG12].

B Analysis: Fixed RSA-based DAA scheme

Section 5 presents an analysis of privacy in the RSA-based DAA protocol, discovers a vulnerability, and proposes a security fix. This appendix provides the scripts used to automatically verify that the revised RSA-based DAA protocol satisfies privacy (the scripts are also available online: `http://www.bensmyth.com/publications/2012-Direct-Anonymous-Attestation-anonymity-definition/`). The free name declarations, function definitions and equations for the RSA-based DAA process specification appear in Listing 1; the join algorithm $\mathsf{Join}_{\mathsf{RSA}'}$ is presented in Listing 2, and the sign algorithm $\mathsf{Sign}_{\mathsf{RSA}'}$ appears in Listing 3. Finally, the Direct Anonymous Attestation game biprocess $\mathsf{DAA\text{-}G}_{\mathsf{RSA}'}$ is presented in Listing 4. (The nonce `XXTERM` is introduced to avoid an over-approximation issue.) ProVerif can be used to automatically verify observational equivalence of Listing 4 and hence the revised RSA-based DAA protocol satisfies privacy.

```
fun accept/0.
fun zero/0.
fun one/0.
fun FJoin/0.
fun FSign/0.
fun clgetnonce/1.
fun clgetprime/1.
fun hash/1.
fun pk/1.
fun commit/2.
fun circ/2.
fun dec/2.
fun checkclsign/3.
fun checkspk/3.
fun clcommit/3.
fun clopen/3.
fun penc/3.
fun spk/3.
fun clsign/4.

equation dec(k,penc(pk(k),r,m)) = m.
equation clgetprime(clsign(xsk,xprime,xrand,xmsg)) = xprime.
equation clgetnonce(clsign(xsk,xprime,xrand,xmsg)) = xrand.
equation checkclsign(pk(xsk),xmsg,
 clsign(xsk,xprime,xrand,xmsg)) = accept.
equation clopen(x,xrand,clcommit(x,xrand,xplain)) = xplain.
equation clopen(pk(xsk),xrand,clsign(xsk,yprime,yrand,
 clcommit(pk(xsk),xrand,xmsg))) = clsign(xsk,yprime,xrand,xmsg).
equation checkspk(FJoin,(xzeta,xpk,commit(xtsk,xzeta),
 clcommit(xpk,xv,xtsk),xmsg),spk(FJoin,(xtsk,xv),(xzeta,xpk,
 commit(xtsk,xzeta),clcommit(xpk,xv,xtsk),xmsg))) = accept.
equation checkspk(FSign,(xzeta,pk(xsk),commit(xtsk,xzeta),
 clcommit(pk(xsk),xw,clsign(xsk,xe,xv,xtsk)),xmsg),
 spk(FSign,(xtsk,xw),(xzeta,pk(xsk),commit(xtsk,xzeta),
 clcommit(pk(xsk),xw,clsign(xsk,xe,xv,xtsk)),xmsg))) = accept.
```

Listing 1: Function definitions and equations for $\mathsf{DAA\text{-}G}_{\mathsf{RSA}'}$

```
in(aj,((pkI,bsnI,KI),DAASeed,cnt,skM));

new v';
let zetaI = hash((zero,bsnI)) in
let tsk = hash((hash((DAASeed,hash(KI))),cnt,zero)) in
let NI = commit(tsk,zetaI) in
let U = clcommit(pkI,v',tsk) in
out(c,(NI,U));

in(c,encNe);
let ne = dec(skM,encNe) in
out(c,hash((U,ne)));

in(c,ni);
new nt;
out(c,(nt,spk(FJoin,(tsk,v'),(zetaI,pkI,NI,U,(nt,ni)))));

in(c,sig);
let cre = clopen(pkI,v',sig) in
if checkclsign(pkI,tsk,cre) = accept then

out(aj',(cre,tsk)).
```

Listing 2: ProVerif script modelling $\mathsf{Join}_{\mathsf{RSA}'}$

```
in(as,((pkI,bsnI,KI),bsnV,m,cre,tsk,xxTERM));
in(c,nv);
new nt;new w;

if bsnV = bottom then (
new zeta;
  let creHat = clcommit(pkI,w,cre) in
  let NV = commit(tsk,zeta) in
  out(as',(zeta,pkI,NV,creHat,nt,
      spk(FSign,(tsk,w),(zeta,pkI,NV,creHat,(nt,nv,m)))))
) else (
let zeta = hash((one,bsnV)) in
  let creHat = clcommit(pkI,w,cre) in
  let NV = commit(tsk,zeta) in
  out(as',(zeta,pkI,NV,creHat,nt,
      spk(FSign,(tsk,w),(zeta,pkI,NV,creHat,(nt,nv,m)))))
).
```

Listing 3: ProVerif script modelling $\mathsf{Sign}_{\mathsf{RSA}'}$

```
free chlP.
free chlM.

fun bottom/0.

let SignerP =
    new aj;new aj';new as;new as';( !join )|( !sign )|(
        new cnt;new DAASeed;
        !out(aj,(wparams,DAASeed,cnt,wek));
        in(aj',(cre,tsk));
        (!
            in(c,(xmsg,=bottom));new XXTERM;
            out(as,(wparams,bottom,xmsg,cre,tsk,XXTERM));
            in(as',z);out(c,z)
        )|(!
            in(c,(xmsg,xbsn));new XXTERM;
            out(as,(wparams,(chlP,xbsn),xmsg,cre,tsk,XXTERM));
            in(as',z);out(c,z)
        )|(
           out(wb,(cre,tsk))
        )
    ).

let Challenge =
    new as;new as';( sign ) | (
        in(bA,(creA,tskA));
        in(bB,(creB,tskB));
        let cre = choice[creA,creB] in
        let tsk = choice[tskA,tskB] in
        (
            in(c,(xmsg,=bottom));new XXTERM;
            out(as,(wparams,bottom,xmsg,cre,tsk,XXTERM));
            in(as',x);out(c,x)
        )|(
            in(c,(xmsg,xbsn));new XXTERM;
            out(as,(wparams,(chlM,xbsn),xmsg,cre,tsk,XXTERM));
            in(as',x);out(c,x)
        )
    ).

process
    new skA;new skB; ( out(c,pk(skA)) | out(c,pk(skB)) |
        in(c,wparams);new bA;new bB;(
            (let wb = bA in let wek = skA in SignerP)|
            (let wb = bB in let wek = skB in SignerP)|
            (Challenge)
    ))
```

Listing 4: ProVerif script modelling privacy in $\mathsf{DAA\text{-}G}_{\mathsf{RSA}'}$

References

[AF01] Martín Abadi and Cédric Fournet. Mobile values, new names, and secure communication. In *POPL'01: 28th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, pages 104–115. ACM Press, 2001.

[And03] Ross J. Anderson. Cryptography and Competition Policy - Issues with 'Trusted Computing'. In *PODC'03: 22nd ACM Symposium on Principles of Distributed Computing*, pages 3–10. ACM Press, 2003.

[And04] Ross J. Anderson. Cryptography and Competition Policy - Issues with 'Trusted Computing'. In L. Jean Camp and Stephen Lewis, editors, *Economics of Information Security*, volume 12 of *Advances in Information Security*, pages 35–52. Springer, 2004.

[ARR11] Myrto Arapinis, Eike Ritter, and Mark Ryan. StatVerif: Verification of Stateful Processes. In *CSF'11: 24th IEEE Computer Security Foundations Symposium*. IEEE Computer Society, 2011. To appear.

[BAF08] Bruno Blanchet, Martín Abadi, and Cédric Fournet. Automated verification of selected equivalences for security protocols. *Journal of Logic and Algebraic Programming*, 75(1):3–51, February–March 2008.

[BCC04] Ernie Brickell, Jan Camenisch, and Liqun Chen. Direct Anonymous Attestation. In *CCS'04: 11th ACM Conference on Computer and Communications Security*, pages 132–145. ACM Press, 2004.

[BCC05] Ernie Brickell, Jan Camenisch, and Liqun Chen. The DAA scheme in context. In Chris Mitchell, editor, *Trusted Computing*, volume 6 of *Professional Applications of Computing Series*, pages 143–174. The Institute of Engineering and Technology, 2005.

[BCL08a] Ernie Brickell, Liqun Chen, and Jiangtao Li. A New Direct Anonymous Attestation Scheme from Bilinear Maps. In *Trust'08: 1st International Conference on Trusted Computing and Trust in Information Technologies*, volume 4968 of *LNCS*, pages 166–178, 2008.

[BCL08b] Ernie Brickell, Liqun Chen, and Jiangtao Li. Simplified Security Notions of Direct Anonymous Attestation and a Concrete Scheme from Pairings. Cryptology ePrint Archive, Report 2008/104, 2008.

[BCL09] Ernie Brickell, Liqun Chen, and Jiangtao Li. Simplified security notions of Direct Anonymous Attestation and a concrete scheme from pairings. *International Journal of Information Security*, 8(5):315–330, 2009.

[BCL11] Ernie Brickell, Liqun Chen, and Jiangtao Li. A (Corrected) DAA Scheme Using Batch Proof and Verification. In *INTRUST'11: 3rd International Conference on Trusted Systems*, volume 7222 of *LNCS*, pages 304–337. Springer, 2011.

[BFG+11] D. Bernhard, G. Fuchsbauer, E. Ghadafi, N.P. Smart, and B. Warinschi. Anonymous attestation with user-controlled linkability. Cryptology ePrint Archive, Report 2011/658, 2011.

[BFG12] D. Bernhard, G. Fuchsbauer, and E. Ghadafi. Efficient Signatures of Knowledge and DAA in the Standard Model. Cryptology ePrint Archive, Report 2012/475, 2012.

[BHM08] Michael Backes, Cătălin Hriţcu, and Matteo Maffei. Automated Verification of Remote Electronic Voting Protocols in the Applied Pi-calculus. In *CSF'08: 21st IEEE Computer Security Foundations Symposium*, pages 195–209. IEEE Computer Society, 2008.

[BL09a] Ernie Brickell and Jiangtao Li. Enhanced Privacy ID: A Remote Anonymous Attestation Scheme for Hardware Devices. *Intel Technology Journal Security*, 13(2):96–111, June 2009.

[BL09b] Ernie Brickell and Jiangtao Li. Enhanced Privacy ID from Bilinear Pairing. Cryptology ePrint Archive, Report 2009/095, 2009.

[BL10] Ernie Brickell and Jiangtao Li. A Pairing-Based DAA Scheme Further Reducing TPM Resources. In *TRUST'10: 3rd International Conference on Trust and Trustworthy Computing*, volume 6101 of *LNCS*, pages 181–195. Springer, 2010.

[Bla04] Bruno Blanchet. Automatic Proof of Strong Secrecy for Security Protocols. In *S&P'04: 25th IEEE Symposium on Security and Privacy*, pages 86–100. IEEE Computer Society, 2004.

[BLP05a] Shane Balfe, Amit D. Lakhani, and Kenneth G. Paterson. Securing peer-to-peer networks using trusted computing. In Chris Mitchell, editor, *Trusted Computing*, volume 6 of *Professional Applications of Computing Series*, pages 271–298. The Institute of Engineering and Technology, 2005.

[BLP05b] Shane Balfe, Amit D. Lakhani, and Kenneth G. Paterson. Trusted Computing: Providing Security for Peer-to-Peer Networks. In *P2P'05: 5th IEEE International Conference on Peer-to-Peer Computing*, pages 117–124. IEEE Computer Society, 2005.

[BMU08] Michael Backes, Matteo Maffei, and Dominique Unruh. Zero-Knowledge in the Applied Pi-calculus and Automated Verification of the Direct Anonymous Attestation Protocol. In *S&P'08: 29th IEEE Symposium on Security and Privacy*, pages 202–215. IEEE Computer Society, 2008.

[BS11] Bruno Blanchet and Ben Smyth. ProVerif: Automatic Cryptographic Protocol Verifier User Manual & Tutorial. `http://www.proverif.ens.fr/`, 2011.

[Ces10] Emanuele Cesena. *Trace Zero Varieties in Pairing-based Cryptography*. PhD thesis, Department of Mathematics, Universitá degli Studi Roma Tre, 2010.

[CF08] Xiaofeng Chen and Dengguo Feng. Direct Anonymous Attestation for Next Generation TPM. *Journal of Computers*, 3(12):43–50, December 2008.

[CH02] Jan Camenisch and Els Van Herreweghen. Design and Implementation of the *idemix* Anonymous Credential System. In *CCS'02: 9th ACM Conference on Computer and Communications Security*, pages 21–30. ACM Press, 2002.

[Che10a] Liqun Chen. A DAA Scheme Requiring Less TPM Resources. Cryptology ePrint Archive, Report 2010/008, 2010.

[Che10b] Liqun Chen. A DAA Scheme Using Batch Proof and Verification. In *TRUST'10: 3rd International Conference on Trust and Trustworthy Computing*, volume 6101 of *LNCS*, pages 166–180. Springer, 2010.

[Che11] Liqun Chen. A DAA Scheme Requiring Less TPM Resources. In *INSCRYPT'09: 5th International Conference on Information Security and Cryptology*, volume 6151 of *LNCS*, pages 350–365. Springer, 2011.

[CL01] Jan Camenisch and Anna Lysyanskaya. An Efficient System for Non-transferable Anonymous Credentials with Optional Anonymity Revocation. In *EUROCRYPT'01: 20th International Conference on the Theory and Applications of Cryptographic Techniques*, volume 2045 of *LNCS*, pages 93–118. Springer, 2001.

[CL03] Jan Camenisch and Anna Lysyanskaya. A Signature Scheme with Efficient Protocols. In *SCN'02: 3rd Conference on Security in Communication Networks*, volume 2576 of *LNCS*, pages 268–289. Springer, 2003.

[CL10] Liqun Chen and Jiangtao Li. A note on the Chen-Morrissey-Smart DAA scheme. *Information Processing Letters*, 110(12-13):485–488, 2010.

[CLR+10] Emanuele Cesena, Hans Löhr, Gianluca Ramunno, Ahmad-Reza Sadeghi, and Davide Vernizzi. Anonymous Authentication with TLS and DAA. In *TRUST'10: 3rd International Conference on Trust and Trustworthy Computing*, volume 6101 of *LNCS*, pages 47–62. Springer, 2010.

[CMS08a] Liqun Chen, Paul Morrissey, and Nigel P. Smart. On Proofs of Security for DAA Schemes. In *ProvSec'08: 2nd International Conference on Provable Security*, volume 5324 of *LNCS*, pages 156–175. Springer, 2008.

[CMS08b] Liqun Chen, Paul Morrissey, and Nigel P. Smart. Pairings in Trusted Computing. In *Pairing'08: 2nd International Conference on Pairing-Based Cryptography*, volume 5209 of *LNCS*, pages 1–17. Springer, 2008.

[CMS09] Liqun Chen, Paul Morrissey, and Nigel P. Smart. DAA: Fixing the pairing based protocols. Cryptology ePrint Archive, Report 2009/198, 2009. *This paper was withdrawn on 4 Dec 2011 because the simulation-based security definition is unsatisfiable, nevertheless, the unforgeability attacks (which we discuss in Appendix A) are still valid.*

[CMS11] Liqun Chen, Paul Morrissey, and Nigel P. Smart. DAA: Fixing the pairing based protocols. Unpublished draft, 2011.

[CPS10] Liqun Chen, Dan Page, and Nigel P. Smart. On the Design and Implementation of an Efficient DAA Scheme. In *CARDIS'10: 8th Internation Conference on Smart Card Research and Advanced Application*, volume 6035 of *LNCS*, pages 223–237. Springer, 2010.

[CS97] Jan Camenisch and Markus Stadler. Efficient Group Signature Schemes for Large Groups. In *CRYPTO'97: 17th International Cryptology Conference*, volume 1294 of *LNCS*, pages 410–424. Springer, 1997.

[DDS10] Morten Dahl, Stéphanie Delaune, and Graham Steel. Formal Analysis of Privacy for Vehicular Mix-Zones. In *ESORICS'10: 15th European Symposium on Research in Computer Security*, volume 6345 of *LNCS*, pages 55–70. Springer, 2010.

[DKR06] Stéphanie Delaune, Steve Kremer, and Mark Ryan. Coercion-Resistance and Receipt-Freeness in Electronic Voting. In *CSFW'06: 19th Computer Security Foundations Workshop*, pages 28–42. IEEE Computer Society, 2006.

[DKR09] Stéphanie Delaune, Steve Kremer, and Mark D. Ryan. Verifying privacy-type properties of electronic voting protocols. *Journal of Computer Security*, 17(4):435–487, July 2009.

[DKR10] Stéphanie Delaune, Steve Kremer, and Mark D. Ryan. Verifying Privacy-Type Properties of Electronic Voting Protocols: A Taster. In David Chaum, Markus Jakobsson, Ronald L. Rivest, and Peter Y. A. Ryan, editors, *Towards Trustworthy Elections: New Directions in Electronic Voting*, volume 6000 of *LNCS*, pages 289–309. Springer, 2010.

[DRS08] Stéphanie Delaune, Mark D. Ryan, and Ben Smyth. Automatic verification of privacy properties in the applied pi-calculus. In *IFIPTM'08: 2nd Joint iTrust and PST Conferences on Privacy, Trust Management and Security*, volume 263 of *International Federation for Information Processing (IFIP)*, pages 263–278. Springer, 2008.

[FS87] Amos Fiat and Adi Shamir. How To Prove Yourself: Practical Solutions to Identification and Signature Problems. In *CRYPTO'86: 6th International Cryptology Conference*, volume 263 of *LNCS*, pages 186–194. Springer, 1987.

[Int09] International Organization for Standardization. *ISO/IEC 11889: Information technology – Trusted Platform Module*, 2009.

[Int11] International Organization for Standardization. *ISO/IEC WD 20008-2 (Working Draft) Information technology – Security techniques – Anonymous digital signature – Part 2: Mechanisms using a group public key*, 2011.

[KR05] Steve Kremer and Mark D. Ryan. Analysis of an Electronic Voting Protocol in the Applied Pi Calculus. In *ESOP'05: 14th European Symposium on Programming*, volume 3444 of *LNCS*, pages 186–200. Springer, 2005.

[LM07] Adrian Leung and Chris J. Mitchell. Ninja: Non Identity Based, Privacy Preserving Authentication for Ubiquitous Environments. In *Ubicomp'07: 9th International Conference on Ubiquitous Computing*, volume 4717 of *LNCS*, pages 73–90. Springer, 2007.

[LRSW00] Anna Lysyanskaya, Ronald L. Rivest, Amit Sahai, and Stefan Wolf. Pseudonym Systems. In *SAC'99: 6th International Workshop on Selected Areas in Cryptography*, volume 1758 of *LNCS*, pages 184–199. Springer, 2000.

[Lys02] Anna Lysyanskaya. *Signature Schemes and Applications to Cryptographic Protocol Design*. PhD thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 2002.

[Mar08] Andrew Martin. The ten-page introduction to Trusted Computing. Technical Report CS-RR-08-11, University of Oxford, 2008.

[PS96] David Pointcheval and Jacques Stern. Security Proofs for Signature Schemes. In *EUROCRYPT'96: 13th International Conference on the Theory and Applications of Cryptographic Techniques*, volume 1070 of *LNCS*, pages 387–398. Springer, 1996.

[RS11] Mark D. Ryan and Ben Smyth. Applied pi calculus. In Véronique Cortier and Steve Kremer, editors, *Formal Models and Techniques for Analyzing Security Protocols*, chapter 6. IOS Press, 2011.

[Rud07] Carsten Rudolph. Covert Identity Information in Direct Anonymous Attestation (DAA). In *SEC'07: 22nd International Information Security Conference*, volume 232 of *International Federation for Information Processing (IFIP)*, pages 443–448. Springer, 2007.

[Smy11] Ben Smyth. *Formal verification of cryptographic protocols with automated reasoning*. PhD thesis, School of Computer Science, University of Birmingham, 2011.

[SRC07] Ben Smyth, Mark D. Ryan, and Liqun Chen. Direct Anonymous Attestation (DAA): Ensuring privacy with corrupt administrators. In *ESAS'07: 4th European Workshop on Security and Privacy in Ad hoc and Sensor Networks*, volume 4572 of *LNCS*, pages 218–231. Springer, 2007.

[SRC11] Ben Smyth, Mark D. Ryan, and Liqun Chen. Formal analysis of anonymity in ECC-based Direct Anonymous Attestation schemes. In *FAST'11: 8th International Workshop on Formal Aspects of Security and Trust*, volume 7140 of *LNCS*, pages 245–262. Springer, 2011.

[Sta02] Richard Stallman. Can You Trust Your Computer? Free Software Foundation, 2002. `http://www.gnu.org/philosophy/can-you-trust.html`.

[Sta10] Richard Stallman. Can You Trust Your Computer? In *Free Software, Free Society*, chapter 32. GNU Press, 2nd edition, 2010.

[Tar10] Christopher Tarnovsky. Deconstructing a 'Secure' Processor. In *Black Hat DC 2010*, 2010. `https://media.blackhat.com/bh-dc-10/video/Tarnovsky_Chris/BlackHat-DC-2010-Tarnovsky-DeconstructProcessor-video.m4v`.

[TCG07] Trusted Computing Group. *TPM Specification version 1.2*, 2007.

[Tru11] Trusted Computing Group. Do You Know? A Few Notes on Trusted Computing Out in the World. `http://www.trustedcomputinggroup.org/community/2011/03/do_you_know_a_few_notes_on_trusted_computing_out_in_the_world`, March 2011.